Off-grid energy policy

Exploring the (un)sustainable nature of off-grid solar energy markets in Africa

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CHAPTER 1

Introduction

1.1. Introduction

Over the past decade, major investments have been made to stimulate the large-scale commercial uptake of solar home systems (>10Wp) and smaller solar devices among off-grid households in sub-Saharan Africa. With nearly 52% of the people living without electricity access, the African region has the lowest electrification rate in the world (World Bank, 2022). Development banks, governments, multinational organizations, and even private impact investors have invested heavily in the off-grid sector, and particularly in large international solar companies (Wood Mackenzie, 2019). Commercial solar markets are increasingly seen as a viable way to connect the world's poorest populations to electricity and ensure '*access to affordable, reliable, sustainable and modern energy for all*' (Sustainable Development Goal 7). Clean energy provision is not only needed to fulfill basic needs; it is also key to act against climate change, create more equal social and economic opportunities, and realize a fair sustainable energy transition (United Nations, 2021; COP26, 2021).

Driven by investments in the off-grid energy sector, the African solar market has experienced rapid growth, currently serving over 420 million people worldwide, and annual sales volumes are expected to grow exponentially in the coming years (United Nations, 2021; Lighting Global, 2020). However, despite the promise of this trend, there are increasingly also signs of toxic solar e-waste, polluting repair practices, and exposure to lower quality and even fake solar products.

These harmful (side) effects raise concerns about the sustainable impact of off-grid solar energy technology and current investments in the industry. Yet, there is still limited discourse on the wider sustainability implications of expanding solar PV markets in Africa (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018; Samarakoon, Munro, Zalengera, & Kearnes, 2022). While much is written on energy and sustainability transitions, few studies consider the possible downsides of shifts to low-carbon energy systems (Köhler, et al., 2019). Instead, primary focus is on the (potential) benefits of renewable energy technologies. Scholars thereby tend to neglect that societal and environmental challenges—and their solutions—are often intertwined, and thus require integral approaches with critical attention for the limitations and risks of sustainable development efforts (Antal, Mattioli, & Rattle, 2020; Stirling, 2009; Nilsson, Griggs, & Visbeck, 2016).

This study responds to this need. More specifically, I investigate the consequences of reliance on 'sustainable' energy markets by exploring the actual impact of these markets. I examine how it drives—or hampers—the pursuit for ensure universal energy access (SDG 7) and integral implementation of the UN Sustainable Development Agenda 2030 and to what extent current investments in the off-grid sector contribute to an inclusive, just, and sustainable energy transition. Understanding these dynamics is key if we are to prevent social and environmental harm and to accomplish equitable transitions that benefit all – be it rural communities, local entrepreneurs, or the natural environment. The central research question is formulated as follows:

How does the commercial uptake of off-grid solar products in sub-Saharan Africa impact progress towards Sustainable Development Goal 7 and other sustainability and development priorities?

To explore this question, I will start from the empirical realities of the solar home systems market in Africa. I will draw on the experiences of people from *within* the sector to examine how commercial solar products affect people's lives and the environments they live in. With this study, I offer the first systematic insights in these broader and underexplored social, economic, and environmental implications. The study sheds a new light on recent developments in the off-grid sector and on the actual impact of solar markets in Africa. The findings of this study help to understand how we can steer towards a more just and plural energy future.

Moving forward, the remainder of this chapter provides a general background on the research in this thesis (section 1.2 and 1.3), followed by a discussion of the research aim and strategy (section 1.4). It then introduces the individual thesis chapters (section 1.5), in which I address different aspects of the central research question. The thesis closes with a general conclusion and reflection on the results.

1.2. Scientific background

Literature on solar PV markets has grown rapidly over the past decade. It has paid critical attention to the role of off-grid solar energy technology and solar entrepreneurs in ensuring universal energy access and enabling sustainable energy transitions in the Global South. Stand-alone solar technologies like solar home systems and 'pico' products (with integrated solar panels and internal rechargeable lithium-ion batteries) offer an opportunity to connect households in off-grid areas to basic electricity services, powered by renewables. Markets act as a vehicle to enable the large-scale diffusion of these technologies (Boon, Magnusson, & Hyysalo, 2021), even more so because African governments have traditionally struggled in the provision of basic services. Scholars have explored both the structural dynamics of these unfolding transitions to clean energy (Byrne, 2009; Hansen, Pedersen, & Nygaard, 2015) as well as the particular business models used by off-grid solar companies to serve low-income 'Base of the Pyramid' (BoP) markets (Ockwell, et al., 2019; Kolk & van den Buuse, 2012). Energy and sustainability transitions generally refer to the radical changes in socio-technical systems which are necessary to enable 'radical transformation towards a sustainable society, as a response to a number of persistent problems confronting contemporary modern societies' – like climate change, resource depletion, or loss of biodiversity (Grin, 2010). The term energy transition is specifically used to describe the ongoing global movement towards carbon neutral sources of energy.

Only recently, interest has grown in the sometimes unsustainable and unfair nature of low-carbon transitions (Castán Broto, Baptista, Kirshner, Smith, & Alves, 2018; Swilling, 2020). This led to a growing number of studies on energy justice, poverty, and equitable distribution (of costs, risks, and benefits) (Sovacool, 2021; Kumar, Höffken, & Pols, 2021). However, these studies often only highlight ethical implications and dilemmas without exploring underlying dynamics (Köhler, et al., 2019). Another limitation is the typical focus on only one sustainability dimension, or on only one marginalized group, thereby overlooking potential conflicts with other social, economic, and environmental aspects of sustainability (or sustainable development). As such, it remains also unclear how unsustainable trends emerge or what drives them (Antal, Mattioli, & Rattle, 2020). However, it is crucial to understand such dynamics if we are to ensure that energy transitions unfold sustainably and in an inclusive, equitable and just manner; and it is key if we are to tackle complex sustainability challenges and support progress towards all UN Sustainable Development Goals.

To better understand such issues, this study integrates insights from other bodies of research. Although these are rooted in various streams of literature, they can be captured in two broad categories: first, studies with a more integral sustainability orientation, and second, literature with a specific focus on markets and innovation in Global South contexts.

1.3. Integrated approaches and perspectives

In an attempt to connect different sustainability dimensions, environmental scientists proposed to analyze the interaction effects (positive 'synergies' and negative 'tradeoffs') between the 17 Sustainable Development Goals (Nilsson, Griggs, & Visbeck, 2016). By focusing on these interactions, we can develop systematic overviews on how progress towards particular goals can constrain, counteract, or cancel the achievement of other goals (McCollum, et al., 2018). While SDG-interaction studies present a somewhat 'flat' picture of a far more complex reality, the interlinkages can help to disentangle negative (side) effects of energy access efforts in a systematic way.

Alternatively, Stirling (2010) proposes a 'Pathways Approach' (Köhler, et al., 2019; Stirling, 2009); This characterizes innovations as 'socio-ecological processes rather than outputs' (Arora & Stirling, 2021). It essentially means that technological solutions must be conceived as outcomes of approaches embedded in wider socio-ecological and technical 'pathways'. Yet, new technologies are often introduced as simple fixes to complex societal problems. Criticizing this kind of techno-fix approach, Arora and Stirling argue that, presently, the focus lies one-sided on technology outputs (such as: modern energy access) while in reality the impact of technologies goes well beyond these outputs. Many direct and indirect effects can develop around the diffusion of new technologies and emerging innovation systems (Stirling, 2009; Stirling, 2011). These collateral effects can conflict with other social, economic, and environmental priorities, and do so in unforeseen ways. Like innovations, the outcomes of these processes are typically uncertain, complex, and hard to predict. Even more so because innovation processes can take decades from first-time invention to large scale diffusion (Stirling, 2009; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Jacobsson & Johnson, 2000). It is crucial to consider these direct and collateral effects if we want to understand the actual impact of renewable energy technologies.

Beyond these more integral sustainability-oriented literatures this study draws pm insights from studies on BoP markets and innovation processes in the Global South. This includes literature on market development in developing countries, as part of their structural transformation, and studies that addresses the role of product quality in particular (Johnston & Kilby, 1975; wa Kabecha, 1999). This literature offers a more nuanced view on the impact of low(er) quality products, which play an important part in the large-scale diffusion of new technologies in the Global South. It also includes literature on trends in economic development paradigms, which describes how development agents from the Global North have historically aimed to foster progress in the Global South (Hunt, 1989). In the era of neoliberal market dominance, development actors are increasingly pursuing a corporate-led market approach to off-grid energy access, focusing on 'trade' instead of 'aid' and on harnessing the potential of large multinationals and social enterprises instead of purely donor driven models to create impact (Sesan, 2014). These perspectives are novel to solar energy research but highly relevant to understand the setting in which off-grid solar energy technologies have started to diffuse.

Hence, these two complementary bodies of research can help us to explore and explain the implications of reliance on commercial solar markets to address Africa's energy challenges. This is relevant to solar energy research because this has so far primarily focused on the benefits of off-grid solar products and failed to develop a comprehensive set of insights on the wider sustainability impact. On the one hand, pathways- and SDG interaction-research can help us to understand how to better approach such complex challenges and steer towards more holistic solutions by taking a more integral perspective and mapping negative tradeoffs. On the other hand, literature on local market development and economic development paradigms has no specific sustainability focus but adds to it by explaining why development actors and local innovators do things the way they do. This is key to explain underlying dynamics

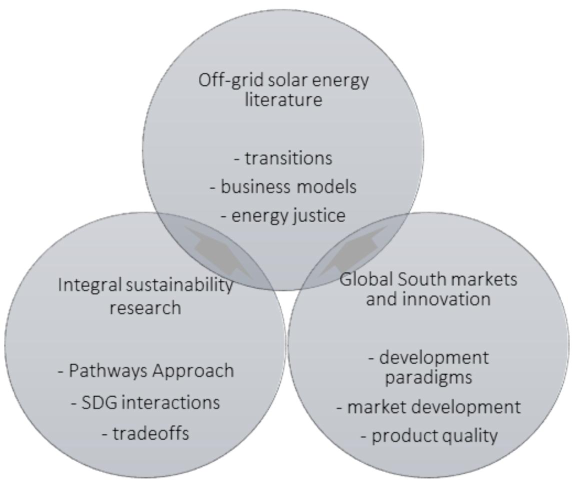

Figure 1.1: Relevant bodies of literature

of *un*sustainable developments, their complexity, and the (possible) structural nature of these trends.

1.4. Research objective and strategy

The aim of this study is to explore how the large-scale commercial diffusion of solar home systems in sub-Saharan Africa affects progress towards SDG 7 and other sustainability and development priorities. I seek to understand what these effects are, how they are shaped, and by whom.

To investigate this, I opt for an exploratory research approach. Exploratory research is useful to investigate problems which are not yet clearly defined (Stebbins, 2001; Casula, Rangarajan, & Shields, 2021). In this case, it is suitable because little is known about the unwanted (side) effects of off-grid solar energy technologies, and, as also argued by Stirling (2010), such impacts can be vast and unpredictable.

The explorative research in this study takes the form of field research, a method of collecting primary qualitative data (with sometimes quantitative aspects) aimed to understand natural phenomena in a real-world setting (Burgess, 2003). It is particularly useful when data is otherwise hard to come by. This study is based on extensive field research, conducted in Uganda in 2018, including 117 interviews conducted by the author of this thesis. For the purpose of this study, conducting field research is also essential because it allows detailed insights in the actual impact of commercial solar products in an empirical market setting. The study draws upon the experiences and perspectives of users, nonusers, international solar companies, local vendors, wholesalers, repair centers, local authorities and research institutes, development actors, and others involved in the off-grid market to acquire new insights into the unsustainable nature of 'sustainable' energy solutions. Through these interviews I explored what exactly is sold to customers; what ends up being installed in people's homes; who is involved in the delivery of the systems; what happens when solar home systems fail; who benefits and who suffers from expanding off-grid solar PV markets. I complemented this with own observations and online data from market reports and company websites.

The insights from this field research are then used to develop more general, systematic insights by analyzing findings from other relevant literature (i.e., on off-grid solar enterprises in sub-Saharan Africa and Southern Asia; published since 2016). These provide relevant insights into recent challenges in the off-grid sector, such as e-waste creation, although it must be noted that most of these studies were published in the last two to three years and thus after this research project was initiated.

Next, the findings from both parts are combined to capture the main effects of commercial solar PV diffusion in sub-Saharan Africa. This is then utilized to assess the implications of current off-grid solar policy, which plays an important role in shaping these effects. To this end, I review recent actions (and inactions), plans, and funding priorities of global-level energy agencies, multilateral development organizations, and impact investors, who are influential in contemporary energy access efforts.

Based on these research findings, I will formulate an answer to the central research question. Hence, the study follows the following research approach:

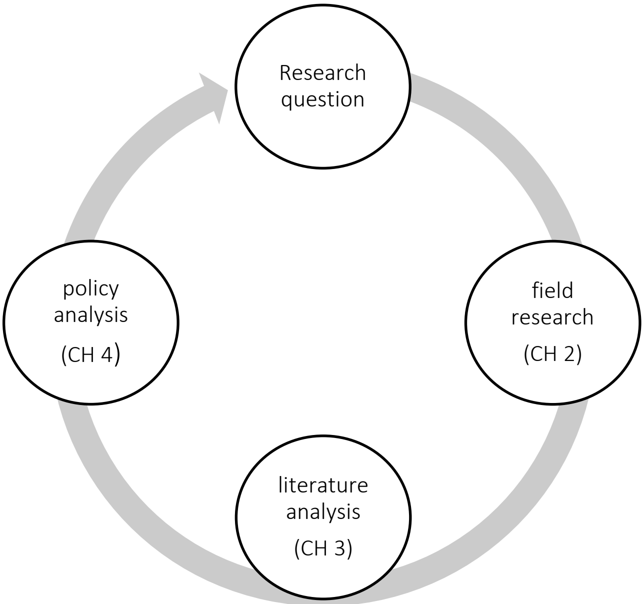

Figure 1.2: Research strategy

1.5. Thesis outline

The chapters in this thesis follow the sequence and logic of the research strategy outlined in Figure 1.2. Each chapter contributes to a better understanding of the impact of solar markets and the market-related and political dynamics that shape these effects. They focus specifically on the implications for SDG 7, coherent implementation of the UN Sustainable Development Agenda 2030, and the pursued inclusive, just energy transition.

Chapter 2 presents the main results of the field research and offers a systematic overview of the different market segments in the Ugandan solar home system market. Starting point for this chapter are the increasing numbers of low(er) quality, and even fake products, that enter the market. It explores the impact of these lower quality products on the envisioned benefits of off-grid solar technology in realizing clean, affordable, and reliable energy access for all (SDG 7). To guide the empirical analysis, I integrate insights from literature on market development and the role of product quality in Base of the Pyramid markets.

Chapter 3 presents the findings of the literature analysis. More specifically, it explores on the limitations of a contemporary corporate-led market approach to off-grid energy access by exploring the issue of 'tradeoffs'. I use this concept to explain why off-grid companies fail to achieve a 'win-win' for people, planet, and profit. While previous studies have analyzed tradeoffs *between* SDGs, I look from *within* the sector; I investigate how the market-based uptake of off-grid solar products affects all seventeen SDGs. I do so by systematically analyzing tradeoffs identified in 36 recent peer-reviewed publications on solar companies in sub-Saharan Africa and Southern Asia.

Chapter 4 presents the findings of the policy analysis. It focuses on the role of policy and policymakers and assess the implications of current and announced policies and plans of influential energy and development actors. While they target the large-scale uptake of off-grid solar products, it is unclear whether their efforts also contribute to an inclusive, just energy transition. To investigate this, I adopt the perspective of a '3D' agenda. The three Ds are central to the Pathways Approach and stand for *diversity*, equitable *distribution* of costs, benefits, and risks, and the *direction* of policies and prioritized goals. They are aimed to support more pluriform, inclusive, democratic, and just sustainability policy. Informed by the results, the chapter closes with a discussion of new policy recommendations to mitigate the harmful effects of market-based solar PV diffusion.

Chapter 5, the synthesis of this thesis, discusses the combined results of the preceding chapters and addresses the central research question (section 1.1). This is followed by a general reflection on the results and a discussion of the scientific contribution of the thesis.

Table 1.1: Publication details of the research chapters		
Chapter	**Status**	**Reference**
2	Published	Groenewoudt, A. C., Romijn, H. A., & Alkemade, F. (2020). From fake solar to full service: An empirical analysis of the solar home systems market in Uganda. Energy for Sustainable Development, 58, 100-111. *Open access*.
3	Published	Groenewoudt, A. C., & Romijn, H. A. (2022). Limits of the corporate-led market approach to off-grid energy access: A review. Environmental Innovation and Societal Transitions, 42, 27-43. *Open Access*.
4	Submitted*	Groenewoudt, A. C., H. A. Romijn & F. Alkemade. (Submitted) Why is off-grid energy policy not promoting an inclusive, just transition in Africa? An analysis and new policy priorities. Energy Research & Social Science.
*A version of this chapter has been submitted for publication and is under review.		

Table 1.2: Contribution to the research chapters					
Chapter	**Conceptualization**	**Data collection**	**Formal analysis**	**Writing – first draft**	**Writing – review & editing**
2	**AG**; HR; FA	**AG**	**AG**	**AG**	**AG**; HR; FA
3	**AG**	**AG**	**AG**	**AG**	**AG**; HR; FA
4	**AG**	**AG**	**AG**	**AG**	**AG**; HR; FA
AG = Aleid Groenewoudt, HR = Henny Romijn, FA = Floor Alkemade					

CHAPTER 2

An empirical analysis of the solar home systems market

Groenewoudt, A. C., Romijn, H. A., & Alkemade, F. (2020). From fake solar to full service: An empirical analysis of the solar home systems market in Uganda. Energy for Sustainable Development, 58, 100-111.

Abstract

Solar technologies promise to provide clean energy to the poorest populations. Motivated by observations of low-quality products in the solar home system market, this study analyzes the role of product quality in the transition to cleaner energy technologies in developing countries. Our systematic empirical analysis of the Ugandan solar home system market reveals several market segments. Plug-and-play and full-service solar home systems offer relatively high quality, whereas component-based mix-and-match systems offer a low-quality, low cost alternative. In addition, we observed a 'no quality' product segment with junk and fake products. Our analysis shows that neither high-quality nor low-quality solar products offer a win-win situation if we are to achieve "access to affordable, reliable, sustainable and modern energy for all" (SDG 7). Rather they are complementary as low-quality products may enhance a swift and inclusive transition, whereas high-quality products offer more reliable and higher quality energy access. This observation calls for reconsideration of the current development approaches that focus only high-quality products to achieve the SDG 7 and seeks to protect markets from low-quality products. More interaction between the different market segments is key to realize the promise of solar home systems for low income populations.

2.1. Introduction

Worldwide, 860 million people lack electricity access and realizing universal access to affordable, reliable, sustainable, and modern energy presents a major societal challenge (SDG 7). The diffusion of solar home systems (SHS) across the Global South is seen as a promising way to address this challenge (e.g. D'Amelio et al., 2016; Ghosh & Rajan, 2019; Ockwell et al., 2018; GOGLA, 2018; Peters & Sievert, 2016; Pueyo, 2018; UNDP, 2017). A solar home system is a combination of a solar panel (typically 10 Wp and up), a battery, a charge controller and one or more appliances, such as light bulbs, phone charging stations, TVs, and radios.

Studies so far have mostly focused on "*high quality"* solar home systems and solar lanterns; technologies that function well and that meet international quality standards (Bhamidipati, Hansen & Haselip, 2019; Hansen, Pedersen, & Nygaard, 2015; Duke et al., 2002; Foster, 2014; Hiteva & Sovacool, 2017; Kaplinsky, 2011; Rolffs, Ockwell, & Byrne, 2015). Increasingly, however, large numbers of lower quality solar home systems, and even fake solar products, have entered the market in countries such as Uganda, Kenya, Ghana, Zimbabwe, India, and Pakistan (Twaha, 2017; Spire Ssentongo, 2018; Kamukama, 2018; Samukange, 2015; Times of India, 2013). While these low-quality products do not offer the same functionality, they are often more affordable for the poorest consumers, the so-called Base of the Pyramid or BOP markets, referring to the world's poorest 40% of the population (Hammond et al., 2007; World Bank, 2018). Concerns have been voiced that these low-quality products reduce consumer trust in the technology and are a barrier to a swift energy transition (Lighting Global, 2019; Bloomberg New Energy Finance and Lighting Global, 2016; Blimpo & Cosgrove-Davies, 2019). This raises questions about the effects of low-quality products on the envisioned benefits of solar technology and its role in realizing Sustainable Development Goal (SDG) 7. In this paper we therefore analyze the role of product quality in the energy transition in the Global South.

To this end, we first review the literature about products quality for BOP markets. We then use the insights from the literature to guide our empirical analysis of the Ugandan solar home system market. In our definition of solar home systems, we include all systems sold to households that have a separate solar panel. Our market research, undertaken in Uganda in 2018, consists of 117 interviews with enterprises, users, government and international development organizations, and market experts, complemented with desk research and observations from field trips. Uganda has a thriving solar home system market and a large BOP population, with 41.7% of the population living below the international poverty line of 1.90 USD a day (World Bank, 2016); it is one of the countries where variable product quality in the solar sector has been observed (UNBS, 2017). Solar home systems are an important energy solution for many households in Uganda, particularly in the off-grid areas where approximately 80% of the population lives (World Bank, 2019). Grid expansion is slow and alternatives for off-grid electricity are limited (SE4All, 2019). Minigrids are scarce, kerosene lights and battery-powered devices offer lighting only, and the operating costs of diesel generators in this landlocked country are high. Furthermore, market regulation and quality control are limited in Uganda, as in many other Sub-Sahara African countries. Prevention of low-quality products from entering the market is very difficult (Aminu & Gwarzo, 2017; Foster, 2014). With our empirical analysis we offer a more nuanced view on the role of high- and low-quality products in realizing SDG 7 and a swift, sustainable, and inclusive energy transition.

Section 2 of the paper reviews the literature on the role of product quality in BOP markets and presents a guiding framework for the empirical analysis. Section 3 outlines the methodology while Section 4 presents the empirical results. Discussion and conclusions are given in Section 5.

2.2. The role of quality in BOP markets

Many studies consider high quality a necessary condition for technology acceptance, trust in solar energy, and a swift energy transition (Sovacool, D'Agostino& Bambawale, 2011; Stojanovski, Thurber & Wolak, 2017; Pode, 2010). High-quality products are often brought to the market by multinationals or social enterprises that aim to serve the needs of the BOP (Bocken et al., 2016; Ghosh & Rajan, 2019). These organizations typically strive to contribute to the SDGs as well as profit making. This requires innovative business models with an attractive value proposition (Chesbrough, 2006; Seelos & Mair, 2007; Yunus, Moingeon, Lehmann-Ortega, 2010). Enterprises therefore combine the sales of high-quality solar technologies with specialized installation and after-sales, and financial services. Through microcredit schemes such as Pay-As-You-Go, relatively expensive high-quality solar technologies can become affordable for at least some segments of the BOP (Casado Caneque & Hart, 2017; Kolk & van den Buuse, 2012; Newcombe & Ackom, 2017; Pai & Hiremath, 2016; Rolffs, Ockwell, & Byrne, 2015; Sesan et al., 2013; Yadav, Heynen & Palit, 2019). These business models are typically first tested and implemented on a small scale. When successful, suppliers scale up and over time, technologies become more widely available (Bocken et al., 2016; Hansen & Coenen, 2015; Jolly, Raven & Romijn, 2012).

Despite these efforts, such high-quality technologies often remain inaccessible for the world's poorest segments of the population (Banerji & Jain, 2007). They remain too expensive, even when produced at large scale and with efficient production methods or may remain unavailable owing to difficulties for suppliers in 'bridging the last mile', especially in rural areas (Barrie & Cruickshank, 2017). These problems are not specific to solar home systems as such, they have been observed in relation to many different products (e.g. Amsden, 1985). In such cases, far cheaper *low-quality* copies may present an attractive alternative. Low-quality technologies are adapted versions of higher quality originals, serving the same general purposes, but with compromises in terms of design, performance, durability of the materials used to construct them, or other quality dimensions. The literature shows that such low-quality technologies, and even fake products are a widespread phenomenon in developing countries. Studies describe low-quality cook stoves (wa Kabecha, 1998), poor quality farm tools (Johnston & Kilby, 1975), LED lights which "*burn out in the first days of use*" (p. 720, Reynolds, Kolodinsky & Murray, 2012; Mills et al., 2015), very cheap artwork jewelry (Sinkovics, Sinkovics & Yamin, 2014), and mobile phones that look expensive but have very limited functionality (Foster, 2014). Product quality is typically "*below international quality standards*" in these products (p. 218, Amsden, 1985).

In studies focused on solar technologies, low-quality products like these are generally considered to be problematic, having negative effects on overall solar energy diffusion by damaging the reputation of solar in general (Duke et al., 2002; Feron, 2016; Grimm, 2014; Jacobson & Kammen, 2007; Martinot et al., 2001; Nygaard, Hansen & Pedersen, 2017; Scott, 2017; Taele et al., 2012). However, while fake and 'no quality' products are indeed correctly recognized as a problem, one could take a different view regarding products whose quality lies somewhere between the two extremes of complete junk on the one hand, and 'western' top quality on the other. Banerji and Jain (2007) find that most BOP markets have a substantial 'low-end' market segment that encompasses many products that are functional to some degree. They argue that a divide between a high-and a low-end market segment (*quality dualism*) is inherent to markets in developing countries with a large informal sector (Banerji & Jain, 2007). However, literature dealing with structural transformation and technological capability acquisition in development provides a nuanced perspective on the role of such technological dualism (Amsden, 1985; Johnston & Kilby, 1975). It is shown that low(er) quality products that could be considered sub-standard by western developed-country standards can yet be 'good enough' for users in low-income environments (Ishikawa, 1981; Romijn, 1999). Low-quality products may offer a more affordable solution to the poorest populations. These technologies typically have simplified product designs and are produced with cheaper materials, using cheaper production methods. Johnston and Kilby observe farm equipment technologies designed following "*bare essentials principles*" (p.354, 1975), simplified and stripped down from any extras until only the bare minimum remains for the temporary working of the technology. An example is a power tiller that was introduced in Taiwan as an adapted version of the original Japanese model; it featured one forward gear instead of four, no reverse gear, no side clutch and no brake (Ishikawa, 1981). This quality downscaling led to a substantial drop in price, making the innovation affordable for the lowest income segments. Disadvantages arising from early breakdowns caused by low-quality materials were compensated for by physical proximity of small metal workshops offering basic repair services quickly and at low cost, making the products 'good enough' in terms of functionality for users. These "*crude quality*" farm tools (Johnston & Kilby, 1975; Romijn, 1999) still enabled farmers to increase productivity during the few weeks a year these tools were needed.

These low-quality products are usually offered by small, local entrepreneurs (Banerji & Jain, 2007; Johnston & Kilby, 1975; De Beer et al., 2013; Mendi and Costamagna, 2017), who play important role in the design and production, as well as in repair (Romijn, 1999) of localized products for which high-quality originals served as the starting point for local indigenization through adaptation. The development of the Taiwanese farm tool sector, for example, was driven by rural artisans and metal workshops which started producing far cheaper, low-quality copycat versions of imported products originating from Japan (Johnston & Kilby, 1975).

As a result, technologies become better adapted to the local conditions and better 'embedded' in the local socio-technical system; they are built with locally available materials, using existing production methods, and entrepreneurs can draw on the regular product performance feedback they receive from customers located nearby. These technologies may be easier to repair than high-end solutions, which get "*helicoptered in*" from outside (Garb & Friedlander, 2014; De Laet and Mol, 2000). Having local repair options is important in reducing waste. Some have also argued that this local development process leads to more 'inclusive' technologies, benefitting the local economy (Onsongo, 2019; Kaplinsky, 2011). In the long run, the involvement of local entrepreneurs may also enable them to learn from frequent breakdowns and users' feedback about their local products. Studies show that this way, local entrepreneurs can develop technological capabilities in product re-engineering and adaptation – that in turn enable quality improvement over time (e.g. Johnston & Kilby, 1975).

Considering these lessons, it could thus be argued that the availability and uptake of low-quality solar energy technologies may foster a faster and 'deeper' energy transition with more equal energy access, despite the tradeoffs in terms of quality. Summarizing, both low-quality and high-quality products may thus contribute to the envisioned benefits of solar home systems in low-income environments, and to the wide diffusion of these systems.

2.3. Method: a study of the Ugandan solar market

This section sets out the methodology for our market research in Uganda. The literature described in Section 2 structures the research and analysis. For each solar home system, data were collected about the design, supplier and business model, and different quality dimensions**.** The design of a solar home system is determined by both the specific components that are used and the way these components are combined and packaged. For each supplier we collected data about their overall business model and general character (e.g., physical shops, location, origin and firm age, nationality of owner, value proposition, and partnerships with donors, distributors etc.). In order to analyze the business models, we collected information about the value proposition, distribution channels, key activities and complementary services (for installation, maintenance, repair and replacements), partners, and customers segments (Chesbrough, 2006; Kolk & van den Buuse, 2012). For an assessment of quality, data were obtained on both technical measures and quality as perceived by market parties. In addition, we collected interview statements relating to the effects on SDG 7 and the broader effects linked to a swift, sustainable and inclusive energy transition. The literature identified embedding of products in local socio-technical system, the greenness (waste), inclusiveness and local economic opportunities, and processes of capability building, learning and quality improvement as relevant themes in this regard. Statements were often discussed at a higher aggregation level than that of a single solar home system, and we therefore collected all these outcome-related statements and information in a second database containing the rich text descriptions. These two databases form the basis for our analysis in Section 4. Table 2.1 summarizes the content of our databases. Appendix A contains a list of all data fields and categories in the databases (Table 2.3, Table 2.4, Table 2.5).

Table 2.1: Data description

Databases	**Data fields**		
1. Product data	• description solar home system (open) • market segment (coded) • size (Wp) • price (UGX, EUR) • brand (open) • purchase (year) • market share (open) • quality accounts and experiences (open) • appliances, uses (open) • installed (coded) • design observations (descriptions) • overall working (coded)	• supplier information (description) • market entrance supplier (year) • business model (description) • supplier (coded) • offered services (descriptions, interview transcripts) • services: system sizing, warranty, installation services, financial services, maintenance services, repair services, user education (coded)	• customer details (open) • data source code (coded) • code name of source (coded) • location (open) • country (open) • audio recording; website; other (coded) • pictures (image)
2. Data linked to effects SDG 7 and a swift, sustainable, and inclusive transition	• trends in market development (transcripts) • uptake by BOP (transcripts) • market shares (transcripts, field observations) • accounts technology reputation (transcripts)	• options for local production, design, installation, and repair of solar home systems incl. involvement local entrepreneurs (transcripts, field observations)	• waste production (transcripts) • recycling practices (transcripts, field observations) • learning (transcripts) • quality fluctuations (transcripts)

The search for SHS started with an online inquiry for solar home systems via dealer websites and with several open interviews with experts in the East African solar market. Through referral, each interview led to new interviews with relevant actors and to the discovery of more products. The search process continued until the search no longer led to significantly new types of solar home systems. Initially, data was also collected about solar lanterns and larger off-grid solar systems for businesses, farmers and community customers, like NGOs, schools, and community centres. While not the key focus of the study reported in this paper, this helped to develop a good overview of the Ugandan solar market as a whole. For this study we used two criteria to distinguish between solar home systems and other solar technologies: First, we included only systems with a separate solar panel, because this distinguishes small SHS from solar lanterns. Second, we only included systems sold to households, to exclude larger systems for commercial purposes.

In total 117 face-to-face interviews were held by the 1st author with the main actors involved in the Ugandan solar market, including suppliers, users, market experts, and institutions involved in quality control. The interview data were complemented with data from company websites, market reports, technical documents, and information from four field trips. Table 2.2 summarizes the data sources used in this study. Interviews with representatives of the Uganda National Bureau of Standards (UNBS), responsible for quality control, and the Centre for Research in Energy and Energy Conservation (CREEC), a private non-profit spin off from the Engineering Department of Makerere University Kampala in charge of one of the two testing labs in Uganda provided insights in the quality of the components on the Ugandan market in relation to standards. This was complemented with accounts and experiences of perceived product quality by users and suppliers. Inspection of users' solar home systems yielded information about the design and actual functioning. Four field trips were undertaken to visit users. Random sampling of users was not possible, but the sample includes communities in different locations and information about different types of solar home systems, offered by different suppliers.

The product data were consolidated in a database providing detailed descriptions of the solar home systems. The information retrieved from interviews was coded and systematically entered in the database by data source and resulted in a product database containing 193 cases. The two databases allowed us to integrate and compare information from different actors, improving validity, and link products with outcome data.

Table 2.2: Summary of field data

Interviews and site visits	**Actor**	**Details**
Users [interview code: U55 - U96]	Solar home system owners	▪ 38 semi-structured interviews were held with users. ▪ Interviews were held in (Ugandan) English. An interpreter was present during interviews as not everyone spoke English and the interviewer did not speak any of the local languages. ▪ In total, 45 installed solar home system were inspected, and pictures were taken. ▪ It was found to be crucial for collecting reliable information to inquire the same matter in several different ways and afterwards checking the system. This was particularly relevant as some users initially indicated that the system was working well, but later came with different stories. ▪ Users were visited in different locations and owning solar home systems offered by different types of suppliers. Users were located in both off-grid and grid-connected areas.
Local vendors [interview code: L7, L16, L29, L37, L40 - L52] [2]	Solar home system suppliers selling to end-users.	▪ 17 semi-structured interviews including some open questions were held. ▪ Pictures taken of products stocked in shops. ▪ Interviews were held in (Ugandan) English and an interpreter was present during interviews. ▪ Local vendors approached for this study were found across Central Uganda.
Wholesalers [interview code: W9, W10, W13, W15, W17, W19, W28, W54-W56]	Solar home system suppliers selling to local vendors and end-users. In some cases it was difficult to classify suppliers as either local vendor or wholesaler. If unclear, suppliers were classified as wholesalers.	▪ 10 semi-structured interviews with some open questions were held. ▪ Interviews were held in (Ugandan) English and an interpreter was present during interviews. ▪ Pictures taken of products stocked in shops. In several cases no permission was granted to record interviews or take pictures. Employees were willing to answer a couple of questions, but many times managers deliberately remained at the back of the shop. Fortunately, there were some exceptions who provided detailed information. ▪ Wholesalers approached for this study were found mainly in Kampala.

Social enterprises [interview code: S8, S11, S24 – S26, S30, S31, S36, S53, S57] [fieldtrip code: FT_2, FT_1]	Solar home system suppliers selling to end-users.	▪ 10 semi-structured interviews including some open questions were held with representatives of 9 different social enterprises. Interview data was complemented with information collected from websites and during field trips with 2 companies. For 3 other social enterprises information from company websites was collected as no interviews could be arranged. ▪ Social enterprises were found through an online search and referral. The 12 companies included in our study represent the far majority of large social enterprises in Uganda. ▪ Interviews were held in English and Dutch.
Market expert n=15 [interview code: M1; M2; M3; M4; M5; M12; M14; M22; M23; M27; M32; M35; M38; M58; Q33; Q34; Q39]	People who were found to be knowledgeable of the Ugandan solar market due to their long working experience in the sector and typically had a good overview of the market as a whole. Amongst them are also representatives of development agencies and *institutions involved in quality control* [Q33; Q34; Q39]	▪ 15 open interviews were held with market experts. ▪ Market experts were found through referral. ▪ Interviews were held in either English or Dutch.
Battery industry n=2 [Site visit code: SV_A, SV_B]	Companies involved in battery manufacturing and repair.	▪ One large battery manufacturer was visited which is also involved in battery recycling. No other manufactures were found in Uganda. One small battery repair shop was visited. More were seen in Uganda, but not approached for this study. No interviews could be arranged. No PV panel manufacturers were found. The only one in East Africa is based in neighboring Kenya.
Non-users n=21 [interview code: NU_97 – U117]	People in off-grid areas without solar home systems.	▪ 21 semi-structured interviews were held with people in a remote off-grid area in Central Uganda. ▪ Interviews were held in (Ugandan) English and an interpreter was present during interviews.
Total number of interviews: 117		

2.4. Results

2.4.1. Empirical analysis of the Ugandan solar home system market

Based upon the empirical data we observe three main product types and corresponding market segments that differ in design and service level: *plug-and-play solar home systems, full-service solar home systems,* and *mix-and-match solar home systems.* These solar home systems have distinctive designs and packaging, price and quality levels, suppliers, and business models. Out of a total of 193 cases in our database, 63 were classified as plug-and-play, 20 as full-service and the majority (108 cases) as mix-and-match. Below we provide a more detailed description of the three types.

Plug-and-play solar home systems are relatively small systems with solar panels, batteries, charge controllers, wires and appliances already attached to each other when imported[1] [S_25, S_26]. Batteries and controllers are sealed in a plastic box, characteristic for the design of these systems. Pre-installed plug-and-plays (literally) require little knowledge to install, are easy to use, and have a function that warns users against deep discharging. Capacities range between 10 and 60Wp, the smallest only offering lighting and phone charging, and the larger versions also having the ability to power a solar-powered TV. This type of solar home system is typically developed by social enterprises: sustainability-oriented solar companies, mostly foreign-owned, that seek to deliver high-quality solar products, often with support from development organizations [S_8; S_25; S_25; S_30]. This group of suppliers features prominently in solar energy research and solar market reports [M_3, M_39] (GOGLA, 2018). We identified around thirty social enterprises supplying solar home systems in Uganda. Twelve of the larger organizations are included in our databases. Each company sells its own brand and typically has around six different product sizes in its portfolio. Systems are easy to transport and install because of their design and relatively small size. Companies work with a distribution network of franchises and affiliated partners such as telecom providers and petrol stations. Most have branch offices and service centres in district capitals that offer sales, maintenance, and repair services. Headquarters are located in Kampala, the capital of Uganda. Customers are offered financial services like microcredit and Pay-As-You-Go schemes, allowing them to spread payment over a period of one or two years. These payments are arranged in various ways, usually through mobile money platforms or similar technologies. Products come with one- or two-year warranties.

The second product type we observed in Uganda are *full-service* solar home systems[2]. These systems are also sold by social enterprises but are less popular than plug-and-play systems [S_8]. Their design is component-based, the components are

[1] Images of SHS examplary to plug-and-play segment are available on https://www.fenixintl.com/.
[2] Examples of full-service SHS are available on https://www.solarnow.eu/

typically imported from China and assembled locally. The companies tend to work with own-brand-only components and a trained sales force and technical team [FT_2, S_8]. A difference with plug-and-play systems is that systems can be much larger, starting from around 40 Wp and going up to 500 Wp and above. They can also be used to power larger electrical devices such as fridges, and customers can receive a custom-made solar home system, including financial services, installation, maintenance, repair services and warranties.

Plug-and-play and full-service systems thus share several characteristics. First, they are sold by social enterprises, which clearly express their ambitions to deliver high-quality products with good services [e.g. S_8, S_25, S_26, S_30]. Second, systems are relatively expensive compared to other solar home systems on the market [M_38; M_39; S_8; S_26; S_31], starting from around 180 EUR for 10 Wp systems. This makes these products less attractive for consumers with the lowest incomes [S_53, S_57, S_25], especially since not all consumers are willing to take out a loan with a repayment horizon as long as 1–2 years [M_32]. Third, according to company websites, products are officially approved for the Ugandan market or are in the process of being approved. For quality assessments companies must follow the International Electro-technical Commission (IEC) standards, which are used by Uganda's National Bureau of Standards. The IEC quality standards offer a universal method to validate the quality of technologies, in which quality can be evaluated based on standard values for defined parameters by means of lab-testing. In Uganda, such tests are, on request of companies, conducted by CREEC and other authorized labs [M_34; M_35; M_38; M_39].

Interestingly, this focus on high quality does not necessarily mean that systems perform well in practice. Of the 18 interviewees owning a plug-and-play system, 75% indicated to have experienced problems and that systems did not live up to their expectations. Amongst users of full-service systems this percentage was 56%. Problems include security lights (meant for lighting around the house at night) that do not last until morning [U_86], and batteries that are depleting fast when watching TV [U_80]. Appendix B contains an overview of all user experiences. Furthermore, the warranties mentioned on company websites suggest relatively short product lifetimes: 1–2 years for plug-and-play systems and 3–5 years for full-service systems [S_31]. These observations indicate that delivering durable, high-quality solar home systems to consumers in Uganda is a challenge. Causes of failures reported in this study were not always clear and could relate to errors in individual components, inaccurate installations and designs, miss-use of systems, and unmet expectations – and sometimes based promises made by suppliers.

Box 2.1

Top: Solar shop stocking a range of solar panels.

Below: installed mix-and-match SHS, consisting of a solar panel, a battery and two battery chargers for mobile phones.

The third and largest market segment we identified is the diverse group of *mix-and-match* solar home systems (sometimes referred to as "improvised systems"). These systems are locally ensembled from components separately available on local markets, including a battery, a solar panel, and appliances. These solar home systems have a more open design than the other segments. This market segment is estimated to account for roughly 50–80% of the solar home systems sold in Uganda [M_3, M_32, M_39, S_8]. These systems are much cheaper than plug-and-plays and full-service models, according to suppliers and market experts [M_38; M_39; S_8; S_26; S_31]. (See also Figure 2.1 for a price comparison). Systems start from around 20–40 EUR for a system with a 10 Wp solar panel and offer thus a solution to the people who cannot afford full-service and plug-and-play systems. The components are sold separately by local vendors and wholesalers and are widely available across Uganda (Box 2.1). Each solar home system is a unique constellation of components and appliances of different brands and sizes. Customers can select the components for their own customized solar home system. Local vendors sell from small shops, stocking a variety of solar components of different brands. Installation and repair services can be arranged on request. Shops are somewhat informal in character (e.g., no website) and are located along main roads in district capitals as well as in smaller towns. Local vendors buy their products from wholesalers, who are locally referred to as "*Chinese importers*" or "*Ugandan solar companies*" and have large outlet stores in the capital Kampala. Wholesalers have close ties with suppliers in South-East Asia, where most components found in Uganda are produced. An exception are batteries from a Ugandan company producing batteries from recycled materials [SV_2]. Products can be ordered online or through Whatsapp, and are shipped across Uganda, on public taxi vans, for example. These wholesalers differ in terms of size and product portfolio and sell directly to end-users. Some wholesalers trade in one brand only whereas others offer a range of brands. In addition to local vendors and wholesalers, this segment includes specialized shops for battery repair.

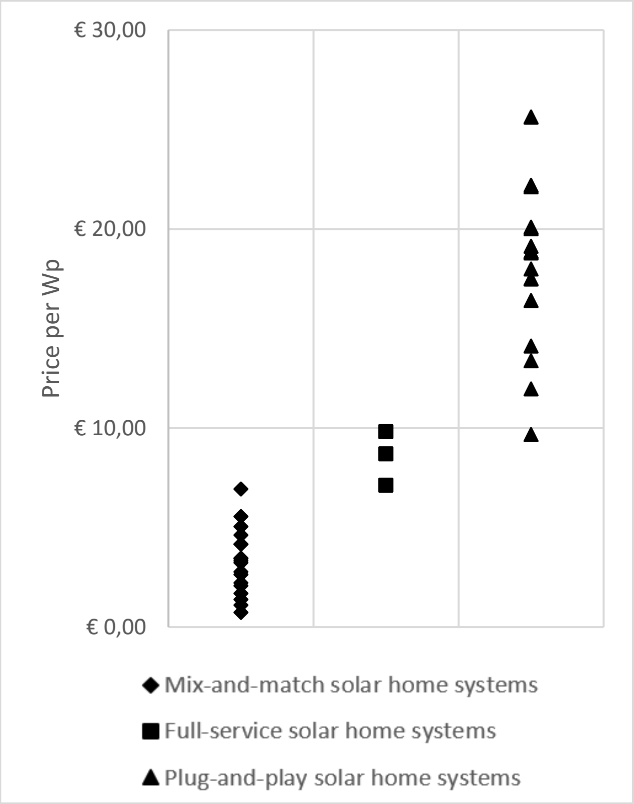

Figure 2.1: Price comparison by market segment. Prices were calculated by controlling for the relative size of solar home systems (price per Wp) for cases data was available (n=43). Solar home systems with TVs included in the price were excluded from the analysis.

Quality of these systems depends in the first place on the quality of the components. Typical quality indicators are *efficiency, capacity, degradation time, durability, and robustness* (e.g. resilience to withstand different weather conditions) (Salas et al., 2006) and depend on, for example, cell material, design of construction, and accuracy of manufacturing. In theory, all components for mix-and-match systems entering the Ugandan market should be checked and certified. However, according to local authorities, a large but unknown proportion of these components does not meet the required IEC quality standards [M_33, M_34, M_39]. Representatives of UNBS and CREEC indicated that so-called sub-standard products are not allowed on the market, but still enter Uganda due to a lack of effective quality control. Several interviewees mentioned that Uganda receives a lot of extremely cheap products, 'junk' from South-East Asia that would not be allowed to enter the European market [S_31, M_38, M_39].

Accounts of local vendors offer more insights with which one can evaluate the quality of the components that enter the market. They reported high failure rates, rapidly degrading batteries, and poor solar panel construction. Several vendors described batteries that degraded so fast that they broke down before they could be sold [L_47; L_52]. The warranties given for batteries can be seen as a quality indicator: the lower the quality, the shorter the warranty, with a maximum of one year for the most durable batteries [W_19; W_56; W_13]. Moreover, the vendors indicated that orders made from wholesalers in Kampala often contain broken products: a batch of ten solar panels can easily contain four to six non-functioning ones [L_51].

Yet, not all low quality is 'no quality'. *Within* the component market for mix-and-match solar home systems, we observed several sub-segments in terms of quality. More specifically, based on accounts by local vendors and wholesalers we observed four perceived quality levels in mix-and-match components:

1. *Genuine original products* are considered the highest quality available in the open solar market, especially batteries and solar panels labeled "*made in Germany*" have a good reputation. They are perceived as stronger and more resistant than other components and are often a little more expensive [L_51, L_16, L_41, L_42; L_46, W_19, M_14].

2. *Used original products:* second-hand, *original* products, claimed to be from Germany or England, although the actual origin often was difficult to establish [S_31, W_15, M_14] are the next-best perceived quality level.

3. *Chinese products*. These products look the same as *originals*, but are of much lower quality and extremely cheap, and therefore attractive for many consumers. They must be handled with care or else they will break [e.g. L_43, L_46, L51, L_52, W_19, M_14]. It is difficult for the average customer to distinguish them from higher quality and fake products on the market.

4. *Fake products.* This refers to products that look very similar to products in the above-mentioned categories but are fake in one way or another. They may work a little (initially), but do not live up to the expectations based on their appearance [M_14, L_47, L51, M_38]. These, too, are difficult to distinguish from other sub-segments through eye inspection by customers. Examples of fake products are batteries that look like regular batteries, but are partly filled with slabs of plates of glass and thus have far lower capacity [L_52, M_39]; solar panels with labels "overselling" their performance, indicating 60 Wp instead of the actual 40 Wp for example [M_32; M_38]; or solar panels with a frontside label stating "*made in Germany*" and another label "*made in China*" on the back [L_45].

High failure rates are reported for Chinese products and fake products [L_43; L_44; L_45; L_47; L_51; L_52]. It should be noted, however, that while products 'from China' have a bad reputation in the local market, this is an unjustified generalization, since also high-quality products are imported from China. Similarly, the label 'German technologies' is used as a synonym for high-quality products in local parlance, even though the products that are referred to in those terms often do not originate from Germany. The terms 'German' and 'Chinese' are used more as a quality label than as an indication of the product origin.

Our data suggest that, overall, the level of quality of components in the mix-and-match segment is low. Moreover, even the use of high-quality components may not guarantee a high-quality solar home system because of installation failures or mismatching components and parts. Technically speaking, an optimal design requires a battery designed to store solar energy with a battery controller that prevents the battery from overcharging or deep discharging, which reduces a battery's lifespan considerably, and leads to system breakdown. Furthermore, solar home systems must be properly ‘sized’ with a correct ratio between components in terms of their capacities (Fouad et al., 2017). Correct assembly thus requires a certain level of technical knowledge. The appropriate system size also depends on the level of consumption and the charging duration. During energy consumption, for example, systems should not be deep discharged. Finally, solar home systems must be properly installed to ensure optimal performance. To this end, it is thus also important to consider the way components are designed, assembled and installed.

According to representatives of UNBS, CREEC and market experts, systems are often not properly designed, sized and installed due to a lack of technical expertise and knowledge of solar installation [M_38; M_39; M_33; M_34: S_31]. The local vendors design the mix-and-match solar home systems. Installation is done either by the vendors, by the users themselves, or by “*some local guy”* who is known to install systems [M_34; M35]. Some vendors and installers are certified by a local training institute, but many have little knowledge about the specific requirements for well-functioning solar installations [L_42, L_43, L_45, L_49, U_62, U_89, U_92, U_95].

In addition to this, local vendors explain that for many of their customers the price is the most important driver and people may be unaware of the implications of improper design for the performance of their system.

“You tell him – before he takes, you tell him now this one you are taking, is not the good one. If you had the money you could take the 17 amps. It will work for you better. He will say no, as you see, I don't have money.” [L_51].

Mix-and-match solar home systems typically get designed following ‘bare minimum design principles’ to keep prices low [L_51; L_47; L_49; L_40; _L41; L_29]. As a result, many solar home systems do not have a charge controller, which saves up to 40% of total system price, but increases the likelihood of overcharging and deep discharging considerably, resulting in battery breakdown within one or two years [L_51]. Eight out of 17 inspected solar home systems installed in the homes of interviewees did not have a charge controller [U_48; U_51; U_52; U_53; U_54; U_92; U_94: U_95]. Another way to save costs is to self-install systems, rather than hire a technician [U_92; U_94; U_95; U_62], or to build systems with car batteries. Car batteries are widely available and argued to be robust but are technically unsuitable for storing solar energy [L_49]. Another cost containment strategy is to buy batteries that ae too small for the system, which also increases the likelihood of battery overcharging and deep discharging. All in all, breakdowns and technical deficiencies are very common in this market segment: users mentioned problems with 93% of inspected systems. While most systems still have some functionality, we observed lights had become dim, phones could no longer be charged, or batteries were broken. Appendix B contains a full list of the problems experienced by users.

Despite these technical deficiencies and breakdowns, our user research showed that in many cases the quality of mix-and-match solar home systems was still perceived as 'good enough' by users. Users typically found ways to work around the problems and did not seem very concerned about breakdowns [U_92, U_95, U_73]. This may also be because alternatives for electricity access were often not available, and because systems still had some functionality, repair is relatively cheap and easily accessible, and expectations are often low. Moreover, the low income levels in Uganda provide a clear rationale for buying the low-price, low-quality products as one interviewee explained:

"Many Ugandans find price the most important thing. So, they go for something really cheap, even if you tell them it will only last three weeks. They will say: let me first try this one. It is only 20.000 UGX, instead of 60.000 UGX for the other one" [M_38].

The empirical evidence indeed shows that users are willing to accept solar home systems with technical deficiencies if the price is attractive [L_47, L_49, L_40, L_41, L_42, L_44]. However, several interviewees also express concerns. Especially representatives of international development organizations were found to be very critical of mix-and-match systems (*"they can't work, and they don't work"*, *"they have a negative impact on the sector"*) [M_8; M_26; M_38*; M_53*]. It is thereby important to note that not all products in the mix-and-match segment are perceived as 'good enough' [U_67, U_72, U_90, L_47, L_50, L_52]. More specifically, users and local vendors report fake products and products that break down within days. One interviewee, for example, bought a solar lantern from a person who used a false company name, he was unable to return it and get his money back:

"At first it was strong, but it died within three days" [U_90]

One interviewee decided to buy a diesel generator after repeated breakdowns and unsuccessful repairs of her mix-and-match solar home system [U_72], and others switched to grid electricity once this became available [U_66; U_86].

Also, several local vendors, motivated to supply decent quality solar home systems to maintain a good reputation, expressed concerns about fake products and unreliable suppliers:

"*They have started duplicating them, producing fake batteries*" *[L_47].*

"*You send 2 million then when you call, then after 2 minutes their phone is off" [L_52].*

They thus risk buying 'no quality' batteries from wholesalers and sell them to customers. Vendors often feel responsible towards clients and offer a refund for faulty products, but they are themselves unable to return the products and get refunds from wholesalers. Even for the vendors, the quality of components is difficult to discern from the outside. Local vendors frequently receive false (or at least highly questionable) information from importers and wholesalers [L_47, L_50, L_52], and warranties turn out to be invalid. This problem was also experienced by the researcher when one wholesaler argued that the batteries would never break down:

"Unless you hit it with a stone […]. The battery breaking is rare" [W_15].

In another interview, with a representative of a company reported in the news for selling fake batteries, the quality of their products was described as "*average*" [W_54, M_39]. Several vendors invested in measuring equipment, like Ampère meters, to identify low quality batteries, although this does not catch fast degrading batteries [L_52]. They also claim the quality of batteries and solar panels has gone down in recent years [L_43, L_44, L_47, L_52]. Possibly this is because such products are most profitable for producers and sellers aiming for a 'quick buck' in the short term in a market where quality is difficult to distinguish by buyers.

To summarize, when looking at the product characteristics of the solar home systems in our sample, we identify three main market segments in the Ugandan solar market: a segment with 'closed' plug-and-play systems sold by social enterprises; a full-service segment with component-based solar home systems, also sold by social enterprises and that come with a complete service package; and an mix-and-match segment with solar home systems locally assembled with locally available components. These mix-and-match systems are far cheaper than other systems and thus more affordable for the poorest sections of the population than their high-quality counterparts. While many of these open systems do not function well, they tend to be ‘good enough’ for users. This is not the case for the very low quality and fake products that also enter the market. Figure 2.1 gives an overview of the system prices in each of the segments, which clearly show the limited overlap between them.

2.4.2. Impact on SDG 7 and beyond

When we relate our findings to the overall goal of affordable, reliable, sustainable and modern energy for all (SDG 7) as well as the broader effects on a swift, sustainable and inclusive transition, we notice several things. While we observe that there are malfunctioning products within each segment, there are differences. Users reported issues with 93% of the mix-and-match solar home systems in our sample whereas this was 75% for plug-and-play and 56% for full-service systems. While we thus observe that the latter segments also defect often, the inconveniences and financial implications of this are limited. Customers may be disappointed [U_80], but, different from the mix-and-match segment, repair or replacements are offered by enterprises. This way, people are less affected by breakdowns and technical malfunctioning [U_90, U_85, U_82].

The mix-and-match solar home system segment has an estimated market share of 50–80% in Uganda and diffused earlier on a large scale than other solar home systems [M_3, M_32, M_39, S_8]. When the plug-and-play and full-service systems entered the market around 2010 [S_8], dealers across Uganda were already selling mix-and-match solar systems on a considerable scale, often in regular electronics shops that added solar products to their product range after the PV price drop in 2007–2008 [L_44. L_43, L_46, L_49, L_51]. The relatively cheap mix-and-match segment also may have benefitted from a relatively simple business set-up that easily scales up: components are simply shipped all across the country by public taxi vans from Kampala. Plug-and-play and full-service systems come with a range of installation and financial services, complicating distribution. This may also be the reason that plug-and-play systems, relatively small and pre-installed, are more widely spread than full-service systems [S_8].

The success of the mix-and-match segment is very visible when travelling through Uganda. Small solar shops by local vendors can be found across Uganda, along main roads of district capitals and smaller towns, where larger social enterprises have no sales points, nor service centers. Over 40 vendors were counted in Mubende, a district capital. The absolute highlight is Kampala's own “Solar Street” in the center of the city, which is crowded with solar shops and distribution centers owned by importers and wholesalers.

Yet, while mix-and-match solar home systems have thus widely diffused and our empirical analysis indicated that their quality is often perceived as ‘good enough’, we also identified some risks. More specifically, the increasing share of fake products and the observed decline in quality in the low-end segment over time, may hamper the overall transition to sustainable energy [M_32, S_53]. When people pay for fake or malfunctioning products [U_90, L_47, L_50, L_52], not only do they remain without sustainable energy access but they may also decide to switch to unrenewable sources [U_72, U_86, U_66, L_47]. If failure rates become too high, the overall transition to solar energy may be at risk.

Regarding the embedding of solar home systems in the local socio-technical system as well as the greenness (waste), inclusiveness and local economic benefits, and the opportunities for capability building, learning, and thus quality improvement, we find the following:

In the mix-and-match segment, systems are component-based, designed and assembled locally, and installed by users themselves, by (skilled) local people, or certified installers [L_42, L_43, L_45, L_49, U_62, U_89, U_92, U_95]. Components to build solar home systems are widely available, sold by local vendors in shops across Uganda, and brands can be combined. Also, car batteries and second-hand solar panels are used [L_47, L_49, W_15]. The modular design with generic components makes local repair relatively easy and cheap. Furthermore, the solar home systems can be repaired locally. Repair options include replacement of broken components, and ‘refurbishing’ batteries by adding new acid to boost the battery [SV_1, L_47]. The options for local repair, refurbishing and re-use of components make mix-and-match solar home systems a potentially green and inclusive solution. However, high failure rates, fake and unrepairable products generate a lot of waste, diminishing potential environmental benefits. Also repair practices are polluting, acid is added to batteries on the streets (outside) and can contaminate the local environment. The effectiveness of this method decreases with every repeated refill. Batteries remain a weak spot in every solar home system. The hot Ugandan climate is unfit for batteries without a cooling system. The average life span is about one, maybe two years [L_51]. Central waste collection is uncommon, and, if collected, waste ends up on large landfills and plastics are burned, making waste a serious environmental concern for SHS.

On the other hand, the involvement of local entrepreneurs in the design, assembly, and repair of mix-and-match systems may enable quality improvement over time. Vendors actively seek to improve their knowledge of solar installations, battery quality, and system sizing, and several vendors had a certificate from a local training institute [L_42, L_43, L_45, L_49]. CREEC aims to support solar installers by setting up trainings [M_33, M_34]. The effects of these efforts, however, can only be fruitful if the quality of individual components is also improved.

In the high-end market segments, the foreign-owned social enterprises engage less with the local socio-technical system. They have set-up their own distribution lines and service centers for maintenance and repair. Plug-and-play systems are 'closed', pre-installed, technologies, with batteries and charge controllers sealed in a plastic box to avoid tampering or tweaking of the systems by anyone but the company itself (e.g., adding more appliances, taking out batteries). The rationale here is that this will lead to fewer breakdowns [S_57]. However, this 'temper-free' design limits options for local learning through repair and re-use of components, a full replacement may be needed. This makes the design potentially less inclusive and green, especially because of the relatively high breakdown rates [S_28, S_31, FT_1]. Companies are concerned about the environmental impact and seek for solutions to resolve this issue by setting up waste collection and sending broken components to battery recycling companies in Kampala [S_25, S_26, SV_1, S_8] (Hansen et al., 2020). This is however not possible for the smaller, more durable lithium-ion batteries that are increasingly used [S_25].

While breakdowns are also common for full-service solar home systems, they tend to be cleaner than the other market segments [FT_2]. Because of the component-based design, full-service solar home systems have a similar potential for repair and re-use of components as mix-and-match systems. In this case, however, maintenance and repair services are offered by a trained technical team operating from the company's service centres and only using company-brand components. Recycling of components is outsourced to recycling companies in Kampala. This business model, as well as the plug-and-play business model, may be less inclusive, but also less harmful to the environment. Furthermore, it is possible that this high-end market segments contributes to overall quality improvement of the solar sector; Companies actively seek to develop high-quality products and train staff. These capabilities may spill over to the mix-and-match solar segment when technicians trained by full-service companies start their own solar shops [FT_2].

Finally, an additional observation, not discussed in the literature, is especially important, namely that there is a substantial 'no quality' market segment with fake and faulty products that are very difficult to distinguish from the low quality components for mix-and-match systems.

2.5. Discussion & conclusion

Motivated by observations of low-quality products in the solar home system market, this study aimed to develop a better understanding of the role of product quality in the transition to cleaner energy technologies in developing countries.

A systematic empirical analysis of the Ugandan solar home system market revealed several market segments. Full-service and plug-and-play solar home systems are relatively high-quality technologies whereas component based mix-and-match systems offer a cheaper, low-quality alternative. In addition, we observed a 'no quality' product segment with junk and fake product that is unfortunately difficult to distinguish from the low-quality products. So far, the mix-and-match solar segment has been largely overlooked in studies discussing solar markets in developing countries, but its effects are profound. Both high- and low-quality products have the potential to contribute to SDG 7 and a swift, sustainable and inclusive transition but our empirical analysis identifies some important barriers to doing so. First, both in the high- and in the low-quality segments we observe a lot of failures, both on product and component level. Second, the existence and apparent growth of fake and junk products is found to hamper the energy transition. Finally, the mix-and-match segment still creates a lot of environmental waste, when broken products are discarded.

To summarize, our analysis shows that, in contrast to what is typically assumed, neither high-quality nor low -quality solar products on their own offer a win-win situation if we are to achieve "*access to affordable, reliable, sustainable and modern energy for all*" (SDG 7) and a swift, sustainable and inclusive transition to clean energy access that contributes to all Sustainable Development Goals. Rather they are complementary as low-quality products may enhance a swift and inclusive transition, whereas high-quality products offer more reliable and higher quality energy access.

In order to address the barriers outlined above high-quality and low-quality segments would benefit from better quality control and increased consumer awareness of main indicators of installation requirements. Here we see a role for NGOs and solar enterprises, and of course policy and regulation, to engage more with the mix-and-match segment. This is in line with recommendations by Trotter and Abdullah (2018). More specifically, quality improvement within the mix-and-match segment may be enhanced through skill development. This could be facilitated by supporting (existing) training centers to increase their training capacity and facilities and offering training stipends for untrained informal sector technicians, for example. Awareness rising amongst customers is equally important as many are unaware of the benefits of e.g., investing in higher quality components or hiring a trained technician on system lifetime and performance, and the risks and disadvantages of self-installation without having the required expertise.

More interaction between actors involved from the different market segments is also key to address the problems with waste and unsafe practices in mix-and-match segment and the lack of inclusiveness and local economic benefits in the plug-and-play and full-service segments. Learning and capability building may be hampered by the fact that most components are imported –there is thus no close link between production and use. Local production of batteries and solar panels could overcome this obstacle. Especially, spillovers and products 'bridging' the gap between the high-end segments and the mix-and-match market segment can be crucial. Currently, the clear divide between market segments prevents such spillovers: Products are sold in different locations and involve different actors. Some high-end technologies (plug-and-play) are entirely 'closed' to avoid tampering, but this also blocks learning processes. High-quality products could serve as a quality example, whereas mix-and-match systems show how technologies with a more open design can become well-adapted to local contexts, inspiring design improvements that can also foster further innovation in the other segments. We argue that forging inter-linkages will eventually benefit all segments as it is the only way to build the domestic capacities needed to bring well-functioning, durable SHS within reach of millions of poor people in a socially inclusive and environmentally responsible manner.

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Appendix A

Table 2.3: Overview of product database

	Column	**Answer categories**
Basic solar home system descriptives	Case - description of solar home system	Open. Based on data source, e.g. code of user interview or supplier interview
	Data level	Categories [1=single product; 2=product type - one specific; 3= product line; 4= product segment; 5=other/selection in shop]
	Product code	Product code - U stands for "User", S stands for "Supplier" P stands for Product, number is based on original database (incl solar lanterns and larger systems)
	Product description	Open
	Type of solar home system	Coded categories [1 = open-market SHS; 2 = component-based full service; 3 = plug-and-play - all with separate panel, U= Unknown]
	High-end | low-end	Coded categories [H=high-end, L=low-end, U=unknown] - categories based on market segments.
	Size in Wp	In Wp
	Price in UGX	Price in Ugandan Shillings
	Price in EUR	Price in EUR
	Brand	Brand of SHS/component
	Year of purchase	Date
	Market share (anno 2018)	Percentage
Supplier and business model	Information about supplier	Open - description from interview
	market entrance - year company was established	Year
	Description of business model	Open - from interviews
	Type of supplier	Categories [A=open-market B= social business/non-profit]
	Information about customers	Open
	Offered services	Open
	System sizing	yes=1 / no= 0 / NA=NA
	Warranty	yes=1 / no= 0 / NA=NA
	Installation	yes=1 / no= 0 / NA=NA
	Financial	yes=1 / no= 0 / NA=NA
	Maintenance | repair	yes=1 / no= 0 / NA=NA
	User education	yes=1 / no= 0 / NA=NA
Quality related	Appliances | uses by users	Open
	Quality experiences and accounts	Open
	Installed	Is the system installed in homes? yes / no
	Design observations	Open
	Overall working	Categories [1 = broken; 2 = sub-optimal/ reduced functioning/partly broken; 3 = works as expected, but cannot power all needed appliances, 4 = works as expected/ "optimal working SHS" - technically speaking]
Source	Data source code	Categories [U=user+code; S=social business; L=local vendor; W=wholesaler]. If uncertain whether classification should be L or W, item categorized as W.
	Code name of source	Code
	Location	Open

	Country	Open
	Code for audio recording [or website]	Code
	Related pictures	Code

Table 2.4: Overview of outcome data and source

Theme	Indicator & data fields		Relevant segment
Diffusion rate	Trends in market development	Interview data local vendors	Mix-and-match
		Interview data wholesalers	Mix-and-match
		Interview data social enterprises	Mix-and-match; full-service; plug-and-play
		Interview data market experts	Mix-and-match; full-service; plug-and-play
	Uptake by BOP	Interview data social enterprises	Full-service; plug-and-play
		Interview data market experts	Mix-and-match; full-service; plug-and-play
		Interview data non-users	Mix-and-match; full-service; plug-and-play
	Market shares	Interview data social enterprises	Mix-and-match; full-service; plug-and-play
		Interview data market experts	Mix-and-match; full-service; plug-and-play
		Field observations by the researcher	Mix-and-match; full-service; plug-and-play
	Technology reputation	Interview data market experts	Mix-and-match; full-service; plug-and-play
Embeddedness in local socio-technical system, inclusiveness and local economic benefits	Options for local production, design, installation and repair of solar home systems; involvement of local actors in aforementioned activities.	User interviews	Mix-and-match
		Interview data local vendors	Mix-and-match
		Interview data wholesaler	Mix-and-match
		Site visits to battery producer and repair shop and field observations by researcher	Mix-and-match
		Interview data social enterprises and observations by researcher on field trips to users with social enterprises	Full-service; plug-and-play

Waste	Waste production	User interviews and battery waste observed by researcher at household visits	Mix-and-match
		Interview data local vendors	Mix-and-match
		Interview data market experts	Mix-and-match; full-service; plug-and-play
		Interview data users and social enterprises	Full-service; plug-and-play
	Waste disposal and recycling practices	Site visits to battery producer and repair shop	Mix-and-match; full-service; plug-and-play
		Field observations by researcher	Mix-and-match; full-service; plug-and-play
Quality improvement	Learning processes	Interview data local vendors	Mix-and-match
		Interview data social enterprises	Full-service; plug-and-play
	Quality fluctuations over time	Interview data local vendors	Mix-and-match
		Interview data social enterprises	Full-service; plug-and-play
		Interview data market experts	Mix-and-match; full-service; plug-and-play

Appendix B

Table 2.5: User experiences and research observations		
***Mix-and-match* solar home systems (n=17)**	***Full-service* solar home systems (n=10)**	***Plug-and-play* solar home systems (n=18)**
User experiences: • Lights are no longer working • Lights are dim • Security light does not last until morning • Mobile phone can no longer be charged [2 cases] • Lighting and phone charging not possible at the same time • Radio can no longer be powered • TV does not work after sunset • Broken battery [4 cases: two after 1 year, one after 2 years]. All had been replacement • Broken charge controller • Solar not able to power all their appliances • One battery stolen Field observations: • No charge controller installed [8 cases]	User experiences: • TV cannot take more than 3 hours (8 hours were promised) • Ironer works only on soft clothes • Inverter oversized (problem was later solved) • System fails to power TV and DVD-player at the same time • Security light drains the system	User experiences: • Phone charging is no longer working well • The system drains very fast. Lights do not last until the morning (5 cases- in two case the problem was later solved) • Customer has been paying, but he does not get power, probably because it is rain season. • Previously one user experienced problem because panel was covered with dust. After cleaning the problem was resolved. • System got weak over time • System broke down after 1.5 year because the panel could no longer charge the battery. • User can charge his phone, but "he fears" because he thinks it may spoil his mobile phone

CHAPTER 3

Limits of the corporate-led market approach

Groenewoudt, A. C., & Romijn, H. A. (2022). Limits of the corporate-led market approach to off-grid energy access: A review. Environmental Innovation and Societal Transitions, 42, 27-43.

Abstract

Markets not only enable wide technology diffusion but also shape sustainability transitions. From this perspective, it is critical to investigate the shaping effects of markets and market formation processes for human wellbeing and the environment. Through a systematic literature review, this study explores the limitations of the dominant corporate-led market development model. This constitutes the global compass for present-day energy access programs and international development policy, framed around the potential of foreign-affiliated corporate enterprises for the market-based diffusion of solar products in the Global South. Findings suggest that due to tradeoffs between people, planet, and profit-directed goals, the companies cannot enable sustainability transitions and equal and sustainable access to the energy poor. Instead, the corporate-led market development route reproduces structural injustices. A more pluralistic route with greater roles for local, non-affiliated entrepreneurs, non-profits, and the public sector is proposed for negotiating the tradeoffs to the extent possible.

3.1. Introduction

Markets are critical for large-scale diffusion of new technologies, as well as crucial enablers of sustainability transitions (Boon et al., 2020; Geels, 2004; Santos and Eisenhardt, 2017). At the same time, how markets are shaped matters a great deal for the outcomes they give rise to (Feola, 2020). Markets can act as the primary vehicles that facilitate the provision and uptake of life-supporting technologies that meet basic human needs. Yet they may also provide incentives that put sustainability at stake, and can reproduce structural forms of injustice by determining who can avail of particular solutions and on which conditions, and who is bypassed (Baurzhan and Jenkins, 2016; Bombaerts et al., 2020). Especially in contexts characterized by extreme poverty, there are rising concerns about unanticipated excesses of markets as vehicles for technology dissemination and development (Arora and Romijn, 2012; Davies, 2018). Adverse effects are more likely when private firms act in situations characterized by pervasive market imperfections: where important resources are not readily available, critical infrastructure exhibits constraints, institutions for regulation and oversight are weak, and clientalism and patriarchal relations are common (Ramos-Mejía and Balanzo, 2018). There is a growing recognition that due to reasons of context, market formation in the Global South and North may unfold differently (Cross and Neumark, 2021; Groenewoudt et al., 2020), just like there are substantial variations in the way overall sustainability transitions take shape in these different environments (Cherunya et al., 2020; van Welie, Cherunya, Truffer, and Murphy, 2018; Wieczorek, 2017).

In the Global South, private market actors play an especially crucial role in the diffusion of new technologies because governments fail to develop adequate public systems for the provision of basic services while donor-driven programs alone don't succeed in creating sufficient large scale durable impact (Hansen et al., 2015; Sesan, 2014). Based on the argument that otherwise people in the Global South won't get equal and sustainable access to basic services, international policy and development programs support a 'corporate-led market development' route (Bensch et al., 2018; Ockwell et al., 2017). The supported companies are typically medium or large foreign enterprises and affiliated to donors and investors from abroad (Sesan, 2014; Serraj et al., 2015). They attempt to create markets by means of developing business models especially designed to serve the 'Base of the Pyramid' (BoP). This way, they aspire to unlock commercial opportunities and guarantee financial sustainability while providing affordable access to the world's poorest populations and addressing wider societal and environmental challenges (e.g. Dembek et al., 2020; Zerriffi, 2011). The firms pursue a win-win for people, profit and planet that is pivotal to foster sustainability transitions. Once established, companies use their business models to increase scale and expand markets (Bocken et al., 2016; Jolly et al., 2012).

Increasingly, however evidence is becoming available that shows that there are limits to this corporate-led market development model, especially in the off-grid solar energy access domain (Cross and Neumark, 2021; Samarakoon, 2020). Corporate market-based development as a primary mechanism for poverty alleviation and welfare might be inadequate to serve the very poor and reproduce structural forms of injustice (Kumar et al., 2019; Sovacool et al., 2020). Schot and Steinmueller (2018) suggest that it could contribute directly to inequality because the internationally supported foreign firms favor high tech 'high quality' solutions, producing innovations that are only accessible for customers with substantial purchasing power. Recent literature and discourse appear to suggest that the contemporary model as such may not enable a sustainability transition along all its essential dimensions and may offer a partial solution at best (Bensch et al., 2018; Conway et al., 2019; Sesan, 2012; Radley, 2021).

This paper acknowledges the necessity of markets for sustainability transitions; however, it critically examines how the current dominant corporate-led market development trajectory shapes the economic, social, and environmental outcomes in the Global South, and offers a response to calls to identify sustainability pathways for socially and environmentally inclusive transitions (e.g. Antal et al., 2020; Köhler et al., 2019; Leach et al., 2012; Nilsson et al., 2013). More specifically, this study assesses the potentials and limitations of the current market-development model by studying the latest developments in the off-grid solar markets. Sub-Saharan Africa's and Southern Asia's solar markets are considered frontrunners in corporate-driven BoP innovation. With an estimated annual sales volume of around 8 million solar devices in 2019, realized by international solar companies that are supported by global energy initiatives such as the World Bank's energy program Lighting Global and the Global Off-Grid Lighting Association (GOGLA) (hereafter denoted as 'affiliate' companies), the sector counts as one the first sustainable technology sectors of substantial size in the international development domain (Lighting Global, 2020).

In areas unreached by the grid, solar products like solar home systems and solar lanterns can help close the gap in the electricity system for poor and rural households (United Nations, 2021; Ojong, 2021). Global off-grid solar capacity increased 10-fold in the last decade. US$ 1700 million was invested in private sector projects in 2020. The World Bank's Lighting Global program claimed to have outfitted 470 million Africans with off-grid solar products (Lighting Global, 2020).

The review presents a systematic analysis of solar business literature, a growing body of literature that offers insights in the sustainability issues that arise in the sector and how companies deal with them, and sheds light on what solar enterprises can, and cannot, achieve in BoP settings. The discourse in this literature is becoming increasingly critical about the impact of international companies (Cross and Neumark, 2021; Ockwell et al., 2017). By identifying so-called sustainability tradeoffs that the firms run into, we synthesize and gain systematic insights from the scientific literature and use this to draw lessons about the *limits* of the dominant market-based development model for the diffusion of solar technology. We find tradeoffs between different sustainability dimensions that cannot always be mitigated, making it impossible to achieve one goal without hampering progress towards another goal and force companies to choose between, for instance, pursuing profit and serving the most impoverished and remotely located populations. These trade-offs prevent companies from realizing a win-win for people, profit and planet and appear to be responsible for undesirable outcomes arising from the fast growth of the solar market that are generated when businesses scale up without succeeding in mitigating them.

This study discusses the implications of the tradeoffs and concludes that expectations about the dominant market creation approach led by foreign companies, in its current form, are too high, and that alternative and complementary solutions need to be explored if we are to achieve universal energy access and sustainability transitions. The study seeks to advance the debate around corporate-led market-based development by pinpointing the gaps and possibilities to create realistic expectations. In this regard the study also responds to recent requests for a re-assessment of the dominant support for Global North-initiated entrepreneurship models based on the argument that alternative market formation models with a central role for local, nonaffiliated enterprises has sustainability potential as well (Groenewoudt et al., 2020; Meagher, 2018; Samarakoon et al., 2021; Sanyal et al., 2020).

The paper starts, in Section 2, with a discussion of the dominant contemporary corporate-driven development paradigm for the market-led diffusion of new technologies to improve lives. Section 3 sets out the method of the systematic literature analysis and Section 4 presents the findings from the review of BoP solar business literature. The study concludes with a discussion on the limitations of the current corporate market development model in the off-grid solar sector in the Global South for sustainability transitions and offers alternative perspectives (Section 5).

3.2. The contemporary market development paradigm

In low-income countries technology dissemination is not only key in a transition to lower carbon energy sources but also in the provision of services for basic human needs. Reaching universal access to essential services is high on the international policy agenda with goals for access to basic life-supporting services and financial services (SDG 1), food and agriculture solutions (SDG 2), healthcare services (SDG 3), education (SDG 4), safe water and sanitation (SDG 6), clean energy (SDG 7), internet, information and communication and financial services (SDG 9), and sustainable housing (SDG 11). Markets are put forward as the main instrument to facilitate the large-scale uptake of SDG-promoting technologies in all these sectors (Ramani et al., 2012; Sesan et al., 2013). In large parts of (rural) Africa, the Indian subcontinent and South-East Asia, and particularly among the poor, the provision of basic energy (and other) services access is no longer seen as the typical role of state-owned power utilities and rural energy agencies (Bardouille, 2012). This role has primarily been taken over by private sector actors functioning as new 'development agents' (Blowfield and Dolan, 2014) who are expected to cover the gaps in inefficient public systems (Dumalanede et al., 2020).

This is a consequence of the fact that the dominant approach to development of poor countries pursued by the world's big aid donors since the early 1980s has been based on neoliberal principles in line with the "Washington Consensus", which advocates free markets as the most efficient means of distributing resources. In broad terms, the approach stands for government policy reform, in particular the pursuit of macroeconomic stability through control of inflation and fiscal deficits; unimpeded trade and investment flows with the rest of the world, and liberalized domestic product and factor markets through privatization and deregulation (e.g., Gore, 2000; Hurt, 2020; Rapley, 2007). In this approach, markets are seen as the main vehicle through which development benefits can - and should be - delivered. In the words of Mendoza and Thelen (2008): "Markets provide myriad benefits to those able to gain access and participate successfully in them. … markets can be an engine not just of overall economic growth but also of individual human development and economic empowerment" (p. 427). Business is seen as the main protagonist in this strategy, rather than governments or NGOs, whose impacts on development in the post-WWII period had come to be viewed with widespread disappointment and disillusion (McKague et al., 2011; Esman et al., 1997; Hunt, 1989). While it is acknowledged that barriers to the full participation in markets by certain groups and individuals can occur, and issues emanating from incomplete markets do exist, this is no longer primarily seen as constituting an agenda with non-commercial actors in the lead. In any case, the importance of areas like institution-building and targeted efforts to improve opportunities for the weakest in society, which are arguably very important in many Global South contexts and which do not lend themselves well to commercial approaches according to leading critics of the approach, became de-emphasized (Stiglitz and Narcís, 2008).

An important consequence of the paradigm shift towards market-based development has been that, especially since the formulation of the Millennium Development Goals (MDGs) in 2000 and the UN Johannesburg World Summit on Sustainable Development in 2002, the clear boundary that previously existed between for-profit businesses and non-profit non-governmental organizations (NGOs) has blurred. These two traditional organizational forms have become the two extremes on a complex continuum with a variety of "hybrid" organizations in between (Bocken et al., 2016). Along the continuum lie different shades of "social", "inclusive", "sustainable", and "green" enterprises for whom profit is a way to sustain their activities, rather than a goal in itself. The development aid landscape, traditionally revolving around funding of governments and NGOs, underwent a sea change in the early 21st century as donors became specifically focused on reaching the MDGs by stimulating firms and NGOs alike to go hybrid, in the direction of "doing business with the poor". Development programs such as those administered by the UNDP (2008) became focused on encouraging business to pursue combined financial viability and anti-poverty impact in the belief that such a win-win strategy is indeed possible (Chesbrough et al., 2006; Martinot et al., 2001). Non-traditional funders such as impact investors have also been fast increasing in importance in developing countries. Many NGOs converted themselves into social enterprises to avoid being annihilated by the shrinking development funding for non-profits in donor countries, while taking advantage of the newly emerging financing opportunities for-profits with a societal mission. Conversely, the for-profit business sector came to embrace stronger societal goals to greater or lesser degree, beyond traditional Corporate Social Responsibility sideline activities (Newell and Frynas, 2007).

The business-cum-development paradigm is centered around the idea of Prahalad and Hart (1999) that the world's poorest populations at the Base of the Pyramid form a large potential customer market full of unfulfilled needs and opportunities for entrepreneurs (Dolan and Roll, 2013). Tapping into these potential markets requires viable business models that can service low income households and deal with context-specific deficits like underdeveloped infrastructure, last-mile distribution problems, and weak formal institutions (Barrie and Cruickshank, 2017; Scott, 2017; Seelos and Mair, 2005; Simanis, 2011; Tigabu et al., 2015; Yunus et al., 2010). These are expected to be developed by, or in partnership with the private sector, more specifically with western corporations or firms with western origins or linkages in a leading role (London and Hart, 2010).

Initially, the BoP argument was introduced as a possibility of combining profit making with serving the poor (known as BoP 1.0) but soon became contested (Blowfield and Dolan, 2014; Karnani, 2006; Simanis, 2012). Especially after ethical criticism, attention shifted to so-called BoP 2.0 approaches aiming for more local embeddedness, emphasizing business co-venturing or partnering between western companies and local parties and moving to models with job opportunities for the BoP population in functions like sales, distribution and even co-invention (Hart and London, 2005; Hart and Sharma, 2004). Most recently, scholarly BoP literature has steered towards a third generation of BoP strategies (BoP 3.0) which extends the scope to environmental sustainability concerns, moving towards a genuine triple bottom line perspective. This indicates that the BoP scholarly community itself has begun to perceive crucial shortcomings in extant BoP strategies and sees the need for a shift towards truly holistic solutions and engagement through wider innovation ecosystems approaches (Cañeque and Hart, 2017; Bradley et al., 2020; Madsen, 2020; Mason & Chakrabarti, 2017; Nosratabadi et al., 2019), thus setting a more ambitious agenda that aligns with the aim of this paper.

Still, especially in the energy sector, the evolution from the initial BoP 1.0 to its later versions appears incremental in the sense that the international policy and aid strategy has remained fixated on market-driven development framed around large international companies affiliated to donors and investors from the Global North (Serraj et al., 2015; Sesan et al., 2013; Ockwell et al., 2017), with local, often small-scale and informal parties without foreign affilations at best seen in dependent subsidiary roles. This is the case notwithstanding a resurging emphasis over the past two decades in the international development discourse on pro-poor and inclusive development, in the face of pervasive human fallouts from the push for strong neoliberal reformism in poor countries in the 1980s and 1990s. Based on the promise that foreign-affiliated companies can deliver high quality products and services to the poor at affordable prices, the corporate BoP players are expected to pull the cart that will ultimately result in widespread development "trickle down" effects. They are the ones that continue to receive support from donors, the World Bank, international development programs and institutions like Lighting Global, UN Development Program (UNDP), Global Off-Grid Lighting Association (GOGLA), International Renewable Energy Agency (IRENA), and impact investors like the Royal Dutch Shell Foundation and Japan's Mitsubishi Corp (Ojong, 2021; Lighting Global, 2020). Energy and development programs call on them for holistic development solutions framed around the integral implementation of the Sustainable Development Goals (SDGs) (Ely & Bell, 2009; Rizza, 2019) and stimulate them to address sustainability problems e.g. by integrating responsible production methods and waste recycling (GOGLA, n.d.; SDG Compass, n.d.).

While the corporate-led market-based development model envisions a triple-bottom-line (people, planet, profit), scholars have begun to raise concerns that these companies cannot live up to the paradigm's high expectations (e.g. Cross and Neumark, 2021). Ockwell et al. (2017) and Bensch et al. (2018) argue, for instance, that the kind of private sector approach that funders and development agents currently prioritize does not function financially sustainably in absence of promotion programs or at least supportive regulatory interventions such as import tariff waivers on product components. Despite upbeat stories of business bringing 'solutions' in the off-grid solar sector, few if any companies appear to have reached their breakeven point and financial independence yet (Ockwell and Byrne, 2016). The bankruptcy in 2019 of a big solar home systems provider operating in East Africa, the German-backed Mobisol, was a big wake up call to the industry as a whole (Bhambhani, 2019). Even with the solar market reaching a substantial size with a sales volume of 30 million in 2018 and 2019 and international companies like BBOXX, SolarNow, and Azuri Technologies scaling up their business activities there is still need for US$ 6.6–11 billion in additional financing to reach the remaining 617 million people with off-grid energy products (Lighting Global, 2020; Kizilcec and Parikh, 2020; Ojong, 2021).

Furthermore, there are signs that companies fall short in delivering on the other central dimensions of the much-anticipated people-planet-profit benefits, suggesting that they cannot create the win-win that is needed for a sustainability transition. Pressurized by the need to pursue their commercial break-even point through fast upscaling strategies, firms appear to target the better-off sections of the BoP and exclude the most impoverished communities, whereas especially for those populations improved energy access is a critical component in the fight against poverty and realization of improved living standards (Grimm, 2020; Szabó et al., 2016). Moreover, there are concerns about companies' production of e-waste in the African solar market (Hansen et al., 2021), and an increasing number of studies highlights such issues in various sustainability domains, especially in the off-grid energy sector. Despite growing concerns, we lack an integral overview of such issues as a response to the sector's possibly too high expectations.

BoP literature points towards the issue of 'tradeoffs' as an underlying problem that hinders companies from designing sustainable and holistic business models that are essential to addressing all three social, economic, and environmental pillars of sustainable development (Kolk et al., 2014). As a result, BoP ventures are co-producing negative along with positive effects for the BoP (Arnold and Williams, 2012; Hall et al., 2012; Likoko & Kini, 2017), for instance, when businesses fail to succeed in their aim to serve deeply impoverished populations because of the slim profit margins and high costs of bridging the 'last mile' in remote locations, factors that interfere with meeting the need for financial viability. Empirical case-based evidence suggests that in the energy sector too, such tradeoffs form a structural problem for the realization of sustainability transitions and that, despite best intentions, such contradictions prevent solar companies from achieving the best outcomes for society and the environment (Balls, 2020; Grimm and Peters, 2016; Groenewoudt, Romijn & Alkemade, 2020). This study reviews the solar business literature through the lens of such tradeoffs. To this end we adopt the definition from sustainability and SDG-focused literature that describes tradeoffs as situations (not in business context per se) where the achievement of one goal constrains, counteracts or cancels progress towards other sustainability goals, and that discusses the issue of tradeoffs in relation to consistent implementation of the UN's agenda for sustainable development (e.g. McCollum et al., 2018; Nilsson et al., 2016; Weitz et al., 2018). The next section sets out the method for the literature review and analysis.

3.3. Method

3.3.1. Literature selection and analysis

To identify and analyze the tradeoffs that hamper the unfolding of sustainability transitions the study started with collecting a primary sample of scientific, peer-reviewed solar business literature for the review. More specifically, we selected literature discussing solar enterprises that deliver solar home systems, solar lanterns and solar 'pico' products to households in sub-Saharan Africa and southern Asia; the areas where the solar household solutions are most popular. The review includes publications from 2016 onwards, as we expect this selection to cover the main publication period for research that describes the impact of established, internationally supported solar companies, most of which were founded between 2011 and 2013 (Lighting Global, 2020). Relevant publications were identified through application of

Table 3.1: Search and selection criteria for literature survey

Database	**Search criteria**	**Selection criteria**
Scopus	Title-Abs-Key ("solar home system*") – ("off-grid") – ("pico product*") – ("solar product*") ("solar lantern*") AND Title-Abs-Key (business*) – (corporate*) – (corporation*) – (initiative*) – (venture*) – (multinational*) – (partnership*) – (enterprise*) – (entrepreneur*) – (company) – (companies) – (shop*) – (dealer*) – (supplier*) – (vendor*) – (firm*) – (market*) – (organization*) – (for-profit*) AND limit to document type "ar" and "re" AND limit to subject area "SOCI" or "ENER" or "ENVI" or "BUSI" AND limit to language "English" AND limit to year "2016" or "2017" or "2018" or "2019" or "2020" or "2021"	• Studies discussing companies active in the off-grid solar market (solar home systems, solar lanterns and solar pico products sold to households), and more specifically; • Including only studies focusing on enterprises, firms, businesses, and other market-based initiatives that commit to pursuing financial viability. Both fully commercial and "hybrid" enterprise forms qualified for they share the common requirement to pursue a break-even point; *non*-profits are excluded. • Providing details on the enterprises, in general terms or through in-depth case studies. • Geographical scope: sub-Saharan Africa and southern Asia.
	Search result: 348 publications	*Criteria applied: 36 publications*

the search and selection criteria set out in Table 3.1. This led to the selection of 36 articles published between January 2016 and August 2021. We selected publications about solar companies that are fully commercial or pursue a financial breakeven point (at least on paper; the term social 'enterprise' is sometimes also used as label to attract financial support from donors) (see for an in-depth discussion: Cross and Neumark, 2021; Ockwell et al., 2017).

The analysis follows the procedure set out in Table 3.2 and consists of a three-step procedure that is based on the protocol by Nillson and colleagues (2018) for a systematic review of so-called interaction effects between Sustainable Development Goals and that was specifically designed to collect and collate lessons of tradeoff cases. Our steps follow the part of their framework that is focused on the appraisal of *trade-offs*; negative interactions that hinder progress towards sustainability goals.

Table 3.2: Literature review procedure

Step	***In review***	***Detailed features***
(1) Article details and context of knowledge claims	Initial sample: 36	▪ Title, authors, year; ▪ Type of study, e.g., empirical, review ▪ Description of context: technology scope; geographical place; ▪ Business-specific context details, e.g., type of organization, actors involved, company names, profitability and/or dependance on donors.
(2) Identification and assessment of trade-offs	Sample surveyed: 36 Identified in: 20	▪ Accounts of incompatibilities and conflicts between social, environmental, and economic goals ▪ Assessment of how trade-offs play out in the given context ▪ Identification of affected goals, and translated to the Sustainable Development Goals to aid the disentanglement of tradeoffs (Figure 2) ▪ Evidence for trade-offs offered in publication, e.g., first-hand empirical data, based on literature review
(3) Mitigation experiences	Sample surveyed: 20	▪ Descriptions of measures taken to mitigate trade-offs ▪ Outcomes and experiences of such actions (quantified if possible), the conditions enabling positive or negative results for aspired objectives

In the first step of our literature analysis, we surveyed general article details and the context of knowledge claims of all studies in the sample (e.g., country; business characteristics). In the second step, we closely examined the articles where we came across accounts of tradeoffs. We considered firms' goal incompatibilities and conflicts between social, environmental, and economic goals as a representation of tradeoffs. In some cases, researchers are very explicit about tensions and the consequences thereof and linking this to drawbacks of the market-based development paradigm, while in other cases we found tradeoffs yielding from circumstantial evidence (for instance: Kolk & van Buuse observe that cheaper solar products have less productive use for users). Figure 3.1 shows that out of the 36 selected articles we identified tradeoffs in 20 of them.

To systematically disentangle tradeoffs and review the effects on the envisioned triple-bottom-line benefits of international companies, we structured tradeoff accounts along their impact on the social, economic, and environmental dimensions of sustainability using the Sustainable Development Goals. Conforming to Nilsson et al.'s protocol we used the tool by the Stockholm Environment Institute [1], a tested method to evaluate tradeoffs (see also Weitz et al., 2017; Fuso Nerini et al., 2018), and mapped them against the 17 Sustainable Development Goals. Doing this, and thus assessing for each of the tradeoffs we came across which SDGs they affected, we developed the heatmap presented in Figure 3.2. This helped to order our findings, and, in the results, we discuss the four most fundamental tradeoffs that are the outcome of an in-depth analysis and synthesis of the literature findings.

In the third step, we reviewed the studies to see to what extent companies tried to mitigate (the consequences of) tradeoffs and how they did this, and how this worked out in the given context.

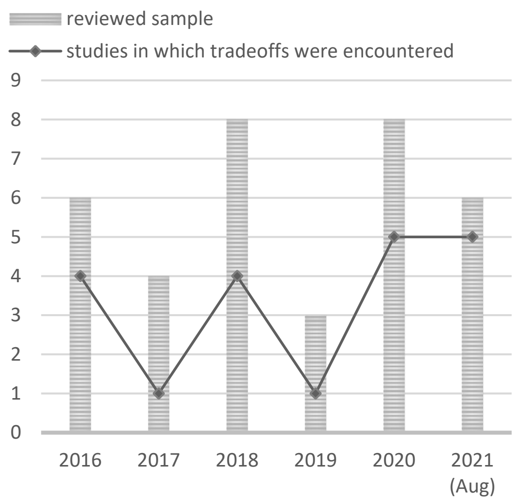
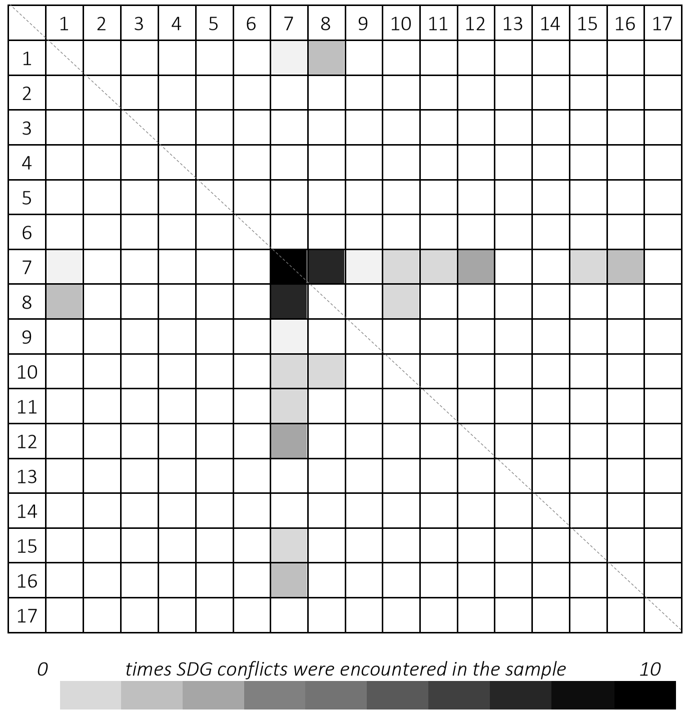


Figure 3.1: Tradeoffs in reviewed literature

[1] https://www.sei.org/projects-and-tools/projects/disentangling-interactions-sustainable-development-goals/

Heatmap explained in four cross-sectional patterns:		
	conflict between:	
one	SDG 8 - economic viability and business **profits**	SDG 7 - energy access for **all** SDG 10 – reduced inequalities
two	SDG 7 - **modern and reliable** energy access	SDG 7 - **affordable** *for all* energy access SDG 10, 16 – equality and justice
three	SDG 7 – physical **distribution** of clean off-grid solar technologies	SDG 12 – zero **waste** SDG 11, 15 – clean environments
four	**short-term** goals such as: SDG 7 – target for number of people with energy access; SDG 8 – economic prosperity, returns on investment	**long(er)-term** sustainability impact; integral part of the sustainable development and linked to goals such as: SDG 1, 10, 16 – no poverty, justice, inclusive societies; SDG 12 – no waste



Sustainable Development Goals: 1 – no poverty, 2 – zero hunger, 3 – good health and wellbeing, 4 – quality education, 5 – gender equality, 6 – clean water and sanitation, 7 – affordable and clean energy, 8 – decent work and economic growth, 9 – industry, innovation and infrastructure, 10 – reduced inequalities, 11 – sustainable cities and communities, 12 – responsible production and consumption, 13 – climate action, 14 – life below water, 15 – life on land, 16 – peace, justice and strong institutions, 17 – partnerships for the goals

Figure 3.2: Heatmap of tradeoffs translated to conflicts between Sustainable Development Goals

3.3.2. Sample

The majority of reviewed studies discusses affiliate high-profile solar companies such as Bboxx, SELCO, Dlight, Greenlight Planet, Azuri Technologies, and M-Kopa, and also described as pay-as-you-go companies (Lighting Africa, 2020). A small portion discusses also a second type of solar enterprises: non-affiliates. Non-affiliates are described as local low-profile businesses operating in an informal setting and that are unsupported by the international market promotion programs. The reviewed studies show that they sell what the World Bank's Lighting Global platform calls ‘unaffiliated’ products, also referred to as ‘nonbranded’ and ‘uncertified’ products (Balls, 2020; Bensch et al., 2018; Groenewoudt et al., 2020; Samarakoon et al., 2021; Samarakoon, 2020). Given the scope of this study our primary interest is the first category of enterprises, yet we will reflect on insights gained with regard to the second group as well. Table 3.3 presents descriptions of all solar companies in the sample and distinguishes between ‘affiliate’ and ‘non-affiliate’ solar suppliers.

Table 3.3: Affiliated and non-affiliated companies operating in solar markets

(1) **Affiliated** companies, associated to international organizations, donors, and investors from the Global North		
Description	*Location*	*Publication*
• Companies with market-based delivery models	Rwanda	Thomas et al. (2021)
• Private market approaches	Tanzania	Ferrall et al. (2021)
• North American and European solar energy companies	East Africa	Cross & Neumark (2021)
• Venture capital backed solar enterprises	Malawi	Samarakoon et al. (2021)
• Renewable energy enterprises	South Africa	Diale et al. (2021)
• Off-grid solar suppliers, GOGLA affiliates	Global South	Hansen et al. (2021)
• High-profile solar businesses	India	Balls (2020)
• SHS companies, Boond and Selco	India	Bandi et al. (2020)
• Suppliers of certified, ‘affiliated’ products	Malawi	Samarakoon (2020)
• Full-service and plug-and-play systems suppliers, proclaimed ‘high quality’	Uganda	Groenewoudt et al. (2020)
• Solar home system business models	Sub-Saharan Africa	Kizilcec & Parikh (2020)
• Pay-as-you-go solar firms	Sub-Saharan Africa	Adwek et al. (2020)
• Market-based dissemination of off-grid technologies of DLight, Greenlight Planet, and ASE	Rwanda	Grimm et al. (2020)
• SHS business model, Infra. Development Company Ltd	Bangladesh	Ahmed et al. (2020)
• London-based solar power company, BBOXX	Rwanda and Kenya	Kennedy et al. (2019)

• Social enterprises	South Africa and Zimbabwe	Conway et al. (2019)
• Off-grid solar PV intervention	India	Joshi et al. (2019)
• Solar lighting social enterprise, Solar Sister	Tanzania	Gray et al. (2019)
• Pay-as-you-go business model	Kenya	Carr-Wilson and Pai (2018)
• Market-based renewable energy services provision model	Sri Lanka and Indonesia	Sovacool (2018)
• Social enterprises, SEWA Bharat and SELCO	India	Ali and Yadhav (2018)
• Off-grid companies	Kenya and Tanzania	Sergi et al. (2018)
• Donor-backed companies offering 'branded' products	Burkina Faso	Bensch et al. (2018)
• Pay-as-you-go provider, M-Kopa Solar	East Africa	Rastogi (2018)
• Solar PV businesses	East Africa	Muchunku et al. (2018)
• Private-led market development	Kenya	Nygaard et al. (2017)
• Solar business	Bangladesh	Hossain et al. (2017)
• Solar home systems provider BBOXX	Kenya and Rwanda	Bisaga et al. (2017)
• Pay-as-you-go business model	Central East Africa	Barrie & Cruickshank (2017)
• Solar Electric Lighting Company (SELCO)	India	Pai & Hiremath (2016)
• Ashden Award-winning for-profit enterprises	Developing countries	Weldon, Sharma & Dobbs (2016)
• USAID supported SHS provider Azuri Technologies	Rwanda	Collings & Munyehirwe (2016)
• Solar-LED lighting companies	Developing countries	Mills (2016)
• Local social enterprise, Boond	India	Urpelainen & Yoon (2016)
• Off-grid solar energy providers	India	Singh (2016)
• Companies with market-based delivery models	Rwanda	Thomas et al. (2021)
(2) **Non-affiliated** enterprises		
Description	*Location*	*Publication*
• Distributors of 'somewhat original' products	Malawi	Samarakoon et al. (2021)
• Informal shops	India	Balls (2020)
• Suppliers of uncertified and 'unaffiliated' products	Malawi	Samarakoon (2020)
• Local vendors and wholesalers selling mix-and-match systems, proclaimed 'low quality'	Uganda	Groenewoudt et al. (2020)
• Suppliers of local market-offered non-branded products	Burkina Faso	Bensch et al. (2018)
Description – uncategorized		
• Off-grid solar enterprises in BoP markets	Developing countries	Scott (2017)
• Private sector approaches	Kenya, Uganda and Malawi	Davies (2018)

The sample includes 29 original research papers and 7 reviews. Literature in the sample appears to become increasingly critical about the industry's performance over time, as scholars more frequently question the feasibility and sustainability of corporate-led market development. Yet, none of them systematically assesses the impact of solar enterprises on the social, environmental, and economic dimensions of sustainability, and this underlines the relevance of a systematic review to collect and combine lessons about the solar industry from dispersed publications.

3.4. Results

Central in the pro-market development argument is the expectation that Global North-affiliated companies should be supported as they can commercialize the uptake of SDG-relevant technologies by the BoP and do so in a socially inclusive and environmentally responsible manner. This section outlines four core tradeoffs (Figure 3.3) that are in the way of a sustainable transition to clean off-grid energy access.

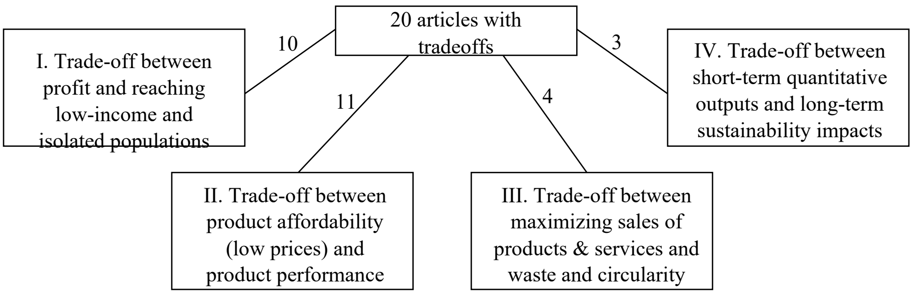


Figure 3.3: Tradeoffs in the literature sample. Numbers referring to the number of articles that mention this tradeoff.

3.4.1. Tradeoff 1: Profit versus energy access 'for all'

Despite hopes of a commercial solar market to realize "*clean and affordable energy for all*", profit generation appears incompatible with the goal of diffusing solar home systems and lanterns among poorest populations and those living in rural areas. A tradeoff arises between profitability and provision of clean energy access 'for all' because companies cannot sufficiently earn from the minor profit margins on small-sized solar products when sold to a clientele with extremely low purchasing power. In addition, many of the world's poorest populations live in sparsely populated places and due to high last-mile distribution costs and relatively dispersed sales, those areas are particularly unattractive to serve. High unit margins are infeasible to attain in BoP markets (Bocken et al., 2016; Jolly et al., 2012) and unit sales volumes must be high and combined with at least reasonable margins in order to recover business costs and attain financial viability (Wigboldus et al., 2016). Only a few solar firms like D.Light, Greenlight Planet and M-Kopa have achieved a large scale (Lighting Global, 2020), and sometimes only because they were subsidized (Balls, 2020). Many studies conclude that solar enterprises thus far have failed to reach breakeven points with pure for-profit models (Ahmed et al., 2020; Conway et al., 2019). Others are more optimistic and suggest that – at least for some parts of the market, companies can be profitable, like Pai and Hiremath (2016) who argue that Selco, after a financial crises, pressure from investors and help from socially-oriented foreign investors, 'returned to profitable ways' (p.154). On its company website, Selco underlines this by stating it has maintained modest profits in the last 8 years with annual average growth rates of 20% (Selco, n.d.).

Accumulating evidence has shown, however, that mainstream solar companies are unlikely to reach the very poor (Grimm et al., 2020; Kumar et al., 2019; Groenewoudt et al., 2020; Balls, 2020). A recent study by Thomas and colleagues shows that market leading firm Bboxx, one of the leading solar company in Africa, and BELECOM (a newer market entrant) sold products to only ~32% of the households in Rwandan refugee camps. Not only academics cast doubt on the BoP premise; also actors from within the industry no longer believe that the extreme poor can be part of the addressable market (Cross and Neumark, 2021). A large group of international solar companies represented by the Global Off-Grid Lighting Association point out that end-user subsidies will be necessary, a form of subsidy to reduce the purchasing cost for end-users, to allow companies to reach the poorest African and Asian households (GOGLA, 2021).

The call from the industry suggests that other solutions such as Pay-As-You-Go, 'downscaling' off-grid products (offering smaller, cheaper products) and creating economies of scale are not enough for the private sector to address this segment of the market (GOGLA, 2021). Where Pay-As-You-Go models were hyped a couple of years ago (Barrie and Cruickshank, 2017; Muchunku et al., 2018; Rolffs et al., 2015), the literature has become more critical towards this financing mechanism that allows customers to make periodic installments (monthly, weekly, or on occasion, depending on the supplier) through a mobile payment platform for the repayment of solar systems over time. PAYG allows companies to increase their customer base and it offers an affordability solution for people with regular incomes and living in areas covered by telecom networks (Rastogi, 2018). Yet, there is a risk that these credit arrangements can place a financial burden on the energy poor that they cannot sustain (Samarakoon, 2020) while instead of just benefiting from economic opportunity of BoP markets “they are making a killing out of them” (quote from Cross & Neumark, p.13). In other words, PAYG reduces existing inequalities but creates new ones. This becomes also visible in cases where systems of indebted PAYG customers were disabled by the supplier because the customers did not keep up repayment, the increase in repossessions of systems, the high prices of systems sold under PAYG because of interest rates charged to buyers, and ethical issues associated with the storage, collection and sharing of user data (Bisaga et al., 2017; Cross and Murray, 2018; Grimm, 2020). Solar firms and financiers also take a credit risk and can only offer PAYG when they have access to sufficient working capital (Adwek et al., 2020; Urpelainen and Yoon, 2016).

In other words, a limitation of the neoliberal development model is that it provides little incentives to deliver electricity to contexts and customers where risks are high and where there is no or little return on investment (Ferrall et al., 2021; Sergi et al., 2018; Thomas et al., 2021). Neglect of unprofitable segments appears inevitable in the market-based development strategy, and in attempts to include them, new ethical challenges and new forms of injustice tend to emerge. Singh's (2016) study points out that off-grid solar technology enterprises can achieve higher unit scale by focusing on fewer product categories and this suggests that those who need electricity access the most may also be the ones with the most limited options.

Cross and Neumark (2021) describe how over the past decade companies became less interested in achieving universal electricity access and instead primarily concerned with sales numbers and financial returns on investments, arguing that ‘underpinning this restructuring of goals was an ambitious commitment to growth’ (p.10) by off-grid energy companies like Mobisol and pressure from investors. Venture capitalist investment funds and private equity and were attracted by the sector, but seeking for short-term returns on investments, some allowed (or induced) companies to scale their business operations beyond the poor. The shift away from the sector's primary off-grid energy access goal is argued to be a growing concern in the industry.

In attractive areas, on the other hand, the market approach leads to competition between energy providers, like between Mobisol and M-Kopa in some parts of Tanzania (Rastogi, 2018). Competition increases product choice for customers, who then become aware of the relative advantages and disadvantages of the products, and puts pressure on firms to lower system prices, but can also be interpreted as inefficient use of funding resources (Steel et al., 2016; Thomas et al., 2021).

Another aspect of the afore mentioned tradeoff is that in areas with low diffusion levels, the costs of maintaining a store permanently is often too high, and companies fail to secure an adequate ecosystem for maintenance or repair of solar products in those areas (Kumar et al., 2019; Thomas et al., 2021). Thomas and colleagues (2021) write for instance that 'Bboxx did not maintain a permanent presence in the Rwandan refugee camps, preferring to use a customer service hotline, and that the Bboxx sales agents were paid on a commission-only basis and were not trained or paid to deal with technical issues' (p.129). In such situations, customers deal with more unrepaired system deficits and breakdowns, or pay higher prices for repairs. Local repair by independent technicians for simple technical issues exists, but such repair invalidates warranties of Bboxx and other international suppliers, many of which work with similar warranties (Groenewoudt et al., 2020; Thomas et al., 2021). This issue was particularly pressing in the Rwandan camps in times of Covid-19 when supply chains and technicians could not access the areas.

The profitability challenges and failing attempts to include the lower strata of the BoP is further exacerbated by a second tradeoff:

3.4.2. Tradeoff 2: (Low) product price versus (low) product performance

Solar energy access should be affordable for all layers of society, but like in any product market, there is an inevitable payoff between product prices and whatever value can be offered to customers at that price. This price-performance tradeoff is problematic, especially in solar product markets in Global South contexts. Challenges of customers' low purchasing power combine with relatively high costs of 'high-tech' solar solutions. For the poor the prices remain high despite the recent decline of global PV module prices and cheap mass production in (especially) China, from where bulk import to other Asian and African countries takes place (Hansen et al., 2015). User-focused studies have shown that the cheapest and most affordable solar products (lanterns) offer little more than a most basic lighting service; they can only sometimes charge a mobile phone (Azimoh et al., 2015; Collings and Munyehirwe, 2016; Peters and Sievert, 2016; Urpelainen and Yoon, 2016). Because of the price-performance tension it is practically impossible to develop solar products that score well on the core dimensions of SDG 7: 'affordability' and 'for all', and 'modern and reliable energy access'. The latter is best achieved with large, high quality, and functionally rich systems that score high on the World Bank's Multi-Tier Energy Access Framework (www.esmap.org).

This considered, scholars vary in their optimism about the advantages of off-grid small solar kits (Hossain et al., 2017; Wheldon et al., 2016). Despite their shortcomings some point out the relative benefits for users especially compared to alternatives, including electricity through a grid connection, which is expensive and not always reliable. Just like large solar systems, electricity from a weak grid is often also not well enough suited for cooking and productive uses (Gray et al., 2019; Sievert and Steinbuks, 2020). Implicitly the tradeoff forces companies to walk a tightrope, balancing between 'leaving no one behind' and the global ambition to bring everyone to Energy Access Tier 4 or higher (Wheldon et al., 2016).

Lower-income segments of the BoP struggle to afford even the smallest solar systems – regardless the availability of PAYG services and people who have less to spend get minimal energy services, placing a double burden on the energy poor and reinforcing structural forms of injustice (Boamah, 2020; Ferrall et al., 2021; Thomas et al., 2021). Although this second price-performance tradeoff is different from the first tradeoff that relates primarily to profitability of sales to poor and rural customers, it produces similar issues with inequality that existing solutions like PAYG cannot completely mitigate. Extending payment periods helps liquidity-constrained customers but not enough to enable them to pay cost-recovering market prices, leading Grimm et al. (2020) to conclude that to 'disseminate off-grid solar to the rural poor via unsubsidized markets might be overly optimistic' (p.30). At the same time, adoption is not only determined by income levels; word-of-mouth advertising and local sales representatives are important factors as well (Kennedy et al., 2019). End-user subsidies could potentially close the affordability gap but has yet to prove its success. Actors from the off-grid sector raise the concern that it may create unfair competition, and that a shift towards structural subsidies constitutes a step away from market-driven development (GOGLA, 2021; Conway et al., 2018).

Importantly, several scholars attribute unaffordability of systems partly to the decision of the PAYG companies to strive for high-quality Lighting Global-certified solar systems. This contrasts with products from ‘nonaffiliate’ small local suppliers who tend to opt for a price-over-quality market strategy and offer lower cost, improvised solar home systems, assembled from readily available solar parts (Balls, 2020; Groenewoudt et al., 2020; Samarakoon et al., 2021; Sanyal et al., 2020). Compared to certified products, their open-source systems are more cost-effective and physically larger. Owners of the small-scale and informal solar shops operate independent of any subsidy or support program – and are no franchise of grassroots initiatives like Solar Sisters and Barefoot's Solar Mamas. They have no international linkages to the Global North apart from their supply chain of solar parts that runs via importers and wholesalers in capital cities (Groenewoudt et al., 2020).

Balls (2020) argues that most of the recent energy literature frames certified products as ‘good solar’ and challenges the assumption based on the grounds that the uncertified solar solutions are functionally flexible (new appliances can be added on) and more easily repairable locally. Similarly, Groenewoudt et al. (2020) conclude that solar products from the affiliates are advertised as ‘high quality’ but do not necessarily perform well in Global South diffusion contexts. Many uncertified lower-cost alternatives that are proclaimed to be of ‘low quality’ (according to representatives of global development agencies) tend to perform well enough for users. Moreover, they find that the suppliers were already on the market before products of subsidized affiliated businesses diffused on a large scale and are still holding their own in the face of that competition, despite the absence of support, whereas the same cannot be said for the affiliates (Balls, 2020). These conclusions from field research in Uganda and India tally with findings by Samarakoon about ‘Somewhat original’ products that are more widely available to the rural masses in Malawi (2021), and from Bensch et al. (2018)’s study of branded and non-branded solar home systems in Burkina Faso, on the basis of which they question the need for promotion programs for Lighting Global quality-verified branded products. The findings suggest that Western-minded organizations opt for a one directional remedy to treat the price-performance tradeoff – at least when compared to local solar initiatives.

The studies discussed above seem to signal the beginning of a debate around global quality standards for solar markets (see for instance: Samarakoon et al., 2021). The

Lighting Global Quality Standard seeks to ensure truth in adverting, durability, system quality, lumen maintenance, and 2-year minimum warranties (Lighting Global, n.d.; Harrington and Wacera Wambugu, 2021) and is currently put forward as the "golden standard". It acts as the main instrument to protect customer markets from unreliable, unwarranted solar products, but the standard is increasingly questioned. Samarakoon (2021) concludes that 'the affiliated products that pass certification are ultimately products with significantly shorter lifespans than systems sold in the Global North' (p.9), and user reports indicate challenges with warranties that are not granted in cases of incorrect use or tampering with systems (Groenewoudt et al., 2020). Furthermore, Samarakoon argues that the standards are not only developed for, but also by, leading solar companies, and this creates a biased market device that risks unfair competition and rules out local vendors. Unlike international companies, they have no access to laboratories and equipment to conduct measures for certification, and few have the skills to comply with the international standards (Davies, 2018).

3.4.3. Tradeoff 3: Distribution of solar products versus zero waste

Another dilemma for off-grid markets is posed by a tradeoff between the aim – or indeed exigency – for wide distribution of solar products and the production of waste that results from it e.g., through end-of-life product disposal, early breakdowns, littering of packaging. With the diffusion of products off-grid companies expose user and local environments to e-waste. The toxic content of solar parts, and batteries in particular, has shown to have a harmful repercussion on health and the environment (Cross and Murray, 2018; Hansen et al., 2021; Sovacool et al., 2020). Rapid growth of off-grid solar markets has led to an increased pressure on the natural environment and the people living the polluted areas. Most pronounced is the impact on low-income countries that lack a central and well-functioning waste management system like Uganda, and (rural) areas where collection of waste is the hardest and broken batteries end up unattended in homes and homesteads (Bensch et al., 2017). This raises yet another fundamental ethical question of fairness towards the energy poor (e.g. Kumar and Turner, 2020; Sovacool et al., 2020).

The linear trajectory from distribution to consumption to waste is exacerbated by the need by companies to maximize sales volumes at the lowest possible profitable prices and provide warrantied products. Short-lived systems are increasingly cluttering landfills, and studies by Balls (2020) and Groenewoudt et al. (2020) suggest that the focus on high quality and quality certificates and pressure on affordability has increased the problem because it has led to the design of closed ‘temper-proof’ solar technologies. Such plug-and-play solar home systems are the most sold affiliated product in off-grid markets, and while the functionally fixed solar kits prevent users from wrong use and enhance high sales volumes and rural distribution, they are harder to repair locally.

So far, the response from the industry have been focused on efforts to minimize the impact of solar home system kits through a western-inspired circular-economy approach. Mitigation of the technology distribution-waste tradeoff goes hand in hand with the ideal sequence for avoiding waste, namely through (Brix-Asala et al., 2016, p.415):

1. *waste reduction* – such as extending product durability, reducing use of (packaging) materials and use of biodegradable materials;
2. *waste re-use* – such as remanufacturing products for a second life;
3. *waste recovery* – such as raw material recycling, and;
4. *waste landfill* – as a last resort.

The Global Off-Grid Lighting Association (GOGLA) is one of the lead institutions in addressing the increasing e-waste problem in this manner. It strives for a circular approach to reduce the footprint of the off-grid solar market with a voluntary ‘extended producer responsibility’ agreement, a requirement for all its members (Lighting Global, 2020). In GOGLA, efforts are solely targeting affiliated solar enterprises, not the earlier discussed nonaffiliate suppliers. The organization is in favor of certified products and attention has been directed towards after-sales care, circularity along the entire value chain through repairability and recyclability in design, extending product lifecycles and by working with trained technicians, high quality spare parts, promoting repair practices, and responsible product disposal through take-back schemes, recovering valuable parts for re-use and fostering responsible recycling practices. As a representative of the private sector, GOGLA seeks cost-recovering waste management solutions and suitable economic inventive structures (Hansen et al., 2021; GOGLA, n.d.). There is also a scheme for establishing new processes for high-quality refurbishment of broken or returned off-grid solar products can help to serve customers with lower-priced products for higher-tier energy access.

However, the initial steps taken by the industry are still in its infancy(Hansen et al., 2021). *Re*-use of energy technologies or parts has only recently gained attention and adequate safe recycling is still relatively new (Bensch et al., 2017; Hansen et al., 2021). A zero-waste scenario is unlikely given that solar technologies consist of hard-to-recycle parts like batteries and many hazardous materials. Permanent sustainability is hard to operationalize because it requires a 'closed loop' where materials are not subject to downcycling or disposal. Waste reduction through "cutting down" in materials is only possible to some extent, and durability of batteries, which are a critical component in solar products, remains a major challenge in tropical countries (2–6 years max, depending on battery type and use) (Groenewoudt et al., 2020; Jacobson and Kammen, 2007). Setting up adequate reverse supply chains in vast rural areas with poor infrastructure is also unwieldy and can become a very costly affair.

Some are exploring the potential of open, modular designs that can postpone end-of-life disposal of entire products through possibilities for local repair or replacement of individual parts and repairability standards rather than quality standards (Spear et al., 2020). Yet, this requires different business models with more advanced supply chains that are unattractive for big international solar companies which seek financial breakeven by moving as many new products as possible. Mitigation of the distribution-waste tradeoff is further complicated by the need for ever cheaper products and commitments to product certification that together may be causing a lock- in locked solar kits around which dominant supply chains and service models are structured.

Hence, a limitation of the market-based development strategy for the off-grid sector is that companies so far have been unable to distribute products without putting an ecological burden on local environments. This problem is not limited to corporate market-based technology diffusion (NGOs and public initiatives would run into it too), but particularly hard to resolve in a market where certified hard-to-repair technologies have been favored and given that business costs for waste related activities need to be absorbed while conditions for attaining economic viability are already unfavorable. Studies focused on nonaffiliated suppliers have shown that uncertified component-based systems have repairability and revaluing benefits (re-use of solar parts, battery 'refurbishing') (Cross and Murray, 2018) although the environmental benefits are diminished by the existence of fake solar parts and spare parts of extremely low quality (Groenewoudt et al., 2020).

3.4.4. Tradeoff 4: Short-term quantitative outputs versus long-term sustainability impacts

A final tradeoff that emerged from the review is between chasing short-term quantitative performance targets and pursuing long-term sustainability impacts. The short-term targets refer to outputs like return on investments, commitments to growth in sales, or the number of people to whom systems are sold. Long-term sustainability, on the other hand, relates to the broader concept sustainability, as defined in the Brundtland report (1987) that describes it as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This tradeoff is interwoven in all three tradeoffs discussed above but should still be mentioned explicitly here because it explains to a large extent how companies deal with the tradeoffs the way they do. Demonstrating this, off-grid solar companies tend pursue quick wins that are 'evidence' of their contribution to SDG 7. Success in those terms is measured as profit and sales units and number of newly connected customers that benefit from what Kumar et al. (2019) describe as a 'drop-and-go' type of intervention that fails to secure proper maintenance and after-sales services for customers (and resulting in more breakdowns and thus waste).

Achieving short-term and long-terms goals simultaneously requires investment of resources in competing directions and this is hard to accomplish, especially in resource-constrained settings. Multiple studies have shown that private-sector led electrification programs aimed for rural development became mere household connection projects providing little more than basic lighting and (just like public-sector led programs) missed out on meaningful progress with addressing energy poverty and achieving productive use through energy connections (Cross and Neumark, 2021; Derks and Romijn, 2019; Mesina, 2016; Peters and Sievert, 2016). Setting up support networks and investing in technological capacity building are time consuming and resource intensive processes. Consequently, emphasis on these activities would imply that the time to market, break-even points, and return on investments are milestones that may need to be postponed further into the future. Possibly similar mechanisms are at work in other resource intense processes with long pay-back times, such as setting up waste recycling systems. Business models that enable long-term sustainable impact can be more difficult to scale and grow fast due to their context-specificity and the managerial complexities that come with it (Almeshqab and Ustun, 2019; Korten, 1980).

The motivation to emphasize short-term quantitative outputs over the pursuit of long-term sustainability appears market driven as well as politically driven. Companies are frequently forced to aim for high sales volumes due to the low unit profit margins, while other goals in the design of their business models have to take a backseat. Donor pressure can aggravate the situation and political priorities can enforce short-term goals by placing a focus on, and providing incentives for, quantitative output targets in line with the way universal access goals are operationalized into leading tracking indicators (e.g., prioritizing the proportion of a country's population with access to electricity over the degree and reliability of the access achieved) (Arora and Stirling, 2021; Derks and Romijn, 2019; Linna, 2013). Social impact investors and other financial donors committed to a patient-capital approach appear to form a minority. The greenhouse gas emission reduction targets agreed by countries in the Paris climate agreement can have a similar performative effect. They can even give rise to a strategic neglect or suppression of evidence about the longer-term unreliability of renewable energy systems that is revealing about lack of actual progress achieved on the ground.

Hence, the tradeoff between short-term and long-term achievements affects the overall sustainability transition that unfolds over time. It reveals a limitation in the ability of corporate-led development to produce pathways that are sustainable, now and in the future, and tends to prioritize short-term goals. The review suggests that strategies to mitigate the tradeoff are an unexplored research area in the solar research and we found no plausible options. Overcoming this tradeoff appears particularly hard because firms deal with limited resources and the interrelatedness with other entangling tradeoffs makes it extremely complex to combine the best of all possible worlds.

3.5. Discussion

The review shows the limitations of the corporate-led market-based approach to off-grid solar energy access and the underlying reasons for this and highlights four main tradeoffs that make it difficult to realize progress towards various SDGs through one single off-grid solution. While the study is likely to underreport tradeoffs because of the used method and there could be more, it is clear that alternative, complementary solutions are necessary to address the shortcomings of the current model and the social and environmental injustices that it gives rise to. This is increasingly recognized by academics as well as people from within the solar industry (Cross and Neumark, 2021). The situation calls for more holistic and pluralistic approaches by Romijn and Caniëls (2011) and scholars from the Science Policy Research Unit (SPRU) and points out a need for 'pluriform pathways' to address global sustainability and developmental challenges (steps-center.org) (Delina and Sovacool, 2018; Ely and Bell, 2009).

More specifically, we see a role for the small-scale and informal sector entrepreneurs, the nonaffiliate solar technology suppliers, in closing the affordability gap that could be further explored. They appear to contribute substantially to universal energy access and reach the masses with more cost-efficient and cheaper solutions and do so without subsidies. Beyond product supply, the informal sector can be important for better waste management, recycling and e-waste handling (Cross and Murray, 2018) – although due to the nature of the materials used in renewable energy technologies it is unlikely that the sector can completely solve the problem of waste by itself. Arguably these enterprises have not been granted the credits that they deserve (although drawbacks are to be acknowledged) (Balls, 2020; Bensch et al., 2018; Groenewoudt et al., 2020; Sanyal et al., 2020). Yet, this phenomenon of 'under the radar' innovations can make a valuable contribution to sustainability transitions (Hanlin and Kaplinsky, 2016; Kaplinsky, 2011). This is done through adaptation of technologies of external origin to local settings in search of solving specific local problems, sustaining local livelihoods and enhancing local technological capabilities in the process (Bhaduri and Kumar, 2009; Kaplinksy et al. 2009). The contributions and further potential of actors in this area have been recognized and documented by many scholars working in the domain of frugal, inclusive and grassroots innovation research in development contexts, already since the advent of the appropriate technology discourse and movement in the 1970s (for more recent contributions see, e.g.: Chataway et al., 2014; Bhaduri and Talat, 2020; Knorringa et al., 2016; Leliveld and Knorringa, 2018; Pansera and Sarkar, 2016; Papaioannou, 2014). However, the implications from this work still remain to be translated into substantial change in support strategies for international energy and development projects by those in executive positions.

Another avenue for further research is the integration of non-market-based routes like non-profit and government-led interventions in the off-grid energy access (and e-waste) solutions in the off-grid sector, especially for those trapped in poverty who remain unserved through a market approach. Research has shown that such approaches have limitations as well and are constrained by, for example, incentives for meeting short-term energy access targets, and weak governance (Derks and Romijn, 2019; Feron, 2016), and should be mindful to avoid running into the same old pitfalls that led to the shift away from donor- and government-led approaches in the first place. Policymakers currently explore end-user subsidies to strengthen the market-based route, but this may not help the segments that firms perceive as too high risk. In this regard, hybrid collaborations between government- donor- or market-led approaches could be further explored as alternatives as well (Conway et al., 2019; Sovacool, 2013). Multistakeholder collaborations are highly complex, and the design of such coalitions may benefit from a design-oriented pluralistic stakeholder approach, as proposed by Kemp and Ramani (2020). Future research should also dive deeper in financial gains of (partially) market-based initiatives to establish a more precise and fine-grained picture of when and where profitability is feasible and realized, and when it is not (e.g., what income levels; what areas; what time frame).

The normativity that the contemporary development paradigm brings to market formation processes and transitions in the Global South can be brought into sustainability transitions research by taking a ‘Pathways Approach’ (Ely et al., 2013; Köhler et al., 2019; Leach et al., 2012). We see this as particularly promising in exploring alternative models because this approach casts aside the idea of one single, normatively ‘good’ development pathway and argues that any development intervention has its strengths and weaknesses (there is thus no such thing as ‘win win’). It opens up the possibility of pursuing a pluriform pathway that draw on the complementarities of multiple different approaches and in this way compensate for the limitations of individual approaches. This study offers a potential starting point by exploring one route of the potentially more pluriform pathway towards off-grid energy access.

Beyond the key findings for the off-grid solar sector, this study offers some insights that are relevant to extant literature on market formation and transition processes in Global South contexts more in general. Social constructivists point out that market formation is a socially and institutionally embedded process, involving the interaction of diverse actors in social arenas (Fligstein, 2001; Fligstein & Dauter, 2007). Transition processes revolving around the same technological innovations can unfold substantially differently in different spaces, owing to the specificities of the social-institutional market formation dynamics (Dewald and Truffer, 2011; 2012). This study shows that in Global South contexts, donors, global development agencies and affiliate companies are important shapers of market formation processes, for example through their attempts to regulate markets by enforcing instruments like global quality standards which downplay local non-affiliate enterprises, or designing financial support instruments in such a way that small players need special assistance to develop the capacity to meet the requirements (Hüls, Raats, Se1astian, Veen, and Ward, 2017). This resonates with findings from previous transition studies in developing countries that have highlighted that donor interventions sometimes hamper radical change and sustainability transitions (Wieczorek, 2017).

Another critical actor in the Global South is the informal sector entrepreneur. Although transition scholars recognize the importance of local actors in effective sustainability transitions, this group is frequently overlooked in energy transition research (Hansen et al., 2015; Nygaard et al., 2017; Tigabu et al., 2015). This calls for a more critical reflection on *all* actors taking part in transitions, especially those who are not involved in such processes the Global North, and stresses the importance of place centric, bottom-up research (Hopkins et al., 2020). Insights from this study show that systems for basic energy services are 'splintered' in developing countries (national grids, microgrids, solar home systems, solar lanterns), similar to what van Welie and colleagues (2018) observe in the Kenyan sanitation sector, and stress that the heterogeneity in solutions is substantially larger and involves also informal actors and unregulated and uncertified technology variants (Balls, 2020; Groenewoudt et al., 2020).

3.6. Conclusion

Markets and market formation processes are crucial enablers for sustainability transitions (Bergek et al., 2015; Boon et al., 2020) but shape their 'sustainability' outcomes as well, *a fortiori* in the Global South. This study engaged critically with the role of markets in areas of the world that are characterized by extreme poverty, and where a 'corporate-led market development model' has been strongly advocated and embraced by development actors as the one and only feasible solution for basic services provision for the Base of the Pyramid for several decades. In the current era of liberalized global markets, international policy and development interventions are widely framed around the promise of market-based development and rely on international companies affiliated to donors and development agents from the Global North for technology diffusion. This market-based approach to technology dissemination is expected to produce the wins for people, profit and planet that are needed for a veritable sustainability transition.

In this study, we explore the *limits* of this contemporary market model by means of a systematic literature review and identify multiple critical sustainability tradeoffs that are hardwired into companies' business solutions and prevent them from producing the anticipated triple wins, raising concerns about the reproduction and reinforcement of structural forms of human and environmental injustice: solar companies are unable to reach the lowest-income and isolated populations and foster a just energy transition, and cannot adhere to the cultivation of energy justice principles by producing dangerous waste. The findings from the energy sector thus suggest that the internationally supported corporate private sector approach cannot support a sustainability transition as such. At this point we did not find sufficient evidence to support the idea that the solar enterprises cannot become profitable at all, as some have implied (Conway et al., 2019; Ockwell et al., 2017). Rather, the corporate-led market-based model is inadequate to serve the poorest and rural populations and puts pressure on firms to choose short-term sales and profit targets over longer-term and less measured sustainability goals.

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CHAPTER 4

Off-grid energy policy: an analysis and new priorities

Groenewoudt, A. C., H. A. Romijn & F. Alkemade. (Submitted) Why is off-grid energy policy not promoting an inclusive, just transition in Africa? An analysis and new policy priorities.

Abstract

Progress in Sustainable Development Goal 7 is often framed as a driver of inclusive, just energy transitions and the 2030 Agenda for Sustainable Development. Yet, equitable transitions entail more than basic access to clean and affordable energy services; they depend critically on pluralistic, democratic, inclusive, and sustainable outcomes. Only recently has the energy and sustainability transitions literature become more critical of the sometimes-unsustainable nature of 'sustainability' transitions. While unsustainable trends clearly emerge frequently, it is generally unknown who or what drives them. This study considers what role policy and policymakers play in shaping sub-Saharan Africa's energy transition. More specifically, it analyzes the implications of off-grid solar policy i.e., actions, plans, and funding priorities of global-level energy and development organizations, investors, and governments, aimed at promoting the uptake of off-grid solar energy products. The study questions whether or not their efforts are actually driving the prioritized inclusive, just transition. Starting point is the African solar PV market—its realities and imminent sustainability challenges, capturing them in a dichotomy-based typology of solar innovation trajectories. As a guiding lens, we adopt the New Sussex Manifesto '3D agenda' (diversity, direction, distribution). This study demonstrates that future energy planning must embrace diversity and the thousands of local solar entrepreneurs to carve out a more equitable energy transition-pathway in sub-Saharan Africa.

4.1. Introduction

Progress in '*universal access to clean and affordable energy'* (SDG 7) is an important enabler of Sustainable Development Agenda 2030 and a fundamental pillar of realizing sustainable, inclusive, and just energy transitions and net-zero emissions by 2050 (HLDE, 2021; United Nations, 2021a; World Bank, 2020). This undertaking has endorsed major investments in the sub-Saharan African off-grid solar sector. About US$ 1.64 billion was invested between 2010 and 2018 in debt, equity, and grants, and specifically in large international solar home system companies (Wood Mackenzie, 2019; Lighting Global, 2020). Approximately 180 million solar home systems (>10 Wp) and smaller off-grid devices sold since 2010 provide 420 million people worldwide with access to at least basic energy services ('Tier 1' and higher) (IEA, IRENA, UNSD, World Bank, WHO, 2021; Lighting Global, 2020; ESMAP, n.d.). The UN's strategic energy roadmap proposes several measures for promoting the dissemination of off-grid lighting and energy products including enabling policies and regulatory frameworks; assisting privately owned solar companies; attacking private investors; scaling results-based financial (RBF) packages; and enforcing quality standards for Lighting Global's certified solar products (United Nations, 2021b). Action is urgently needed as the IEA's Stated Policy Scenario projects that 560 to 660 million people in Africa will remain without electricity unless more ambitious and effective plans are implemented (IEA, 2021).

The question is, however, whether current investments and plans are contributing to an inclusive, just energy transition that benefits all—be it rural communities, workers, businesses, or the natural environment (COP26, 2021). Recent energy and sustainability transitions literature suggests that we must consider critically the notions 'sustainable' and 'just' low-carbon transitions (Sovacool, 2021; Antal, Mattioli, & Rattle, 2020). Processes of socio-technical change can also foster (new) inequalities, social injustice, exclusion, and unsustainable developments (Kumar, et al., 2019; Hansen, Nygaard, & Dal Maso, 2021; Cross & Neumark, 2021; Samarakoon, Munro, Zalengera, & Kearnes, 2022; Bisaga, Parikh, Tomei, & To, 2021; Pedersen & Wehrmeyer, 2020; Groenewoudt, Romijn, & Alkemade, 2020; Zaman, Das, van Vliet, & Posch, 2021; Samarakoon, 2020). Calling for more reflexivity in transitions research, Antal, Mattioli, and Rattle (2020) stress that it is crucial we understand how these negative trends emerge, who is driving them, and how we can avoid becoming trapped in harmful transformations. Policy could play an important role: specific policies and actions can steer transitions in a certain direction

(Köhler, et al., 2019; Schot & Steinmueller; Müller, Neumann, Elsner, & Claar, 2021) and conscious policy efforts are required to ensure that sustainability transitions are inclusive, sustainable, and just (Sovacool, 2021; Truffer, et al., 2022). In Africa, policy supported actions have been pivotal in shaping the diffusion of solar home systems. Yet, while these target one particular goal: SDG 7, it is unclear how they address other Sustainable Development Goals and pursuing an inclusive, just energy transition (United Nations, 2021a; COP26, 2021).

The study analyzes the implications of current and announced policies aimed at promoting SDG 7 through the dissemination of solar home systems among households in sub-Saharan Africa. We review the actions (and inactions), funding priorities, roadmaps, and regulatory interventions by international energy and development organizations, global governments, and impact investors. As these actors have traditionally been influential in promoting the uptake of solar energy systems through rural electrification programs and global energy access initiatives, it is relevant to evaluate their efforts (Ockwell, et al., 2017; Groenewoudt & Romijn, 2022; Bensch, Grimm, Huppertz, Langbein, & Peters, 2018). An analysis of policy implications is relevant because, presently, possible conflicts between sustainability and developmental priorities is typically overlooked, both in political debates and academic literature (Schot & Steinmueller; Antal, Mattioli, & Rattle, 2020). It can help to assess whether changes are necessary to achieve a more inclusive, just transition pathway.

To support the analysis of policy implications, the study starts from the empirics and realities of the African solar PV markets and adopts a '3D' policy approach (Stirling, 2009). The three Ds stand for *diversity*, equal *distribution* of costs, benefits, and risks, and the *direction* of policy and prioritized goals. These dimensions are considered critical for sustainability politics in any domain and have been developed by scholars at the Social, Technological and Environmental Pathways to Sustainability (STEPS) Centre of the University of Sussex (Leach, 2012; STEPS centre, 2021; Ely & Bell, 2009). The 3Ds can help policymakers pursue a more pluriform, democratic, and just transition pathway. As such, they provide a suitable lens to examine the outcomes of off-grid energy policy. The underlying rationale of the 3D principles is that nurturing diversity and deliberately selecting pluriform and open pathways allow for greater variety and context-sensitivity. Pluriformity can help to cope with the uncertainties and vulnerabilities (winners and losers) that inevitably accompany the diffusion of new technologies (Stirling, 2011; Caniëls & Romijn, 2011).

Before explicating the specific 3D lens approach, we summarize the characteristics of two main solar innovation trajectories. These two distinct routes have emerged as dominating the market-based diffusion of residential solar PV (solar home systems) in sub-Saharan Africa. They are critical for assessing what could potentially jeopardize the equal distribution of costs, risks, and benefits for stakeholders. We subsequently elaborate on the research methods for our policy analysis and present the results. Finally, we discuss six new policy priorities and conclude with the study's implications and limitations.

4.1. Starting from market realities

Developments in the off-grid solar sector have seen the emergence of two broad solar innovation trajectories: two recognizably different unfolding routes for the commercial diffusion of solar home systems in sub-Saharan Africa. Rather than a hard-and-fast distinction, we identify these routes based on various dichotomies such as the main actors, incentives and drivers, market rationales, distribution models, and product characteristics, along with the associated costs, risks, and benefits. The insights presented here are derived from recent empirical studies, including our own (published) work on Uganda's solar home system sector (Groenewoudt, Romijn, & Alkemade, 2020; Grimm, Lenz, Peters, & Sievert, 2020; Groenewoudt & Romijn, 2022; Samarakoon, Barlett, & Munro, 2021; Samarakoon, 2020; Cross & Neumark, 2021; Balls, 2020; Kumar, et al., 2019; Kumar & Turner, 2020).

The first route, which we call the *global affiliates* trajectory, is led by large international solar companies and global development and energy agencies. These actors advocate modern and reliable energy access through distributing high-quality solar products (Ockwell, et al., 2021). This means products delivered to customers must comply with international quality standards and Lighting Global Quality Standards that set an international baseline of quality, durability, lumen maintenance, truth in advertisement, and 2-year minimum warranties (https://www.lightingglobal.org/) (Lighting Global, 2021). The international companies involved are typically affiliated with the Off-Grid Global Lighting Association (GOGLA), Lighting Global, or similar organizations, and these 'affiliate' companies' products meet the Lighting Global standards or are considered similarly good quality.

This trajectory is driven by energy access goals and business interests developed from earlier philanthropic and rural electrification projects. It is thus not, as sometimes suggested, the mere achievement of commercial parties and 'first-generation' off-grid companies established between 2010 and 2013 (van der Vleuten, Stam, & van der Plas, 2013). Many of the firms involved are European and Northern American such as Greenlight Planet, D.Light, Azuri Technologies, Bboxx, M-Kopa and Fenix International, and other companies providing 'pay-as-you-go' plans (Ojong, 2021). These allow customers to make periodical installments through mobile payment platforms and spread the cost over multiple months or years (Ockwell, et al., 2019; Rolffs, Ockwell, & Byrne, 2015). Scale is critical for these off-grid companies to compensate the minor profit margins from small off-grid products. Only a dozen international firms appear to have reached large enough sales volumes to operate at a profit (Lighting Global, 2020; Cross & Neumark, 2021). External investment and subsidies are often required in less densely populated and poorer areas. Recently, high-profile off-grid companies have attracted venture capital and financing from multinationals investing in clean energy (Ojong, 2021).

The second route, the *local solar* innovation trajectory, is more informal and rooted in local entrepreneurial activities, to address local needs and generate income. Central in this route are numerous local, small-scale vendors and capital-based wholesalers who discovered that PV systems are an attractive niche market (Groenewoudt, Romijn, & Alkemade, 2020). Some originate from rural electronics shops and added PV products to their range or gained experience from jobs in battery-charging services and electrics maintenance. Others were trained by solar equipment suppliers of larger power back-up systems or by private sector pioneers in the off-grid system (Ockwell & Byrne, 2016). These local solar entrepreneurs are typically *not* affiliated to global organizations and do not necessarily need scale (or subsidies) to be financially self-sustaining (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018). The term 'local' refers here to businesses established, owned, and managed by indigenous people, originating from the operating country or neighboring countries. They represent the large group of 'nonaffiliate' suppliers—though not all nonaffiliates are local; Chinese and Indian-owned solar companies are also part of this group.

Today, local solar entrepreneurs in Africa deal in a wide range of new and second-hand solar parts, distributed through a large decentralized and informal network of local solar shops and retail centers. Most components are imported from China, just like international companies' products (Samarakoon, Barlett, & Munro, 2021). Solar PV panels, batteries, and other solar equipment are used to locally assemble 'improvised' solar home systems from generic parts that can be mixed and matched. Users can rely on extensive repair shops, local technicians, and equipment suppliers and are not restricted to one individual company for sales, installation, maintenance, or repair services (Cross & Murray, 2018; Balls, 2020). This is in contrast with international firms that do not allow for repairs by local technicians as clients risk losing their 2-year warranties (Thomas, Williamson, & Harper, 2021).

While the literature has not focused on this trajectory, local solar entrepreneurs account for the majority of annual product sales (about 72%). In 2018, an estimated 23 million nonaffiliate solar products were sold, against 7.6 million affiliate products (Lighting Global, 2020). Data on nonaffiliate market or local sales and repair activities is scarce.

Both trajectories apparently originate from the same initial technological development of the African PV market. Commercial retail of solar PV to small households took off especially after 2010. There were already small business developments in rural areas and NGOs pioneering rural electrification projects, installing institutional PV systems in schools and hospitals. (van der Vleuten, Stam, & van der Plas, 2007; Lighting Global, 2020). From the late 1990s, a consumer market for PV was already evolving in frontrunner countries like Kenya and Tanzania (Hansen, Pedersen, & Nygaard, 2015). The first installation of small photovoltaic supply systems for rural electrification dates back to the 1970s (Lorenzo, 1997; Krauter, 2004).

Especially after the introduction of Lighting Global quality standards, developed as part of the Lighting Africa initiative launched in 2009, the distinction between the two trajectories has become pronounced. Recent reports and studies distinguish between affiliate and nonaffiliate suppliers and between certified and noncertified products. The World Bank initiative aimed to create markets for quality products and deal with the off-grid sector's performance issues (Verasol, n.d.; Lighting Africa, 2009). Today, there are standards for pico-products and solar home systems kits (TS 62257-9-8), as well as interim standards for component-based systems, comprising international standards with system design guidelines, installation, and warranty requirements (Lighting Global, 2020). In 2017, 94% percent of the nonaffiliate suppliers' systems tested by Lighting Global failed to meet the truth-in-advertising, safety, and durability requirements (Lighting Global, 2020).

The two routes have produced different technological solutions. The global affiliate trajectory has traditionally favored integrated solutions, "tamper-proof" to ensure reliable performance over time and reduce the risks of customers adding on extra appliances without permission or consulting a technician. This explains the popularity of 'plug-and-play' solar kits: all-in-one, pre-assembled, solar home systems that require no skill to install. In Eastern Africa, where most large off-grid companies operate, only a few companies work with non-pre-assembled components. Only a couple do so on a large scale because of the challenge that these systems must always be installed by trained technicians. Firms have to carefully tailor systems to consumption patterns to prevent blackouts, deep battery drain, shorter battery lifecycles, and early breakdowns (Groenewoudt, Romijn, & Alkemade, 2020). This adds to the complexity of managing supply channels and after-sales services, whereas plug-and-play companies like Fenix International and D.Light are able to collaborate with MTN, a mobile money provider, and Total Energies' petrol stations, to expand their distribution network.

Placing less emphasis on integrated solutions, entrepreneurs developed a local, low-cost adaptive alternative, less reliable in terms of quality and performance but much cheaper and still providing access to basic energy services. Unlike affiliate products, most solar home systems from local suppliers do not comply with international or Lighting Global's quality standards. Nevertheless, the more cost-effective ones (yielding more Wp for lower prices) offer a 'good enough' solution for people in areas unserved by international companies and an attractive alternative for those with limited financial means. Local vendors are inclined to serve all their clients, including those with very tight budgets, and are therefore willing to make concessions in quality if needed, by leaving out a battery controller for instance. Large scale customer surveys are lacking; however, several studies show that customers are satisfied with the locally assembled systems (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018; Groenewoudt, Romijn, & Alkemade, 2020; Balls, 2020) and that noncompliance with standards does *not* necessarily mean systems are of poor quality or perceived as such by clients. They can function decently, meaning that, mistakenly, noncertified products are thus sometimes framed low quality.

It is currently not known what share of the installed noncertified systems is still performing decently and what is actually perceived as poor quality. At any rate, quality issues have not caused major market disruptions, despite warnings by proponents of quality standards. Importantly, people's perception of quality differs and can be influenced by expectations and a lack of (affordable) alternatives. Availability of repair services can also play a role; if repairs are easy and cheap, malfunctions will affect customers less. This is often the case with improvised local systems: individual components are easy to replace, spare parts are widely available, replacements can be made by local technicians, in return for a small fee, or even by customers, and shops 'refurbish' batteries by adding new acid. For the lowest income households, however, there is still the risk that they cannot afford to buy a new battery, and this is the most vulnerable component.

At the same time, studies illustrate that products which *pass* Lighting Global certification do not necessary perform well (Samarakoon, Barlett, & Munro, 2021; Groenewoudt, Romijn, & Alkemade, 2020). Certified systems appear to perform somewhat better than noncertified products. But system performance depends on many different things, including proper use and maintenance. According to studies, failure rates remain high, product lifespans are short with 2-year maximum warranties, and products lose functionally over time (fewer lighting hours because batteries run down).

Relatively little exists 'in between' the two solar trajectories. There are several very large international market players, smaller foreign-owned companies, and many local solar enterprises, of whom only a few have professionalized and expanded beyond the regular small-scale rural shop. These exceptions, large local companies, are more common in mature off-grid solar markets, like Kenya. International companies vary to what extent they involve local people in top management positions, technical jobs, call-centers for customer services, sales (on payroll or commission), staff training, etc. and some are therefore considered more local.

Table 4.1: Solar innovation trajectories in sub-Saharan Africa

	***Global affiliate* innovation trajectory**	***Local solar* innovation trajectory**
Type of development	Global: top-down movement, led by international actors from public and private sector	Local: bottom-up movement, uncoordinated and decentralized
Influential policy instruments	Implementation and enforcement of quality standards, import regulations and taxes, energy access promotion programs, public and private investments, business support, voluntary agreements (e.g., Customer Protection Codes)	Implementation and enforcement of quality standards, import regulations and taxes
Key actors	Large international pay-as-you-go companies, impact investors, global energy and development organizations. Firms affiliated with GOGLA, Lighting Global and similar industry bodies	Local vendors and small-scale solar shops, repair shops, local technicians, capital-based outlet stores and retailers, importers Entrepreneurs not affiliated with GOGLA, Lighting Global and similar industry bodies
Drivers and incentives	Promoting clean, affordable, reliable, and modern energy services Profit-oriented, external investment and financing	Business opportunities Sustaining local livelihoods
Market rationale	Integrated high quality solutions Follows traditional corporate-led market development approach: firms pursue financial viability through scale and high sales volume	Low-cost business operations, often small-scale Lower cost 'good enough' off-grid solutions; Follow 'bare minimum design principles' if necessary to achieve lowest possible price point
Quality benchmark	International quality standards, Lighting Global Quality Standards	Based on perception of local market actors and end-users
Product characteristics	Certified, conformity to international quality standards, 2-year minimum warranties Higher priced Integrated plug-and-play solar kits and (some) component-based full-service systems	Noncertified, nonconformity to international quality standards Lower priced Locally assembled from generic solar parts, component-based improvised solar home systems
Distribution and service model	Offered with pay-as-you-go payment plans and after-sales services Distribution of products and services managed by international off-grid companies Branch offices in central district towns, headquarters in capital city	Cash payments, usually no payment plans offered Decentralized system for sales, distribution, installation, maintenance, and repair Supply chain of solar parts runs from importers via wholesalers in capital cities, to small scale shops Some entrepreneurs run a network of multiple outlets and stores
Benefits	Enables household access to basic lighting and electricity services from clean energy sources Customers benefit from more reliable and durable energy services; system performance is better than nonaffiliate products	Enables household access to basic lighting and electricity services from clean energy sources A wide clientele is served, including those with a tight budget and living in less densely populated and less economically developed areas

	Customers benefit from prepaid after-sales services and 2-year minimum warranties Workers benefit from jobs created by off-grid companies International solar firms benefit from returns on investment and profit (if applicable); in turn enabling them to penetrate new areas and reach more people The environment benefits thanks to avoiding CO2 emissions from fossil fuel-based alternatives	Customers benefit from low product prices (more Wp for lower prices) and flexible off-grid solutions Customers benefit from wide availability of repair services, technicians, and spare parts Local solar entrepreneurs, repair shops, local technicians, wholesalers, and retailers benefit from business opportunity and profit Countries benefit from a self-reliant ecosystem for diffusing solar PV The environment benefits thanks to avoiding CO2 emissions from fossil fuel-based alternatives
Costs	Lower income strata and rural areas remain unserved or underserved Customers pay high prices, especially if they require pay-as-you-go services for purchases Customers' energy services are sometimes disrupted by breakdowns Customers' warranties expire after 2 years, and they have difficulty securing warranties or requesting repairs and maintenance in areas where firms are not permanently present Natural environments suffer unsafe product disposal and solar e-waste from integrated hard-to-repair solar solutions Costly for global energy and aid agencies to stimulate firms to serve less economically attractive customer segments	Customers' energy services are frequently disrupted by breakdowns; systems are less reliable and durable than certified products Customers need to pay for repairs and replacements Customers and local vendors receive no or only short warranties Natural environments suffer e-waste from influx of 'no quality' and fake products, unsafe product disposal, abandoned unrepairable components, and environmentally unfriendly repair practices (battery 'refurbishing')
Risks	Customers risk taking on financial responsibilities they cannot sustain by buying on pay-as-you-go terms; if they cannot keep up payments, they risk disconnection from energy services and aggressive repossession of units	Local vendors and end-users risk becoming victims of 'no quality' and fake solar products and scams i.e., no refunds from wholesalers and importers for malfunctioning products

Looking at the costs, risks and benefits, the global affiliate trajectory has the advantage that it enables access to relatively reliable energy services. Yet it does not necessarily drive an inclusive, just transition. It has the advantage of regulated customer protection and after-sales services. Interviewees also mention employment opportunities for locals in sales and technical jobs (Kolk & van den Buuse, 2012). At the same time, international off-grid companies leave many off-grid communities unserved and underserved (Castán Broto, Baptista, Kirshner, Smith, & Alves, 2018; Sovacool, 2021; Kumar, et al., 2019; Zaman, Das, van Vliet, & Posch, 2021; Moore, et al., 2020). For some, even the smallest and cheapest products are unaffordable, despite pay-as-you-go payment plans, and those who can just afford them may receive little more than basic lighting services (Cross & Neumark, 2021). Firms typically don't penetrate the lowest segments of the Base of the Pyramid (BoP) and have no economic incentive to operate in sparsely populated areas unless they are subsidized.

Additionally, it is often too costly for companies to maintain permanent presence in such areas with few paying customers. There are for example refugee camps where firms operate without branch offices for after-sales services, thus clients find it harder to secure warranties and request repairs and maintenance (Thomas, Williamson, & Harper, 2021). In these areas it is also harder to recollect worn-out systems to prevent unsafe product disposal and minimize firms' ecological footprint (Hansen, Nygaard, & Dal Maso, 2021; Kumar & Turner, 2020).

Pay-as-you-go was introduced to close the affordability gap yet it also nudges customers into taking on a huge financial responsibility. Plus, firms charge interest rates that nearly double the costs for clients, who risk repossession of the system and disconnection from energy services if they cannot keep up repayments (Cross & Neumark, 2021; Grimm, Lenz, Peters, & Sievert, 2020). Another issue is that pay-as-you-go can create cashflow problems for companies.

The local solar trajectory, on the other hand, is an important enabler of widely available cheap solar products across sub-Saharan Africa (Grimm & Peters, 2016). In other words, it enables access to affordable energy services and a swift transition to clean energy. Local solar home systems are more cost-effective, more widely accessible for the rural masses, and suppliers operate without subsidies. This had led some to question the added value of promotional programs for rural electrification (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018).

From an economic point of view, the local solar trajectory is interesting too, because it not just creates jobs: an entire local, self-reliance ecosystem has developed around it. Despite little research, evidence from other sectors shows that bottom-up market development can enhance local capacity building. Frequent repairs, usually necessary to keep systems operating, and repeated interaction with clients, enable technicians to learn from client feedback (Groenewoudt, Romijn, & Alkemade, 2020). If local entrepreneurs can tweak and adjust technology designs, like with the component-based 'mix-and-match' systems, this can stimulate learning processes, enabling local entrepreneurs to improve their skills and potentially their systems' performance over time. This is less likely if entrepreneurs work with 'closed' technologies such as plug-and-play solar kits.

This trajectory does, however, experience technology performance issues and frequent breakdowns. Systems have the advantage that individual components can be replaced locally, avoiding the disposal of entire systems, as is sometimes necessary with solar kits; nevertheless, there is the huge problem of accumulating solar e-waste over time. This is particularly problematic because solar parts contain toxic and hazardous materials, and in many, especially rural areas, safe disposal facilities and recycling infrastructure are scarcely available. In contrast with affiliate suppliers, local solar businesses usually do not recollect unrepairable components—in practice, broken batteries regularly end up in people's homes and gardens.

The risk of early system breakdowns is severe due to the many fakes and 'no quality' solar parts on the sub-Saharan African PV market (Twaha, 2017; Spire Ssentongo, 2018). Fake products look identical to regular parts and are hard to distinguish from decent quality components for local vendors and end-users. This means that they risk buying things that almost immediately wear out. There are records of Ugandan vendors struggling to get refunds from retailers and warehouses in Kampala for fraudulent products: wholesalers disappear, don't pick up their phone, claim products were subject to improper use, etc. (Groenewoudt, Romijn, & Alkemade, 2020). In interviews they also mentioned the stream of extremely low quality and fake products had increased in recent years, making reliable and decent quality components harder to come by, part of a wider trend in sub-Saharan Africa (Kamukama, 2018; Samukange, 2015; Nkirote, 2020). Clearly, this poses a major risk to buyers and is making Africa's solar e-waste problem even bigger.

These implications of the two trajectories are summarized in Table 4.1 and form the basis of subsequent policy analysis.

4.2. Research method

This study made a '3D' policy analysis of the directionality, diversity, and equal distribution of costs, risks, and benefits. Policy can be defined as a series of actions (and inactions), regulatory measures, funding priorities, or voluntary practices by governments or organizations to achieve a specific goal. We investigated the consequences of policies created by multilateral energy and development organizations, global governments, and public and private investors aimed at promoting universal energy access through off-grid solar product diffusion in sub-Saharan Africa. In this exercise we integrate insights from the previous section captured in Table 4.1. To enable a systematic analysis of policy outcomes we focused on the following guiding questions:

- To what extent is *diversity* promoted within, between, and beyond the two innovation trajectories?
- How are costs, risks, and benefits *distributed* among stakeholders and what actions are taken to mitigate risks?
- What is the *direction* of current policies i.e., what are the prioritized goals and to what extent are the implications of these priorities acknowledged?

The study's analysis is based on primary field data from research undertaken in Uganda in 2018 and complementary desk research in 2021. Our field research included 117 interviews with stakeholders in the Ugandan solar home system sector such as customers, local vendors, international entrepreneurs, market experts and GOGLA representatives, the German Association for International Cooperation (GIZ), and the Ugandan National Bureau of Standards (UNBS). The desk study included a review of policy documents such as global energy access roadmaps,

Table 4.2: Details of field research and desk study

Method	Year	Sources	Details*	Geographical scope
Field research	2018	Interviews Field trips	117 semi-structured and open interviews with international and local solar enterprises, market experts, representatives of UNBS, CREEC, GIZ, GOGLA, solar home system users and nonusers	Uganda
Desk study	2021	Policy documents and roadmaps Investment reports Online events and 1-to-1 discussions Websites	HDLE 2021, Energy Compacts, SE4All, World Bank, Lighting Global, Lighting Africa, Verasol, United Nations, Power Africa, ESMAP, ESRAF, RISE, USAID, RVO, GIZ, BuZa, FMO, IEA, IRENA, EnDev, SNV, Acumen, Energy4Impact, SunFunder, Norfund, etc.	Sub-Saharan Africa

* Uganda National Bureau of Standards (UNBS), Centre for Research in Energy and Energy Conservation (CREEC), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Global Off-grid Lighting Association (GOGLA), High-level Dialogue on Energy (HLDE), Sustainable Energy for All (SEforALL), Energy Sector Management Assistance Program (ESMAP), Energy Subsidy Reform Assessment Framework (ESRAF), Regulatory Indicators for Sustainable Energy (RISE), United States Agency for International Development (USAID), Netherlands Enterprise Agency (RVO), Dutch Ministry of Foreign Affairs (BuZa), Dutch entrepreneurial development bank (FMO), International Energy Agency (IEA), International Renewable Energy Agency (IRENA), Netherlands Development Organization (SNV).

statements on websites, investment and High-Level Dialogue on Energy (HDLE) reports (see also Table 4.2). This review focused on the actions, investment plans, announcements, and regulatory interventions of global actors involved in the off-grid sector. It did not cover national policy documentation because this study aimed to unpack the dynamics of the global-level strategy for clean energy access pursued by leading international institutions and investors like FMO, World Bank, UN's SE4All, and others listed in Table 4.2. Part of the desk study was holding online discussions with policy experts from the Dutch Ministry of Foreign Affairs, SNV's Global Energy Team, and the Dutch entrepreneurial development bank FMO.

4.3. Results

4.3.1. Diversity

The analysis shows there is limited diversity in off-grid policy: action plans and interventions primarily aim to promote the global affiliate trajectory. This was discerned from the active role that global programs like Lighting Global play in shaping this trajectory. Additionally, support programs focus on affiliate suppliers and increasingly certified solar products. For example, to prepare for its High-level dialogue on Energy on 24 September 2021, the United Nations published an energy access report (United Nations, 2021b). It contains priority recommendations for the off-grid sector, stating that national electricity strategies need to be backed up by "least-costs, best fits plans relying on a mix of technologies and user-centered implementation and business models […]" (United Nations, 2021b, p. 4). However, it highlights the increased adoption, implementation, and enforcement of international quality standards in at least 45 more countries, implying that non-certified products are not part of this 'mix'. The local solar trajectory, on the other hand, is hardly mentioned. The latest Off-Grid Market Trends 2020 report, that counts as one of the leading reports for the off-grid sector and is produced by GOGLA, the World Bank Group, Lighting Global, and ESMAP, mentions non-affiliate companies distributing non-certified products but 'the non-affiliate market is not well understood' (Lighting Global, 2020, p. 5). The report does focus on affiliate suppliers and calls for US$ 6.6–11 billion additional financing arguably necessary to unlock commercial opportunities and close the affordability gap (p. 3).

In addition, financial support has been concentrated in a small group of large pay-as-you-go companies like Zola Electric, M-Kopa, D.Light, Lumos, Greenlight Planet, Mobisol, Bboxx, and Azuri (Wood Mackenzie, 2019). The top-9 recipients of investments absorb about 80% of the total investment in the solar home system sector—nearly US$ 1 billion between 2010 and 2018 (Lighting Global, 2020). World Resources Institute (WRI) research shows that the majority of pay-as-you-go companies operating in Africa are foreign-owned and foreign-managed (Sanyal, Chen, & Caldwell, 2020). The big companies regularly receive support for distributing millions of solar home systems in Africa (Cision, 2017). The World Bank, for instance, recently approved a $200 million off-grid electrification project to attract large market players to West Africa, co-financed by the International Development Association (IDA) (150 million), DTF (74.7 million), the Energy Sector Management Assistance Program (ESMAP) (2.5 million), and the PHRD (2.7 million) (World Bank, 2019a; World Bank Group, 2021). In general, it appears that the suppliers granted assistance are those who can quickly deliver measurable and verifiable sales results that increase the number of people with a Tier 1 energy access connection and higher.

The issue of investment concentrated in a select group of foreign-owned and -managed firms has come up in several industry-level discussions (Sanyal, Chen, & Caldwell, 2020). Some organizations' program managers have tried to limit their share of investment in large corporate players, invest in firms' preliminary market development activities like training technicians in new markets, and create financial incentives to ensure firms penetrate unserved market areas—not merely 'pick the low hanging fruit' in wealthier regions. Some projects have allocated particular budgets to promote broader accessibility of grants for local off-grid companies (ROGEP, 2019) and parties like EnDev and Acumen are attempting to diversify their portfolio by also investing in smaller agents. Yet, with a minimal application of EUR 200,000 and provided on a results-based financing (RBF) basis, organizations are unlikely to attract typical small-scale local enterprises (Open Capital Advisors and Acumen, 2019; EnDev, 2021). In the past, there have been efforts to help local solar enterprises grow and professionalize. In Uganda, for example, GIZ partnered with a Ugandan enterprise called Solar International Ltd. This company deals in solar parts and operates from a department store in Kampala, but according to a GIZ representative, the collaboration ended after unconvincing results.

While collaborations with local enterprises exist, the local market actors are less likely to receive financial support. They typically lack the resources and connections to apply for assistance and don't meet the necessary application requirements.

Application processes tend to be bureaucratic, and applicants are increasingly asked for product certifications and compliance with the Lighting Global Quality Standard. Lighting Africa, for instance, works exclusively with product suppliers that meet Lighting Global Quality Standards (Lighting Africa, 2009); the Lighting Global programs hold the standards as a requirement for participation; GOGLA has asked all its members to adhere to the standards and customer protection codes (GOGLA, n.d.), and ESMAP, too, promotes only the uptake of high-quality products, services, and implementation of the Lighting Global Quality Standards framework (ESMAP, 2020).

In principle, local solar suppliers can meet Lighting Global standards, but the majority do not. Just like any other nonaffiliate supplier, they apply for certification but there are costs involved for quality certificates (paid by the applicant). This creates an obstacle for local entrepreneurs in Africa, especially those who earn a meagre living from small-scale sales to rural households, despite possessing the necessary expertise, measurement equipment, and the ability to deliver solar home systems of similar quality. Local solar companies are less likely to attract impact investors because they traditionally lack visibility and are often perceived as high risk and suffer from a reputation as suppliers of low-quality products ("*they can't work, and they don't work*" and "*they have a negative impact on the sector*" (Groenewoudt, Romijn, & Alkemade, 2020, p. 106; Peacock & Mungai, 2019).

4.3.2. Distribution

Current investment patterns and the focus on dissemination of quality certified products have implications for the equal distribution of benefits, costs, and risks among stakeholders in the off-grid sector. First, it is typically the local solar entrepreneurs who are excluded from financial support, for the reasons discussed above. The Global Off-Grid Lighting Association is now calling for additional funding and end-user subsidies to help affiliate members reach the lowest income strata and last-mile customers (GOGLA, 2021). The question, however, is whether this is fair towards nonaffiliate local solar entrepreneurs who operate widely across sub-Saharan Africa and distribute more cost-effective systems (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018).

Second, because impact investors and energy access programs focus on international pay-as-you-go companies for disseminating solar home systems, this automatically excludes the poorest people mainly in remote rural off-grid areas. Investors also have to consider other societal and environmental costs and risks associated with a global affiliate solar trajectory (summarized in Table 4.1). Organizations and programs promoting SDG 7 have taken steps to address the downsides and these have led to some necessary improvements in recent years. GOGLA, for instance, has developed an E-waste Toolkit and asked its 170+ members to commit to ‘extended producer responsibility’ principles, a voluntary agreement to stimulate take-back schemes, recollection of e-waste, and improved circularity along the entire value chain (GOGLA, n.d.). GOGLA, having devised a Customer Protection Code in partnership with investors CDC, FMO, and DOEN Foundation, encourages companies, investors, and other stakeholders to commit to principles of transparency in sales, fair and respectful treatment of clients, responsible pricing, good customer services, good product quality, and personal data privacy, to be reviewed within daily operations and monitored through a self-assessment tool. Similarly, the World Bank calls on funding applicants to develop mitigation strategies that will avoid social and environmental damage and counteract poor waste management, aggressive repossession of units, non-replacement of products, and workers’ inappropriate behavior violating the codes of conduct and safe working practices (World Bank, 2019b).

These and similar initiatives have not, however, been able to mitigate all the flaws in the global affiliate trajectory and many of the nonaffiliate market issues remain unaddressed. GOGLA’s efforts only target its members and the World Bank’s requirements only relate to those applying for funding, whereas a global-level response to the rise in fake products is lacking. The issue of counterfeit products has been left to national governments and local authorities like the Ugandan National Bureau of Standards (Samarakoon, Barlett, & Munro, 2021). In Uganda and also in other countries, these bodies seem to be failing to regulate the markets (Kamukama, 2018; Samukange, 2015; Nkirote, 2020). Global regulatory measures are not tailored to this specific problem and Lighting Global Quality Standards are more likely aimed at keeping all noncertified products off the market. Likewise, a global response to solar e-waste from the nonaffiliate market seems nonexistent. Efforts are being made locally and on a small scale. While our analysis does not focus on actions at a national level, we came across a Ugandan company named Uganda Batteries Limited (UBL) that takes in old batteries to extract valuable materials for new batteries. The re-use of PV panels and refurbishment of batteries in local repair shops can also be seen as (unintended) waste management activities. Interestingly, GIZ published a report in

2018 on the end-of-life management of batteries, arguing that the local practice of 'refurbishing lead-acid batteries should be completely discouraged' (possibly due to pollution) (Manhart, Magalini, & Hinchliffe, 2018, p. 24).

Third, we see an indirect effect of the focus on affiliate market suppliers, namely that it jeopardizes all those who could benefit from the local solar trajectory. These include local solar entrepreneurs but also repair shops, local technicians, and other stakeholders in local economic activity and self-reliant industry development.

The implications of these findings are twofold. They highlight that certain groups benefit more than others, with urban high-income households and employees of international firms as notable winners, and natural local environments, local solar and repair businesses, and unserved or underserved populations as losers. The distribution issues on the other hand illustrate once again that global actors with a vested interest in off-grid energy policymaking consider the global affiliate trajectory the preferred option to realize SDG 7 and ignore the local solar trajectory.

4.3.3. Direction

This study analyzed the outcomes of current policy promoting clean and affordable energy access. We note that the main target is to increase the percentage of the population that has access to electricity, and generally ensure everyone's connection is at least Tier 1. The Multi-Tier Energy Access Framework that measures global progress in energy access, defines Tier 1 as energy services providing a minimum of 4 hours light per day, of which 1 hour in the evening and a minimum capacity of 3Wp (ESMAP, n.d.). The global affiliate trajectory is generally considered the preferred route to realize universal energy access. However, while we found indirect evidence, this direction is not explicitly stated in policy documents and the mainstream strategy's fundamental principles. Neither the implications from pursing this trajectory, nor the imminent costs and trade-offs, are discussed.

4.4. Discussion: six new policy priorities

The study uncovers several flaws in off-grid energy policy. We recommend that future clean energy planning concentrates on integrating the *global affiliate* trajectory and the *local solar* trajectory to carve out a more inclusive, just energy transition-pathway in sub-Saharan Africa. We outline six new policy priorities that can facilitate this process.

1. *Build on complementarities* – different innovation trajectories can compensate each other's weaknesses (Stirling, Direction, distribution and diversity! Pluralising progress in innovation, sustainability and development, 2009). The potential benefits are: first, small-scale local actors could play an important role for unserved population groups. Unless radical action is taken, 560 to 660 million people in sub-Saharan Africa will still be without electricity in 2030. Local solar enterprises are better positioned to tap into markets unreached by international suppliers and do so without subsidies; furthermore, unlike corporate firms, they are already active in most African regions and rural areas. Second, involving local solar entrepreneurs in global energy transition-strategies is preferable from a social justice perspective. Third, engaging with the nonaffiliate sector could be an opportunity to push the uptake of higher Tiers of energy services and productive use leveraging solar energy (PULSE). Solar systems that enable users to generate income by powering solar water pumps, fridges, and other productive-use appliances are typically larger, thus more expensive and local market actors have the advantage of producing more cost-effective systems.

   Building on complementarities requires stepping away from Lighting Global Quality Standards as 'the golden standard' and adopting a more lenient approach towards 'good' quality and product performance. Integrating nonaffiliate suppliers in off-grid electricity plans is a controversial strategy and disliked by policymakers because noncertified product markets are unregulated and deemed poor quality. However, this study highlights that such concerns are only partially valid because nonaffiliate products can perform well enough regardless of no certification. Essentially, the belief in the value of standards as a policy tool is based on Western norms and values and standards are sometimes mistakenly taken as a guarantee for durable (or even sustainable) products. This diverging market reality has yet to trickle down to energy policy.

   Global industry bodies probably embrace pluriformity and invest more in developing human capital than in programs for top-down implementation of standards and supporting certain certified product suppliers. One can think of country-wide roll-outs of free skills training for local vendors, or awareness campaigns to warn customers about the risks of battery inverters shutting off, disregarding warning lights that indicate battery drain, and economizing on battery sizes, as well as increasing vendors' ability to distinguish fake products from decent-quality components. Providing 'internal' incentives to stimulate quality improvement may also be more effective (or rather: less ineffective) in countries with poor border control, where it is generally unknown what enters the country and finds its way to people's homes. There is a lot of variety, every system is unique, and testing every improvised solar home system is not a realistic option. Institutions may also want to invest in 'repair standards' instead of 'quality standards' to improve repairability rather than extend product lifespans by attempting to make technologies tamper-proof.

2. *Mitigate risks* – both trajectories must have protection measures to avoid (sometimes irreversible) social and environmental damage and counteract the 'dark side of the sun,' as Hansen and colleagues call it (2021). With e-waste a lurking problem, the risks are currently not sufficiently addressed and even less in the local solar trajectory. Currently, international energy programs do not feel it is their job to tackle the problems created by nonaffiliate suppliers, yet someone needs to take responsibility because the sustainability of the entire off-grid sector is in jeopardy. GOGLA's voluntary agreements for affiliate companies are initial steps, but more action is needed.

   Fake and no-quality products pose another major threat to the market and international parties need to support actions against outright fakes. The current attempts to keep all unaffiliated products off the market through pushing western-style quality assurance programs may be counterproductive: this is an incentive for clandestine activities hidden from formal control bodies. A more lenient quality approach should be tailored to the specific problem of fake products and try to make it easier for buyers to distinguish between good and identical looking or 'no quality' parts, for instance by making measurement equipment more widely available. We see this as important new priority for policymakers that must not be left to only national governments if they cannot cope.

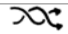
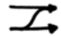
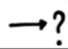
3. *Harness synergies* – pursuing more pluriform pathways increases the likelihood of fruitful synergies between different innovation approaches (Stirling, 2011; Stirling, 2009). Interplays between the two solar innovation trajectories and purposeful policy interventions can advance both tracks. For instance, a sustainable energy transition-pathway would benefit from more collaboration

between corporate market players and local repair industries to serve users and reduce the off-grid sector's waste footprint (Cross & Murray, 2018). Users could have simple repairs done by local technicians and dealers' repair shops could become part of the global solution to electronic solar waste by letting them re-use parts left over from affiliate suppliers and helping them recollect (and revalue) broken components. Technically and practically speaking, such policy solutions are highly complex and require amendments to warranty schemes. Nevertheless, this is worth the investment, especially in countries like Uganda that lack a sustainable e-waste management system and where there is large-scale unsafe disposal of batteries. To tackle these issues, governments could invest in innovation projects finding ways to repair solar technologies safely and refurbish them locally. It is worth taking a look at an existing project, Solar What (www.solarwhat.xyz), that has designed a solar-powered lamp and charger for simple repairs, re-use, and recycling that can be done anywhere.

4. *Stimulate cross-fertilization and learning* – a diversity of interconnected approaches fosters cross-fertilization and creativity in innovation (Stirling, 2009). Currently, interactions between the two solar trajectories are not actively promoted, and sometimes even discouraged. Yet, there are signs that Africa's energy transition is benefiting from more deliberate promotion of spillovers between the two trajectories, as previous examples illustrate. First, technicians trained at affiliate off-grid companies sometimes leave their employer to start their own local business. Such spillovers can stimulate local capacity building, the development of technological skills, and potentially quality improvement of local nonaffiliate systems. Second, affiliate suppliers can learn from local solar entrepreneurs how to design more resilient and cost-effective systems. One example is SolarNow, who extensively studied local solar home systems before designing its own. Drawing lessons from its findings, the company designed component-based systems with the advantage of individually replaceable components (unlike plug-and-play systems). Another interesting example of interaction comes from the nonaffiliate market in Uganda, where there are incidences of copy-cat brand names on products. While perhaps a fraudulent practice, it is also a sign that affiliate products can serve as exemplary model for local vendors and thereby set the quality bar. We see a potential role for knowledge institutions and global energy associations like GOGLA in coordinating more purposefully the efforts to improve cross-fertilization.

5. *Nurture hybrids* – hybrid 'in between' initiatives have the potential to bridge the gap between opposite innovation trajectories or approaches (Ely, Smith, Stirling, Leach, & Scoones, 2013). Hybrids come in different shapes and sizes and operate across different political, institutional, financial, and knowledge dimensions; they combine characteristics from divergent tracks (for instance: cheap *and* good performance) but are usually scarce because they embody an uneasy combination of values. With commercial solar models, certain business principles tend to 'lock in' or 'crowd out' alternative traits, preventing firms from combining the best of both worlds. This may have played a role in the emergence of the two 'opposite' solar innovation trajectories. In the more mature Kenyan market, a larger group of domestic enterprises has professionalized and collaboration with Kenyan owned companies is apparently fruitful—possibly also thanks to the more favorable national regulatory frameworks. This scenario is an avenue for further research and an alternative direction for subsidizers and investors willing to step away from conventional promotion.
6. *Articulate priorities* – Articulating priorities towards innovation, and acknowledging the implications are key, because decisionmakers tend to pursue 'progress' and 'sustainability' without further specifying a choice of direction or prioritized values (Stirling, 2009). Such ambitions imply a scenario where wins are produced for every economic, social, and environmental facet of sustainable development, while in reality, actors make (and need to make) choices. The aim to achieve modern, reliable, affordable, and sustainable energy access for all (SDG 7) embodies this kind of thinking. Political debates focus on the shared

Table 4.3: summary of policy recommendations

distribution	*diversity*	build on *complementarities*	
		harness *synergies*	
		stimulate *cross-fertilization*	
		nurture *hybrids*	
	directio	mitigate *risks*	
		articulate *priorities*	

common goal without questioning underlying norms and prioritized values or discussing alternative routes. However, the implicit underlying preferences (e.g., high quality) must be articulated more explicitly to enable greater critical consideration of the implications and tradeoffs for wider sustainable development goals. This is also key in exploring and exploiting the potential complementarities of the two existing solar trajectories.

4.5. Conclusion

The dissemination of clean energy technologies can—and will—threaten progress in sustainability and developmental areas, yet the conditions under which such unsustainable trends emerge are not well understood (Antal, Mattioli, & Rattle, 2020). Research findings indicate that through current actions, global actors are failing in their efforts to promote an inclusive, just transition in sub-Saharan Africa and support coherent implementation of the 2030 Sustainable Development Agenda. This study demonstrates that the current focus is predominantly the global affiliate solar trajectory, whereas the local solar innovation trajectory tends to be ignored. Yet, both trajectories come with benefits, costs, and risks and neither presents a 'win-win' for all stakeholders. The study therefore calls for a pluriform, democratic, inclusive, and sustainable energy transition-pathway and outlines six new policy priorities for pursuing this (building on *complementarities*, harnessing *synergies*, stimulating *hybrids* and *cross-fertilization* in innovation, mitigating *risks*, and acknowledging *priorities*).

Reflecting on our findings, we observe two major issues. First, a lack of reflexivity on policy outcomes. Throughout policy documents and discussions, clashes with other developmental and sustainability priorities are largely ignored. Avoiding this discussion blurs the prospect of coordinating an inclusive, just, or sustainable transition. As other researchers have described (Ockwell & Byrne, 2016, p. 10; Stirling, 2009), the tendency is to pursue one individual, incontestable, and normatively 'good' development pathway, directed at 'fixing' the global rather than embracing the local solar trajectory as an equal or complementary solution to clean and affordable energy for all. This greater focus on corporate players and less on local innovation actors features in other political innovation strategies (Ely, Smith, Stirling, Leach, & Scoones; Bhaduri & Talat, 2020). While perhaps overlooked in policy, the emergence of a thriving local solar sector surely does not come as a surprise, given that Africa is known for its cheaper local equivalents of basic consumer goods (e.g., unregistered taxies, sub-standard phones, second-hand clothing) (Banerji & Jain, 2007). Local products can sometimes form a good alternative and a more ‘appropriate’ fit for local contexts (Kaplinsky, 2011). Of course, the degree of reflexivity varies between program managers and policymakers, as we noted in the interviews, and some take deliberate steps to make energy transition-strategies more inclusive and just, by opening up subsidy schemes for smaller market players.

The second issue is that policymakers face the extremely complex challenge of providing the remaining 759 million people in sub-Saharan Africa with off-grid energy access, by 2030, and in a responsible manner. Accelerating the global energy transition is critical to keep the Paris Agreement goals within reach (COP26, 2021). This puts major time pressure on realizing SDG 7. Moreover, inclusive, just transitions require the involvement of many different stakeholders, and weighting their interests every step of the way may hamper the speed of the transition (Schot & Steinmueller). Adding to the complexity of this challenge, it is often hard to predict upfront what unsustainable trends may emerge later on; some only become visible once transitions gain momentum. Unforeseen and ‘collateral’ effects emerge over time, as innovation processes can take decades to unfold from first-time invention to large scale diffusion—and do so in unpredictable ways. Navigating a sustainable energy transition-pathway thus becomes highly complex. While the lack of reflexivity in policy allows room for improvement, this may restrict the potential to realize transitions that benefit ‘all’. These are important considerations for future research seeking to unpack the unsustainable nature of sustainability transitions.

This study responds to previous calls to support more pluralistic, democratic, and just transitions through interdisciplinary research in all contexts, particularly understudied geographical areas, and develop more prescriptive policy recommendations (Sovacool, 2021; Delina & Sovacool, 2018; Caniëls & Romijn, 2011; STEPS centre, 2021; Ely & Bell, 2009). It also follows up on previous studies criticizing off-grid energy access strategies (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018; Groenewoudt & Romijn, 2022; Cross & Neumark, 2021; Ockwell, et al., 2017). Some of the earlier critiques and recommendations are accommodated in the new policy agenda, like the need to abolish Western style quality standards (Samarakoon, Barlett, & Munro, 2021), engage with local market actors (Bensch, Grimm, Huppertz, Langbein, & Peters, 2018; Balls, 2020; Groenewoudt, Romijn, & Alkemade, 2020; Sanyal, Chen, & Caldwell, 2020; Ngoasong, Paton, & Korda, 2015), and focus more on repair (Cross & Murray, 2018; Spear, Cross, Tait, & Goyal, 2020; Samarakoon, Munro, Zalengera, & Kearnes, 2022).

The 3D approach proved useful for a critical assessment of off-grid energy policy. Mapping the 3D against a dichotomy-based typology of innovation trajectories allowed for a focused and systematic analysis. This methodological approach is similar to how Ely et al. (2013) analyzed science, technology, and innovation perspectives at past UN sustainable development summits (Ely, Smith, Stirling, Leach, & Scoones, 2013). Future research may benefit from this approach as well in order to conduct a systematic analysis of policy implications.

Like any study, this research has its limitations. First, the list of costs, benefits, and risks in Table 4.1 derived from the literature and is likely inconclusive. While it forms the basis for our evaluation of equal distribution (of costs, risks, and benefits), undiscussed effects may exist, and new dilemmas may crop up in years to come. Constant reflection is thus necessary. Especially when it comes to the local solar trajectory, the data is limited, and studies cover only a selection of sub-Saharan African countries. Second, the literature focuses more on local 'victims' than global beneficiaries such as impact investors and aid agencies. This implies a kind of bias that must be considered when interpreting the results. Third, due to the level of analysis and the scope of most policy documents, this study could not account for cross-country differences. Many of the online roadmaps and documents report only on continent-level policies without specifying country-level actions. We decided not to include the regulations and plans of the 46 individual countries in sub-Saharan Africa, to keep the review scope clean and doable. Consequently, the findings may not be as accurate for locations where market information is scarce, such as Mali, Chad, Angola, and many other African countries seldomly covered in academic research (Groenewoudt & Romijn, 2022; Sovacool, 2021). Results are most accurate in locations relatively well covered by recent empirical studies such as East Africa and the southern coast of West Africa. Future research could focus on developing a better picture of markets in other regions and explore national and regional differences.

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CHAPTER 5

Conclusion

5.1. Conclusion

There is growing recognition that environmental and societal challenges require integral solutions. Yet, literature on energy transitions and off-grid solar markets has long avoided discussing issues of tension and conflict with other sustainability and developmental priorities. Instead, it has focused on the potential of solar energy technologies to achieve energy and climate goals.

In this study, I explored the wider sustainability implications of expanding solar markets in Africa. The study shows how the commercial diffusion of off-grid solar products has also harmful consequences for present and future generations. Drawing on rich empirical data, I uncover how these effects are shaped by the emergence of two distinct *solar innovation trajectories*. The global affiliate trajectory, led by large internationally oriented solar companies, is increasingly emerging as the dominant route for donors and investors to promote SDG 7. The local solar innovation trajectory, led by local informal sector entrepreneurs in Africa, is often associated with low(er) quality products, but produces also more cost effective and widely accessible solar energy systems. This study highlights the potential, limitations, and risks of both trajectories (summarized in Chapter 4, Table 4.1). The downsides range from accumulating amounts of solar e-waste to people losing their money on fraudulent products. While problems are more severe in the local trajectory (e.g., fake products, poor quality, scams), neither of the routes realizes a 'win-win' and ensures access to affordable, reliable, sustainable, and modern energy for all.

The study uncovers several structural problems that stand in the way of a more integral, equitable and sustainable approach, most importantly, the dominant perspective and approach of development actors and the direction of off-grid energy policy. Policymakers and investors often envision modern energy access as a prerequisite of a fair energy transition. It is typically assumed that this requires 'high quality' technology solutions and Western-style quality assurance. Lighting Global states: '*modern, high-quality off-grid lighting and energy products offer a real and sustainable alternative to the off-grid population*' (Lighting Global, n.d.). From this perspective, corporate solar enterprises contribute to a sustainable energy solution. Yet, it disregards the limitations of private entities and the pernicious consequences of expanding off-grid solar markets. Engaging with local low-cost enterprises, as proposed in this study, is seen as a controversial strategy, and disliked by many policymakers because the nonaffiliate market is largely unregulated and associated with inferior, lower quality products—even though it may be fruitful for sustainable impact creation.

Another issue is that corporate market players are often confronted with the reality that sometimes they need to choose between people-, profit-, and planet-oriented goals. Illustrating this, many have developed more advanced, but less affordable integrated solutions to provide more reliable energy services. Such dilemmas appear almost inevitable, especially when operating in contexts characterized by extreme poverty, remote rural areas, and poor infrastructure. In such contexts, where the necessary resources are hard to come by, it is common for actors to focus on primary outputs and becoming less concerned about secondary outcomes. Often it also means drifting away from initial ambitions (a problem also known as 'goal displacement') (Derks & Romijn, 2019). Indeed, large solar companies have become increasingly focused on quantitative targets and less on long-term sustainability results.

All in all, the study concludes that solar markets have the potential to power off-grid communities but also create a setting in which customers are highly vulnerable to exploitation, the natural environment is polluted, and existing inequalities are further amplified. As markets are expected to experience rapid growth in the coming years, the situation is likely to worsen, leading to more toxic e-waste, exposure to fraudulent products, etc., unless action is taken to resolve these issues. The study discusses six new policy priorities to guide these efforts, viz: building on *complementarities*, harnessing *synergies*, stimulating *hybrids* and *cross-fertilization* in innovation, mitigating *risks*, and acknowledging *priorities*.

5.2. Contribution to the literature

5.2.1. Two solar innovation trajectories

The main contribution of this thesis lies in the identification and analysis of the two solar innovation trajectories. By analyzing these trajectories, it provides a more accurate and complete picture of the actual impact of solar markets in sub-Saharan Africa and offers first, systematic insights into the sustainability implications of these markets. The study illustrates, as also predicted by Stirling (2009), that many direct and indirect effects can emerge around the uptake of new technologies and do so in unanticipated ways. The study also discusses important interactions between sustainable and unsustainable dynamics and provides insights into the market-related and political dynamics that shape these effects, such as; the necessity of, and pressure on, off-grid companies to become profitable; the push from political actors and impact investors to focus on increased connection rates (measured in 'Tier 1' or higher access) and measurable impact results; concessions that need to be made to significantly reduce costs in order to serve the world's poorest populations; the general lack of effective quality control in many African countries; and a local demand for ever cheaper off-grid solar solutions.

On a more systemic level, the study uncovers a kind of normative '*directionality*' in the trajectories. Directionality refers to a tendency to pursue one single normatively 'good' approach to address societal challenges, while there are in fact different options (Schot & Steinmueller, 2019; Stirling, 2011). It is reflected in the dominant approach of Global North-affiliated actors (and firms) in Africa and hidden in the underpinnings of current energy decision making; the moral claims made about off-grid solar products; the widely celebrated role of donor backed solar companies; and the push for western-style quality assurance. This directionality is key to understand *why* unsustainable trends emerge and sustainability transitions unfold *un*sustainably. It becomes also visible from the general lack of attention for the alternative local solar innovation trajectory (see also: Chapter 3, Table 3.3) and the limited discourse on the tradeoffs associated with the global affiliate trajectory, both in political debates and academic literature.

According to Schot and Steinmueller (2019), directionality is one of the reasons of failure of sustainability transformations. They argue that current policy approaches focus on innovation benefits and insufficiently recognize that 'many technologies are deeply implicated in persistent environmental and social problems' (Schot & Steinmueller, 2019, p. 1562). In other words, we often fail to acknowledge the direction of innovation, which may directly contribute to inequality because decisionmakers tend to 'favor high tech solutions which assume high quality and pervasive infrastructure, and produce mass-produced products aimed mainly for consumers with substantial purchasing power' (Schot & Steinmueller, 2019, p. 1562; Elzinga, Janssen, Negro, & Hekkert, 2021; Arora & Stirling, 2021; Kaplinsky, 2011). Similar, Ely et al. (2013) argue that policymakers tend to opt for global 'top-down' types of innovation approaches (while locally derived 'bottom-up' approaches and grassroots innovations can sometimes better respond to local situations and sustainability needs) (Romijn & Caniëls, 2011; Knorringa, Peša, Leliveld, & van Beers, 2016; Cozzens & Sutz, 2014; Dolan & Roll, 2013; Bhaduri & Talat, 2020; Ely & Bell, 2009). The study demonstrates the preference for high tech 'high quality' solutions and top-down implemented innovation approaches empirically and illustrates how this affects Africa's energy transition. As such, it highlights an important structural issue that limits our possibilities to realize integral sustainability solutions and shows, empirically, why it is necessary to pursue plural and open transition pathways.

Schot and Steinmueller (2019) also discuss other reasons of failure, including the lack of reflexivity in policy and policy coordination failure, referring to the inability to coordinate and align sustainability policies across various domains. By reflecting on current off-grid energy policy, this study demonstrates these failures too (Chapter 4) and illustrates how they have pernicious consequences for the people in Africa.

An important lesson for future research is for scholars to gain more awareness of the normative quality of the directionality of transitions and the implicit assumptions made about sustainable technologies and dissemination strategies. This study shows that it is key to become more critical towards the outcomes of energy and sustainability transitions and reflect on the prioritized goals and SDG targets. This requires profound empirical research and challenging expectations about 'good' innovation approaches. In this case, it proved useful to draw on older development literature on economic development paradigms to better understand the contemporary approach and the underpinning rationales and assumptions.

5.2.2. A local alternative

In addition to distinguishing between the two trajectories, this study is one of the first to describe the dynamics and role of the local solar innovation trajectory in depth. Prior to this research project only one study, by Grimm et al (2016), had extensively studied the noncertified product segment. While more followed in the course of executing this project (see for example: Samarakoon (2020; 2021) and Cross & Murray (2018)), this thesis constitutes one of the first research projects to provide such detailed accounts of the activities of local solar entrepreneurs and low(er) quality products in the renewable energy market in Africa. The discovery of this local solar innovation trajectory demonstrates the necessity of extensive field research, especially in understudied locations outside Europe, North America, and other Western contexts. Energy researchers and policymakers have so far overlooked the locally rooted solar innovation trajectory – and the benefits thereof. The insights of this study into this alternative route are also relevant for a broader scientific movement that calls for greater recognition of local 'below the radar' innovations in unfolding transitions (Kaplinsky, 2011; STEPS centre, 2021).

5.2.3. Towards an integral approach

Moving on towards potential policy action, this study discusses possible complementarities between the global and local innovation trajectories. These may help to think differently about the potential of the competing routes and offers prospects for more integral solutions. These insights may also be relevant for a broader audience as similar trajectories may unfold in other sustainable technology domains like clean cooking or sanitation. (Some write for instance about low quality cookstoves made by micro-enterprises in Kenya (wa Kabecha, 1999)). The study also underlines the risks and limitations of pursuing one particular 'good' trajectory without considering alternatives or recognizing of the normative quality of the directionality of innovation, sustainability, and development approaches.

The findings of this study fully align with recommendations by other researchers who argue that we must think radically different about sustainability challenges— and their solutions—if we are to realize sustainable progress (Stirling, 2009). Sustainability calls for reflexive governance and new modes of handing societal problems (Voss, Bauknecht, & Kemp, 2006). As stressed by Antal, Mattioli, & Rattle (2020, p. 361), 'Investigating unsustainable trends would benefit transitions research by making it more plural and more radical. Unless more effort is put into understanding ongoing unsustainable trends, transitions studies may not live up to their goal of "helping to move society in the direction of sustainability" (Köhler, et al., 2019)'. This study shows how this can be supported through research that takes a more holistic perspective, draws on 'bottom-up' empirical research, and is open to insights from alternative theoretical traditions (Hopkins, Kester, Meelen, & Schwanen, 2020).

In conclusion, the study makes an important contribution by highlighting what it will take to develop more integral sustainability solutions and realize inclusive, just, and sustainable energy transitions.

5.3. Policy recommendations

This thesis demonstrates that the international development community mainly focuses on a global affiliate innovation trajectory to pursue universal energy access. Yet, simply stimulating the adoption of renewable energy technologies through investments in international solar companies and promoting quality certified products is not enough and has even counterproductive effects. The main policy recommendation is therefore to develop more pluriform and integral solutions to address the energy challenge. In this context, this dissertation discusses the possibilities of closer interaction with the local solar innovation trajectory. If we are to achieve an equitable sustainability transition, it is essential that progress in energy access targets is not reached at the expense of core ethical principles like inclusive development, justice, or long-term sustainability outcomes. Rather than focusing on specific electricity targets, the energy challenge must be approached as being part of a wider global sustainability challenge and transition. The study also illustrates the dominant role of Western norms and values in off-grid energy policy that affects the direction of the unfolding transition. It shows that current decisions are to be challenged from an ethical perspective as they lead to missing out on opportunities for local economic development and increasing social equality.

Governments, development actors, and investors must place their energy-related actions within a wider frame and acknowledge the directionality of interventions. Designing more integral and pluriform solutions may prove a highly complex as so many different interests and stakeholders. Yet there are possibilities to do so and actors who are well positioned to support this. Already working on the e-waste challenge, GOGLA may also focus on interactions with other SDGs. In addition, the study shows that there are actors who are currently not taken into account, such as small local vendors and Chinese importers. They, too, should be given the opportunity to get on board and stop the harmful consequences of solar energy markets in Africa.

Appendix

6.1. References of the introduction (CH 1) and conclusion (CH 5)

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6.2. Summary

Ensuring '*access to affordable, reliable, sustainable and modern energy for all*' (Sustainable Development Goal 7) is key to support poverty reduction and development efforts and act against climate change. The International Energy Agency (IEA) estimates that still 759 million people worldwide live without electricity access. Off-grid technologies like solar home systems and solar lanterns offer an opportunity to connect these households to basic electricity services, powered by renewables. Especially in Africa, electrification through decentralized solar-powered solutions is gaining momentum. This development has been bolstered by major investments in the African off-grid solar sector, particularly targeting large-scale diffusion activities by large international solar companies. Since 2010, over 180 million off-grid solar products have been sold on a commercial basis. Solar markets are increasingly seen as a sustainable solution to serve the world's poorest population and achieve net-zero emissions by 2050.

However, despite the promise of this trend, there are increasingly also signs of harmful (side)effects like unsafe product disposal, solar e-waste accumulation, and exposure to low quality and even fake solar products. While much is written on energy and sustainability transitions, there is still limited attention for such adverse consequences of shifts to low-carbon energy sources. Scholars tend to disregard that societal and environmental challenges—and their solutions—are often intertwined, and thus require integral approaches with critical attention for the limitations and risks of 'sustainable' energy solutions.

This doctoral research investigates wider sustainability implications of such solutions. More specifically, it focuses on commercial solar markets in sub-Saharan Africa and explores how the market-based uptake of off-grid solar products impacts progress in other sustainability and developmental domains. It does so by taking an explorative research approach and starting from the empirical realities of the off-grid solar market, including insights from a large field survey undertaken in Uganda.

The study shows how the direct and 'collateral' effects of solar energy diffusion in sub-Saharan Africa are essentially shaped by the emergence of two distinct solar innovation trajectories: a global affiliate trajectory, led by large internationally oriented solar companies and focused on the delivery of high quality solar products that meet international quality standards, and a local solar innovation trajectory, led by local informal sector entrepreneurs in Africa. While the first is increasingly

emerging as the dominant route for donors and investors to promote SDG 7, the second produces more cost effective and more widely available off-grid solutions. The study highlights the potential, limitations, and risks associated with each of these trajectories.

The research demonstrates that the commercial diffusion of solar home systems and smaller solar devices also has harmful consequences for present and future generations. The downsides range from accumulating amounts of solar e-waste to people losing their money on fraudulent products. While problems are more severe in the local trajectory (e.g., fake products, poor quality, scams), neither of the routes realizes a 'win-win' and ensures universal access to affordable, reliable, sustainable, and modern energy for all. The study concludes that solar markets have the potential to power off-grid communities but also create a setting in which customers are highly vulnerable to exploitation, the natural environment is polluted, and existing inequalities are further amplified. As markets are expected to experience rapid growth in the coming years, the situation is likely to worsen, leading to more toxic e-waste, exposure to fraudulent products, etc., unless action is taken to resolve these issues. The study discusses six new policy priorities to guide these efforts.

Important contribution of this doctoral research is that it offers a more accurate and complete picture of the actual impact of solar home systems in Africa. It demonstrates how sustainable and unsustainable outcomes can yield from the diffusion of renewable energy technologies and emerging innovation systems. These effects tend to be unpredictable and can unfold in unforeseen ways. The study also uncovers several structural problems that stand in the way of more integral, equitable and sustainable energy solutions, including the direction of off-grid energy policy. The study observes a kind of normative 'directionality' in the dominant perspective and approach of global development actors. Directionality refers to a tendency to pursue one single normatively 'good' approach to address societal challenges, while there are in fact different options. Policymakers and investors often focus on high tech solutions and Western-style quality assurance, but tend to overlook the threat of negative tradeoffs and the unrecognized potential of local innovation. This dynamic is important because it helps us to understand why sustainability transitions may unfold unsustainably, and hence, what it will take to address this.

6.3. Curriculum vitae

Aleid Groenewoudt was born on 13 September 1991 in Deventer. After finishing her VWO, she studied Innovation Sciences (MSc) at Eindhoven University of Technology. In 2016 she graduated *cum laude* and her thesis was nominated for the TU/e Master Thesis Award and published in an academic journal.

In 2017 she started her doctoral research on energy innovation in the Global South at the Technology, Innovation and Society (TIS) group at TU/e. As part of her PhD project, she undertook field research in Uganda and visited rural communities and upcountry dealers. The results of her research are presented in this dissertation.

During her PhD research Aleid was also involved in education activities and earned her University Teaching Qualification (UTQ). From July 2019 onwards she combined her PhD with project management for the Interreg cVPP project. After finalizing her PhD, she started working at the Project Management Office (PMO) of ASML.

6.4. List of publications

Publications in this thesis

Groenewoudt, A. C., Romijn, H. A., & Alkemade, F. (2020). From fake solar to full service: An empirical analysis of the solar home systems market in Uganda. Energy for Sustainable Development, 58, 100-111. https://doi.org/10.1016/j.esd.2020.07.004

Groenewoudt, A. C., & Romijn, H. A. (2022). Limits of the corporate-led market approach to off-grid energy access: A review. Environmental Innovation and Societal Transitions, 42, 27-43. https://doi.org/10.1016/j.eist.2021.10.027

Submitted for publication

Groenewoudt, A. C., H. A. Romijn & F. Alkemade. (Submitted) Why is off-grid energy policy not promoting an inclusive, just transition in Africa? An analysis and new policy priorities. Energy Research & Social Science.

Other academic publications

Groenewoudt, A. C., Rooks, G., & van Gool, P. J. (2019). When problems lead to ideas: the roles of daily vigor and social interactions. The Journal of Creative Behavior, 53(3), 286-297. https://doi.org/10.1002/jocb.179

Groenewoudt, A. (2018). Book Review: Cooper, E. and Pratten, D., editors. 2015: Ethnographies of Uncertainty in Africa. https://doi.org/10.1177/1464993418786401