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Research article

The solar E-waste challenge: A Zambian case study of informal disposal, counterfeit technologies and low literacy

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ABSTRACT

The exponential growth of off-grid solar photovoltaic (PV) systems across Sub-Saharan Africa (SSA) has significantly improved rural electrification but has also introduced new environmental management challenges related to end-of-life disposal. In Zambia, where over one million solar devices were sold between 2018 and 2022, the short lifespan of many solar kits, often under four years, has resulted in a growing and unregulated stream of solar electronic waste (e-waste). More than 90% of these products are technically repairable yet rarely serviced. This study examines the environmental impacts of informal solar e-waste disposal practices in rural Zambia, where obsolete products are typically buried, burned, or repurposed, posing risks to both ecosystem and human health. Using the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM), the research investigates how counterfeit technologies, low literacy, and informal market dynamics intensify poor waste handling. Fieldwork conducted between October 2022 and May 2025 included 28 interviews and 2 focus group discussions across four rural districts (Mkushi, Kapiri, Chongwe, and Luano-Chingola). The study identifies key drivers of e-waste mismanagement, including inadequate policy frameworks, counterfeit solar imports, poverty, and low consumer awareness. Recommendations include the development of a national e-waste policy, enhanced border controls, formalisation of informal markets, and community-based solar literacy initiatives. The findings contribute empirical insights to environmental governance and waste policy debates in SSA, empasising the need for lifecycle-based solar waste strategies. This work holds practical relevance for environmental managers, policy-makers, and researchers focused on sustainable energy and waste systems in off-grid, low-income contexts.

1. Introduction and background

The exponential growth of off-grid solar photovoltaic (PV) systems in Sub-Saharan Africa (SSA) has emerged as a pivotal pathway to achieving Sustainable Development Goal 7 (SDG 7) - ensuring affordable, reliable, sustainable, and modern energy access for all (Keane et al., 2024; Munro et al., 2023b). Propelled by technological advancements, cost reductions, and innovative market-based business models, the solar sector has revolutionised energy access in dispersed, off-grid communities where traditional electrification remains financially and logistically prohibitive (Chanda et al., 2025a; Nygaard et al., 2016). This surge in adoption is particularly likely to occur in countries like Zambia, where rural electrification rates remain critically low and over 80% of rural households still depend on wood fuel for cooking (Chambalile et al., 2024; Makai and Chowdhury, 2017; ZamStats, 2022)

However, while the rapid expansion of off-grid solar systems offers tangible socio-economic and environmental benefits, it also introduces complex unintended consequences, notably in the form of electronic waste (e-waste) accumulation (Munro et al., 2023b; Nalwamba, 2021). E-waste refers to all items of electrical and electronic equipment (EEE) and its parts that have been discarded by its owner as waste without the intent of re-use (UN-ITAR, 2024). E-waste is one of the fastest growing and most complex waste streams in the world, affecting both human health and the environment, and proliferating a loss of valuable raw materials. The majority of solar energy kits (SEKs), including lanterns, solar home systems (SHSs), and associated appliances, are designed with short lifespans, often less than four years, resulting in accelerated product obsolescence (Keane et al., 2024; Kinally et al., 2023). The expected surge in discarded solar photovoltaic (PV) panels presents a growing challenge for global e-waste management, with projections indicating a fourfold increase to 2.4 million tonnes by 2030 from 600, 000 tonnes in 2022 (See Fig. 1) (UN-ITAR, 2024).

In Zambia alone, approximately one million small-scale solar products were sold between 2018 and 2022, yet many of these have already ceased functioning, with more than 90% being technically repairable yet rarely serviced (Keane et al., 2024; Munro et al., 2023a). These

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dynamics have positioned solar e-waste as a critical and overlooked facet of the clean energy transition, necessitating urgent attention from scholars, practitioners, and policymakers.

Notwithstanding the progress in solar energy adoption, Zambia and SSA at large, continues to grapple with profound systemic deficits in e-waste management infrastructure, regulatory frameworks, and enforcement capacities (Avis, 2021; Hansen et al., 2022; Nalwamba, 2021). Existing waste management practices in these contexts remain overwhelmingly linear and informal, with most e-waste either disposed of through rudimentary methods such as burial, open burning, or repurposing, or exported to neighbouring countries (Kinally et al., 2023; Munro et al., 2023a; Nalwamba, 2021). Informal recycling, particularly of lead-acid batteries, introduces acute health and environmental risks, exacerbated by weak institutional governance, porous borders, and underfunded regulatory agencies (Avis, 2021; Bates and Osibanjo, 2019; Kinally et al., 2023).

Further compounding these challenges is the pervasive influx of counterfeit and substandard solar technologies, often indistinguishable from genuine products due to deceptive labelling practices and weak border controls (Mubita and Chowa, 2021). For low-income, rural consumers, these counterfeit products provide an appealing, albeit problematic, alternative due to their lower prices and immediate availability through informal markets (Munro et al., 2023a). The result is an accelerated accumulation of prematurely failing solar products, fostering a self-perpetuating cycle of energy poverty, environmental degradation, and consumer exploitation (Chambalile et al., 2024; Munro et al., 2023a).

These complexities are further exacerbated by low literacy levels and limited consumer awareness of solar e-waste hazards, particularly in rural Zambia, where illiteracy rates remain high, especially among women (Kanyamuna et al., 2021). Studies from Zambia and across SSA indicate that end-users lack the technical capacity, knowledge, and institutional support to manage solar systems safely and sustainably throughout their lifecycle, including at end-of-life disposal stages (Hansen et al., 2022; Kinally et al., 2023; Mugendi et al., 2024). Consequently, end-users resort to unsafe disposal behaviours such as burning or burying solar panels and batteries, often unaware of the toxic chemicals and health risks involved (Kinally et al., 2023; Munro et al., 2023a).

Despite the growing scholarly recognition of solar e-waste issues in SSA, the discourse remains nascent and heavily concentrated in countries like Nigeria, Ghana, and South Africa, with minimal empirical studies focused on Zambia (Maphosa and Maphosa, 2020). Moreover, few studies explicitly investigate the interplay between informal disposal practices, counterfeit technology proliferation, and socio-cultural factors such as low literacy, leaving critical knowledge gaps that hinder the formulation of context-specific interventions (Keane et al., 2024; Kinally et al., 2023; Munro et al., 2023a). There is also a dearth of applied energy scholarship exploring how these dynamics intersect with broader policy, health, environmental, and socio-economic considerations within the clean energy transition paradigm, particularly for vulnerable rural communities in Zambia (Chambalile et al., 2024).

Against this backdrop, the present study seeks to address these research gaps by investigating the emerging solar e-waste challenge in rural Zambia, focusing specifically on informal disposal behaviours, the prevalence of counterfeit technologies, and the influence of low literacy on e-waste management practices. Through this case study, the article aims to advance energy research by critically examining the underexplored dimensions of solar waste governance, technology justice, and user behaviour in off-grid rural contexts, contributing new empirical insights to inform sustainable energy policy, infrastructure design, and community engagement strategies.

To this end, the study is guided by the following research questions.

- What are the solar waste disposal practices reported in selected study areas within rural Zambia?
- What are the main drivers contributing to solar e-waste challenges in selected study areas of rural Zambia?
- What are the risks and implications for environment, health, and policy?

This study contributes to the expanding body of knowledge on renewable energy transitions, energy justice, and sustainable waste management in low-income settings, aligning with current discourse on applied energy systems, environmental sustainability, and policy challenges in the clean energy transition. By engaging with these issues, the study further supports the United Nations' SDG 7, while highlighting the urgent need for integrated energy-waste governance frameworks that ensure the transition to low-carbon energy systems does not exacerbate socio-environmental vulnerabilities (Avis, 2021; Hansen et al., 2022; Nalwamba, 2021).

2. Literature review

This section examines the nexus between solar electrification and the growing e-waste burden in Sub-Saharan Africa (SSA), with a particular focus on Zambia. The literature is organised thematically to underline the current knowledge base on solar PV deployment, waste generation, governance constraints, consumer behaviour, and the informal solar economy. In doing so, it highlights specific empirical and conceptual gaps that the present study addresses, particularly the absence of rural-focused evidence on solar e-waste pathways, informal market dynamics, and the role of literacy in shaping disposal behaviours.

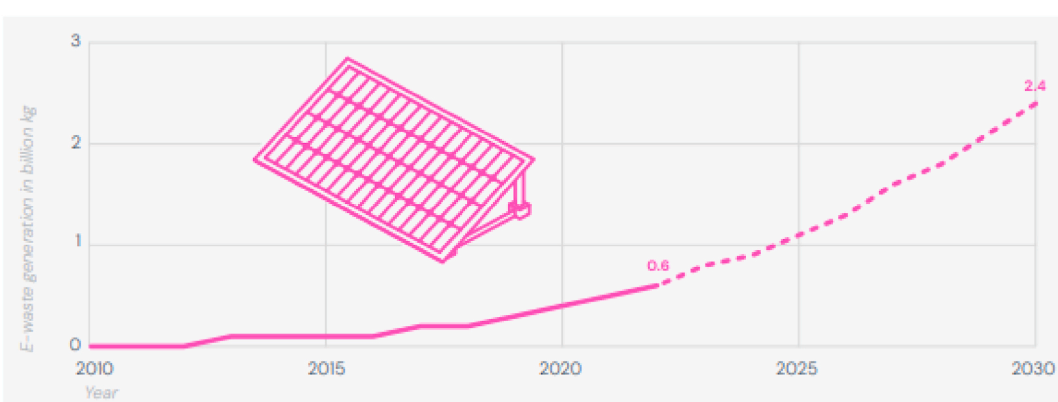

Fig. 1. Total E-waste generated from photovoltaic panels (source: The Global E-waste Monitor, 2024).

2.1. Solar PV electrification in rural SSA

The deployment of solar photovoltaic (PV) systems across off-grid rural regions in SSA has emerged as a key strategy in addressing chronic energy poverty (Chanda et al., 2025a, 2025b, 2025c; Nygaard et al., 2016; Tinta et al., 2023). Technological innovation, declining PV costs, and decentralised, market-oriented distribution models have contributed to their uptake, contrasting with previous donor-led grid expansion efforts (Nygaard et al., 2016). Zambia reflects this broader trend, with a marked increase in solar PV adoption in underserved rural regions. However, affordability challenges, limited maintenance infrastructure, and policy fragmentation constrain deeper integration (Chambalile et al., 2024; Mulenga et al., 2023). Importantly, despite the momentum in solar investment and deployment, there remains a lack of systematic attention to downstream challenges - particularly the management of defective and expired solar components. This omission uncovers a significant research gap: the need to explore how solar systems are disposed of or repurposed once they reach end-of-life in rural, off-grid settings, especially where institutional oversight is weak and market regulation is absent (Munro et al., 2023a).

2.2. Solar E-waste in the context of the clean energy transition

Although solar PV systems are widely regarded as central to sustainable development, they also contribute to a new and underexplored category of electronic waste. Globally, over 250 million of the 375 million solar energy kits distributed since the early 2000s are estimated to have deteriorated into e-waste (Keane et al., 2024). In Zambia, sales of over 1 million small-scale solar devices between 2018 and 2022 (Munro et al., 2023a) suggest a similar trajectory, particularly given the limited availability of repair services and poor aftersales support in rural zones. This situation presents dual challenges. On the one hand, discarded solar components pose serious environmental and health risks due to the resource-intensive materials they contain (Shokrgozar et al., 2024). On the other hand, if managed properly, the sector offers opportunities for circularity through resource recovery. Avis (2021) notes that the global value of recycled e-waste surpassed €55 billion in 2020. However, how these dynamics unfold in marginalised rural contexts where institutional frameworks are minimal remains insufficiently examined.

2.3. E-waste disposal practices in rural SSA

A recurring issue in the literature concerns the prevalence of informal and unsafe e-waste disposal methods in rural SSA. These include open burning, unregulated landfilling, and burial of solar products and associated lead-acid batteries (Kinally et al., 2023). Such practices expose communities to lead and other toxicants, particularly in the absence of accessible recycling infrastructure (Orisakwe et al., 2020). In Zambia, Munro et al. (2023a) document a growing trend of repurposing or discarding failed devices with little awareness of associated risks. Importantly, disposal is not merely a technical issue, but one shaped by knowledge gaps, socio-economic conditions, and absent governance mechanisms. Yet much of the literature remains focused on urban recycling streams or national-level statistics, with scant attention paid to the specific disposal behaviours and practices of rural solar users. This study responds to that gap by offering fine-grained insights into how communities manage end-of-life solar products in the absence of formal pathways.

2.4. Counterfeit technologies and their contribution to E-waste

The problem of solar e-waste in Zambia is significantly compounded by the infiltration of counterfeit and substandard solar technologies into rural markets (Munro et al., 2023a). Informal vendors often supply low-quality products that lack durability and warranty, leading to premature failure and increasing the volume of discarded equipment. Mubita and Chowa (2021) argue that counterfeit items are frequently indistinguishable from certified products, particularly for consumers with limited technical knowledge or exposure to product standards. This situation is facilitated by porous borders, weak regulatory enforcement, and inadequate testing facilities (Bates and Osibanjo, 2019). As a result, rural households are doubly burdened, first, by the economic cost of replacing failed systems, and second, by the environmental and health risks of disposing of unusable technologies. The literature largely treats these trends in isolation. This study brings these threads together by exploring the intersection of counterfeit proliferation, low literacy, and informal market dynamics as drivers of unsafe disposal.

2.5. Health impacts associated with solar E-waste

The toxicity of solar waste components is well documented. Damaged PV panels and batteries can leach hazardous elements such as cadmium, lead, chromium, and arsenic, contaminating soil and water resources (Motta et al., 2016; Petroli et al., 2024). Lithium-ion batteries also pose fire and explosion hazards through thermal runaway, particularly when improperly stored or dismantled (Kumar, 2019; Usmani et al., 2020). In Zambia, awareness of these risks remains extremely low, especially in rural areas lacking education campaigns or regulatory enforcement (Munro et al., 2023a; Sinvula et al., 2021). The literature makes clear the physiological risks of e-waste exposure but offers limited exploration of how community-level awareness or lack thereof, influences actual disposal choices. This study addresses that gap by investigating how knowledge, or the absence of it, shapes household practices around solar system failure and reuse.

2.6. Governance and institutional gaps

E-waste governance in Zambia remains nascent. Despite the exponential growth of the solar market, the country lacks a coherent regulatory framework for managing solar-specific waste (Clube and Hazemba, 2024). As noted by Nalwamba (2021), existing national e-waste strategies are fragmented, urban-centric, and reactive. Attempts to move towards a circular economy are hindered by the absence of enforcement mechanisms, weak coordination among institutions, and limited incentives for private sector engagement (Chambalile et al., 2024). This institutional vacuum has been contrasted with more proactive approaches in countries like Ghana and Nigeria, where e-waste legislation has been implemented (Maphosa and Maphosa, 2020). In Zambia, however, rural communities are often left to navigate solar waste challenges on their own, without support, regulation, or infrastructure (Hansen et al., 2022; Munro et al., 2023a). This study contributes by examining how this policy void translates into grassroots experiences and coping strategies in rural settings.

2.7. Lifecycle behaviours and end-of-use decisions

A further issue raised in the literature is the need to consider user behaviour and product lifecycle responsibility in addressing solar e-waste (Gilal et al., 2022; Keane et al., 2024). Studies show that households frequently retain non-functional solar products in the hope of repair, even in the absence of appropriate tools or services. In Zambia, Keane et al. (2024) found that nearly 89% of users stockpile defunct devices, largely due to limited disposal options and a belief in residual utility. Moreover, Munro et al. (2023b) note that many solar products are intentionally designed to be non-repairable, thereby reducing consumer agency and increasing turnover. This design logic, driven by profit motives, accelerates e-waste accumulation and disincentivises sustainable practices. Existing scholarship calls for stronger consumer education and better product design but rarely interrogates how these dynamics play out in practice, particularly in rural economies characterised by low literacy and informal governance. By focusing explicitly on the interface between user knowledge, informal reuse, and structural gaps in waste handling, this study fills a crucial empirical and theoretical gap. It adds to the body of work advocating for circularity in energy transitions by foregrounding the lived realities of solar technology end-users - realities that remain underrepresented in policy, theory, and practice.

Taken together, the reviewed literature illustrates an emerging crisis in solar e-waste management across SSA, particularly in rural Zambia. Yet, current research often adopts a macro-institutional lens, lacking nuanced accounts of how end-users, informal vendors, and community structures interact with solar waste on the ground. This study addresses that void by exploring solar e-waste through the intertwined lenses of informal disposal, product quality, and literacy. It responds to the need for rural-grounded, lifecycle-oriented frameworks that inform both theory and solar energy governance in low-income, off-grid contexts.

3. Theoretical and conceptual framework

This study applies the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) (Chanda et al., 2025a, 2025b, 2025c, 2025d, 2025e) (see Fig. 2) to investigate solar e-waste management within Zambia's rural energy transition. This paper draws on RUDSHAM to examine the emergent solar e-waste crisis in rural Sub-Saharan Africa (SSA), with a specific focus on Zambia. Developed as a context-sensitive and integrative framework, RUDSHAM offers a multi-dimensional lens through which to analyse how socio-technical systems evolve under conditions of informality, limited literacy, and weak policy enforcement. Rather than layering several independent theories, RUDSHAM unifies key elements from existing behavioural and social models including the Technology Acceptance Model (TAM), the Theory of Planned Behaviour (TPB), Diffusion of Innovations (DOI), and Social Learning Theory (SLT) to provide a more coherent understanding of technology use, governance gaps, and sustainability trade-offs in rural energy transitions.

In the context of solar e-waste, RUDSHAM is particularly effective in capturing how perceived ease and usefulness influence rural consumers' choices, even when those choices lead to unsafe or unsustainable disposal practices. It recognises how social norms and observational learning shape community responses to product failure, such as reusing damaged panels or accepting counterfeit goods. Further, RUDSHAM embeds structural considerations such as policy support, economic cost, and financial model suitability, enabling analysis of how macro-level governance failures intersect with micro-level behaviour. The model is especially valuable in low-literacy, decentralised settings where formal recycling infrastructure is absent, and waste management decisions are shaped by communal improvisation, misinformation, and market asymmetries.

By adopting RUDSHAM, this study moves beyond conventional adoption analysis to address the afterlife of solar technologies, a topic often neglected in clean energy discourse. It positions solar e-waste as a systemic challenge emerging from interlinked behavioural, institutional, and market dynamics. Ultimately, this theoretical lens allows for a more

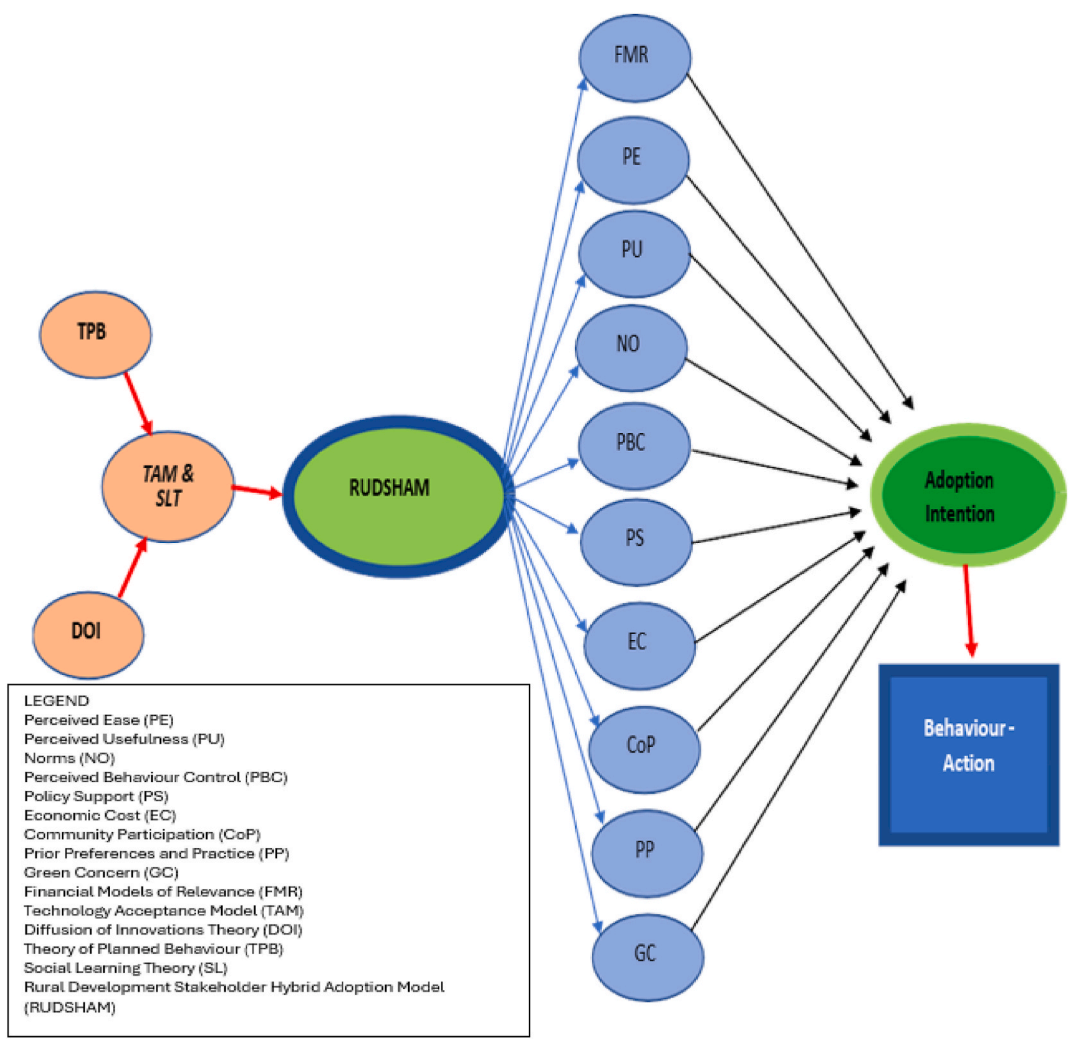

Fig. 2. RUDSHAM hybrid adoption model.

nuanced, contextually grounded understanding of how rural communities navigate the unintended consequences of energy transitions, thereby informing more inclusive and responsive policy interventions across SSA (see Appendices A and B).

4. Research methodology of the study

This study adopted a qualitative case study approach, underpinned by the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM) (Chanda et al., 2025a, 2025b, 2025c, 2025d, 2025e), to investigate the multifaceted solar e-waste challenge in rural Zambia. The research specifically examined informal disposal practices, the circulation of counterfeit solar technologies, and the implications of limited literacy among users, framing these within the broader socio-technical and environmental dynamics of energy transitions in off-grid communities.

4.1. Research design and process overview

The methodological process comprised four sequential phases: (i) site selection and stakeholder mapping, (ii) participant recruitment, (iii) primary data collection, and (iv) thematic analysis. These steps were designed to ensure contextual sensitivity, theory-guided inquiry, and rigorous data interpretation.

4.2. Site selection and sampling strategy

The research was conducted over 30 months (October 2022–May 2025) across four rural districts: Mkushi Rural and Kapiri Rural (Central Province), Chongwe Rural (Lusaka Province), and Chingola Rural - Luano (Copperbelt Province) (see Fig. 3). These sites were purposively selected due to their high reliance on off-grid solar PV, prevalence of informal markets, and lack of formal e-waste infrastructure. They also represent areas with heightened socio-economic vulnerability, lower literacy levels, and marginal policy attention regarding electronic waste, making them highly relevant for the study objectives. A multi-stage, non-probability sampling strategy was employed. Initial engagement through a broader research programme involved 21 interviews with charcoal burners, 40 with smallholder farmers, 16 with commercial farmers, 10 Focus Group Discussions (FGDs), and 3 key informant interviews with solar companies (see Appendix C). These activities provided foundational insights, enabling the identification of households and individuals specifically affected by solar technology malfunction, disposal burdens, or counterfeit issues. A trained research assistant, alongside local facilitators proficient in English and multiple Zambian languages (Bemba, Tonga, Soli, Lamba, and Nyanja), supported access and dialogue with diverse stakeholders.

4.3. Primary data collection

In the focused phase, the study conducted 28 in-depth interviews (IDIs) and 2 focus group discussions (FGDs) with rural solar PV users, drawn from both household and microenterprise contexts (see Appendix D). The IDIs explored participant experiences with solar technology breakdowns, disposal habits, perceived authenticity of products, and comprehension challenges linked to literacy. The FGDs enabled triangulation of these narratives through group-based reflection, peer validation, and communal discussion of shared risks and practices.

A gender-sensitive approach was applied, including separate discussions for women and men when appropriate, to ensure inclusivity and respect for cultural dynamics. Local interpreters facilitated communication in participants' preferred languages, promoting participant comfort and data richness.

Fig. 3. Map of Zambia (UN, 2022).

4.4. Data analysis procedure

Audio recordings from interviews and FGDs were transcribed and translated, then analysed thematically using NVIVO 14. Coding was informed by the ten RUDSHAM attributes, focusing on constructs such as perceived ease and usefulness, social norms, counterfeit-related risk perception, behavioural control, and policy awareness. A four-week pilot study in Luano helped pre-test the data collection tools, resulting in revisions that improved both cultural relevance and construct validity.

4.5. Ethical considerations

Ethical approval was obtained in line with University of Reading guidelines. Informed consent was secured from all participants, who were assured of anonymity and confidentiality. All data were stored securely in encrypted folders on the University's OneDrive system. To acknowledge the time and insight of participants, modest refreshments and non-monetary tokens were provided.

5. Findings

5.1. Counterfeits and rural consumer solar deception

The findings in Table 1 reveal widespread use of counterfeit solar products results from poverty, deception, and inability to distinguish genuine systems, leading to financial loss, safety risks, and declining trust in solar technology.

5.2. Fire hazards from unsafe practices

Participants in Table 2 reported that unsafe charging methods like battery boosting and improper disposal of damaged panels have caused fires, injuries, and household hazards, worsened by poverty, ignorance, and lack of technical understanding.

5.3. E-waste disposal and awareness issues

The study (see Table 3) uncovered that improper disposal practices, burning, burying, and gifting panels, reflect a critical lack of awareness, with participants noting no sensitisation from companies or authorities on solar waste dangers and environmental impacts.

Table 1
Counterfeits and consumer solar deception.

#	Participant	Illustrative direct quotation
a	*Luano FGD 1*	*"Many of us have been cheated because we are usually unable to tell the difference between real products and counterfeits; only after using the panels are we able to find out that we were duped."*
b	*Kapiri Interview 2*	*"We rarely buy from the big shops because the solar panels there are expensive. We usually buy from unregistered vendors who go around as they are cheaper and willing to give huge discounts."*
c	*Chongwe FGD 1*	*"I bought a big solar panel from someone who came to the village. It was a dream come true, but little did I know that it was fake because it only worked for a month and packed up. I couldn't trace the seller. I have just kept the panel on the roof as a decoration … very painful."*
d	*Mkushi Interview 19*	*"Counterfeits are quite dangerous because they heat and at times smoke and burn, risking fire, especially when used for a long time."*
e	*Chongwe Interview 4*	*"Fake products are half the price or less of the original, and the discounts are usually easily given when asked but not for originals. So, the price and discounts help us to know the original or fake products."*
f	*Kapiri FGD 3*	*"The counterfeits are so similar to the originals that it's difficult to tell the difference. Sometimes they even pretend to be from original brands. Sometimes, to confuse consumers, the brand names will be similar to known brands except the spellings will be wrong."*

Table 2
Fire hazards from unsafe practices.

#	Participant	Illustrative direct quotation
a	*Chongwe FGD 2*	*"When the solar panels break, sometimes people use them to make makeshift battery chargers using direct charging locally known as 'boosting' but if you leave the battery charging for a long time, it explodes violently and has been known to injure people and cause fires".*
b	*Mkushi FGD 2*	*"Fires have been reported on several occasions due to battery 'boosting' (direct charging of batteries without regulation)."*
c	*Luano FGD 2*	*"Phone batteries have caused fires but mostly they are caused due to wrong connections and bypasses, which at times emanate from ignorance. Poverty also contributes as it forces people to create dangerous battery charging shortcuts."*
d	*Kapiri Interview 13*	*"From experience, we are careful when dealing with batteries because they explode, but we don't know the other dangers associated with solar, especially chemicals and things that we can't see."*
e	*Kapiri Interview 9*	*"Some of the solar panels and bulbs are burnt, but we don't know whether exposure to the smoke of these products is harmful to health, etc."*
f	*Luano FGD 2*	*"When you get wounded from broken solar glass, the wound really takes long to heal … maybe it's because of the chemicals, so we are very careful and ensure that children are kept well away from such risks."*

Table 3
E-waste disposal and awareness issues.

#	Participant	Illustrative direct quotation
a	*Kapiri Interview 6*	*"When the solar panels stop working, especially the cheap smaller ones, we just give them to children to play with or throw them in the pit latrine or bury them because the broken sharp pieces can injure the children."*
b	*Mkushi FGD 2*	*"Sometimes we burn or just bury the solar panels so that we safely get rid of them to protect children."*
c	*Mkushi FGD 1*	*"We have not been sensitized on how to properly and safely dispose of solar panels and solar batteries, and there is no provision for a place of disposal specifically for solar or electronic waste."*
d	*Luano Interview 3*	*"You are the first people to come and tell us about solar waste disposal; no one has ever told us about that. Companies like SunKing come to promote their systems, but they don't talk about disposal and the dangers of careless disposal."*
e	*Chongwe Interview 3*	*"We are ignorant about the dangers of solar waste because no one has cared to give us knowledge about that … so we don't know whether these things contain dangerous chemicals."*
f	*Kapiri FGD 1*	*"Many of us throw solar waste, especially broken glasses, in the toilet to ensure the children are not at risk."*

5.4. Low literacy and technical challenges

Participants in Table 4 highlighted that low literacy and language barriers hinder users' ability to operate solar systems safely, prompting calls for vernacular, audio-visual guides to improve understanding, maintenance, and safety compliance.

5.5. Theft and economic vulnerability factors

Findings in Table 5 below show that solar systems are targets for theft due to their high value; despite risks, communities prefer cheap counterfeits due to poverty and lack of access to secure, affordable authentic alternatives.

5.6. Warranty, brand trust and reliability

Participants (see Table 6) value branded systems for reliability and warranties, yet distrust persists due to counterfeit sellers offering no

Table 4
Low literacy and technical challenges.

#	Participant	Illustrative direct quotation
a	*Luano Interview 6*	*"Illiteracy is a big problem in the village, especially among us women, so we make wrong connections or have to rely on others to help us."*
b	*Luano FGD 1*	*"Instruction manuals are in English and sometimes use difficult symbols which I don't know … it makes it difficult to understand and follow the instructions."*
c	*Mkushi Interview 4*	*"I think the manuals are too detailed and difficult to read everything; hence many of us just look at the basic things and depend on explanations from others … maybe audio instructions in vernacular can work very well."*
d	*Kapiri FGD 1*	*"Knowledge dissemination and sensitisation is important for rural people using the language they understand."*
e	*Mkushi Interview 4*	*"Because of ignorance and lack of education, we are easily deceived into buying counterfeits."*
f	*Chongwe FGD 2*	*"Even reading instructions is a problem for many of us, so asking us to repair the broken panels is a tall order … additionally, the systems come sealed, so we can't open them to fix them up."*

Table 5
Theft and economic vulnerability factors.

#	Participant	Illustrative direct quotation
a	*Mkushi FGD 1*	*"Because of poverty, original solar products are sometimes targeted and stolen and resold, although this is mostly inside jobs."*
b	*Mkushi CF Interview 4*	*"Solar panels are very desirable for local thieves. Because of theft, I have employed a watchman just to watch the solar pump system."*
c	*Chongwe Interview 3*	*"Because you have to keep buying them every now and then, counterfeits prove to be expensive in that way, but they are a short-term solution, so we have no option but to keep buying them."*
d	*Kapiri Interview 7*	*"Apart from being cheap, counterfeits also have extremely short warranty periods of maybe*3 months *or less … the sellers are without fixed abode and will rarely give a brand name or contact details."*
e	*Kapiri Interview 19*	*"We are reluctant to throw the big solar panels easily, but we easily throw the smaller ones as soon as they pack."*
f	*Luano Interview 5*	*"Sometimes the parts from dismantled solar systems are used like I.Cs which are used for simple radios or fixing other things."*

Table 6
Warranty, brand trust and reliability.

#	Participant	Illustrative direct quotation
a	*Luano FGD 2*	*"My expensive original solar panels have been working well for the past 10 years, but batteries have been giving me problems. Good quality solar panels come from brands like SunKing, MySol, Ready Pay, Fenix, MTN, TopStar etc."*
b	*Luano FGD 1*	*"SunKing even allows the buying of individual replacement parts, which is a very good thing."*
c	*Kapiri FGD 2*	*"The Chinese (counterfeit) solar systems don't come with warranty/guarantee. Many of us have bought these systems which have parked up just after a few days, and you can't be allowed to take it back."*
d	*Chongwe FGD 2*	*"Apart from being cheap, counterfeits also have extremely short warranty periods of maybe*3 months *or less … additionally, the sellers are without fixed abode and will rarely give a brand name or contact details."*
e	*Luano Interview 2*	*"The reliability of the solar system is measured using length of proper function, e.g., if it lasts for 6 to 7 years or more, then it's original. Fakes last for around 2 to*3 months *before starting to give major problems or even completely parking up."*
f	*Mkushi FGD 1*	*"I have had a solar lighting system from MySol for the past 9 years, but I was disappointed with RTD TV and battery which I bought and started giving me problems within a year, but they were willing to have a look."*

support, location, or accountability, undermining consumer confidence in solar products.

5.7. System overload and improper usage

Findings below indicate that overuse of low-capacity solar systems for power-hungry appliances leads to frequent breakdowns, revealing a widespread misunderstanding of energy ratings and system limitations in rural communities.

Illustrative direct quotations for 5.7.

a) "We just buy solar systems that look big and attractive to the eye without much inquiry about the quality and without reading the power output." (Luano interview 2)
b) "I bought a very nice big solar system which was giving very poor output because though it was big, only a small part was effective for solar, and the rest of the panel was just a decoration." (Luano FGD 2)
c) "Some people use small solar systems meant for only lighting to power big systems like radios and TVs, and this is sometimes the problem. Hence a system meant to last 10 years ends up lasting only a few years." (Mkushi Interview 3)
d) "Counterfeits display fake power ratings such that they may show a bigger output, but when you just charge a phone from the system, the power runs out and it means you won't have lights at night." (Chongwe Interview 4)
e) "Because of ignorance and lack of education, we are easily deceived into buying counterfeits." (Kapiri FGD 1)
f) "Many of us just look at the basic things and depend on explanations from others … maybe audio instructions in vernacular can work very well." (Kapiri Interview 18)

5.8. Adaptive solar E-waste reuse strategies

Narratives below revealed that communities creatively repurpose damaged solar parts for practical use, showing resilience but also exposing users to unregulated, hazardous practices due to the absence of formal reuse guidelines.

Illustrative direct quotations for 5.8.

a) "When the solar panels are broken, some clever people manage to make smaller makeshift chargers, but it's very risky, and you use them at your own peril." (Kapiri Interview 15)
b) "Sometimes the parts from dismantled solar systems are used like I. Cs which are used for simple radios or fixing other things." (Kapiri Interview 12)
c) "Damaged solar panels are normally given to kids to play around with unless they are broken, but others burn them or bury them." (Luano FGD 2)
d) "When batteries stop working, people buy them and fix the cells, but there is no such option for solar, so they are disposed of easily as they have no afterlife value." (Chongwe Interview 1)
e) "We just give them to children to play with as plates or tables etc., but when broken, we throw the broken solar pieces in the pit latrine or bury them because the broken sharp pieces can injure the children." (Mkushi Interview 3)
f) "Sometimes we burn or just bury the solar panels, so they safely get rid of them to protect children." (Mkushi Interview 4)

5.9. Awareness of solar waste hazards

Participants below lamented that despite exposure to hazardous solar waste, participants lack accurate knowledge and rely on unsafe practices, stressing the need for education on health risks and proper disposal methods.

Illustrative direct quotations for 5.9.

a) “We are ignorant about the dangers of solar waste because no one has cared to give us knowledge about that.” (Chongwe Interview 2)
b) “No solar company has sensitized us about the risks of unsafe solar panel disposal.” (Kapiri FGD 1)
c) “Some of the solar panels and bulbs are burnt, but we don’t know whether exposure to the smoke of these products is harmful to health.” (Luano Interview 3)
d) “We have been told that powder which comes from energy-saving solar lamps is very dangerous to skin when injured.” (Mkushi FGD 1)
e) “From experience, we are careful with dealing with batteries because they explode, but we don’t know the other dangers associated with solar especially chemicals and things that we can’t see.” (Mkushi Kapiri FGD 1)
f) “We are careful with battery acid when it froths during charging because it burns skin and clothes, so we ensure that we don’t touch or let the children get exposed to it.” (Chongwe FGD 2)

6. Discussion

The findings of this study reveal the complex, layered challenges of solar technology adoption and disposal in rural Zambia, highlighting intersections between consumer vulnerability, environmental hazards, and systemic governance gaps. While solar PV is celebrated as a cornerstone of Africa’s clean energy transition, this case demonstrates how the spread of counterfeit products, unsafe repair practices, and informal e-waste handling undermine both sustainability and equity. In discussing these findings, this section situates participants’ experiences within wider debates on energy justice, environmental governance, and circular economy approaches in the Global South. Each thematic area is discussed in turn, demonstrating how issues of affordability, safety, awareness, and institutional neglect converge to shape the solar e-waste challenge.

6.1. Consumer deception and accessibility issues

The study’s findings in Table 1 confirm that accessibility constraints, pervasive counterfeit proliferation, and systemic consumer deception form a critical triad affecting rural solar adoption in Zambia. Participants’ accounts (5.1a–f) reveal how the absence of affordable, authentic solar technologies in formal markets drives rural consumers to informal, unregulated vendors who exploit these vulnerabilities through the distribution of counterfeit products at discounted prices (5.1b, 5.1e). These findings resonate with existing evidence highlighting the dominance of low-quality solar products in SSA, exacerbated by inadequate testing at borders, porous regulatory mechanisms, and limited consumer awareness (Groenewoudt et al., 2020; Mubita and Chowa, 2021). Participants detailed their inability to distinguish counterfeits from originals due to deceptive branding tactics and subtle imitation of reputable brands (5.1f), aligning with Hansen et al. (2022), who reports a lack of consumer protection mechanisms in Zambia’s off-grid solar market. Moreover, the health and safety implications of these counterfeit products, such as overheating, smoking, and fire risks (5.1d), are consistent with documented risks in Munro et al. (2023), where the sector neglects aftersales services and lifecycle responsibility, leaving users to bear the burden of systemic failures. This interplay between affordability, deception, and poor product quality reflects broader challenges documented by Nygaard et al. (2016), where rapid PV market expansion is accompanied by inequities and consumer vulnerabilities that demand urgent regulatory interventions. These findings reveal that unsafe practices are not only the result of user choices but are deeply rooted in systemic market failures. The next section explores how these vulnerabilities manifest in the form of hazardous everyday practices with direct health and safety implications.

6.2. Fire hazards and risky practices

Building on the market-related vulnerabilities above, participants’ testimonies demonstrate how inadequate access to safe technologies translates into risky improvisations during solar use and maintenance. Participant narratives in Table 2 (5.2a–f) reveal widespread hazardous practices associated with informal solar system repairs and battery handling. Makeshift charging techniques such as ‘boosting’ (5.2a, 5.2b) have become survival strategies for many rural households but are fraught with safety hazards, including violent explosions and recurring fire incidents. These observations affirm findings by Kinally et al. (2023) and Usmani et al. (2020), who report similar patterns of unsafe battery charging and informal recycling practices in SSA, often exacerbated by poverty and lack of technical capacity (5.2c). Participants further expressed deep concern over the health risks associated with solar system components, particularly battery acid and broken panels. Reports of skin burns from frothing battery acid during charging (5.2d, 5.9f) and slow-healing wounds from shattered solar glass (5.2f) highlight direct personal and household health hazards. These reflect findings by Orisakwe et al. (2020), Sinvula et al. (2021) and Kinally et al. (2023), who documented severe health consequences from improper handling and disposal of e-waste, including lead-acid batteries. Additionally, the lack of awareness regarding the toxicity of smoke from burnt panels and components (5.2e) reveals gaps in user safety knowledge, resonating with Nalwamba (2022) on the broader neglect of health risks in Zambia’s emerging solar waste discourse. Such unsafe practices point toward a deeper structural absence, the lack of organised e-waste infrastructure and awareness. The following section turns to these systemic gaps in disposal and sensitisation.

6.3. E-waste challenges and public awareness

From individual hazards, the discussion now shifts to the collective implications of disposal practices, situating household experiences within broader questions of environmental governance. Improper disposal practices of solar waste are prominent among participants (5.3a–f), ranging from burying/burning panels to using them as toys, exposing users to both environmental and health hazards (see Table 3). The testimonials expose the absence of structured e-waste disposal infrastructure (5.3c) and the complete lack of sensitisation by solar companies (5.3d), echoing findings by Nalwamba (2022) and Kinally et al. (2023), who identify Zambia’s e-waste management system as underdeveloped and poorly enforced. Participants’ limited awareness of the dangers posed by solar waste, including exposure to toxic chemicals (5.3e), and practices like discarding sharp fragments in pit latrines (5.3f), are indicative of the broader neglect of rural communities in national and corporate e-waste narratives (Lema et al., 2021). These disposal practices present serious environmental justice concerns, as communities bear the brunt of pollution in the absence of regulatory safeguards, a pattern documented by Avis (2021) and Munro et al. (2023). These systemic deficiencies cannot be separated from users’ limited technical capacity and literacy levels. Accordingly, the next section highlights how knowledge gaps exacerbate unsafe practices and reinforce exclusion.

6.4. Capacity gaps and energy sensitisation

The findings on e-waste stress the centrality of human capacity. Literacy and technical knowledge emerge as critical mediators of whether solar adoption enhances well-being or produces new risks. Illiteracy and limited technical skills emerged as significant barriers to safe solar usage and disposal (5.4a–f) (Table 4). Participants’ struggles to comprehend English manuals (5.4b, 5.4c) and reliance on peer explanations (5.4f) demonstrate the structural exclusion of low-literate populations from the off-grid solar sector’s mainstream service models (Kanyamuna et al., 2021; Munro et al., 2023b). Participants advocated for localized, culturally appropriate sensitisation (5.4d), supporting Hansen's et al (2022) recommendation to integrate end-user education into renewable energy transitions, particularly in low-literacy settings. Moreover, the expressed vulnerability to deceptive sales tactics (5.4e) reiterates the need for consumer empowerment strategies within Zambia's off-grid solar expansion efforts, as also observed by Hansen et al. (2022). This knowledge asymmetry not only perpetuates unsafe usage and disposal but also exacerbates the environmental injustice faced by rural communities who are systematically excluded from energy justice discourses (Samarakoon et al., 2022). These capacity gaps are further complicated by how users perceive the economic and social value of solar technologies, which in turn drives new forms of vulnerability such as theft and insecurity.

6.5. Perceived value and solar theft

Moving beyond literacy, participants' reflections illustrate how solar systems are embedded in wider livelihood strategies, with their perceived value generating both adaptive and problematic behaviours. Participants' reflections in Table 5 (5.5a–f) reveal that the perceived economic value of solar technologies, especially authentic products, has led to increased theft and insecurity. Households reported employing watchmen to protect solar systems (5.5b), while also acknowledging the cycle of repeated purchases of cheap counterfeits due to financial constraints (5.5c). These findings are congruent with Munro et al. (2023), who report the tension between profit-driven off-grid solar models and their limited sustainability in vulnerable communities. Participants' adaptive behaviours, such as retaining and repurposing parts from broken systems (5.5f), mirror findings by Kinally et al. (2023), who describe similar informal resource recovery practices in SSA, though these remain environmentally hazardous and economically unsustainable. The unwillingness to dispose of larger systems (5.5e), despite functional failure, reflects both sentimental attachment and the economic burden of replacement, reinforcing findings by Keane et al. (2024), where users perceive defunct solar kits as retaining residual value. These perceptions directly shape levels of trust in solar products and suppliers. The next section explores how warranties, durability, and aftersales services affect consumer confidence and system sustainability.

6.6. Warranty issues and trust challenges

Trust, or the lack thereof, emerges as a pivotal factor that links consumer experiences with product quality, market regulation, and long-term sustainability. Participants' narratives (5.6a–f) (see Table 6) revealed contrasting perceptions between counterfeit and branded solar products. While counterfeits lack warranties and quickly fail (5.6c, 5.6d), authentic systems from trusted brands were credited for their durability and customer support (5.6a, 5.6b), in line with the arguments by Munro et al. (2023) regarding the value of formal supply chains and aftersales services. However, even these brands have occasionally disappointed (5.6f), raising questions about the consistency of customer experiences across products and services. These findings align with Chambalile et al. (2024), who highlight the need for improved maintenance infrastructure and user support to enhance trust and system longevity. Participants' methods of assessing reliability through usage duration (5.6e) also highlight the lack of technical literacy, confirming earlier findings (5.4f) and reinforcing the call for accessible, community-level sensitisation and repair services as suggested by Hansen et al. (2022). Yet, trust is undermined not only by inconsistent warranties but also by how systems are used. The following section examines how misuse, overloading, and unrealistic expectations compound technical failures.

6.7. Misuse, overloading, and system misapplication

Beyond supply-side challenges, user practices themselves often accelerate system breakdowns, reflecting the interplay between technical limitations and consumer misperceptions. Misuse of solar systems is a recurring theme among participants (5.7a–f), where systems designed for basic lighting are routinely overloaded to power energy-intensive appliances (5.7c), resulting in premature failure. Participants also noted deceptive marketing of counterfeits with exaggerated power ratings (5.7d), leading to unmet expectations and user frustration. These practices reflect broader patterns identified by Kinally et al. (2023), where misinformation and lack of technical understanding compromise the safe application of solar technologies in rural SSA. Moreover, the prioritization of aesthetic appeal over technical specifications when purchasing systems (5.7a, 5.7b) reinforces the disconnect between user expectations and product capabilities, as also highlighted by Munro et al. (2023). Participants' reflections suggest that capacity-building interventions, such as local-language, audio-visual guides (5.7f), could bridge these knowledge gaps and foster safer, more sustainable solar usage, consistent with recommendations by Hansen et al. (2022) and Kinally et al. (2023). These misapplications inevitably contribute to patterns of informal reuse and premature disposal, which reveal both user ingenuity and systemic neglect of lifecycle planning.

6.8. Informal reuse, improvisation, and disposal of solar components

Informal reuse and improvisation represent the community's adaptive response to structural neglect, yet they also expose users to new safety and environmental risks. Adaptive reuse and informal disposal practices emerged as a common theme among participants (5.8a–f). In response to the lack of formal e-waste systems, broken solar panels are repurposed into makeshift chargers or household objects (5.8a, 5.8b, 5.8e), often without technical guidance, exposing users to electrical hazards. This informal reuse culture reflects both user ingenuity and systemic gaps in repair infrastructure, particularly in under-regulated and low-literacy rural contexts (Kinally et al., 2023; Munro et al., 2023a). In most cases, solar panels are either burned or buried once they become hazardous (5.8c, 5.8f), with the intent of protecting children from injury. Similar to findings by Nalwamba (2022), participants acknowledged that non-functional solar systems had little perceived afterlife value (5.8d), exacerbated by the absence of circular economy approaches and take-back programmes in Zambia (Clube and Hazemba, 2024). These trends are consistent with regional patterns where poor lifecycle accountability, short product lifespans, and high repair costs drive premature disposal (Keane et al., 2024). In this context, while reuse practices reflect local adaptation, they also highlight systemic neglect in e-waste planning and signal a pressing need for policies that integrate safe reuse, repair, and recycling strategies (Chambalile et al., 2024; Kinally et al., 2023). Such improvised practices underline a critical gap, the absence of awareness and sensitisation regarding the hazards of solar waste. The final section addresses this dimension directly.

6.9. Limited awareness of solar waste hazards

Ultimately, participants' limited awareness of solar waste hazards encapsulates the cumulative effect of counterfeit markets, risky practices, poor infrastructure, and low literacy. Participants repeatedly highlighted the absence of formal education or sensitisation around solar e-waste hazards (5.9a–f). Respondents stated that no solar company or public agency had informed them about health or environmental risks associated with improper disposal (5.9a, 5.9b), despite common practices such as burning bulbs or handling broken battery components (5.9c, 5.9f). Awareness of specific risks, such as battery acid burns or exposure to lamp powders, tended to arise from personal experience rather than institutional knowledge (5.9d, 5.9e). These findings align with Hansen et al. (2022) and Mugendi et al. (2024), who emphasise the disproportionate burden placed on rural communities in the absence of structured e-waste education and regulatory enforcement. The limited awareness reported here mirrors broader challenges in Sub-Saharan Africa, where low literacy levels and weak infrastructure hinder risk communication (Kanyamuna et al., 2021; Kinally et al., 2023). In Zambia, the situation is compounded by a lack of solar-specific waste systems, weak policy implementation, and informal disposal habits (Munro et al., 2023a; Nalwamba, 2022). Without targeted outreach and stakeholder engagement, hazardous waste disposal behaviours may persist, undermining the environmental gains of the clean energy transition (Avis, 2021; Chambalile et al., 2024). Taken together, these findings highlight the urgent need for integrated policies that combine consumer protection, technical capacity-building, and structured e-waste management to ensure that solar energy transitions do not reproduce environmental injustice.

Taken together, the discussion reveals that Zambia's solar e-waste challenge is not a single-issue problem but the outcome of intertwined dynamics such as market deception, hazardous practices, systemic neglect, literacy barriers, and limited awareness. Addressing these requires integrated, multi-scalar interventions that safeguard consumers while strengthening environmental stewardship. The next section concludes by outlining the broader implications of these findings for policy, practice, and future research.

7. Policy recommendations

This study's findings highlight the urgent need for a holistic and multi-scalar policy response to the emerging solar e-waste challenge in rural Sub-Saharan Africa. The Zambian case study reveals that while off-grid solar PV systems are expanding energy access, they are simultaneously creating new socio-environmental risks due to unregulated markets, weak consumer protections, and an absence of structured e-waste disposal systems. Addressing these challenges requires an integrated policy strategy that prioritises lifecycle responsibility, grassroots participation, and inter-sectoral collaboration.

A key entry point for reform is solar import regulation and consumer protection. The proliferation of counterfeit products stresses the necessity for enhanced border control mechanisms. Institutions such as the Zambia Bureau of Standards (ZABS), Zambia Revenue Authority (ZRA), and Zambia Compulsory Standards Agency (ZCSA) must establish testing and certification systems at major entry points to screen imported solar technologies. Simultaneously, the Ministry of Commerce, Trade and Industry (MCTI) should strengthen the regulation of informal solar markets, with support from civil society organisations like the Zambia Consumer Association (ZACA) and Consumer Unity & Trust Society (CUTS Zambia). These actors can lead public education efforts focused on product authenticity and consumer rights, while empowering rural users to demand quality. Equally vital is the formulation of a national solar e-waste policy tailored to the off-grid energy sector. The Ministry of Green Economy and Environment (MoGEE), in partnership with the Zambia Environmental Management Agency (ZEMA), should spearhead the development of a dedicated framework that addresses the unique waste streams of solar PV systems. This policy must ensure that decentralised regions are not excluded; take-back schemes, recycling centres, and mobile collection units should be piloted in rural districts. Collaboration with international partners like SolarAid, IRENA, and GIZ Zambia can bring technical expertise and help operationalise pilot models grounded in local realities.

Addressing the knowledge gap among end-users is critical. The study found widespread limitations in system understanding, disposal awareness, and maintenance skills. A unified Community Education and Awareness strategy is thus essential. The Ministry of Energy (MoE), Ministry of General Education (MoGE), and Rural Electrification Authority (REA) should jointly develop national energy literacy campaigns. These initiatives should integrate information on safe solar use, counterfeit risks, and disposal hazards into culturally adapted, multilingual formats, leveraging community radio, faith-based platforms, and traditional leaders for wider dissemination. Furthermore, the Energy Regulation Board (ERB) should require all licensed solar vendors to provide standardised end-user education materials as part of their compliance obligations. The policy framework must also address the structural vulnerabilities of the informal solar market. The Ministry of Small and Medium Enterprises Development (MSMED), in collaboration with UNCDF and local microfinance institutions, should support the formalisation of rural solar enterprises. This could include microcredit schemes for certified vendors, tax incentives for quality-compliant distributors, and support for decentralised repair hubs. Empowering local entrepreneurs and cooperatives in this way will promote sustainable, locally embedded energy economies, and reduce reliance on exploitative or low-quality supply chains.

To foster durability and trust in solar technologies, product design and aftersales service require policy attention. The ERB should enforce warranty and repair obligations, encouraging providers to adopt modular and repairable designs suited for rural conditions. Public-private partnerships with NGOs like Practical Action and private sector actors can support the establishment of local service centres and technician training schemes. These measures would mitigate safety risks linked to poor system handling while extending product lifespan and user satisfaction. In tandem, safe solar reuse and refurbishment pathways must be promoted. Informal repurposing is often a survival strategy in rural Zambia but carries environmental and health risks. The Ministry of Green Economy and ZEMA should introduce clear national guidelines on reuse, working alongside solar associations to pilot safe repurposing workshops. Investment in second-life product innovation, backed by partners such as UNDP or GIZ, can reduce premature disposal and support circular economy principles in marginalised areas.

Lastly, a cross-cutting issue is the lack of public knowledge about e-waste hazards. The Ministry of Health and REA should co-lead targeted e-waste hazard awareness campaigns, integrating these into public health messages and school curricula. Solar vendors should be required to provide clear disposal instructions, and community health workers can serve as frontline educators. Ensuring basic e-waste literacy will empower rural communities to manage solar waste safely and protect both environmental and human health. This study advocates for an integrated governance approach to solar e-waste, where product regulation, education, infrastructure, and market reform are pursued simultaneously. Such a strategy is essential to achieving Sustainable Development Goal 7 in a manner that is just, inclusive, and ecologically sound.

8. Conclusion

The rapid expansion of off-grid solar in Sub-Saharan Africa has been celebrated as a pathway to bridging energy access gaps, yet this study demonstrates that such transitions are also accompanied by unintended consequences that are often overlooked in policy and scholarship. Drawing on qualitative evidence from rural Zambia, the research illuminates how the proliferation of counterfeit technologies, unsafe disposal practices, and low literacy converge to produce a mounting solar e-waste challenge. This conclusion synthesises the study's key findings, highlights its contributions to knowledge, outlines future research trajectories, acknowledges limitations, and reflects on broader implications for just and sustainable energy transitions.

The study critically examined the emerging solar e-waste challenge in rural Zambia, highlighting the interplay between informal disposal practices, the influx of counterfeit solar technologies, and the implications of low literacy levels. The findings reveal that rural communities predominantly engage in unsafe disposal methods, burning, burying, or repurposing solar components, without awareness of the associated environmental and health risks. The proliferation of counterfeit technologies, often indistinguishable from authentic brands, has further intensified the accumulation of dysfunctional solar products. The study also established that low literacy and limited technical capacity exacerbate unsafe behaviours and obstruct users from engaging with safe disposal practices or understanding product warranties and maintenance requirements. These issues are compounded by the absence of formal e-waste management infrastructure, regulatory deficits, and weak enforcement, positioning solar e-waste as an urgent, yet overlooked, environmental justice issue within Zambia's clen energy transition. Building on these findings, the study contributes new empirical and theoretical insights that advance academic and policy debates on energy transitions in the Global South. By adopting the Rural Development Stakeholder Hybrid Adoption Model (RUDSHAM), the study moves beyond purely technical or market-centric analyses, presenting a holistic understanding of the socio-technical, behavioural, and governance dynamics shaping rural solar e-waste challenges. In doing so, the research extends the discourse on energy justice, technology misuse, and consumer vulnerability within off-grid solar adoption narratives, providing actionable insights for sustainable energy transitions that are both inclusive and context-sensitive. It also identifies critical gaps in the current renewable energy governance frameworks that neglect end-of-life solar system considerations, thereby enriching applied energy scholarship with interdisciplinary perspectives on technology justice and environmental health.

While these contributions are significant, they also open avenues for further inquiry into the evolving landscape of solar e-waste in rural contexts. The complexities identified in this study suggest several pathways for further inquiry. Longitudinal, cross-seasonal research is necessary to explore how disposal behaviours and system misuse fluctuate with agricultural cycles, income variability, and seasonal weather patterns. Further studies should also investigate the economic and cultural logics underpinning consumers' acceptance of counterfeits and informal markets, employing participatory and ethnographic methods to deepen understanding of user perspectives. Additionally, action research examining the efficacy of localized, culturally tailored solar literacy interventions could provide valuable lessons for integrating energy-waste education into broader rural development strategies. While future research can deepen and expand the scope of these findings, it is equally important to acknowledge the limitations of the present study. The study was conducted over a relatively short fieldwork period, and as such, seasonal variations in disposal practices, income streams, and solar system utilisation may not have been fully captured. Future research employing year-round monitoring would be instrumental in unpacking these temporal dynamics. Moreover, the study's focus on specific districts may limit generalizability; however, the selected sites' strategic relevance offers critical insights into contexts where informal solar markets, policy neglect, and socio-economic vulnerabilities converge.

Despite these limitations, the study provides compelling evidence that can inform both academic discourse and policy reform. It highlights the dual-edged nature of off-grid solar PV diffusion in rural Zambia. While it aligns with Sustainable Development Goal 7 by improving access to clean and affordable energy, it simultaneously reveals a range of unintended socio-environmental consequences. Counterfeit technologies, limited consumer literacy, and the absence of structured e-waste disposal mechanisms pose significant risks to both human and ecological well-being. These findings suggest that achieving SDG 7 in rural Sub-Saharan Africa requires more than expanding energy access, it necessitates embedding principles of equity, environmental stewardship, and institutional accountability throughout the technology lifecycle. The research contributes to the growing literature on just energy transitions by advocating for user-centred, locally contextualised governance frameworks. Addressing solar e-waste through participatory policy mechanisms and targeted capacity building will be critical in preventing the marginalisation of vulnerable groups. Overall, the study calls for holistic, anticipatory planning to ensure that energy transitions are not only accelerated, but also inclusive, ethical, and sustainable.

CRediT authorship contribution statement

Hillary Chanda: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eugene Mohareb:** Writing – review & editing, Validation, Supervision, Software, Methodology, Funding acquisition, Data curation, Conceptualization. **Michael Peters:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Chris Harty:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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