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Solar home systems in Malawi: Commercialisation, use and informal waste management

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A R T I C L E I N F O

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A B S T R A C T

To address electricity deprivation, the Malawi Government aims to provide off-grid solar products to 45 % of the country's population by 2030, currently in the absence of a waste management strategy. This paper addresses research gaps in the life cycle of solar home systems (SHSs) in Malawi, describing the flow of materials from import to waste disposal, to investigate potential environmental and energy justice issues relating to the national electrification policy. Fifty semi-structured interviews were conducted to describe the practices and perspectives of the actors in the SHS life cycle and informal waste management chain surrounding Malawi's capital city of Lilongwe: users, electronics repairers, scrap dealers, and informal lead-acid battery recyclers. The life cycle of SHSs is highlighted to be significantly impacted by the unregulated market landscape that suffers from a lack of supplier accountability, users' affordability constraints and a low understanding in SHS design and operation, resulting in frequent SHS failures. An established network of informal repairers and scrap dealers is described, effectively compensating for SHS faults and aggregating valuable waste fractions to sell to international buyers. The SHS waste flow is found to be dominated by lead-acid batteries, and the first description of an active informal lead-acid battery recycling industry in Malawi is made – posing severe health risks from the release of significant quantities of lead pollution into densely populated communities. Accordingly, Malawi's national electronification strategy is criticised for unjustly placing the responsibility for the management of the toxic off-grid solar waste flow onto energy-poor communities that are not aware of the associated hazards and do not have means for safe waste disposal. Finally, key principles for the development of effective safe waste management interventions are outlined from an energy perspective: fairly distributing responsibilities by recognising the perspectives and valuable roles of the existing actors within the waste management chain.

1. Introduction

Malawi has one of the lowest rates of electricity access in sub-Saharan Africa. Only 15 % of the population has access to electricity, although, the majority of Malawi's population lives in rural areas where the access rate falls to just 7 % (World Bank, 2023). The Malawi Government has recognised that increasing electricity access is vital for the county's future stability and has committed to the seventh Sustainable Development Goal (SDG 7) of universal electricity access by 2030 (UN General Assembly, 2015; Govenrnment of Malawi, 2017b). However, the poor financial performance of the national grid operator Electricity Supply Corporation of Malawi (ESCOM) is considered a key hindrance to increasing electricity access. With regular load shedding, the utility company faces challenges maintaining the existing grid connections, let alone extending the grid (Taulo et al., 2015; The World Bank, 2019). Accordingly, the Malawi Government's national electrification strategy primarily depends on off-grid technologies. Specifically, the 2017 Malawi Renewable Energy Strategy (Government of Malawi, 2017a) defines the target that 45 % of the population (approximately 11.2 million people (United Nations, 2022)) will gain electricity access through purchasing household scale off-grid solar (OGS) devices by 2030, distributed through the private OGS market.

Since becoming an established electrification strategy across sub-Saharan Africa (SSA), the private OGS market has gained controversy within energy justice literature: a framework to apply principles of distributional, procedural, and recognition justice to energy policy

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(Jenkins et al., 2016). To date, the private OGS market has been framed as a means of addressing the inequity in the distribution of electricity access (Cross, 2013; Cross and Murray, 2018). However, significant ethical criticisms have been raised in recent literature. Samarakoon (Samarakoon, 2020) has highlighted that Malawi's national OGS electrification strategy represents a shift in responsibility for the provision of electricity infrastructure from the state onto the energy poor. Samarakoon (Samarakoon, 2020) shows that the privatisation of electricity access risks reproducing existing socio-economic inequities, and also describes the ethical complexities presented by the unregulated landscape of Malawi's OGS market. This unregulated market landscape reflects that, globally, only an estimated 28 % of OGS sales are affiliated with the industry body: The Global Off-Grid Lighting Association (GOGLA). Whereas, the remaining 72 % of OGS sales are through the unregulated sector, representing a market of affordable bottom of the pyramid products, not monitored by GOGLA or subjected to centralised quality regulation (Foster, 2014; Lighting Global et al., 2020; Groenewoudt et al., 2020). This unregulated OGS market is praised for making OGS products more affordable and electricity services more accessible, although suffers from a lack of supplier accountability and is criticised for the prominence of substandard and counterfeit products – exposing energy-poor households to exploitation (Groenewoudt et al., 2020; Samarakoon et al., 2021). However, the dynamics of SSA's unregulated OGS market are still unclear due to a lack of research as literature has predominantly focused on the regulated minority of the OGS market (Kinally et al., 2022).

Meanwhile, the widespread uptake of short-lived OGS products in SSA has resulted in an already significant and rapidly growing OGS waste flow: an estimated 12,000 t of waste was generated in 2020, growing by 545 % from 2016 (Magalini et al., 2016; Hansen et al., 2020). This growing OGS waste flow is concerning because, similar to other countries across SSA, Malawi has no legislative or physical infrastructure to manage electronic waste (e-waste), while household waste is commonly buried, dumped in nature or burnt (International Telecommunication Union (ITU), 2018; Manda, 2009; Government of Malawi, 2010). With the general absence of formal e-waste management infrastructure, OGS waste management practices in SSA have been highlighted to present severe environmental and human health risks from the potential release of toxic pollutants (Kinally et al., 2022; Mukoro et al., 2021). However, the consensus on how to address SSA's OGS waste flow from the industry body and emerging legislation – aiming to establish centralised waste collection and formal recycling solutions by mandating that OGS suppliers finance the waste management of their products (extended producer responsibility) – has also received ethical criticisms (Corbyn et al., 2019). Cross and Murray (Cross and Murray, 2018) emphasise that the framing of OGS waste as an environmental issue necessitating formal recycling solutions fails to recognise the valuable roles of the actors within the existing informal waste management chain. In particular, Cross and Murray highlight that prioritising the recycling of OGS waste overlooks the role of informal electronics repairers in compensating for the high rate of OGS product failures – supporting the OGS market and solar users. Furthermore, these authors (Cross and Murray, 2018) argue that any waste fraction that cannot be processed within the existing informal waste management sector is a feature of design. Hence, (Cross and Murray, 2018) responsibility should be directed towards OGS suppliers to manufacture products that can be sustainable with the existing OGS market dynamics, rather than relying on complex end of life financing mechanisms and recycling infrastructure that does not exist in SSA. Samarakoon et al. (Samarakoon et al., 2022) also highlight the valuable role of informal repairers in Malawi, supporting local OGS users and reducing the OGS waste flow by extending the lifetime of OGS products. Kumar and Turner (Kumar and Turner, 2020) reinforce this narrative by emphasising that the current framing of OGS waste fails to recognise, and threatens to marginalise, the actors in the informal waste management chain who depend on their interactions with e-waste as a source of livelihood.

Whilst the energy justice literature calls to move away from the framing of OGS waste as an environmental hazard and to gain a better understanding of the complex 'afterlives' and social interactions with OGS waste fractions, there are still significant research gaps considering the environmental impacts of OGS waste. Most concerningly, none of the energy justice literature acknowledges the substantial human health risks relating to the informal recycling of lead-acid batteries – a primary vector of lead exposure in SSA and cited as the world's largest source of toxic pollution that directly affects human health (Manhart et al., 2016; Ballantyne et al., 2018; Rees and Fuller, 2020; Pure Earth, 2016). An isolated study attributed the death of 18 children to a single informal battery recycling operation in Senegal (Haefliger et al., 2009). Nonetheless, SSA's informal lead-acid battery recycling industry and the health burdens that it imposes on surrounding communities are still poorly understood due to a paucity of research (Kinally et al., 2022). In this sense, the current informal OGS waste management practices potentially also present justice issues by imposing significant health and environmental burdens onto energy-poor populations. Furthermore, the lack of transparency of the current waste management practices limits the capacity for the environmental performance of OGS technologies to be accurately quantified, for example by life cycle assessment studies. In Malawi, Samarakoon et al. (Samarakoon et al., 2022) have described the practices of informal electronics repairers, notably, describing repairers to perform simple battery repairs (cleaning battery plates and terminals and refilling battery acid), to aggregate OGS waste, and to sell disused plastic battery cases to scrap dealers. However, the informal waste management practices for lead-acid batteries and other OGS waste fractions beyond repair have not previously been described in Malawi, and neither have activities relating to OGS waste materials in Malawi's scrap market. Hence, the fate of OGS waste materials beyond repair is still unclear, yet, presents potentially significant health and environmental risks and justice concerns regarding Malawi's national electrification policy.

This paper addresses the gaps highlighted in the energy justice literature by considering a life cycle perspective to investigate the practices throughout the life cycle of OGS products in Malawi. With the variety of OGS products and the level of electricity services that they provide, this study focuses on solar home systems (SHSs) (>10 Wp), as smaller pico solar products do not typically provide the minimum level of service to qualify as (tier 1) electricity access (Bhatia and Angelou, 2015). In particular, this study aims to describe the actors in the life cycle of SHSs in Malawi, their perspectives, and their interactions with SHS materials. Specifically, to increase the transparency of i) the dynamics of Malawi's OGS market and how SHS are commercialised, ii) user practices and the level of electricity services from SHSs, iii) the flow of materials between actors in the SHS life cycle, and iv) end of life waste disposal practices for SHS materials. Finally, the results of the study are then used to expose environmental risks and justice issues associated with Malawi's national OGS electrification strategy, and key principles for the development of effective waste management interventions are outlined based on an energy justice perspective.

Considering the structure of the paper, Section 2 details the methodology of the study. Section 3 presents the results and discussion, describing the perspectives and practices of the actors in the SHS life cycle and the material flow between them. Then, Section 4 discusses the environmental risks and justice issues presented by the current informal SHS waste management practices and highlights key principles for initiatives to address the OGS waste flow from an energy justice perspective. Section 5 discloses the limitations of the study and outlines impactful directions for future research. Finally, conclusions are provided in Section 6.

2. Methodology

During a three-month period (May–July 2022), a total of 50 semi-structured interviews were conducted with stakeholder groups in the informal waste management chain for SHSs surrounding the capital city of Lilongwe, shown in Table 1. The stakeholder groups of solar vendors, solar users, electronics repairers and scrap dealers were purposefully selected – previously identified in the region of Lilongwe by Samarakoon et al. (Samarakoon et al., 2022). A previously unrecorded stakeholder group was identified during the study: informal lead-acid battery recyclers, and were also interviewed. Semi-structured interviews (SSIs) were selected as the primary data collection tool. Each stakeholder group had their own set of structured interview guides (shown in Supplementary Information), designed to address the research objectives and each group's specific interactions in the SHS life cycle. Meanwhile, responsive follow-up questions were used to provide the flexibility to explore participants' responses and previously unrecorded practices in greater depth, although, the conversation was constrained to topics relating to the life cycle of SHSs. Some common questions were asked to all of the stakeholder groups, specifically, asking if the interviewees perceived waste from SHSs to pose a threat to the environment or human health. Convenience sampling (Battaglia, 2008) was used to gain interview participants, justified due to the lack of sufficient prior data to enable probability sampling. Participants were identified by asking community leaders and local residents for directions; by visually identifying potential participants while walking through peri-urban villages (off-grid communities) and commercial districts (within a 20 km radius of the city centre); and by snowballing – asking interview participants for directions to other potential interviewees (Naderifar et al., 2017). Meanwhile, the number of interviews was maximised within the three-month data collection window. The interviews ranged between 30 and 60 min long and were carried out in a mixture of English and Chichewa with the assistance of a translator. The interviews were transcribed and then analysed by thematic analysis (manually) (Cho and Lee, 2014). For each of the stakeholder groups, information relevant to the defined research objectives was identified as codes. Then, patterns between the participants' responses and codes were identified as themes – discussed in Sections 3.1–3.6. These identified themes were then compared with prior literature to generate theories relating to the energy justice concerns of OGS waste management, presented in Section 4. The features of this methodology (semi-structured interviews, convenience sampling, and thematic analysis) were pragmatically selected due to their capability to address specific research objectives within topics where there is a lack of prior knowledge or subjective understanding (DiCicco-Bloom and Crabtree, 2006; Merton and Kendall, 1946; Morse and Field, 1995; McIntosh and Morse, 2015). Technical surveys (appendix 2 in the SI) were also carried out alongside the interviews with the solar users, recording the design of their SHSs, indicating the quality of the SHS design and installation and the material composition of the waste flow. A total of 15 technical surveys were completed. For the analysis in this study, a conversion rate of 1 USD = 815 MWK is considered, reflecting the rate at the start of May 2022, when the study commenced.

Table 1
Frequency and location of the stakeholder groups that participated in interviews.

Location	Frequency				
[Interview codes]	Vendors [V1–7]	Users [a] [U1–18]	Repairers [R1–9]	Scrap dealers [SD1–8]	Informal lead-acid battery recyclers [IR1–8]
Lilongwe Area 2	6				
Village 1		5	2	1	1
Village 2		4	4[b]		3
Village 3		4	2	1	2
Village 4	1	5	1	1	1
Village crossroads				4	
Commercial districts				1	1
Total	**7**	**18**	**9**	**8**	**8**

[a] Users are defined as households using the minimum of an 11 Wp solar panel connected to a battery.
[b] One of the electronic repairers was presented as a vendor of refurbished electronic devices and was considered separately within the analysis.

3. Results and discussion

The results describe the complex life cycle of SHSs that are used in peri-urban villages surrounding Lilongwe. The actors in the SHS life cycle and the material flow between them are summarised in Fig. 1, and the practices of the interviewed vendors, users, electronics repairers, scrap dealers and informal lead-acid battery recyclers are summarised in Table 2. The OGS market is found to depend on unregulated SHS components predominately imported from China, subject to a district lack of supplier accountability. Local OGS vendors are separated from the product manufacturers and purchase components from wholesalers in Malawi, meanwhile, false advertising and counterfeit products are confirmed as common. A market of second-hand and refurbished SHS components is also found within peri-urban villages, catering to low-income energy-poor SHS users. Meanwhile, SHS design and user practices are found to reflect affordability constraints, a lack of technical expertise, and safeguarding practices, resulting in frequent SHS faults and short expected product lifetimes. However, informal electronics repairers are found to effectively compensate for the high rate of SHS faults not relating to batteries, providing a highly valued service supporting local SHS users. Hence, lead-acid batteries occupy the majority of the waste flow, while other components and materials are kept in circulation. Beyond repair, valuable SHS waste fractions (including aluminium, copper, steel, circuit boards and lead-acid battery scrap) are effectively aggregated by established networks of scrap collectors and dealers and are exported to buyers across SSA and in China. Whereas, SHS waste is also commonly dumped and buried in pits alongside household waste within communities, and the burning of waste at community dumpsites is common to manage waste volumes. Meanwhile, small informal lead-acid battery recycling operations were found within all of the peri-urban villages visited and within the city centre, providing a valued service inexpensively compensating for the short lifetimes of SHS batteries. However, the identified informal lead-acid battery recycling practices present severe public health risks and justice concerns from the release of significant quantities of lead pollution into densely populated communities – highlighting an urgent need for interventions, discussed in Section 4. Furthermore, the dumping, burying and burning of hazardous waste, and the unregulated transboundary movement of toxic battery scrap pose significant environmental and health risks, but are currently less well-understood. The practices and perspectives of each of the stakeholder groups are discussed in detail in subsequent Sections 3.1–3.5.

3.1. Solar vendors

The solar vendors were found to be concentrated within Lilongwe Area 2, the busy central market district of the city, where most general electronics shops were found to display solar products. Some SHS vendors were also found presenting small market stalls or shops within peri-urban villages but these were less common. Only one of the interviewed vendors [V2] represented the regulated solar market category (Kinally et al., 2022) as a MERA (Malawi Energy Regulatory Authority) approved solar wholesaler. This regulated wholesaler provided commercial and institutional solar installations as well as catering to walk-in customers from the local villages. Whereas the other solar vendors interviewed represented the unregulated sector of the OGS market and were presented as general electronics shops – reflecting the vast majority of the OGS vendors observed across the city centre and villages.

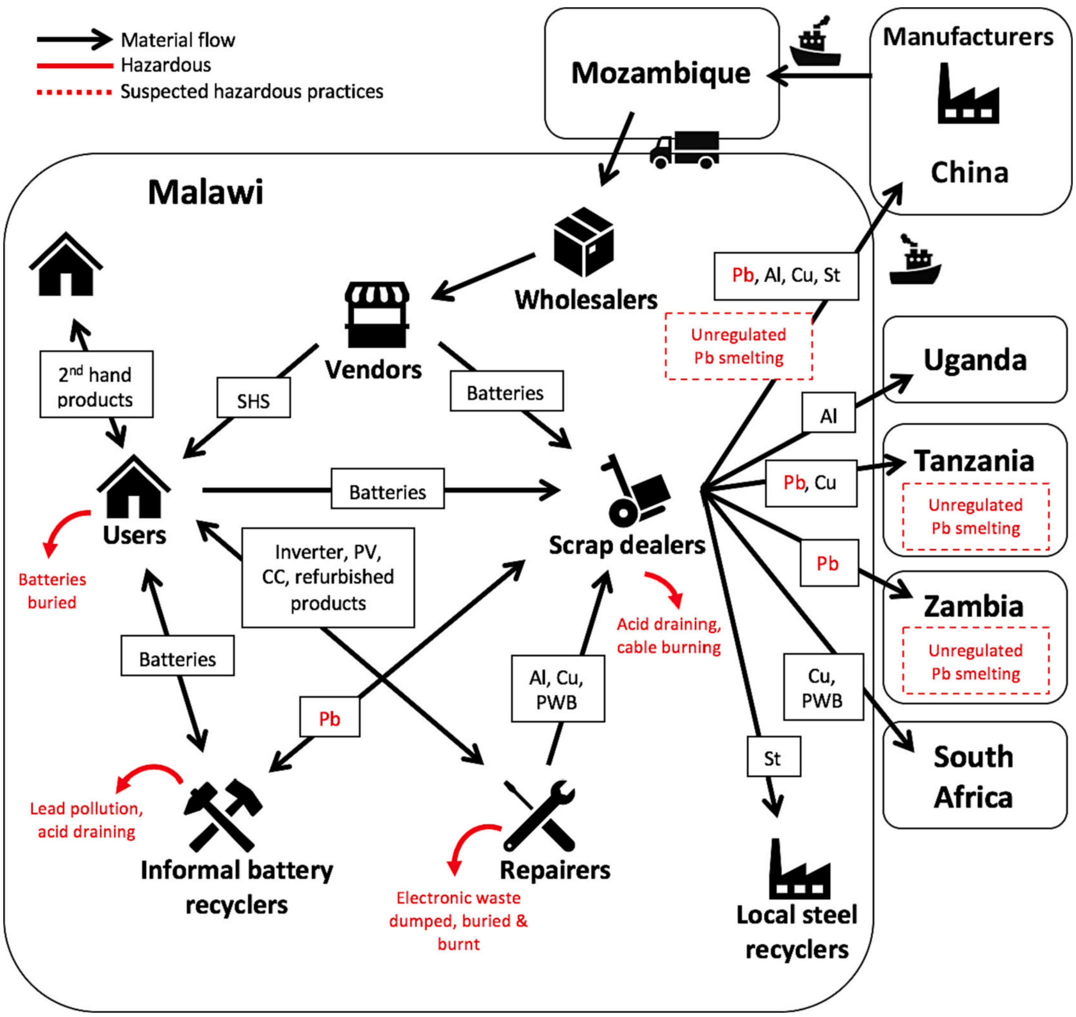

Fig. 1. The life cycle of solar home systems in Malawi. SHS = solar home system, PV = photovoltaic panel, CC = charge controller, Pb = lead, Al = aluminium, Cu = copper, St = steel, PWB = circuit boards.

3.1.1. Solar products

All of the vendors sold SHSs as separate individual components by upfront cash payments, requiring SHSs to be designed and installed. Only the regulated wholesaler [V2] sold complete plug-and-play (PnP) OGS products, stocking one model: a 5 Wp system for 39,000 MWK (49 USD). This 5 Wp system was disproportionately expensive considering that the components for a 50 Wp system could be purchased from an unregulated vendor for 80,000 MWK (96 USD) (40 Ah gel battery, 50 Wp polycrystalline silicone panel, PWM charge controller, 300 W "Solar Africa" inverter and copper wire). The regulated wholesaler was also the only vendor to sell lithium-ion batteries and praised their superior performance to lead-acid batteries. However, the regulated vendor reported lithium-ion batteries (low-toxicity) to be unaffordable for most customers – roughly three times the price of lead-acid batteries (high-toxicity) with a comparable storage capacity. The unregulated vendors only sold lead-acid batteries. The PV panels sold by the unregulated vendors were categorised and priced between "German" and "Chinese" types – reflecting public perceptions of product quality. Among all of the stakeholder groups, "Chinese" products were perceived to represent affordable lower-quality products with shorter expected product lifetimes, often referred to as "not original" – reflecting bottom of the pyramid markets that are typically dominated by Chinese suppliers (Foster, 2014). Whereas "German" products were perceived to be of higher quality, although, some users labelled "German" products as unaffordable. However, most of the solar panels that were inspected, boldly labelled as "German Technology" on their face, showed references to Chinese manufacturers on the back of the panels, showing how these public perceptions of quality are manipulated as a marketing strategy. Similar false advertising practices have been confirmed with solar vendors across central and northern regions of Malawi by Samarakoon et al. (Samarakoon et al., 2021) and in Uganda by Groenewoudt et al. (Groenewoudt et al., 2020).

3.1.2. Product import and tax exemption

All of the unregulated vendors purchased their stock from Chinese manufacturers, predominantly through local wholesalers. One vendor added that their products are shipped via Mozambique. Whereas the regulated wholesaler purchased directly from manufacturers in China, India, Germany, South Africa and the USA. Another vendor explained that, since VAT and import duty were removed from solar products, selling SHSs has become financially very appealing and reported a 20 % profit margin from solar panels. The import duty exemptions (2013) and VAT exemptions (2019) were announced by the Malawi Government as a strategy to increase national electricity access by promoting the uptake of solar products (Government of Malawi, 2019; Africa Clean Energy Technical Assistance Facility and Open Capital, 2021). However, the regulated wholesaler expressed their concern that, since the government "opened up" the solar market, the market has become flooded by cheap sub-standard products, reducing public trust in solar technologies.

Table 2
Main findings for each stakeholder group.

Stakeholder group	Main findings
Vendors	- Incentivised to sell solar by VAT and tax exemptions - Sell SHSs as individual components, requiring system design and installation - Purchase SHS components through local wholesalers and often have no contact with product manufacturers - No regulation on the quality of products imported - False advertising common - Adequate warranties uncommon
Users	- Electricity services restricted by affordability - Often purchase second-hand and refurbished components - Typically design and install SHSs through trial and error - User error, poor SHS design, and low-quality components result in frequent faults and unreliable electricity services - Use affordable lead-acid batteries with an expected lifetime of one year - Purse local battery repair services, sell used batteries to scrap dealers, or bury batteries
Repairers	- Informal electronics repairers are common in village markets - Repair, refurbish and fabricate SHS components from spare parts and electronics scrap - Compensate for the high rate of SHS failures - Sell valuable waste fractions to scrap dealers
Scrap dealers	- Effectively aggregate valuable waste fractions (metals and electronics) from surrounding communities - Sell scrap to buyers across SSA and in China - Often drain battery acid on soil and burn cables - Potential to redirect the waste flow with financial incentives
Battery recyclers	- Capitalise on the significant lead-acid battery waste flow and compensate for short battery lifetimes - Perform battery repairs and sell cheap refurbished batteries - Accessible trade using available tools and rudimentary techniques - Releases alarming quantities of lead and sulphuric acid pollution into densely populated communities

VAT = Value-added tax, SHS = solar home system, OGS = off-grid solar, SSA = sub-Saharan Africa.

> *"[the] government is losing a lot of revenue, at the same time the customers in the villages are being duped with sub-standard equipment."*
> – Regulated solar wholesaler [V2]

Legislation exists in Malawi mandating solar suppliers to be licenced by MERA, requiring their products to be assessed and approved by the Malawi Bureau of Standards (MBS) *(*Government of Malawi, *2017a;* Malawi Bureau of Standards, 2017*)*. However, even the Malawi Bureau of Standards have recognised their enforcement of this legislation as ineffective. In 2019, the MBS publicly acknowledged that Malawi's solar market is "flooded with counterfeits" and emphasised that it was the customer's responsibility to be informed about product quality (requiring a high level of technical understanding) (Malawi Bureau of Standards, 2019). Hence, even before the exemption of VAT, unregulated OGS products appear to have been imported without restriction. The regulated wholesaler suggested that tax exemptions should only be provided to vendors certified by MERA and MBS to address the influx of sub-standard products. This complex policy has shown to be fiscally effective in Rwanda but requires the effective enforcement of quality regulation and market transparency – both lacking in Malawi (Africa Clean Energy Technical Assistance Facility and Open Capital, 2021; Scott and Miller, 2016). In the meantime, the unrestricted importation of uncertified solar products and the high profit margins reported by the unregulated vendors offer a plausible explanation for why the majority of electronics vendors in Area 2 were seen to be selling solar products.

The Malawi Government announced that the Lighting Global product quality standards were to be adopted in 2018, mandating a minimum of two-year warranty periods for SHSs, replacing the previous MBS standards that required only a one-year warranty (Government of Malawi, 2017a; Lighting Global, 2018). The regulated wholesaler was the only vendor to satisfy the warranty requirement; by purchasing directly from a certified manufacturer, the wholesaler was able to extend the manufacturers' warranties to their customers. Whereas the unregulated vendors often offered warranties of up to 6 months for batteries, between three months and two years for PV panels, or offered no warranties at all because their local wholesalers do not accept returns.

3.1.3. Waste management practices

None of the vendors collected end-of-life products from their customers. However, broken products often accumulated in their shops, either from accidental breakage from handling or from returns. Cracked PV modules (with reduced functionality) were offered to customers at a significant discount, and one vendor mentioned that they were visited weekly by a scrap dealer offering to buy broken solar panels. There were no other reports of a scrap market for broken PV panels throughout the study, although, solar panel repairs were reported to have high success rates (see Section 3.3). Meanwhile, all of the vendors sold broken lead-acid batteries to scrap dealers who were reported to regularly visit the vendors' shops.

3.2. Solar users

The composition of the recorded SHSs, reported electricity services and battery lifetimes are shown for Users 1–18 in Table S1 in the Supplementary Information. The electricity services from the users' SHSs included: lighting, mobile phone charging, radios and sound systems, and TVs. However, the observed quality of SHSs and the users' levels of electricity services varied significantly. The lowest level of service was reported by User 4, who had an improvised SHS composed of a second-hand 20 Wp solar panel mounted on a pile of bricks, wired directly to a second-hand 7 Ah motorcycle battery, powering only a single light bulb. User 4 emphasised that these were the only affordable components and experienced battery faults after only one week.

> *"there weren't any other options… to be in light."*
> – Solar home system user 4

Whereas other users were able to power TVs for several hours a day, although all of the SHS users reported having to ration their energy consumption. Less than a third of the users had charge controllers to protect their batteries from being damaged by deep-discharging and overcharging. Meanwhile, the users commonly reported using appliances until their battery stopped providing power – deep discharging their batteries every day. Notably, User 14 had a charge controller presented as a wooden box, hand fabricated by a local informal electronics repairer (see Section 3.3). User 14 purchased the wooden charge controller for 3000 MWK (3.6 USD) and expressed that these inexpensive charge controllers were popular among local solar users. All of the recorded SHSs used types of lead-acid batteries (sealed, flooded, and gel batteries), and two of these systems used automotive batteries – expected to degrade quickly in SHSs. Lithium-ion batteries were not reported during the interactions with any of the stakeholder groups in the villages.

3.2.1. Solar home system installation

The majority of the users travelled to purchase their SHSs from Area 2 (where the vendors are concentrated) using public transport. Users often purchased their SHS components in phases, waiting to save money to be able to afford each component. While other users, purchased SHS components or entire systems from vendors at their local village markets, or purchased second-hand SHS components from neighbours that were experiencing financial difficulties or that had gained a grid connection. Most of the users designed and installed their SHSs themselves, with assistance from friends or by experimenting and connecting components until their system worked. Whereas, other users employed technicians to install their SHSs, either from the shop where the SHS was purchased or local informal technicians. Few of the roof mounted solar panels were optimally oriented facing north (Table S1 in SI) (Kamanga et al., 2014). The orientation of solar panels generally reflected the direction of the front-facing roof pitch of the user's house, keeping panels in their field of view due to concerns of theft. Messy and dangerous exposed wiring was also common.

Users commonly specified buying more affordable "Chinese" products (synonymous with lower quality, see Section 3.1.1) and second-hand or refurbished components to save costs (such as recycled batteries, see Section 3.5.1). Some users also labelled charge controllers as unaffordable additional costs or were not aware of the need for charge controllers to protect their batteries. Hence, the level of expertise in SHS design and installation was found to be low, and the design of SHSs reflected affordability constraints and a lack of education on SHS design and safeguarding habits, rather than the technical optimum.

3.2.2. Panel safeguarding and cleaning habits

Most of the users mounted their solar panels permanently on their roofs, either secured on metal stilts, raised on bricks, or placed flat on roofs (Table S1 in SI). However, theft of SHS components was commonly reported as a concern, particularly PV panels; three users had experienced theft and others reported witnessing solar panel theft in their village. Accordingly, many of the users temporarily placed their panels flat on their roofs or leant against objects during the day, so that they could bring their panels inside for safeguarding at night or when they were not home.

The safeguarding practice of bringing panels inside also impacted users' solar panel cleaning practices. Failing to clean panels in SHSs can severely reduce battery lifetimes, resulting in chronically undercharged and overstrained batteries (Maghami et al., 2016). A few of the users [U9–11, U15] specified that they notice increased performance from their SHSs after cleaning their panels, and explained that their panels need to be cleaned regularly because condensation and the windy dusty climate make their panels prone to collecting dust. Generally, panels that were permanently mounted on roofs were less regularly cleaned and were visibly covered in dust – typically mounted at the top of corrugated iron roofs and difficult to access. Whereas, the temporarily mounted panels were cleaned more regularly, showing these safeguarding practices to have a secondary benefit to the performance and maintenance of SHSs. These panel cleaning practices were also explained to be a housekeeping practice to avoid bringing dust from solar panels into homes.

3.2.3. Solar home system faults

SHS faults were very common, resulting in unreliable electricity services, unexpected costs for users from repairing and replacing components, and significant waste volumes. Lead-acid batteries were reported as the single greatest source of failure. The average reported battery lifetime is approximated to be one year (Table S1 in SI), significantly shorter than the three to five year expected lifetime shown in literature (Crossland et al., 2015). Batteries were often reported to fail within six months [U1, U4, U6, U16], whereas battery lifetimes were rarely reported to exceed two years [U7, U18]. Although some of the users had relatively new SHSs (up to 18 months old) and had not yet experienced battery faults. These short lifetimes are not surprising considering the strain on batteries due to the lack of charge controllers, regular deep-discharging, the lack of expertise in SHS design and installation, and often insufficient solar panel cleaning schedules – all known to result in rapid battery deterioration (Charles et al., 2019). To compensate for the high rate of battery failures, battery repair shops were present in all four villages (see Section 3.5). The users that had pursued local battery repair services [U8, U15, U16, U18] were generally satisfied with the level of service of their repaired batteries. One user [U16] had taken their battery to a repair shop in their village every six months for the three years that their SHS had been in operation. Another user [U8] had been using their battery for a year without faults after being repaired, in line with the average reported battery lifetime.

Inverter faults were also common, reported by most of the users that owned them. The electronics repairers explained that the high rates of inverter failures were a result of poor user understanding and detrimental usage habits (see Section 3.3.1). Solar panel faults were found to result from safeguarding practices. Broken wiring at the junction box of solar panels was commonly reported, although exclusively by the users that temporarily mounted their panels – who moved their panels every day stressing the wired connections. Another user reported accidentally short-circuiting their solar panel while mounting it on their roof – also confirmed as common by the repairers. Charge controller faults were not reported (by the five users that used them), although were reported as common by the local electronics repairers. The only other SHS faults reported by the users were burnt wires from using wires that were underrated for their application [U4, U10].

When the users experienced faults, they often attempted to diagnose the cause and perform minor repairs themselves. This approach typically involved inspecting for loose connections and manually twisting exposed wires back together, purposefully short-circuiting batteries to see if it produced a spark (indicating that the battery held charge), and sometimes disassembling components. Some of the users were not aware of the solar repair services within their own villages, although, aside from battery faults, these users had not yet needed to seek out repairers. When faced with a fault that they could not repair themselves, users typically asked their friends for advice or to direct them to a repairer. Some of the users made inconvenient journeys to visit repairers in other districts, rather than pursuing the repair services within their own villages, showing a preference to pursue endorsed solutions.

3.2.4. Waste management practices

When SHS components broke, users were keen to regain their electricity services and repair was a priority before selling and disposing of waste. None of the interviewed users had experienced faults with their inverters or solar panels that could not be fixed by the local repairers (see Section 3.3.1). Hence, some users held broken inverters in their homes, waiting to save money to pursue repair services, but none of the users had ever disposed of broken inverters or solar panels. One user had disposed of burnt copper wires in a waste pit. Otherwise, lead-acid batteries were the only SHS component that the users reported to have disposed of – occupying the majority of the waste flow.

Several of the users reported selling batteries for between 500 and 6000 MWK (0.6–7.4 USD) to scrap dealers, who regularly walk or cycle through the villages shouting or using megaphones to advertise that they are buying broken batteries [U1, U2, U7, U12, U16, U18]. Other users planned to sell their (still functioning) batteries to local scrap dealers when they eventually broke [U3, U4, U11]. Some users had pursued local battery remanufacturing services [U8, U15, U16, U18] (see Section 3.5). While the remaining users were not aware of the scrap value of their batteries or the local battery remanufacturing services [U5, U8, U9, U10, U13, U14, U17], and reported hoarding broken batteries, burying batteries alongside household waste or had not yet considered waste disposal.

3.3. Repairers

Solar repair services were available in all of the villages from informal electronics repair shops located on the busy market streets, each shop filled with broken electronic devices hoarded for spare parts. The repairers were in high demand, although were often not able to work due to the regular grid load shedding – except for two of the repairers [R1, R2] that used SHSs to power their shops. None of the repairers specifically catered to solar, although, repairing SHS inverters typically represented a significant share of their business. Notably, one of the repairers [R8] had a relationship with a business that regularly delivered broken components from commercial solar installations to be fixed, showing the informal repair economy to be integrated into the formal economy. A vendor selling second-hand solar components at a stall within one of the village markets was also interviewed (Repairer 9). Repairer 9 purchased broken electronics and SHS components from local villagers to repair and then resell at a significant discount compared to new products. Repairer 9 was also found to be selling the improvised wooden type of charge controller (Fig. S2 in SI) that was recorded in User 14's SHS (see Section 3.2). Only one of the repairers [R5] had received formal training, having taken a short technical training course offered by an established organisation. The remaining repairers were either self-taught through observation and experimentation or had been taught by mentors or their parents. Despite the lack of formal training, the repairers all exhibited high levels of technical expertise and provided a valued service to their surrounding communities compensating for the high rates of SHS failures and unreliable electricity services. This service from informal electronics repairers – providing an effective support mechanism for the local OGS market – is in line with prior findings from Samarakoon et al. (Samarakoon et al., 2022) across central and northern regions of Malawi and Cross and Murray (Cross and Murray, 2018) in Kenya.

3.3.1. Solar home systems repairs

Some of the repair shops offered lead-acid battery repairs [R1, R3, R4, R6], replacing degraded cells (see Section 3.5), although battery repairs were not a priority. Aside from batteries, the repairers explained that overloaded inverters were the most common SHS fault. Inverter breakdowns were reported to be caused by SHS users' lack of technical understanding of their electrical loads and the vulnerability of inverters to overuse.

> *"it's difficult since our understanding depends on the level of education for each person… some people may be using items [appliances] which are too big for the solar and not knowing and they maybe end up destroying the solar."*
>
> – Informal electronics repairer 6

Charge controller faults were also reported as common, although less frequent, partly because charge controllers are often omitted from SHS designs. Inverter and charge controller repairs were reported to have high rates of success. Broken components within circuit boards were identified using digital multimeters and were easily replaced, typically using spare parts held in the shops. The majority of the recorded inverters represented a generic elementary design (Figs. S1 and S2 in SI), often branded as "Solar Africa" or "Sunlight Solar", and spare parts were readily available. Inverters and charge controllers were explained to share electrical components with common devices such as TVs, Radios and DVD players, so components from other broken devices were often used in SHS repairs. If the repairers did not have the necessary spare parts to carry out a repair, they travelled into the city to buy new replacement components. Used circuit boards that housed various reusable electronic components were also found on sale at the markets in Area 2. Complications arose when the part numbers of broken integrated circuit (IC) chips were obscured by burns. In these cases, the repairers rendered the circuit boards beyond repair but were able to fabricate new circuit boards to replace the original. Some of the repairers [R3, R4, R6, R9] also explained that they were able to fabricate solar charge controllers entirely from spare components from electronics scrap (such as wooden type of charge controller Fig. S2 in SI). Furthermore, the design of these fabricated charge controllers was often tailored to meet the specifications of the customers' SHS, showing a high level of technical expertise.

Solar panels were reported to have long lifetimes and faults were less common. However, the repairers explained that faults can result from user error. Users were reported to accidentally short circuit panels (see Section 3.2.3) – causing diodes to burn. Also, accidentally dropping solar panels was reported to shatter the glass panels and cause "cut lines" in the busbar grids within the PV cells. All of the repairers were able to replace burnt diodes, and some of the repairers [R3, R4, R7] were able to fix "cut lines" – scratching through the glass on the face of the solar panel with a metal object and soldering the broken connections within the PV cell. Meanwhile, solar panels with broken glass or partially broken cells were commonly reused in lower-power applications.

3.3.2. Waste management practices

With the low rates of solar panel failures and high success rates of repair, the repairers that could fix PV cells [R3, R4, R7] emphasised that they had never received a solar panel that they were not able to fix, albeit with reduced efficiency, and had never disposed of a solar panel. However, other repairers [R1, R5, R6] reported burning broken solar panels or dumping them in nearby pits alongside household waste. Waste from small broken electronic components such as transistors, diodes and IC chips was generally regarded as insignificant due to their small size, and broken components were reported to be thrown on the ground, in waste pits, in nearby rivers, burnt, or given to kids as toys. All of the repairers were either regularly visited by scrap dealers or walked to a nearby warehouse (within 5 km) that purchased scrap metal. The repairers all reported selling aluminium, steel (such as inverter casings) and copper (wires and transformer coils) to scrap dealers, and some repairers also sold circuit boards, although, often prioritised keeping components that could be used in repairs or to fabricate refurbished products. Meanwhile, the repairers that fixed batteries [R1, R4, R6] also sold used lead battery cells to scrap dealers.

3.4. Scrap dealers

Scrap dealers were very visible, characteristically presenting substantial piles of scrap metal on the sides of main roads, on the outskirts of villages, and within industrial sites. Only one of the four villages did not have a local scrap dealer, although was only five kilometres away from a commercial district with two well-established scrap dealing sites. The scrap dealing businesses revolved around a set of scales, where the dealers purchased scrap from visiting customers by weight in quick well-rehearsed transactions. This established scrap market very effectively collected valuable waste materials from the surrounding communities. Accordingly, some of the scrap dealers expressed views that their businesses compensated for the lack of public waste management services.

> *"to trust or to rely on the city council is something that can't be"*
>
> – Scrap Dealer 2

3.4.1. Buying scrap

The scrap dealers catered to local villagers who walked, cycled or took public transport to the sites carrying small quantities of scrap by hand or in sacks. Some of the scrap Dealers [SD2, SD8] also employed scrap collectors to visit the surrounding villages, while the other dealers purchased from independent scrap collectors. These scrap collectors were confirmed by all of the other interviewed stakeholder groups to regularly visit their place of work or homes looking to buy valuable scrap materials. Whereas, the two largest scrap dealing businesses (Scrap Dealers 3 and 6) focused on buying larger volumes of commercial and institutional waste, and explained that organisations advertise scrap for sale in local newspapers. Scrap Dealer 3 reported regularly purchasing scrap from Airtel (Malawi's leading telecommunications and mobile money provider) and Chinese construction companies. Hospital equipment was also seen at scrap sites 3 and 6, showing the informal scrap market to be embedded into Malawi's formal economy.

Used lead-acid batteries and various scrap metals were purchased across the scrap dealing businesses, including aluminium, copper, steel, iron, brass, and lead battery cells. Aluminium was a priority and was purchased by all of the dealers, followed by used lead-acid batteries. Used electronic devices were also often purchased to salvage copper wiring. However, one scrap dealer [SD7] explained that they were cautious when dealing with copper, as it could attract police attention due to the local history of electricity cable theft. Scrap Dealers 3 and 6 also collected circuit boards from electronic devices, although, explained that circuit boards were not a priority for their business and were often collected as a by-product from purchasing waste electronic devices to salvage metal casings and copper wires.

3.4.2. Waste disposal

When the dealers were valuing scrap to purchase, undesired materials were removed before the scrap was weighed. Batteries were valued without acid, so battery acid was drained on the soil at the scrap sites – releasing kilograms of sulphuric acid into the environment from a typical battery. Concerningly, used battery acid is known to carry dissolved lead, highlighting another vector for lead pollution (World Health Organisation, 2017). Scrap Dealer 8 explained that they occasionally sold used battery acid to local battery recyclers for 100 MWK/kg (to be used to fabricate batteries), although usually discarded acid on the soil. The scrap dealers [SD7, SD8] reported that they often found fake glass battery cells within "Chinese solar batteries" (bottom of the pyramid products – see Section 3.1.1) – adding weight and occupying space inside the battery but not contributing to its function. These glass plates were removed before weighing batteries to determine their scrap value, and piles of glass plates accumulated next to the scrap dealer's scales. Similar solar batteries with fake glass cells from Chinese suppliers have also been reported in Uganda (Groenewoudt et al., 2020; The Observer, 2017). Finally, some of the scrap dealers [SD6, SD7] confirmed burning electrical cables at their site, removing the plastic wire insulation to yield the enclosed copper wires – known to release carcinogenic furan and dioxin gasses (Manhart et al., 2018).

3.4.3. Selling scrap

Scrap Dealer 8 explained that they were employed by a central office called "Sunrise" and that a company truck regularly collected their scrap to take back to the Sunrise main office. Scrap Dealer 8 believed that the scrap was then exported to China and also explained that Sunrise controls many similar scrap sites across the city. Whereas, all of the other scrap dealers ran independent businesses and had multiple buyers for their scrap, but some of these scrap dealers [SD2, SD5, SD7] did sell certain scrap materials to Sunrise. Steel was the only material that was reported to be sold to a recycler within Malawi, and reusable aluminium sheets were also sold locally. Scrap Dealer 2 also reported reselling used lead-acid car batteries that still held a charge to local villagers for second-life applications in SHSs for lighting. All of the other materials sold by the independent scrap dealers were exported to buyers across sub-Saharan Africa, as described in Fig. 1.

The chain for selling scrap metal was unstandardized and complex. Scrap Dealer 1 transported their materials directly to buyers in neighbouring countries, while some scrap dealers [SD3, SD6, SD7] sold their scrap to transporters who dealt with international buyers. Other scrap dealers [SD2, SD4, SD5, SD8] only acted as local aggregators of scrap and sold their materials to larger scrap dealers within Malawi, extending the waste management chain. The scrap dealers described the scrap market as competitive and the value of scrap as volatile, emphasising that the volatility in fuel prices particularly impacts their businesses. Meanwhile, the independent scrap dealers had no committing relationships and actively sought out new contacts that could potentially offer higher prices for their scrap.

Lead-acid batteries were reported to be sold to buyers in Tanzania [SD3, SD7] and Zambia [SD1]. Concerningly, informal lead-acid battery recycling is known to be well-established in Tanzania (AGENDA, 2016), and Zambia has a history of informal lead mining and smelting (Lombe et al., 2021). Therefore, there is a significant risk these exported batteries are being sold into the informal recycling industry, causing substantial human health burdens in these countries. Meanwhile, three of the scrap dealing sites [SD2, SD7, SD8] delivered batteries to Sunrise. These batteries were reported to be melted at the Sunrise office (which showed a "Sunrise Smelting" sign) and then exported to China.

3.5. Battery recyclers

An industry for informally recycling lead-acid batteries has not previously been reported in Malawi. However, between one to five informal lead-acid battery recycling operations were recorded within each of the four villages and were also found within industrial districts near the city centre. These informal recycling operations were typically presented as "battery repair" shops (Fig. S3 in SI), although were all found to recycle batteries by melting scrap lead to fabricate improvised battery cells or terminals. Batteries were commonly recycled on the street exposing densely populated communities to significant quantities of lead pollution, and battery repair shops were recorded within 150 m of nursery schools and community water wells. Similar informal lead-acid battery recycling operations have also been identified in Ethiopia by the Lead Recycling Africa Project (Manhart et al., 2016) and were labelled as informal battery refurbishment. The scale of the recycling operations ranged from a shop with four workers that recycled up to fifteen batteries each week [IR3], to an individual who occasionally recycled batteries outside of their barbershop [IR5]. With their experience dismantling batteries, the informal battery recyclers also reported a prominence of counterfeit batteries in the local OGS market, using fake glass cells or smaller cells that do not match the battery's nominal capacity (in agreement with the findings from the scrap dealer interviews).

3.5.1. Services

All of the battery recyclers fixed broken batteries and also sold recycled batteries – typically for less than half of the price of an original battery. The battery recyclers travelled to purchase broken batteries from local villagers and businesses to recycle and resell, acting as scrap collectors. The demand for recycled batteries was explained to be high because many of the local villagers could not afford to buy new batteries. The demand for recycled batteries also extended beyond the local villages. Battery Recycler 7 reported having customers that travelled over 100 km from rural districts, and Battery Recycler 1 advertised their services on social media and reported having customers that travelled from Mozambique to buy recycled batteries in bulk. All of the battery recyclers catered to SHS users, although, some of the recyclers [IR5, IR6, IR8] explained that most of their business was occupied by automotive batteries. Whereas the other recyclers predominantly [IR1, IR2, IR7] or exclusively [IR3, IR4] exclusively dealt with SHS batteries. Battery Recycler 7 explained that they rarely receive automotive batteries because end-of-life automotive batteries are often repurposed to provide lighting in SHSs before being recycled.

The informal lead-acid battery recycling industry was also integrated into the formal economy. Local businesses were reported to hold large volumes of used lead acid batteries in warehouses. Battery Recycler 8 handed out business cards and regularly received deliveries of broken batteries from local businesses. Meanwhile, Battery Recycler 7 emphasised the surplus in both the supply of used lead-acid batteries and the demand for (cheap) recycled batteries. Recognising the economic opportunity presented by the lead-acid battery waste flow, Battery Recycler 7 wanted to expand their business but expressed frustration that they could only afford to buy a small number of batteries at a time.

3.5.2. Battery recycling process

Used lead-acid batteries were either repaired by replacing degraded battery cells or remanufactured by fabricating improvised cells from the degraded battery materials. Various methods of fabricating battery cells were recorded, although, all following the same general principles, described in detail in SI. Batteries were opened and dismantled using manchettes and saws, battery acid was drained on soil, lead was melted over a charcoal stove, degraded battery plates were crushed and mixed with acid into a paste, and improvised battery cells were fabricated by hand, shown in Fig. 2. However, the practices of each battery recycler depended on their available resources, level of expertise, preferences, the condition of the battery being recycled, and the intended application

Fig. 2. Melted lead grids being coated in lead oxide paste to fabricate battery plates for a solar home system battery.

of the recycled battery (SHS or automotive).

The recyclers commonly referred to crushed degraded battery plates as "sawdust", reflecting the brittle physical properties of dried degraded battery cells. From the moment that battery cells were removed from their battery casings, and throughout every stage in the informal recycling process, significant quantities of lead were visibly lost to the environment. Lead was released as dust and shrapnel, either accidentally spilt to the soil or purposefully swept away and discarded. Furthermore, degraded lead plates and lead dust were left to openly dry on the streets, often exposed to windy conditions (Fig. S3 in SI). Livestock (chickens and goats) commonly passed through the recycling sites (Fig. S4 in SI), and chickens were seen pecking at lead scrap – highlighting another potential vector for lead ingestion. Meanwhile, all of the recyclers performed their battery recycling processes in densely populated areas, on busy market streets in the villages or in busy commercial districts. The few health studies (Haefliger et al., 2009; World Health Organisation, 2017; Lomotey, 2010; Etiang' et al., 2018) that have been carried out in communities surrounding informal lead-acid battery recycling operations have attributed elevated blood lead levels, neurological defects and even fatalities to the informal recycling activities. Therefore, in line with these studies, the informal lead-acid battery recycling practices recorded in Malawi potentially present substantial health risks.

Most of the informal battery recyclers [IR2, IR4, IR5, IR6, IR7] reported being self-taught through experimentation after observing the rudimentary recycling process that only requires readily available tools (cooking stove, tin can, steel rod, and a saw) – showing informal battery recycling to be an accessible trade. Whereas, some of the recyclers [IR1, IR3, IR8] had been taught by a mentor. After being taught by a mentor and refining their trade, Battery Recycler 1 explained that they had written a battery recycling manual and offered battery recycling classes as a way to generate extra income. Some of Battery Recycler 1's students were reported to eventually move to South Africa and Blantyre (in southern Malawi), propagating and exporting the trade.

3.5.3. Waste management practices

The recyclers commonly traded lead scrap and battery scrap with local scrap dealers that regularly visited the batter repair shops, and also sometimes traded materials with other local battery recyclers. Battery Recycler 8 specified that their scrap dealer took degraded battery cells to Zambia. Furthermore, Battery Recycler 7 explained that before the local scrap market for used batteries and cells became established, scrap collectors travelled to their shop from Tanzania, Mozambique and Zambia to buy degraded battery cells to melt into bullets for hunting.

3.6. Awareness of hazards

Within each of the stakeholder groups, the majority of participants considered SHS waste as a risk to the environment and human health. The majority of the environmental and health concerns expressed related to battery acid: polluting rivers and drinking water, destroying soil fertility (critical in an agricultural economy), causing skin burns and blindness, and potentially being fatal to children if they accidentally drank acid. Other health concerns were commonly expressed regarding fumes released while charging batteries – potentially referring to hydrogen sulfide, a highly toxic and explosive gas with a rotten egg odour, known to be released from overcharging lead-acid batteries (Robinson and Tarascon, 1994). The battery recyclers also commonly reported that they were worried about inhaling fumes released during their recycling activities and drank milk as a remedy.

"*the air we are breathing in here is quite different to the air outside*"
– Battery Recycler 1

Finally, fumes from burning plastic waste were also reported to cause coughs, although, plastic was reported to often be used as a fuel for cooking when there is a shortage of wood. These perceived risks from SHS waste show a strong awareness of visible hazards or pollutants that have an immediate impact, such as visible fumes, gasses with strong odours, or acid burns. However, across the entire study, there was not a single mention of lead toxicity from the fifty interview participants. This shows how, without education, environmental and health hazards that are not immediately visible, such as lead toxicity, can remain undetected.

Furthermore, some of the users articulated a clear understanding that the health of their communities depends on the local environment.

"the environment is being damaged, and people are in that environment"
– User 8

However, due to a general lack of awareness of the hazards associated with SHS waste and the limited options for waste disposal, most of the users placed emphasis on 'where' waste is disposed of, rather than 'how' the waste is disposed of. Burying hazardous waste in specific pits was commonly regarded as responsible practice, and some of the users [U11, U15, U18] expressed beliefs that SHS waste should be burnt to protect the environment.

4. Just and effective waste management interventions

The results highlight concerning themes associated with the life cycle of SHS in Malawi, such as the lack of supplier accountability, high rates of SHS failures, and hazardous waste disposal practices. Most concerningly, this study finds a direct correlation between Malawi's national off-grid solar electrification strategy and informal lead-acid battery recycling, which is expected to impose severe health impacts on the surrounding communities in line with prior health studies (Haefliger et al., 2009; World Health Organisation, 2017; Lomotey, 2010; Etiang' et al., 2018). Uncontrolled acid draining and e-waste dumping and burning are also highlighted as concerning OGS waste disposal practices, although, the environmental impacts of these practices are less well-understood and deserve further research (detailed in Section 5). However, these issues should be recognised as a reflection of the economic, socio-economic, legislative and infrastructural context of Malawi's OGS market, rather than a fault of OGS technologies. In this sense, inclusive bottom of the pyramid markets are an established means of catering to low-income groups, and the unregulated OGS market reflects the harsh economic landscape for regulated OGS suppliers and the lack of legislative capacity to regulate the quality of the products imported. Detrimental SHS design and operation practices reflect a lack of education. Meanwhile, there is a general absence of formal waste management infrastructure for e-waste or even household waste in Malawi. Therefore, effectively addressing the environmental, health, and justice concerns associated with the current SHS life cycle requires a holistic perspective. Prior literature framing OGS waste as a justice issue has overlooked the severe health and environmental risks associated with the incumbent informal waste management practices. In the meantime, these unjust health and environmental burdens threaten to be exacerbated by the target of importing millions of OGS products without safe waste management interventions. However, the research, industrial consensus, and emerging waste management legislation framing OGS waste as an environmental issue has failed to recognise the current actors in the informal waste management chain, raising significant ethical concerns and likely hindering the efficacy of these waste management interventions. Therefore, interventions to address the health and environmental issues posed by the OGS waste flow should be rooted within an energy justice framework: to develop just procedures that fairly distribute responsibilities by recognising the perspectives and valuable roles of the existing actors in the SHS life cycle. Key principles for the development of just and effective waste management interventions are outlined in the following sections.

4.1. Distribution of responsibility for waste management

The current distribution of the responsibility for managing the toxic OGS waste flow is unjust – placed on OGS users who are not aware of the severe hazards and do not have available options for safe waste disposal. Hence, the state should have a responsibility to ensure that the national electrification strategy does not endanger the health of its population and should effectively regulate hazardous industries. This responsibility has been legally recognised in Kenya. In 2020, the Government of Kenya was ordered by the Kenyan Court to pay $12 million USD in damages for failing to regulate a lead-acid battery smelter, as compensation for the health burdens imposed on the surrounding community in the suburb of Mombasa (Ligami, 2021). In this sense, interventions to mitigate lead exposure should be seen as an effective area for public subsidisation. The loss of economic productivity due to the impairment of brain development caused by childhood lead exposure was estimated to cost Malawi 6.2 % of the country's GDP in 2011 – more than double the international aid funding received that year (Attina and Trasande, 2013). Furthermore, the ineffective implementation of Malawi's hazardous waste legislation risks being exploited by foreign companies to inexpensively export valuable materials, such as lead, while causing substantial domestic environmental damage. And while Malawi ratified *The Basel Convention* in 1994 (Basel Convention: Parties & Signatories, 1994) (an international treaty to control the transboundary movement of hazardous waste, including lead-acid battery waste), lead-acid battery scrap appears to be informally traded with other countries without restriction, potentially supporting toxic informal lead-acid battery recycling industries in neighbouring countries.

The consensus on how to manage OGS waste from both the industry body and emerging legislation, based on the principle of extended producer responsibility (EPR), places responsibility for waste management onto OGS suppliers. This consensus fails to recognise that the majority of the OGS waste flow is from the unregulated sector, where the product suppliers are disconnected from local OGS vendors and enforcing EPR may not be feasible. Meanwhile, Hansen et al. (Hansen et al., 2022) highlight that even leading regulated OGS businesses are reliant on subsidies and their financial capacity to address OGS waste is limited. Hence, placing additional financial burdens on regulated OGS suppliers will inevitably transfer the costs onto customers, making regulated OGS products more expensive and less accessible, favouring the already dominant unregulated OGS market (Kinally et al., 2022; Hansen et al., 2022). In this sense, governments should not expect OGS suppliers to compensate for both the lack of electricity and waste management infrastructure (services typically provided by the state), and governments should financially contribute to OGS waste management as a means of facilitating their electrification targets. Nonetheless, donor-funded electricity access projects should also plan and include a budget for end-of-life waste management. In particular, enforcing the proper waste management of commercial solar installations and donor-funded solar energy access projects (that are subject to accountability) offers an opportunity to establish policies and reverse logistics chains.

4.2. Recognise the actors in the waste management chain

In line with prior literature (Cross and Murray, 2018; Samarakoon et al., 2022), informal electronics repairers are found to compensate for regular SHS faults, providing an invaluable support mechanism for SHS users, extending the lifetime of OGS products and reducing the waste flow by keeping materials in circulation. Hence, emerging waste management legislation that undermines the role of informal repairers in supporting OGS users can be expected to have a negative impact on OGS adoption rates, hindering electrification targets (Cross and Murray, 2018; Kinally et al., 2022). Furthermore, while the negative recycling value of the OGS waste flow is regarded as a key hindrance to waste management initiatives, this study finds informal repairers to keep the low and negative recycling value SHS components in circulation (inverters, charge controllers and solar panels) (Kinally et al., 2022). Hence, the SHS waste flow is found to be predominantly occupied by lead-acid batteries – the most toxic waste component but also the most profitable to recycle. Therefore, there is a potential for initiatives to safely manage the lead-acid battery waste flow to be driven by profit, rather than relying on the enforcement of complex legislation and (potentially counterproductive) producer financing mechanisms.

Meanwhile, an established effective reverse logistics system already exists: the network of scrap collectors and scrap dealers. Independent scrap dealers sell their scrap to whoever offers the best price – showing a potential for the waste flow to be redirected with financial incentives. Specifically, the SHS waste flow could be aggregated and directed to safe formal recycling infrastructure by offering scrap dealers a higher price for batteries than they receive from the informal recycling market. A third-party organisation could manage the aggregation of SHS waste or intermediate the relationship between local scrap markets and regulated international recycling companies – reflecting the recommendations in the United Nation's e-waste policy framework report (International Telecommunication Union (ITU), 2018). However, in establishing this reverse logistics chain, it is imperative that the market value of lead-acid batteries mandates the inclusion of acid to prevent uncontrolled acid draining. It is also crucial that the Environmental Health and Safety (EHS) performance of recycling companies is audited before establishing relationships, as outlined by GIZ (Manhart et al., 2022). The use of financial incentives to collect lead-acid battery waste was trialled by ENGIE Energy Access in Uganda as part of the Global LEAP Solar *E*-Waste Challenge (Blair et al., 2021) and proved to be effective – the collection sites were inundated by the volume of batteries delivered by scrap dealers. Furthermore, there is potential for distributed waste collection points to purchase SHS waste directly from SHS users and electronic repairers; SHS users specified that they would be prepared to travel to sell their waste as long as they do not incur disproportionate transport costs.

4.3. Education of sustainable user practices and waste hazards

Low user understanding and detrimental practices in SHS design, installation and operation currently significantly reduce the lifetime of SHS components (particularly lead-acid batteries), resulting in unreliable electricity services and additional costs for users and accelerating the OGS waste flow. Therefore, education campaigns on sustainable SHS design and usage habits offer an inexpensive mutually beneficial opportunity to increase the level of service for SHS users and reduce the waste flow. Specifically, raising users' awareness of i) the use of inexpensive charge controllers to extend battery lifetimes and reduce costs from battery replacements; ii) the importance of regular solar panel cleaning and the associated performance benefits; iii) the short lifetime of automotive batteries in SHS applications; and finally, iv) the vulnerability of batteries and inverters to breakdowns with overuse. Community leaders and informal electronics repair shops are trusted local authorities and offer effective vectors for distributing this information. Education campaigns to increase public awareness (amounts all stakeholder groups) of the environmental and health hazards associated with OGS waste, particularly concerning lead toxicity, should also be a priority alongside sustainable waste management solutions. Specifically, establishing an understanding of the benefits to communities is expected to significantly increase participation in OGS waste management solutions and waste collection rates due to the strong values of stewardship.

5. Limitations and areas for future research

The main limitation of this study is the potential lack of generalisability due to the small sample size and non-probability sampling. Hence, the results are not expected to reflect the perspectives of all of the members of each stakeholder group, and the life cycles of SHSs are expected to vary across Malawi. In particular, this study highlights that SHSs are commercialised through unregulated markets, their service life is influenced by various social factors, and SHS waste is processed through informal industries with unstandardized practices – all subject to variation. Nonetheless, this study provides a valuable insight into Malawi's OGS market and describes previously unrecorded waste management practices, highlighting energy justice concerns and environmental and human health risks – emphasising the urgency for further research and waste management interventions.

Furthermore, the recorded life cycle of SHSs in Malawi significantly differs from prior studies that have quantified the environmental performance of SHSs and OGS technologies in the Global South. Specifically, prior life cycle assessment studies (Mukoro et al., 2021; Bilich et al., 2017; Alsema, 2000) have assumed lead-acid batteries to achieve theoretical lifetimes of up to 13 years and assumed end of life waste to be formally recycled following European standards or disposed of in sanitary landfills. Whereas, this study finds lead-acid batteries to have one-year average lifetimes in SHSs in Lilongwe and highlights significant health and environmental risks from informal recycling practices. Therefore, there is a need for future life cycle assessment studies to address this disparity between the theoretical and the actual environmental performance of SHSs. In this sense, the transparency of the environmental impacts of the other recorded informal e-waste disposal practices is also currently low. In particular, the impacts of openly dumping and burning e-waste in nature (including circuit boards, small electronic components and lead-acid batteries from SHSs) are unclear, but present significant risks from the release of toxic pollutants into the environment. Furthermore, this study finds that scrap circuit boards are collected in the informal scrap market and are exported from Malawi to South Africa. The fate of these circuit boards is currently unclear, but informal recycling practices for circuit boards (backyard hydrometallurgical leaching) have been reported in SSA, openly handling highly toxic and hazardous chemicals such as mercury and cyanide (Manhart et al., 2018; Ichikowitz and Hattingh, 2020; Mir and Dhawan, 2021). The export of toxic lead-acid battery scrap through the informal scrap market is also highlighted – potentially bypassing *The Basel Convention*. Hence, future research should quantify the environmental impacts of informal e-waste management practices and continue to investigate potential justice concerns relating to the management and trading of e-waste across SSA.

6. Conclusions

This paper takes a life cycle perspective to investigate the environmental and justice concerns of Malawi's national OGS electrification strategy which aims to import millions of OGS products in the absence of formal e-waste management infrastructure. Prior energy justice literature is found to have overlooked the environmental and health impacts of OGS waste beyond repair. Meanwhile, emerging OGS waste management interventions have been criticised for failing to recognise the current actors in the informal waste management chain, posing ethical concerns and likely hindering the efficacy of these waste management interventions. This paper addresses these research gaps and controversies by describing the flow of materials through the life cycle of SHS in Malawi from import to informal waste disposal, revealing the practices and perspectives of the actors in the life cycle and informal waste management chain.

Semi-structured interviews are conducted with SHS vendors, users, electronics repairers, scrap dealers, and battery recyclers surrounding Malawi's capital city of Lilongwe. Lilongwe's OGS market is highlighted to be unregulated, dependent on a bottom of the pyramid market for SHS components imported from China, reducing the affordability barrier to accessing electricity services but suffering from a distinct lack of supplier accountability. False advertising and counterfeit SHS components are found to be common, attributed to the lack of legislative capacity to regulate the quality of the products imported and the disconnection between the international product suppliers and local vendors by wholesalers. Affordability constraints, low user understanding, and detrimental SHS design, installation and operation are found to exploit the technical vulnerabilities of SHS components, resulting in high rates of failures and short product lifetimes. The main cause of SHS failures is identified as the regular deep-discharging of lead-acid batteries, restricting typical battery lifetimes to only one year. An established network of informal electronics repairers is found to successfully compensate for SHS faults not related to batteries – providing a valuable service supporting SHS users and keeping SHS components and materials in circulation. Meanwhile, lead-acid batteries are highlighted to occupy the vast majority of the SHS waste flow. An established informal waste collection network managed by scrap dealers is recorded, effectively aggregating and exporting valuable waste materials to buyers across sub-Saharan Africa and China. The dumping, burying and burning of SHS materials are also recorded as common waste disposal practices, posing significant environmental risks. Most concerningly, the first description of an active informal lead-acid battery recycling industry in Malawi is made. SHS batteries are found to be informally remanufactured within densely populated communities and potential industrial-scale unregulated lead smelters are also identified – expected to cause severe health impacts from lead pollution.

Therefore, Malawi's national electrification strategy is highlighted to impose health risks on energy-poor communities that are unjustly burdened with the responsibility for managing the toxic OGS waste flow without safe options for waste disposal or awareness of the associated hazards. To address these risks, key principles for effective waste management interventions are outlined from an energy justice perspective: increasing the level of service for users through education, reinforcing the effective incumbent waste management infrastructure, and regulating hazardous practices. Finally, further research is urgently recommended to investigate the health burdens that informal battery recycling practices impose on their surrounding communities, and to address this disparity between the theoretical and the actual life cycle environmental performance of SHSs.

Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

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Appendix A. Supplementary data

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