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Equal goods, but inequitable capabilities? A gender-differentiated study of off-grid solar energy in rural Tanzania

A. Gill-Wiehl [a,*], I. Ferrall [a], D.M. Kammen [a,b]

[a] Energy and Resources Group, 345 Giannini Hall, University of California, Berkeley, CA 94720, United States of America
[b] Goldman School of Public Policy, University of California, 2607 Hearst Avenue, Berkeley, CA 94720, United States of America

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ABSTRACT

Women and low-income households experience a disproportionate burden of energy poverty and have different capabilities to utilize access to energy. Despite this, many electrification plans insufficiently address gender and low-income households. Off-grid solar has and will continue to play a role in expanding access to electricity in rural Sub-Saharan Africa; however, off-grid solar is rarely examined across gender. We draw on a quantitative survey and qualitative interviews from a case study in rural Tanzania to investigate the energy justice implications of off-grid solar. We are the first article to evaluate and compare the primary goods approach and the capabilities approach for off-grid solar. We ask how the distributional benefits of off-grid solar are mediated by gender and class, filling a key gap in the literature of off-grid solar's impact. We find little evidence of gender differentiation from a primary goods approach, suggesting equality within off-grid solar usage, but inequity through a capabilities approach lens. Solar home systems remain out of reach for the lowest-income households. In our case study, off-grid solar is used both as a primary source for low-and-middle-income households, and as a back-up source for middle-and higher-income households. We find that solar energy is under-used as a means of income generation and that payment schemes may not be the key to achieving energy justice. We provide concrete recommendations for rural energy policy and global tracking frameworks to ensure that women and low-income households have not only equal, but equitable access to obtain the capability benefits of off-grid solar.

1. Introduction

Sustainable Development Goal 7 (SDG7) calls for "universal access to affordable, reliable, sustainable, and modern energy services" [1] (pg. 1). Women and low-income households carry a disproportionate burden of energy poverty and lack of services. These burdens materialize prominently as higher air pollution exposure for women [2] and a higher percentage of income spent on fuel for low-income households [3]. These disproportionate burdens are core motivating factors for the theoretical and practical pursuit of universal energy access. Additionally, the United Nations reports that energy access enables the pursuit of at least nine other SDGs including eradication of poverty, gender equality, and increased work and economic growth [4].

Although providing the level of service currently provided by high-quality grids is the ultimate goal, decentralized systems – such as mini-grids, solar home systems (SHS), and solar lanterns – represent a vital interim level of access. Decentralized systems have played a prominent role in providing electricity access, particularly in East Africa [1]. The International Energy Agency (IEA) projects that 55 % of the population lacking access will first gain electricity through mini-grids (30 %) or stand-alone systems (25 %) [5].

Despite this, much of the grey and peer-reviewed scholarship of off-grid solar access, usage, and impact rarely differentiates by gender [6–8]. Anditi et al. 2022 suggests a gender-analysis framework for

Abbreviations: CA, Capabilities Approach; ESMAP MTF, Energy Sector Management Assistance Program Multi-Tier Framework; IEA, International Energy Agency; PAYG, Pay-as-you-go financing model; PGA, Primary goods approach; PPI, Progress out of Poverty Index; REA, Rural Electrification Agency; SDG7, Sustainable Development Goal 7; SHS, Solar Home Systems.

* Corresponding author.
E-mail addresses: agillwiehl@berkeley.edu (A. Gill-Wiehl), Isa.ferrall@berkeley.edu (I. Ferrall), kammen@berkeley.edu (D.M. Kammen).

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energy policy in Africa, but only for urban informal settlements [9]. Research finds that even gender-positive approaches of utility-scale solar in India disempower women and exacerbate economic exclusion [10,11]. As off-grid solar[1] plays a growing role in rural electricity access worldwide, studies evaluating its impact are increasingly important.

This article investigates the energy justice implications of off-grid solar in relation to gender and low-income households using a case study in rural Tanzania. We ask, "How do gender and social class mediate the benefits of off-grid solar technologies at the household level?"

In Tanzania, 77 % of the population lacks direct access to electricity,[2] placing it among the top twenty access-deficit countries. The provision of access in Tanzania is keeping pace with population growth [1], but rapid improvement is needed in order to meet SDG7's goal of universal access by 2030. Despite Tanzania's focus on expanding the national grid, investment in off-grid solar continued to rise, particularly between 2014 and 2017 during drought-related power outages [12]. Overall, the 2017–2018 Tanzanian Household Budget Survey found that 29 % of the population used the national grid as their main lighting source, while 26.5 % used off-grid solar. This leaves 55.5 % of the population to rely on torches (rechargeable lamps), kerosene, candles, paraffin, etc.[3] This case study focuses on a rural town, Shirati, located in the Mara Region, where in 2017–2018, 20.7 % of the population used the national grid as their main lighting source and 26.6 % used off-grid solar [13].

Despite the prominence of off-grid solar in Tanzania, ethnographic articles are rare. Existing works find energy to be a "relational and gendered configuration of people, nature, labor, and sociality that makes and sustains human and natural life" [12] (pg.71) and document the tumultuous, and unjust, relationship between rural, low-income customers and solar energy companies [14]. Our case study set in rural Tanzania builds off this emerging work and adds to the growing body of energy justice literature on off-grid solar, specifically regarding gendered and low-income access through a quantitative survey, qualitative interviews, and observation.

Our article contributes theoretically to the field as the first to distinctly evaluate and compare both the primary goods approach (PGA) and the capabilities approach (CA) for energy access in an individual case study, specifically focusing on gender, low-income households, and off-grid solar.

We find little evidence of gender differentiation from a PGA, suggesting equality within off-grid solar usage, but inequity through a CA lens. Off-grid solar remains out of reach for low-income households. In our case study, off-grid solar is used both as a primary source for low-and-middle-income households, and as a back-up source for middle-and higher-income households. We find that solar energy is underused as a means of income generation and that payment schemes may not be the key to achieving energy justice. We provide concrete recommendations for rural energy policy and global tracking frameworks to ensure that women and low-income households have not only equal, but equitable access to obtain the capability benefits of off-grid solar.

[1] When 'solar' appears in this text without qualifiers, we refer to off-grid, home-scale, paneled, photovoltaic solar systems rather than grid-connected systems or pico-solar products such as solar lanterns, or solar thermal systems. 'Off-grid solar' or 'SHS' can be interpreted as equal to 'solar'.

[2] The IEA defines access to electricity, as "a household having access to sufficient electricity to power a basic bundle of energy services – at a minimum, several lightbulbs, phone charging, a radio and potentially a fan or television – with a level of service capable of growing over time" (pg. 1), but practically measures it as a grid connection or stand-alone system that provides the above basic energy bundle [17].

[3] Note, diesel generators were not considered in the survey. However, the "other" category comprised only 1 % of the population.

2. Off-grid solar

Off-grid solar has rapidly expanded in the last ten years to provide lighting to millions across low- and middle- income countries, particularly in Sub-Saharan Africa, and is expected to expand to 823 million users by 2030 [15]. Products range from pico-solar lanterns to high-capacity SHS, but lanterns represent the majority of sales (83 %) [15].

The World Bank's Energy Sector Management Assistance Program (ESMAP) developed a Multi-Tier Framework (MTF) whose Tiers range from 0 to 5 to reflect differing levels of energy access based on capacity, duration, reliability, quality, affordability, legality, health and safety, and consumption. Tier 4 corresponds to the IEA's definition of access to electricity (1250kWh annually) [16,17]; However, solar lanterns only enable Tier 0 and SHS generally only reach Tier 1 or 2[4] [16].

Prior research documents the technical, social, and economic aspects of SHS for the interim level of access provided. Technical evaluations of SHS find challenges regarding quality [18,19], installation and maintenance [20], and monitoring [21]. Other studies find that SHS impacted household energy spending, the time and quality of children's education, and improved rural livelihoods [20,22]. However, SHS largely remain out of reach for low-income households [23–25] and affect women and men differently based on time spent in the home [26,27].

Despite its documented limitations, off-grid solar is still the preferred technology in some rural areas [25,28]. There is a recent focus on productive uses of solar energy and payment schemes to support the market's continued expansion. Therefore, our case study examines productive uses and payment schemes as two key pathways through which gender and class can mediate the distributional benefits of off-grid solar.

2.1. Productive uses

The United Nations defines a productive use in these contexts as the "creat[ion] [of] goods and services either directly or indirectly for the production of income or value" [29]. While the academic community has long cited the need for consumers to use off-grid energy for productive uses to increase the financial viability of these systems [30,31], the sector has largely ignored productive uses within the home. ESMAP claims that "increasing productive uses of mini-grid electricity creates a win-win-win-win scenario for mini-grid developers, rural entrepreneurs, communities, and national utilities over time," [30] (pg. 17). However, it is unclear if all individuals within the household receive the same level of benefit [32,33], and studies rarely disaggregate their analysis by gender. Focusing on income generation without explicitly focusing on gender, may unwittingly perpetuate gender inequalities. It remains to be seen if (and how) women benefit equitably.

2.2. Payment schemes

Many off-grid solar companies in East Africa offer their systems to households on payment schemes to lessen the barrier of large upfront costs [34]. Various models exist within the umbrella category of payment schemes, primarily differentiating across two dimensions. First, in terms of long-term system ownership, l*ease-to-own* models transfer ownership to the household upon payment completion, while *energy-as-a-service* models allow companies to retain system ownership and sell only the energy generated [34]. Second, models may sell different units, namely kWhs of energy or hours of time. For the purposes of this article, payment schemes are defined generally as small payments made over time as opposed to a single upfront cost.

The common pay-as-you-go (PAYG) financing model is used for both

[4] GOGLA defines SHS as having more than 11Watts (Wp) solar (Tier 1 access). Systems below 3Wp are considered lanterns (Tier 0 access) and those 3-11Wp are considered multi-light systems [15]

lease-to-own and energy-as-a service models [34]. PAYG offers more flexible payment amounts and timelines often enabled by mobile money. Although Suri and Jack find that mobile money disproportionately benefited women [35], it is not clear that mobile money combined with SHS do as well [36] (pg.1).

3. Conceptualizing and operationalizing energy justice and ethics

Energy justice scholarship is concerned with the achievement of equity in both social and economic participation in energy systems, while also remediating social, economic, and health burdens on marginalized communities [37]. Prior theorization organizes the concept into three core tenets: distributional, procedural, and recognition justice [38], or into eight principles [39–41] (discussed and operationalized in Section 3.2). Distributional energy justice evaluates the allocation of the benefits and burdens of energy. Procedural energy justice is the equitable engagement of all stakeholders in decision making, and requires "participation, impartiality and full information disclosure" [38] (pg.2). And finally, recognition energy justice calls for the fair representation and the offering of complete and equal political rights to all individuals [38]. While framed as distinct, there is considerable overlap within this framework, particularly between procedural and recognition justice. This article primarily focuses on distributional and recognition energy justice in alignment with Sovacool et al.'s observation that energy poverty is a clear violation of distributional justice [39] and women's (and children's) daily energy supply is often ignored. All three tenets require additional research [42]. Here, we discuss the topics of finance, intersectionality, and productive uses of solar energy, which have implications regarding decision making processes and agency, and map onto wider patterns of injustice. Thus, this work ultimately engages all three tenets.

According to Sovacool, "Distributive justice deals with three aspects: what goods, such as wealth, power, respect, food, or clothing, are to be distributed? Between what entities are they to be distributed (for example, living or future generations, members of a political community or all humankind)? And what is the proper mode of distribution – is it based on need, merit, utility, entitlement, property rights or something else?" [39]. This article evaluates what goods from off-grid solar are distributed and between what entities.

3.1. Primary goods versus capabilities approaches to energy justice

In a novel theoretical contribution to the energy justice literature, we operationalize our concept of energy justice using two modes of distribution inspired by two of the most influential political philosophers of the 20th century, John Rawls and Amartya Sen. We define:

i. ***A primary goods approach*** (***PGA***) in which every individual has a minimum level of said good, inspired by John Rawls egalitarian perspective in 'A Theory of Justice' [43]. This is to say to each in equal parts – referred to as *equal*.
ii. ***A capabilities approach*** (**CA**) in which every individual receives according to the level needed to enable the individual to achieve equivalent capability, inspired by the work of Amartya Sen and Martha Nussbaum [44–46]. This is to say to each according to need – referred to as *equitable*.

As an example, while an approach prioritizing equality may value equal access to, usage, and impact of off-grid solar, an equity approach would account for the disproportionate burden felt by electricity's absence. Women and low-income households are most impacted by energy poverty, and therefore stand to gain the most from access. Equal and equitable both stand distinct from a utilitarian approach which is prone to reproducing existing gender and class-based social power asymmetries [43].

We build off recent literature that has theorized and applied either the PGA or the CA to energy justice. PGAs to energy access often prescribe a minimum or total amount per person per year, such as ESMAP's MTF's Tiers and the IEA's definition of access to electricity (1250kWh annually) [16,17]. These PGAs are constructed from the capabilities that the amounts provide, and assume that each individual requires equal amounts and is equally able to employ that standard share. For example, studies evaluated actual consumption and modeled suspected basic needs for lighting, health, education, and community services to set average primary-good minimum-energy thresholds [16,47–49].

Sovacool (2014) conceptualizes energy poverty as fundamentally an issue of energy justice through the CA. Day et al. outlines a framework for low-, middle-, and high-income countries to evaluate distinct types of capabilities from energy access [50]. These works frame energy as a means to an end rather than a good itself. These works do not explicitly outline the difference between equal and equitable as we do; however, it is embedded in their arguments. For example, Day et al. explains that the amount of energy needed for heating will depend on factors such as climate, weather, physical well-being, heating system efficiency, and housing quality [51]. A PGA would prescribe a certain amount of heat, while the CA would consider these needs and adjusts the amount of heat provided accordingly. Day et al. further distinguishes between primary, secondary, and tertiary capabilities [51], which others build on as well [52]. To utilize solar lighting as an example, a primary capability is to engage in social interaction or perform basic tasks, while the secondary capability is to sufficiently light your home. Secondary capabilities allow the enactment of primary capabilities. Finally, a tertiary capability would be to manage your energy supply and use within your home. However, Middlemiss et al. critiques this framework arguing that these levels of capabilities are a complex web within social conditions and energy access [53].

Researchers have applied the capability framework to energy justice case studies of grid and mini-grid systems in Australia, Mexico, Afghanistan, India, Peru, Bolivia, and the Philippines [52,54–57]. These studies highlight that the literature must consider what the services are for and account for how different users can benefit (or not) from that service, not simply target the fuel, energy source, or amount of supply. Our work adds to this literature as the first article to distinctly evaluate and compare both the PGA and the CA for energy access in an individual case study, using these approaches to distinguish equality and equity. Further, we are the first to evaluate energy justice through the CA for SHS, which provide a significantly different, yet important level of access. Finally, we are the first energy justice work utilizing the CA to explicitly focus our considerations across gender and low-income households.

3.2. Eight core principles within energy justice

In addition to the three tenets, the literature defines energy justice using eight core principles: availability, affordability, due process, transparency and accountability, sustainability, *intra*- and *inter*-generational equity, and responsibility [39–41]. We focus on three of these principles: availability, affordability, and intragenerational equity. Availability is access to high quality energy resources, namely high quality SHS; affordability demands that access to energy is not a large financial burden; finally, intragenerational equity is the ability for all individuals to access the available and affordable energy services, namely women and lower income groups [39].

3.3. Energy ethics

Despite our reliance on these guiding tenets and principles, we also lean into a distinct, yet complementary literature on *energy ethics* [58]. Rather than a framework, this approach relies on how individuals themselves view energy's role in their lives and communities and the associated ethnical concerns. This approach additionally allows us to understand how our respondents in rural Tanzania place value on energy, in ways that may or may not be just, yet still offer valuable insights.

4. Energy justice through off-grid solar energy access

Critical energy access, energy poverty, and energy (in)justice research regarding both grid and off-grid electricity in Africa has grappled with the implications of post-paid and pre-paid meters [59], heterogenous infrastructure [60], and even SDG7, arguing that the goal marginalizes 'traditional' energy sources [61].

Focusing on off-grid solar, there is a growing body of literature questioning whether the market is truly attempting to include low-income households and act as a social and economic good [14]. Emerging research finds inequities in affordability particularly for low-income households [33], unfair distributions of electricity reliability [19], and unequal engagement, transparency, and distributed benefits for all stakeholders [62]. Studies critique off-grid solar for adding additional financial burden and expectations onto low-income households [25,63,64], and question whether it alone can transform low-income lives [65,66].

Other literature reveals that off-grid solar companies while focusing on financing hardware and entrepreneurship, fail to meet the needs of their low-income customers even with microfinance [33,67–69] leading to the exploitation and ultimate exclusion of rural, low-income households [14,63].

In comparison to affordability, intragenerational energy justice of off-grid solar's impact regarding gender is seldom investigated. The studies that do exist have evaluated the impact of solar energy on gender empowerment in Peru and Bangladesh and found that women using solar energy spent less time on agricultural activities, more time awake, less time collecting firewood, more time reading, and more time on other chores [70–72]. Overall, discussions regarding the *potential* benefits of electricity access to women [73,74] are far more common than studies evaluating whether they occur and to whom they accrue. The call for further research and delivered outcomes on the gendered implications of solar energy technology is clear [10,75].

Notably, there is limited, yet growing, literature on the intersection of gender and solar energy enterprises or income generation in Tanzania, but also globally [32]. Only one evaluation of rural solar energy microenterprises in Tanzania differentiates their findings by gender. They find that most businesses were owned by men, and men-owned businesses consumed more electricity than their female-owned counterparts [32].

In the public sector, Tanzania's 2015 National Energy Policy promotes gender equality, and Tanzania's Rural Electrification Agency (REA) specified a 'Gender Strategy and Action Plan' [76]. Within the private sector, there are female focused solar energy companies such as Solar Sister and the Tanzania Gender and Sustainability Energy Network [77].

Despite this emerging literature alongside public and private sector initiatives, there are still many unanswered questions surrounding energy justice implications of off-grid solar in Tanzania regarding gender and low-income households.

5. Methods: case study

This case study draws from a household energy survey ($n = 187$), in-depth household interviews ($n = 30$), follow-up interviews (10), key-stakeholder interviews, participant observation, and personal experiences in Shirati, Tanzania throughout multiple fieldwork experiences between 2017 and 2021.

During the first fieldwork in 2017, we conducted a household energy survey with 187 households within four villages in Shirati, Tanzania to understand the energy landscape within the villages. We chose respondent households through random sampling of every fourth house throughout each village. The baseline survey included questions on the national grid, off-grid solar (for lighting and cooking), kerosene, and other fuels. Rather than collecting direct income information, we incorporated the Progress out of Poverty Index (PPI) into the survey to gauge the socio-economic status and class of households surveyed. The PPI is a ten question survey customized for each country to gauge relative poverty on a scale of 0–100, which indicates the likelihood of being below specific poverty lines [78]. The index comprises indicators such as household size, building materials, and the presence of appliances, tables, animals, and crops. During this time, we also interviewed key informants (i.e., solar energy vendors, medical directors, school headmasters, REA Representatives, mechanics) regarding their solar energy use throughout the villages.

Following a constant comparison method under a grounded theory approach, we concurrently collected and analyzed data [79]. The baseline survey and interviews inspired further questions regarding primary sources, productive uses, and payment systems. We conducted additional fieldwork throughout June–August of 2018 and 2019. To further unpack questions arising about off-grid solar, the authors decided to conduct additional qualitative fieldwork over the summer and fall of 2021. We focused explicitly on the role of gender and off-grid solar uptake by conducting interviews resulting in 30 semi-structured and 8 follow-up interviews with female respondents from both female- and male-headed households. This work combines the initial quantitative work with the later qualitative methods to answer not just whether gender and socio-economic status interacted with off-grid solar energy use, but also how and why. Throughout all the fieldwork from 2017 to 2021, the first author observed shops selling solar systems (panels, batteries, etc.), shops using solar energy for productive uses, solar technicians, and households utilizing off-grid solar throughout their day-to-day life. We selected these points of observation to evaluate human, social, and potentially gendered behavior surrounding SHS.

We selected interview respondents through the snowball method; however, as the interviews progressed, the first author and her research assistant subsequently selected respondents to be representative of socio-economic status, tribe, and religion in each village based on local knowledge and observation. We gauged socio-economic status through observation of building materials (roof, walls, and floor), compound size, and any visible appliances (motorbikes, panels, satellite dishes, etc.). Later, the interviews included reported monthly income.

The first author and her experienced translator conducted the survey for quality assurance. The same experienced research assistant conducted all in-person interviews as the first author was unable to travel due to COVID-19 restrictions; however, the first author and her research assistant conducted all follow-up interviews. The survey in 2017 (pre-COVID-19) were conducted either within or just outside of participant's homes. The first author and research assistant attempted to always interview the respondents when they were alone. We held all interviews (during COVID-19) outside participants' homes with social distancing and masking recommended. The field team and first author transcribed, translated, and annotated the interviews within the immediately following weeks.

The first author and her research assistant collected all data as described above; the first author coded interviews for emergent themes and then grouped those themes into code families [79]. She consulted with her research assistant on these themes. Second, the first author re-analyzed all interviews to ensure replicability and the quality of this work. She wrote the results and discussion in collaboration with her research assistant who solely collected the interview data, as well as the last two authors. Finally, the first author analyzed the data a final time in Dedoose, a qualitative data analysis software, for code co-occurrence and frequency. All authors and the research assistant were engaged in interpreting the data. The key stakeholder interviews, participant observation, and personal experience are not included in the formal analysis, but inform the survey, interviews, and discussion.

6. Results

6.1. Study area and socio demographic characteristics

The case study was conducted in Shirati, Tanzania; in the Rorya District and Mara Region (see Fig. 1). Shirati is a rural town of roughly 50,000 people situated two miles from Lake Victoria and ten miles from the Kenyan border. Shirati experiences distinct dry and rainy seasons (light rains from October–December and heavy rains from March–June) with a tropical climate. The survey focused on four villages within Shirati, namely Kabwana ($n = 43$), Michire ($n = 39$), Nyamagongo ($n = 40$), and Obwere ($n = 44$), but additional responses were collected from other, farther villages (i.e., Other ($n = 21$)) within Shirati. Table 1 summarizes selected characteristics of survey respondents by village. The average household size was 6.3 individuals, while the average respondent was 39 years-old. We targeted main cooks as primary respondents as they are typically female in Tanzania and are the most knowledgeable regarding the household's energy consumption because cooking requires most of a household's survival energy needs [80]. Eighty percent of main cooks (primary respondents) were female. Most respondents interviewed were married, had only completed primary education, and obtained some income from agriculture or business. However, most households pursued farming as a supplemental income source in addition to their primary occupation. The average PPI was 50, which implied that the average household in the study had a 72.2 % likelihood to live on less than $4USD per day.

Obwere has the largest trading center in Shirati. Women from surrounding villages flock to Obwere on Mondays for market day to buy food, clothing, and other goods. The main road to the market is hugged by electricity grid lines and lined by rows of small shops. At nine shops, customers can purchase solar panels and solar lanterns. Solar lanterns can also be found at most shops selling drinks, bread, soap, and other items. The solar shops sell both branded and generic solar products; however, the most trusted brand in Shirati is Sundar. Solar vendors order their products from Mwanza or Dar es Salaam (the two largest cities in Tanzania) or retrieve the products themselves. Forty-five percent of households rely on the market for most of their income. Obwere households are slightly wealthier ($PPI_{avg} = 53$).

Kabwana village has a smaller trading center with roughly fifteen shops ranging from salons, pharmacies, vegetable stands, to multipurpose shops selling household necessities. Grid lines run alongside the main road. Thirty-three percent of households there rely on the trading post for their income. Kabwana had a slightly higher percentage of female-headed households (40 %) and is slightly wealthier ($PPI_{avg} = 57$).

Nyamagongo is just north of Kubwana. Construction of the electricity grid is proceeding slowly along the main road. Thirty-five percent of respondents farm for most of their income. Nyamagongo has a slightly higher percentage of respondents attending university (12 %), but a lower percentage of female-headed households (25 %), and the lowest average PPI (43).

Michire is a fishing village on the shores of Lake Victoria. There is one trading post with small shacks selling vegetables, soda, paraffin, and other small supplies. Most households rely on farming and fishing for their income. The REA was working in conjunction with TANESCO to reach houses in Michire along the main road. Thirty-eight percent of households are farmers. Michire has the highest rate of marriage (72 %), the lowest percentage of female-headed households (21 %), and a lower average PPI (48).

6.2. Solar and grid use

Table 2 describes SHS, solar lanterns, and national grid prevalence among respondents. Twenty-two percent of households were connected to TANESCO (the grid). The grid tariff operated on a prepaid system and customers paid 11,700TSH (~5USD) monthly through their mobile phones, 1000TSH (~0.5USD) at a time. No household used electricity for cooking.

Although 97 % of households wanted to connect to TANESCO, there was a lack of knowledge of what it costs, how construction proceeds, and how initiate the process. The monthly grid tariff was not perceived as expensive, but the upfront cost of connection is considered prohibitive. Overall, the survey revealed that women value electricity primarily for lighting, followed by radio and television, with cooking last. Women additionally praised off-grid solar for the lack of smoke when it replaced kerosene.

Of the payment schemes available for off-grid solar, the *lease-to-own* model was the most common throughout the villages with relatively short payment terms of 5–6 months. However, families often perceived these payment plans to be unjust. Women often asked, "[if] the energy is free, why do we keep having to pay every month?" This perception of injustice may explain the lower-than-expected prevalence of payment schemes (18 %). Solar energy companies that offered payment schemes were generally disliked by the community. Respondents viewed the payment agreements as expensive after comparing the total cost of the payment plan to the one-time cost of a panel. Therefore, the qualitative interviews further expanded upon why these payment plans, designed to aid affordability for low-income households, were perceived as less just.

Surveyed SHS ranged from 5 to 250 W. The average system from the survey ($n = 187$) was 68 W, but 60 W in the 30 in-depth interviews.[5] Of surveyed households, 9 % had only a solar panel, 36 % had only a solar lantern, 8 % had both a panel and lantern, and 22 % had only TANESCO.

We investigated the relationship between SHS, solar lanterns, PPI, and head of household gender using ordinary least squares regression while controlling for education, religion, and other sociodemographic characteristics. Neither PPI nor having a female-headed household was correlated with the presence of or size of a solar panel or lantern. SHS and solar lantern use disaggregated by phone charging, radio, or tv was not statistically affected by gender or PPI. This result was surprising as participant observation and informal conversations with key informants revealed socio-cultural disparities and exclusion of women and low-income groups.

Women in Shirati have fewer economic opportunities than men. Work for women in Shirati is mostly limited to selling vegetables at the trading post or braiding hair. The only option for a low, yet consistent income (~20USD/month) is to cook and clean for wealthier families. The hospital in Shirati does employ female nurses, but these positions are often filled by nurses from other parts of Tanzania who are stationed in Shirati. There are very few prominent working women in Shirati, but several women have strong social capital within the village. However, this is largely a product of their husband's status (e.g., preacher, hospital director, accountant, etc.). Women in Shirati do not typically determine how much money the household saves and do not have control over what is saved. There are women's savings groups that rely on their network for larger purchases, although no respondent mentioned these groups during the survey or interviews. Rather, the authors discovered this saving tactic through parallel research on the affordability of liquified petroleum gas [81].

Low-income households also suffer from disparities and exclusion in Shirati in their struggle to: pay school fees; cook food other than daga (small fish) and ugali (a corn flour porridge); build brick houses (as opposed to mud and grass huts); and/or contribute to church, wedding, or funeral funds on which Tanzanian culture places extreme importance. Low-income households also lack access to financial tools as there is only one formal bank in Shirati, and households complain about prohibitive transaction fees for mobile money. Women and low-income households in Shirati are both socially and economically vulnerable.

[5] However, most interview respondents did not know the size of their system extempore; therefore, these numbers reflect only the system sizes known by respondents.

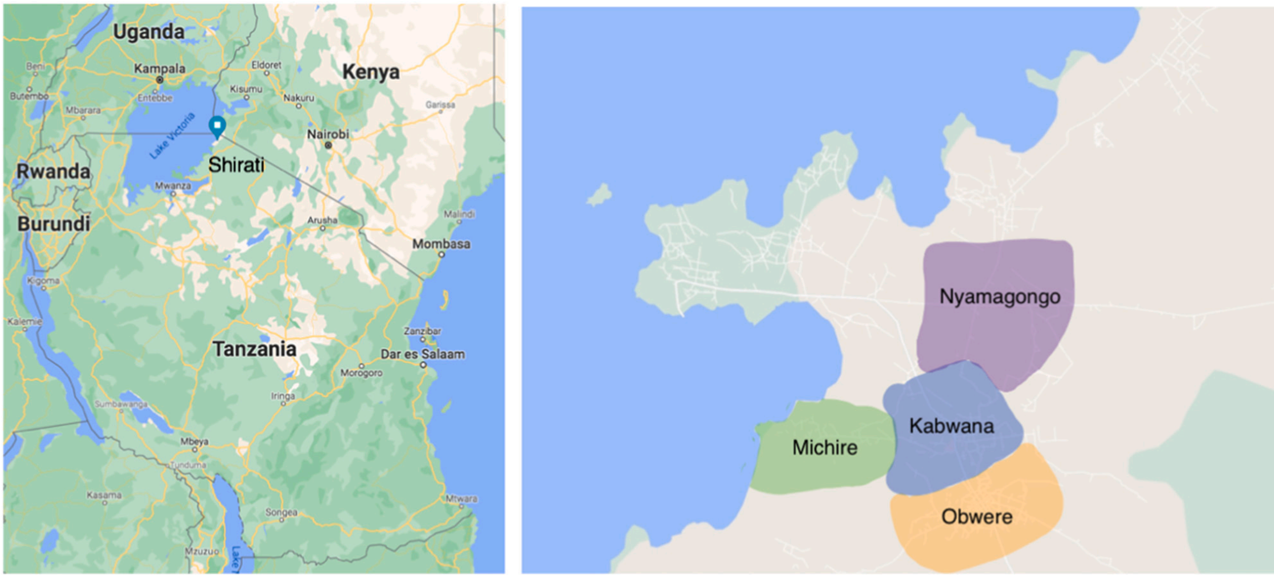

Fig. 1. Left: Shirati within the country of Tanzania. Right: The villages of Michire, Kabwana, Nyamagongo, and Obwere within Shirati.

Table 1
Household demographic information from the survey.

	Overall (N = 187)[a]	Kabwana (n = 43)	Michire (n = 39)	Nyamagongo (n = 40)	Obwere (n = 44)	Other (n = 21)
Household Size (Individuals) Mean (s.d.)	6.3 (3.6)	5.9 (2.6)	5.8 (3.5)	6.5 (3.2)	6.6 (4.8)	7.2 (3.2)
Age (Years) Mean (s.d.)	39 (16)	37 (16)	40 (18)	41 (16)	38 (16)	42 (13)
Female-headed Household (%)	30 %	40 %	21 %	25 %	27 %	38 %
Female Main Cook (%)	80 %	91 %	64 %	73 %	82 %	90 %
Occupation (%)						
Cares for Home, Children	17 %	21 %	26 %	15 %	16 %	0 %
Farmer	31 %	23 %	38 %	35 %	14 %	62 %
Business	31 %	33 %	21 %	28 %	45 %	24 %
Other	21 %	23 %	15 %	22 %	25 %	14 %
Marital status (%)						
Single	12 %	23 %	8 %	10 %	11 %	4 %
Married	65 %	54 %	72 %	68 %	68 %	64 %
Divorced	1 %	0 %	2 %	0 %	2 %	0 %
Widow	20 %	21 %	18 %	15 %	18 %	33 %
Education Level (%)						
No education	10 %	15 %	15 %	5 %	5 %	5 %
Primary School	62 %	51 %	62 %	63 %	61 %	86 %
Secondary School	21 %	28 %	15 %	20 %	27 %	5 %
University	7 %	6 %	8 %	12 %	8 %	4 %
Progress Out of Poverty Index Mean (s.d.)	50 (13)	57 (12)	48 (13)	43 (13)	53 (13)	45 (12)

[a] All percentages and indices are rounded to whole numbers leading the sum to differ from 100 %.

Table 2
Solar, solar lantern, and grid use from the survey in 2017.

	Overall (N = 187)	Kabwana (n = 43)	Michire (n = 39)	Nyamagongo (n = 40)	Obwere (n = 44)	Other (n = 21)
Only a solar panel	9 %	0 %	3 %	35 %	0 %	5 %
Only a solar lantern	36 %	42 %	36 %	30 %	32 %	32 %
Both solar panel and lantern	8 %	7 %	10 %	13 %	2 %	10 %
TANESCO (grid)	22 %	44 %	15 %	5 %	32 %	0 %
TANESCO and solar	7 %	16 %	0 %	5 %	7 %	5 %
Given that household has a solar panel or solar lantern						
Solar is used for Lighting	100 %	100 %	100 %	100 %	100 %	100 %
Phone charging	21 %	4 %	15 %	32 %	30 %	25 %
Radio	17 %	4 %	12 %	20 %	26 %	25 %
TV	17 %	4 %	12 %	20 %	19 %	42 %
Paid for on Payment Scheme	18 %	40 %	7 %	27 %	25 %	0 %

The lack of a statistically significant relationship between gender, socioeconomic status and solar energy usage suggests that while solar panels and lanterns were not disproportionately absent from the lives of low-income or female-headed households, they were not disproportionately present in it either. These findings simultaneously challenge a study from rural Ethiopia that finds that female-headed households were more likely to adopt solar, and a study from Senegal finds that single, divorced, or widowed women were less likely to adopt solar [27]. Our results suggest relative equality in the adoption of off-grid solar across female-headed and low-income households; however, these results do not imply equity.

To explore beyond the equality suggested by the survey from a PGA, we conducted 30 in-depth interviews with women to investigate equity under the CA. Given existing socio-cultural disparities and exclusion, we wanted to further qualitatively investigate both equality and equity of off-grid solar in Shirati.

These interviews focused on off-grid solar energy as a primary source of energy, source of income, and financial burden on households. Thirty female respondents were selected from households that already had solar systems and were representative of socio-economic status, tribe, and religion in each village. We excluded households with only a solar lantern as lanterns constitutes only Tier 0 of ESMAP's MTF [16] and do not meet IEA's definition of electricity access [17]. SHS typically do not reach the IEA's definition of electricity access (ESMAP's MTF Tier 4); however, no household obtained Tier 4 electricity access through solar energy. Thus, to study solar energy in Shirati, we included Tiers 2 and 3. In excluding households without access to solar panels, the interview results may not include the lowest income percentiles. Only four of these 30 households were female-headed, reflecting either Shirati's traditionally patriarchal structure, or that female-headed households cannot afford solar systems. Twenty-one women reported inconsistent income sources. When asked about her income, one woman responded, "we have no consistent income, we just work and expect to get what is enough for a day." The average annual household expenditure was 1140USD, slightly higher than the country's GDP per capita (1090USD).

6.3. Low-quality products

Respondents complained about off-grid solar product quality even before the interviews began. Multiple respondents had broken components, and others complained that quality rapidly decreased over time, explaining that they use solar energy "for lights, no longer to charge the phones as the battery is not good." Another lamented that "the solar [energy system] is not as good as it used to be in the only two years since we bought it. But now, we cannot watch our television." Respondents were often required to purchase a new battery every year. Poor quality even led one respondent to say, "I think we had a fake one because as the days goes on it is reducing its functioning." Respondents viewed the poor (or declining) quality of the solar energy product as injustice, particularly if they purchased their SHS at a higher price than the current market rate. Their responses around quality decline also revealed the value placed on the capabilities solar energy provided: charging phones for communication or watching tv for entertainment.

One of the largest solar shopkeepers in Shirati explained that higher quality products were available in Mwanza and Dar es Salaam, but he didn't stock them because "the people of Shirati are not used to very expensive products." Although the respondents viewed the low-quality products as an injustice, the shopkeeper viewed it as simply the reality of the town's economic situation. This implies that Shirati has not obtained higher quality solar energy products because of the shop owners' gatekeeping role. We were unable to track the ratio of generic to branded products; however, shopkeepers noted that customers preferred the generic lanterns that were 5000TSH (∼2USD) cheaper.

The predominance of low-quality products in Shirati can be further explained by the paucity of wealthy families in Shirati, and its remote, rural location. Solar vendors complained of the additional transport costs of higher quality products, given the perception that they would not sell. Therefore, as found in Kenya [83] and Malawi [84], residents of Shirati do not receive equal or equitable access to high quality off-grid solar products.

Through a PGA lens, this result may ultimately suggest that Shirati residents should have equal quality off-grid solar products; however, a CA could imply that female headed, or low-income households may require an even higher quality product.

6.4. Primary use

Although SHS are designed to provide primary access to unelectrified populations, households across Africa often rely on SHS as secondary, back-up electricity sources in the face of unreliable grids [85,86]. In this configuration, homes have "stacked" systems in which the grid and SHS run parallel circuits throughout the home, using one when the other fails. In general, wealthier households are more likely to use off-grid solar energy this way, seemingly taking a step down the traditional energy ladder as found in Rwanda [87].

The semi-structured interviews investigated whether SHS were mostly used as primary or secondary electricity sources. Roughly half of the households interviewed used solar only as a back-up during the frequent grid outages – a striking increase over the 2017 results (Table 2). This may reflect that households who could originally afford solar systems obtained grid electricity in the interim 4 years. When solar was the primary electricity source, households prioritized lighting, phone charging, and watching television, but rarely ironing. Their off-grid solar systems could not run larger electric appliances. Households felt they could not rely solely on solar either, particularly during the rainy season. These results confirm previous literature [14].

Households using off-grid solar as their primary electricity source had lower average annual expenditure (948USD) than households using solar as a back-up (1560USD). This suggests that SHS are within reach of households hovering around the national GDP/capita but play an equally prominent role as a back-up source for wealthy rural households. The survey results show that solar lanterns reach even low-income households, but as previously mentioned, a single lantern does not constitute any tier of energy access. Primary solar users paid on average 55 % of their monthly income for their system, compared to secondary users who paid 74 %. This suggests that secondary solar systems were larger or more extensive. High- and low-income households may have equal access to the presence of any solar energy system, but difference between primary and secondary usage leads to inequitable access to electricity.

All female-headed households in our in-depth interviews used off-grid SHS as a secondary source of energy. The sample size for female-headed households is very small, possibly suggesting that SHS are not accessible to female-headed households. None of the sector's major reporting agencies or databases record whether off-grid solar is a primary or secondary source. Overall, our research attempts to contribute to the insufficient literature regarding whether and how gender affects household use of off-grid.

In relation to a CA, a PGA would not distinguish between a primary or secondary source of electricity, but rather focus on the overall amount of energy.

6.5. Equal benefit

There was a common perception of equality regarding solar system usage as shown in Fig. 2. When asked how different family members benefited from off-grid solar, a respondent utilizing their SHS for light, charging, and tv explained that "no one benefits the least because we all have the same kind of use," while another woman said, "I don't think I benefit more from solar than other members of my household because we are all using solar for the same reason." However, A woman who used a SHS for lighting, television, and phone charging, explained "my

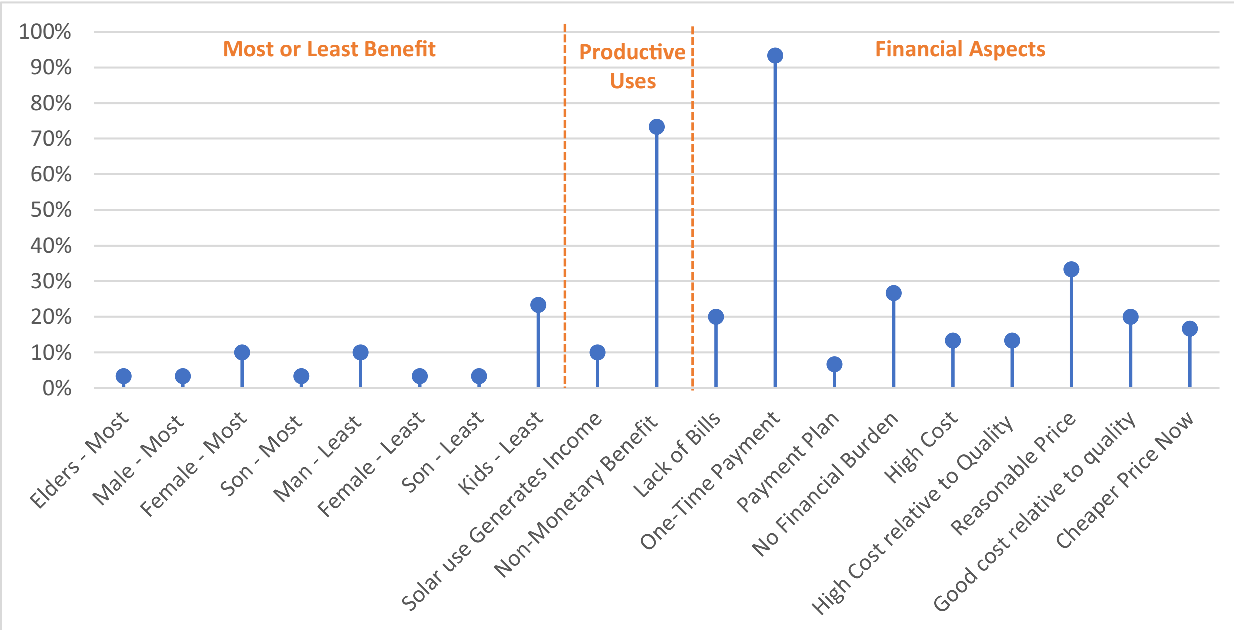

Fig. 2. Frequency of selected codes in qualitative interviews from 2021. Themes are ordered into groups regarding: i) who the respondents felt benefited the most or least if the distribution was not equal, ii) how the solar was used productively (income and non-monetary benefits), and iii) respondent perceptions of the system's financial aspects.

husband benefits the least because he normally leaves very early in the morning and returns late at night, so he does not watch TV and rarely charges his phone at home." However, another said, "I think my husband benefits more than me because he watches television a lot more than any other person" and explained that her son benefited the least "because he only uses solar to charge his phone though not regularly." Other respondents described that "the ones who benefit the least are the children because they do not have phones to charge." Overall, the respondents who reported inequality in access and benefit reflected more on the amount of time each household member utilized each use of solar energy with some resentment, while those who reported equality reflected on each member's number of uses.

That the majority cited equality suggests that most respondents placed value on the number of uses associated with off-grid solar energy, rather than the personal time or benefit derived from each use (i.e., the capability provided). This suggests that the respondents who perceived equality around their SHS were evaluating it through a PGA lens, while respondents reflecting on the associated capabilities perceived inequity. In a recent study on off-grid solar in Ghana, women reported that the solar micro-grid provided equity in accessing light as their husbands would not take the flashlight, kerosene lamp, or candle with them for nighttime fishing. In this case, women reported appreciating the capabilities solar provide (i.e., to extend working hours) [88].

Previous studies that labeled household spaces and tracked the presence and use of electric appliances found inequity in access [89]. Although the women in this study reported benefiting equally from the solar system, no household had solar-powered lighting within the kitchen area – a nearly exclusively female space. This noteworthy paradox has also been observed in Kenya [90]. All households, even those with electricity and solar as a back-up, continued to have the predominantly female cooks hold a phone flashlight in their mouth while cooking the family dinner.

This study did not explicitly report if the cooking area was outside or inside; however, a recent survey of ~500 households in Shirati for ongoing research found that 51 % and 38 % of firewood users cook outside and inside respectively, while 46 % of charcoal users cook outside and 37 % cook both inside and out [91]. Therefore, the cook's use of a cell-phone light as opposed to solar energy may partially be due to a need for portability to inspect the food closely. However, the authors observed that female cooks also did not utilize portable lanterns, and when households had at least one bulb powered by solar energy outside, it was not in the vicinity of – or did not extend light to – the outside cooking area. Finally, in many cases, there was only one cellphone belonging to their husband further hindering their control over access to light.

Claiming to know about SHS was a ubiquitous theme, but respondents also asked to know more. Female respondents would often go to ask their husbands how much the system cost before returning to the interview. Spousal control over off-grid solar energy has also been documented in Ghana [88]. This lack of involvement suggested a procedural injustice, although the women did not indicate perceiving this as unjust. This ambiguous result seemingly conflicts with our survey that recorded confusion surrounding the payment schemes. Previous literature confirms information injustices regarding solar energy [92]. We conducted the survey and in-depth interviews in 2017 and 2021 respectively, signaling that the increased diffusion of information regarding solar energy in Shirati has not been sufficient to achieve full knowledge and confidence regarding the systems, particularly for women.

6.6. *Solar is productive, but rarely generates income*

Respondents stressed the value derived from off-grid solar energy, regardless of whether it was a source of income, commenting that their households greatly appreciated the opportunities for lighting and phone charging (Fig. 2). A primary user explained that "we benefit from solar [energy] since we do not stay in the dark at all… It's better than not having anything at all." A secondary user noted, "with solar [energy] I can still have some activities done as usual [when the electricity is out] … so with solar [energy] I benefit even if not monetarily." Another secondary solar energy user said "With Shirati, electricity tends to be a little bit disturbed sometimes. With solar [energy], we are sure of getting all the services we need." A final secondary user commented on their children by saying, "the kids are not bored since they can still watch television as usual when the electricity goes off." Under an intra-household PGA, the same amount of solar energy would be provided to all household members; however, women may need this back-up solar energy to benefit as much as men as they are typically in charge of housework and the children. In this sense, the back-up light would equitably benefit women by entertaining the children and allowing for more hours to complete household tasks. Additionally, from an energy ethics perspective, we note that the female respondents placed value on solar energy's ability to help maintain consistent schedules, rather than constantly adjusting around power outages.

Only 3 of the 30 households interviewed used off-grid solar energy for income generating purposes (Fig. 2). These included a barber shop and phone charging station, a small theatre, and a household only charging phones. All three respondents reported using the money obtained from these enterprises to purchase food and school fees for their children; however, none of these households were female-headed.

A respondent's husband opened the barber shop in 2019 with solar as the only source of electricity but connected to the national grid in 2020. The shop uses both off-grid solar and the grid because the respondent's spouse is afraid that the solar battery will die if left unused. Therefore, the shop uses the grid to boil water and to power a fan, tv, and speaker, while the solar system powers the haircutting and styling tools. The solar system is too small to boil water or power the larger appliances, but both solar and the grid provide lighting. The shop typically has 10 customers daily (both men and women) and charges 1000TSH (0.5USD) per cut. The respondent explained "through solar he is sure to work throughout the day and may continue providing service to customers in case there is no electricity … it's the work we depend on." The respondent's husband hired another male barber but claimed to be unable to hire a woman as they must be hired at female salons.

Another respondent's spouse ran a theatre for movies and soccer games using a projector and a sheet in their living room. The theatre runs films 1–2 nights weekly, charging 500TSH (0.25USD) per ticket. Roughly 10–20 people attend each viewing depending on the movie. During soccer games, 50–60 individuals huddle to watch.

The third respondent charges phones for a small fee; 200TSH (0.115USD) for non-smartphones and up to 400TSH (0.25USD) for smartphones. However, the respondent explained that customers came primarily when the grid was out.

A PGA may suggest that equal amounts of solar energy will result in an equal amount of productive use; however, women or low-income individuals utilizing solar energy for productive uses may engage in less profitable applications due to capital constraints, less frequented shops, and larger systematic barriers limiting their economic mobility. Thus, these groups may require more energy or resources than their male counterparts.

Some respondents, particularly those using off-grid solar only for light or those from low-income households, charged their phones or batteries (if their panel was broken) on a neighbor's off-grid solar or grid electricity for free. A respondent explained that "[the female neighbor] is just giving me help." This revealed that some households had the opportunity to generate income from their solar energy but chose otherwise to help their neighbors. Charging neighbors' phones may not have generated income but did build social capital and capabilities demonstrating non-monetary priorities.

6.7. Upfront cost vs the burden of frequent payments

Previous literature documents that the low, irregular, and inconsistent incomes of the poor [93] plague households with constant worries about recurring bills [94]. Most interview respondents (26/30) reported purchasing their off-grid solar system with a one-time payment, rather than a payment plan noting that the one-time payment did not pose a financial burden (Fig. 2). A woman explained that "we only paid for the solar once, so we had no financial burden." Another respondent explained that "paying little-by-little [through a payment plan] seems like a burden to us. I fear that I may not get the money." Fear of debt is emphasized in the literature, which has further documented shameful experiences of off-grid solar system repossession after non-payment [14].

Generally, respondents had unfavorable views of payment plans, although these perceptions were not from personal experience. A respondent, having heard about payment plans from a neighbor, said it was very expensive, requiring 2000TSH (∼1USD) every two days for an entire year. A respondent's husband, who joined an interview to provide further details about the barber shop, acknowledged that he'd rather pay for a less expensive SHS, even with a one-time cost. A respondent who purchased a SHS on a lease-to-own model paid 40,000TSH (∼17USD) monthly for three months. However, they did not view it as a financial burden as they now owned the product, noting "we did not pay for it for so long." The four households who chose payment schemes to purchase their SHS now own their system. The perceived financial burden of the payment plan was less associated with the total amount than its length.

The low rate of payment plans may also be attributed to other feelings of injustice. Low-income households cannot afford SHS even with financial payment plans while households purchasing SHS can afford the systems without a plan. Another possibility is that households dislike frequent or lengthy payments, even if individual payments are smaller. Finally, it appears that local solar vendors offered an alternative to contractual agreements with foreign solar energy companies.

The interviews revealed a unique arrangement in which some households brought money to shopkeepers little-by-little until they reached the full amount for the system. A shopkeeper explained that when a customer pays any amount, he provides a receipt. Once the full amount is paid, the customer can pick up their SHS. In this arrangement, the customer does not have to sign an agreement with a foreign solar company and can take as much time as needed. Households considered this arrangement as saving for a one-time payment through the shop rather than a form of payment scheme.

Overall, respondents preferred a one-time payment or paying at the shop little-by-little because "I might not have the money when I need it according to the agreement, so I would rather stay with the less expensive one that I can pay one-time." Households explained how they additionally benefited from off-grid solar because after that one-time payment "there are no charges." They specifically appreciated the freedom from continuing financial obligations, revealing an energy ethics consideration and possibly explaining the low frequency of energy-as-a-service models. One woman explained, "I usually get money once, so by the time I get money I just want to buy everything that is required, so when I got the money, I could not think of anything else, I just went to buy the solar." These observations reveal the difficulty households face in smoothing irregular incomes, which small, recurring payments require.

Other households saved up for their off-grid solar system at home through a lockbox. One woman explained that she used to save for her SHS at home because "the family was not that big, I could manage [the money]"; however, she now brings the shopkeepers money little-by-little because her family is larger, and if the money was at home it may be used for something else. Through an energy ethics lens, respondents placed value on having freedom from pressure within the home to purchase for other needs with money saved for their energy needs.

This is an interesting finding as payment schemes are often touted as a way to alleviate the financial burdens of the poor. In theory, the schemes break down high upfront costs into small payments, easing liquidity constraints [93]. The results from this case study, however, seem to suggest that the frequent of small payments adds an additional burden onto low-income households. With a one-time payment for SHS, households are freed from this seemingly endless financial struggle at least for one need. Even households who save through shopkeepers are freed from burdensome contractual agreements.

A segment of prior energy justice research suggests that financial schemes are a path to increase accessibility of solar energy to low-income households [33,95,96], while other literature questions the affordability of PAYG technology for low-income households [25,63], even with partitioned upfront costs [97] and theoretically low interest rates.[6]

Payment plans may increase access in some instances, but this increased access should be balanced against an acknowledgment of parallel injustices regarding the psychological burden of frequent, regular payments. Low-income households may not have 50–70 % of their monthly expenditure readily available to spend consistently. Therefore, payment schemes can alleviate the inequity of access but may increase inequity in the overall burden of financing access.

6.8. Solar home systems are not reaching low-income households

Our ethnographic work revealed that low-income households can only afford solar lanterns, not systems. Throughout the random survey selection, the authors noted that housing materials (floor and roof), the presence of furniture within and outside the home, visible cooking fuels (freely collected firewood or purchased charcoal or LPG), and the quality of the respondent's clothes all qualitatively correlated with the size of the solar system. Additionally, the survey revealed that owning a solar lantern was twice as prevalent as owning a solar panel (36 % vs. 17 %) (Table 2). Therefore, off-grid solar perpetuates energy access disparities across class.

7. Discussion

Our case study reveals mixed results surrounding gender's mediating effect on off-grid solar energy use. We find that although off-grid solar energy does not seem to actively disadvantage women, off-grid solar's deployment is not a clear win for gender equality as was previously promised. Achieving equity from a CA would call for solar energy's benefits to be distributed equitably according to individual circumstances, while a PGA would lead to everyone obtaining equal levels of electricity access. Our case study reveals that off-grid solar may achieve equality under a PGA, but primary goods do not map to the same capability for every person [44,45]. This is particularly salient in terms of gender as revealed by the in-depth interviews. Respondents that perceived an equal distribution were primarily evaluating shares using a PGA (how many uses), while those who recognized a difference in access focused on the time utilizing each service and the capability achieved from that use. Other literature finds different experiences for women in regard to access to electrification [57,95,98–103]; however, we are the first to find and distinguish explicit energy justice differences in terms of equality and equity along gender and income.

This distinction illuminates the limitations and gaps of the PGA and provides concrete recommendations along the specific types of observed injustices for both rural energy policy in low-income setting and global tracking frameworks, such as the SDGs and ESMAP's Multi-Tier Framework.

In terms of the availability principle of energy justice, we find that high quality solar products were not available in Shirati because shopkeepers perceived the rural, low-income community to be unable to afford these products. Additionally, higher quality products were practically not available. Respondents preferred a lower quality product over a payment scheme for a higher-quality product. Poor quality products led respondents to limit their electricity uses and appliances, purchase new batteries frequently, or use a neighbor's panel to recharge their own battery. Therefore, there is an availability injustice in the off-grid solar market in Shirati when it fails to provide “sufficient energy resources of high quality” [39] (pg. 5). Low quality products may provide a basic level of energy (PGA), but the capabilities achieved by low-income households are limited by the inability to purchase appliances to utilize the energy produced (CA).

In our case study, off-grid solar is the primary energy source for most low- and middle-income households and serves as a back-up source for middle- and higher-income households. This is not inherently problematic; reliability and back-up sources are very important given the intermittency of grids in Sub-Saharan Africa. However, energy access literature and optimization models rarely acknowledge this widespread secondary use of SHS, or its income disparities.

At the intersection of the affordability and intragenerational principles of energy justice, we find that payment schemes for off-grid solar systems may be further burdening low-income households, as previously found [25,63]. Future research is needed to investigate the psychological effects of financial payments, particularly regarding off-grid solar. These results may only be applicable to the income levels that can currently afford solar energy. For extremely low-income households, affording energy access may be worth the psychological burden. However, the literature should investigate this trade-off.

Finally, we find a lack of income generating uses of solar energy, but a plethora of non-monetary benefits. Despite increasing interest in income generating uses of off-grid solar energy [30], our results suggest that these modalities have not reached rural, low-income communities, and do not seem to be disproportionately helping women. We find that women often benefit from solar energy in other non-monetary ways such as lighting, phone charging, and entertainment for their children. There is a general bias in the off-grid solar community towards income generating “productive uses” rather than “reproductive uses,” i.e., uses associated with non-paid domestic labor. Despite this, reproductive uses within the private sphere still offer great benefit within and outside of the household [105]. This bias inherently disadvantages women due to embedded gender roles within communities. The off-grid solar community should focus on the services and value that solar adds to these households regardless of monetary benefit.

7.1. Gender & income cognizant solar energy policy

Specific actions should be taken in light of our results to address these availability, affordability, and intragenerational injustices in rural Tanzania. Local government could work with shopkeepers in low-income communities and distributors in Mwanza and Dar es Salaam to subsidize higher quality products along supply chains to these vulnerable communities. Additionally, policy makers could partner with solar energy companies to target (and subsidize solar energy systems for) women and low-income household which have typically not been seen as profitable customers [14]. Additionally, policies could incentivize off-grid solar companies to offer warranties or subsidized replacement parts for vulnerable groups, specifically those utilizing solar energy as their sole energy source.

Tanzanian and rural village policy should focus on increasing the capabilities of women and low-income groups associated with access to solar energy. These capabilities should not only focus on income generating uses, but rather promote a suite of uses for solar energy. Practically, they could target established women's savings groups to help women obtain larger SHS or appliances for their solar systems for uses that the women themselves define as productive (whether or not they produce income). If obtaining feedback from individual women is not feasible, the village leaders could target the type of productive and reproductive uses of solar energy that women typically perform (or other literature has found to be productive (i.e., rice cookers, water heaters, blenders, etc.) [99,102,104]. Specific village level context will aid impact. For instance, in Nyamagongo, water pumps may be the most critical for female farmers furthest from the lake. In terms of income production, the village could help local government target female owned shops. To increase the equity, rural policy needs to provide women with the financial services, education, and other resources that, in the absence of intervention, benefit men more [32]. This could include building pathways for women to obtain capital, technical and soft training skills, interventions, also suggested by other studies

[6] In practice, interest rates on payment schemes for SHS are nontrivial.

[101,106], which have benefits beyond increasing solar energy's productivity.

In terms of payment schemes, solar energy companies operating in Tanzania could design specific programs for low-income or female headed households in which the individual establishes an account to save up for their off-grid solar systems on their own financial schedule. The individual could decide if they would like to take their solar system home, which would be a typical *pay-as-you-go*, *lease-to-own* model or wait until they have reached the full amount, which would mirror the informal agreements they currently have with shop keepers. More creative and less restrictive financial strategies around off-grid solar systems and associated appliances could expand access and lower the associated shame and psychological burden of current models. However, most off-grid solar systems are still purchased through shops, and thus, local authorities could encourage shop owners to pursue these informal financial agreements with customers. Although informal, these financial arrangements are a key tool for female and low-income solar energy users.

7.2. Implications of the capabilities approach for tracking global energy access

Beyond local rural Tanzanian development policy, our work has implications for large scale global tracking frameworks as well. Fundamentally, SDG7 takes a PGA in wanting to achieve a basic bundle of electricity for all [1]. However, in pursuing approaches that insufficiently address gender and income, SDG7 ignores existing culturally bound disparities that limit individual capabilities. SDG7's targets under the overarching goal of universal, affordable access should specify prioritization of women and low-income households. Currently, the UN does not specifically track SDG7 delineating by gender or income, and SDG5, which calls for gender equality and empowerment, does not have a target for energy access. SDG7 should track access across gender and income to ensure that the blanket goal does not cover up further inequities, even if every individual technically has the same amount of kWs.

To track the equality and equity of household energy access, ESMAP's MTF needs to delineate by gender and income-level and adjust the tiers for these groups to recognize the differences in associated capacity. For example, this could include relative rather than absolute thresholds for affordability as low-income households spend more on their energy needs [3]. Additionally, ESMAP's MTF has separate frameworks for household electricity consumption, services, and supply [16]. These three related frameworks highlight the important distinction between energy amount, services users can access with that amount, and the social, technical, and economic quality of that energy. However, a household electricity capacity framework, perhaps built from Day et al.'s framework for energy, services, and outcomes [51], could highlight and expand on the differences in subsequent capabilities for different users that a PGA threshold amount of electricity misses. All household electricity frameworks could expand to specify services or availability that typically affect women, such as explicitly noting kitchen lighting or appliances that research has found to be gendered. ESMAP also include a separate matrix for access to productive uses, which should also be updated to include adjusted standards for female headed and low-income households.

It is crucial that the SDGs and ESMAP expand their frameworks through a CA lens as it would change global messaging to reframe the issue of energy access from one of simply providing kilowatts to providing users capabilities from those kilowatts. This could ultimately affect national and local governments, and shift user perspectives to recognize energy inequity within their communities, even if energy access is equal. Energy justice and ethical considerations should be included in global guidance, national policy, and local implementation [107].

7.3. Limitations

In our quantitative work, we are limited by our data which span only a single cross-section. There is possible bias from sampling error. The first author and her research assistant worked with community leaders to ensure limited coverage error. Rates of non-response or refusal were small (1 woman out of all approached households). Additionally, measurement error was minimized through thorough piloting and testing of the survey and interview guides. We note limitations deriving from collecting household level information from individual female respondents. Our qualitative work is vulnerable to both interview and social desirability bias; however, the first author and her research assistant attempted to mitigate this bias through explanation that there were no right or wrong answers; they simply wanted to understand. We note that our result detailing the perception that women have equal access with men could be gender-biased, as we mostly only surveyed and interviewed women. Another limitation is that the first author was not present for the in-depth interviews and is not originally from Shirati. The first author's participant and direct observation may be biased from misinterpretation. However, we attempted to mitigate these risks through the first author's nearly five years of fieldwork in this village and the thorough training and engagement of her research assistant who is originally from (and still lives) in Shirati on these results and discussion. Finally, we offer a single case study that may have limited application beyond Northwest Tanzania; we encourage researchers and policy makers to evaluate our results and suggestions given this context.

8. Conclusion

This work evaluates how the distributional benefits and burdens of off-grid solar energy are mediated by gender and class, specifically within a rural setting in Tanzania. Our case study does not find clear benefits specifically for women or low-income households, suggesting that off-grid solar usage may be equal, but is still not equitable. We find that off-grid solar users benefit, although not always monetarily.

At the center of this discussion lies a paradox: SHS are promoted to increase the quality of life and economic prospects for women, children, and low-income households, but solar systems beyond lanterns remain out of reach of the low-income households and women and children do not seem to benefit substantially more than men. Our findings can be interpreted to mean that current energy policy does not sufficiently address the needs of different genders and low-income households, which have a disproportionally lower baseline level of energy access.

Further work in the field is needed to ensure that women and low-income households are included and prioritized in both the distribution of benefits and in the decision-making process. Researchers and policymakers can contribute by taking gender and income-cognizant approaches and differentiating reported impact data by both gender and income. Our work provides concrete recommendations for local and national policy as well as the SDGs and ESMAP's MTF to increase and measure equitable energy access.

Rural economic and energy policy should consider these differential capabilities to benefit from solar energy, and thus track and prioritize progress for these group explicitly. Theoretically, our study outlines the different implications of evaluating energy access through a PGA versus a CA and calls for the energy community to prioritize the capabilities approach for energy justice. Energy equality and primary goods approaches are no longer enough; the global community must actively recognize and prioritize marginalized genders and low-income households within off-grid solar and electricity access. Although energy access has the potential to enable a wide range of SDGs, for now, the justice gap remains.

Ethical clearance

This work was approved under Exempt Research under the

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniel Kammen reports financial support was provided by Google Inc.

Data availability

Data will be made available on request.

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