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Review

Off-grid solar waste in sub-Saharan Africa: Market dynamics, barriers to sustainability, and circular economy solutions

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ABSTRACT

The rate of access to electricity in sub-Saharan Africa (SSA) is just 42 %. The private market for household-scale off-grid solar (OGS) products (pico solar and solar home systems) is regarded as a key tool for increasing electricity access in SSA. However, the growing volume of unabated waste from OGS products poses a significant environmental risk. Based on a systematic literature review of 52 papers, the dynamics of SSA's OGS market, the drivers of OGS waste, the environmental and health impactions of OGS waste, the barriers to waste management, and potential circular economy solutions to address SSA's OGS waste flow are analysed. The market landscape is decentralised and predominantly unregulated. The lifetime of OGS products is found to be short (less than four years), limited by affordability constraints, the lack of local technical expertise, detrimental usage habits, and low access to maintenance and repair services. The widespread uptake of OGS products and short product lifetimes has resulted in rapidly increasing waste volumes across SSA (an estimated 12,000 tonnes of waste generated in 2020, a 545 % increase from 2016). The current informal recycling practices are found to have extremely severe environmental consequences. In particular, the informal recycling of lead-acid batteries is a primary driver of lead exposure in SSA. Formal waste management initiatives are hindered by competition with informal practices, inadequate legislation, the complexity of reverse logistics, the negative recycling value of some OGS products, and the absence of sophisticated formal recycling infrastructure. Furthermore, the emerging consensus on how to address SSA's OGS waste, from the industry's body and legislation across SSA, is found to be inadequate as it fails to address the majority of the waste flow. Finally, the authors recommend circular economy solutions such as promoting local resource conservation activities and pursuing effective public-private partnerships to capitalise on domestic value generating activities within the OGS waste chain.

Contents

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Introduction

In 2015 the United Nations (UN) set the Sustainable Development Goal (SDG) 7 of "affordable, reliable, sustainable and modern energy for all" by 2030 (General Assembly & "Transforming our world: the 2030 Agenda for Sustainable Development", 2015). Nonetheless, the UN has forecasted that by 2030 around 620 million people will still be without access to electricity – 85 % of this population will be in sub-Saharan Africa (SSA) (International Energy Agency, 2020). Electricity deprivation is a leading cause of poor health and low quality of life in SSA. The lack of electricity restricts opportunities for modern economic activity and mandates a reliance on natural resources for livelihoods: agriculture is the largest source of employment and the burning of solid biomass is the greatest source of energy (IEA, 2019; Adzawla et al., 2019). This strain on natural resources is accelerating deforestation and land degradation, which continues to be amplified by the rapidly growing population (Franks, 2005). Furthermore, SSA has been recognised as the world's most vulnerable region to climate change, as electricity deprivation, dependency on natural resources, and widespread poverty limit its capacity to adapt to the forecast increase in the frequency and severity of climatic shocks (Watson et al., 1997).

Providing electricity access is regarded as a means of breaking the cycle of poverty, enabling sustainable development, and building climate resilience (Fuso Nerini et al., 2018). However, electrification efforts in SSA are obstructed by the unreliability of the existing electricity infrastructure and the high costs of extending electricity grids to reach predominantly rural populations (Blimpo & Cosgrove-Davies, 2019). In this sense, off-grid solutions have become increasingly popular (IEA, 2019). The sale of household scale off-grid solar (OGS) devices through the private OGS market is recognised as an effective strategy to provide electricity access to rural households (IEA, 2019; Blimpo & Cosgrove-Davies, 2019). These household scale OGS products (pico solar and solar home systems) are microgeneration technologies, typically between 0 and 100 Wp, that enable the provision of basic electricity services ranging from task lighting to powering TVs and refrigerators (GOGLA, 2019a; IRENA, 2016). Since becoming established in 2010, the global market for household OGS products has received substantial investment (mostly equity and grants) from international energy suppliers (Lighting Global et al., 2018; Climatescope, 2018). For example, Shell, Total and Engie respectively aim to fund the provision of electricity access for 100 million people (by 2030), 25 million people (by 2022), and 20 million people (by 2022), through facilitating the sale of OGS products (Climatescope, 2018). Consequently, the global market for OGS products is forecast to become an 8-billion dollar industry within the next two years (Lighting Global et al., 2018). The global OGS market is predominantly contained within SSA, representing 67 % of the reported OGS product sales in the second half of 2019 (GOGLA, 2019b).

Similar to other electrical and electronic devices, OGS products contain precious, critical and toxic materials (Aberilla et al., 2020; Mukoro et al., 2021). Hence, the management of waste from OGS products has significant socioeconomic and environmental implications, such as the depletion of finite critical materials and the discharge of toxic pollutants (Manhart et al., 2018). Despite the known hazards, there is a general absence of formal electrical and electronic waste (e-waste) management infrastructure across SSA, and the improper management of e-waste is recognised as a serious threat to public health (Orisakwe et al., 2020). OGS products currently only contribute a small percentage to SSA's total e-waste flow: approximately 7 % in Kenya in 2020 (SSA's largest OGS hotspot) (Magalini et al., 2016; Forti et al., 2020). However, OGS products typically have short lifetimes, and with the aim of providing OGS products to hundreds of millions of people by 2030, waste volumes are growing rapidly (Climatescope, 2018). An estimated 12,000 tonnes of OGS waste was generated across SSA in 2020, which was a 545 % increase from 2016 (Magalini et al., 2016; Hansen et al., 2020). The growing volume of improperly managed waste also poses a reputational risk to the OGS industry, public concern and a loss of funding would directly hinder the potential for OGS to facilitate the realisation of SDG 7 (Murray & Corbyn, 2018; Mukoro et al., 2022).

The environmental and socioeconomic burdens associated with the improper management of end of life OGS products are symptoms of a linear 'extract-produce-use-waste' economic model. This is contrary to a circular economy described by the Ellen MacArthur Foundation as "an industrial economy that is restorative by intention" (Ellen MacArthur Foundation, 2013). The concept of a circular economy represents a sustainable economic system founded on a holistic life cycle perspective. In the circular economy, social, environmental and economic sustainability is achieved through conserving materials and energy within closed restorative cycles (CIRAIG, 2015). From a sustainable life cycle perspective, every stage in a products life should be considered. The utility, durability and recyclability of products should be maximised in order to reduce the demand for virgin materials, recover materials from end of life products, and reduce waste. This decoupling of economic activity from the consumption of finite materials can be realised through initiatives such as circular business models, sustainable design, repair, reuse, and recycling. Hence, incorporating a circular economy approach into SSA's OGS market could reduce the environmental burden associated with achieving SDG 7.

The issue of SSA's OGS waste has gained recent attention from policymakers, academics, and from within the industry itself. The UK's Department for International Development commissioned a report in 2016 (Magalini et al., 2016) outlining an international strategy to recycle SSA's OGS waste. Whereas the academics Cross and Murray challenge the emerging consensus of recycling as the panacea to OGS waste management, and argue that OGS products should better integrate into the existing repair economy with SSA (Cross & Murray, 2018). Meanwhile, OGS products are starting to be considered in national e-waste legislation and there is growing pressure on the OGS industry to define and implement waste management strategies (Corbyn et al., 2019a). Since 2019, the Global off-grid Lighting Association (GOGLA) has produced five briefing documents to help OGS companies formulate waste management strategies (Corbyn et al., 2019a; Corbyn et al., 2019b; GOGLA, 2019c; Corbyn et al., 2019c; Rhodes et al., 2020), and the Global LEAP Awards Solar *E*-Waste Challenge (Blair et al., 2021) was launched to fund various private OGS waste management pilot projects. These fragmented reports, academic studies, and waste management initiatives have produced conflicting conclusions, revealing the landscape of SSA's OGS market to be complex. How emerging waste management policies integrate with (and influence) the complex OGS market landscape has implications for the efficacy of waste management initiatives, but also may impact electrification efforts and the prospective of achieving SDG 7.

To address the discrepancy of previous waste management investigations and initiatives, this study represents the first review of the literature published on OGS waste in SSA. The objectives of this article are to increase the transparency of the environmental burdens currently posed by OGS waste in SSA and the challenges facing the introduction of effective waste management strategies. This is with the aim of establishing a contextual foundation for the development of waste management solutions. Regarding the structure of this article, the following section describes the methodology used to perform the literature review. Then, the *Market dynamics* of SSA's OGS market are discussed, followed by a description of the factors accelerating SSA's OGS waste flow in the *Waste drivers* section. The *Environmental and health impacts of the current waste management practices* are then described. Next, the factors hindering the implementation of formal waste management are discussed in the *Barriers to waste management* section. Finally, the authors propose potential *Circular economy solutions* to address SSA's OGS waste flow.

Method

As illustrated in Fig. 1, a systematic literature review was carried out using the Scopus database. A comprehensive search was performed to find all the published articles relating to the circular economy of off-grid solar technologies in sub-Saharan Africa. The search string was defined so that all resulting literature must simultaneously contain at least one of each of the defined "Solar", "Circular Economy" and "sub-Saharan Africa" keywords (Table 1). The (TITLE-ABS-KEY) search field code was used, allowing for the specified keywords to be contained within the combined field of the resulting literature's title, abstract and keywords.

The word "solar" yields a range of results, including technical terms such as "solar home systems" and "pico-solar". Abbreviations often used such as "PV" (photovoltaic) and "SHS" (solar home system) were also included. The circular economy key words were selected from systematic literature reviews on circular economy (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Gallego-Schmid et al., 2020; Merli et al., 2018). Additional keywords (quality and literature review) were also included in the circular economy search criteria to broaden the scope of the search. The keyword "quality" was included as it is commonly used to describe OGS product durability. The term "literature review" was also included to yield articles that could provide additional context on the OGS market. The keywords for sub-Saharan Africa (geographic restriction) include the names of all of the countries in SSA (World Bank Open Knowledge Repository, n.d.) as well as the more general terms: "sub-Saharan Africa" and "Africa".

The search was refined so that only articles, conference papers and reviews, published in English from 2010 (when the OGS market become established (Lighting Global et al., 2018)) up to December 2021 were included. The refined search yielded 1114 results, which were screened by reading their titles and abstracts. Only results that related to: i) the private market for off-grid solar products; ii) lifecycle of off-grid solar

Table 1
Keywords used in the Scopus database search.

Solar keywords	Solar, photovoltaic, PV, SHS, off grid
Circular Economy key words	Circular, closed loop, reuse, recycling, durability, quality, maintenance, repair, end of life, life cycle, upcycling, manufacture, remanufacturing, supply chain, reverse logistics, take back, extended producer responsibility, waste, WEEE, Industrial symbiosis, resource use environmental impact, literature review
Sub-Saharan Africa keywords	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, South Africa, Tanzania, Togo, Uganda, Zambia, Zimbabwe, Africa, sub-Saharan Africa

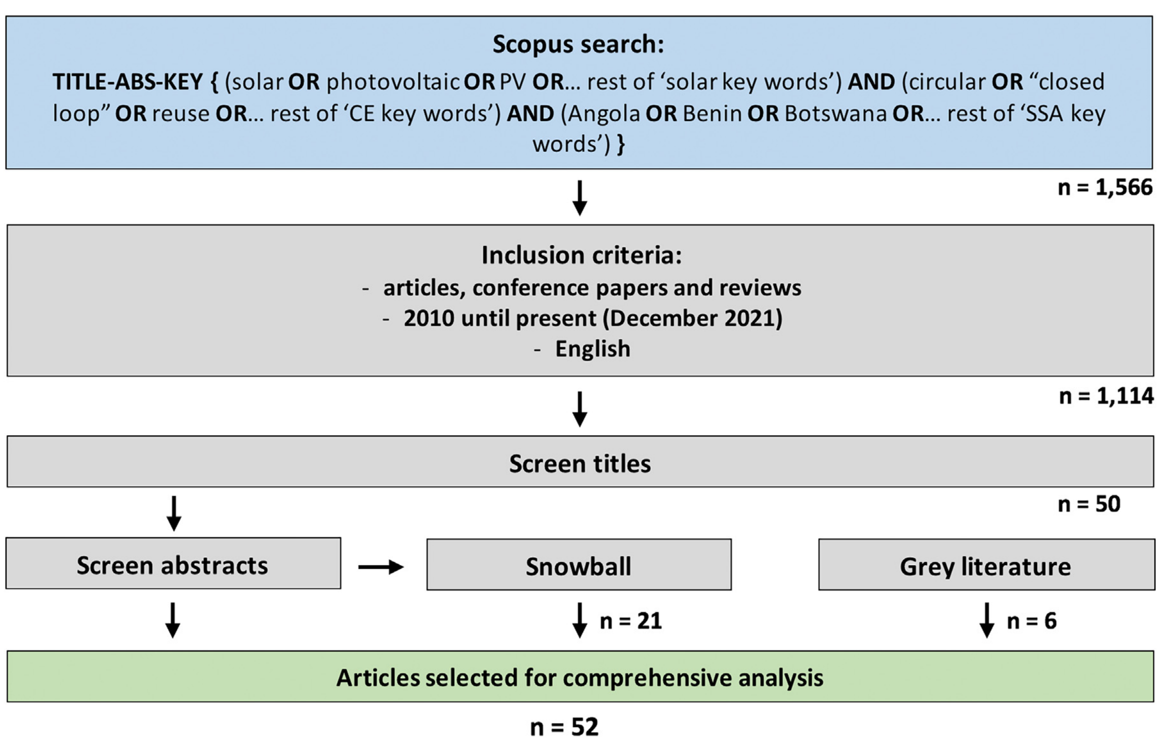

Fig. 1. Literature search method. CE = circular economy, SSA = sub-Saharan Africa, n = number of resulting documents.

products; or iii) the environmental performance of off-grid solar products were considered. Results that focused on geographies outside of SSA were not considered. This screening resulted in the selection of 25 papers. For each of the papers selected for analysis, a ‘snowball’ method was used to gather additional documents. This involved screening the paper's bibliography for relevant documents (Wohlin, 2014). Non-academic reports (grey literature) were also considered in the snowballing process. The grey literature included was considered to be credible, having been referenced in scientific peer-reviewed journals. The snowballing process yielded a further 21 articles. To complete the sample, additional grey literature published by GOGLA (the Global Off-Grid Lighting Association), Lighting Global, and the Efficiency for Access Coalition was also considered for review. These organisations are regarded as credible because they all represent the global OGS industry at policy level (6 added).

In total, 52 documents were selected for comprehensive analysis (Tables S1–S3 in Supporting Information). The review yielded a broad range of relevant information, which was broken down into five main categories: i) the dynamics of SSA's OGS market; ii) the factors accelerating the waste flow (waste drivers), iii) the environmental and human health implications of OGS waste in SSA, iv) the barriers to effective waste management, and v) potential circular economy solutions to address SSA's OGS waste flow.

Results and discussion

The findings of the review have been structured to define and comprehensively discuss the key themes that have been identified within the literature that must be considered to develop effective OGS waste management strategies across SSA. The *Market dynamics* section describes the landscape of SSA's OGS market to provide a contextual foundation for the discussions throughout the review. The economic landscape of SSA's OGS market presents inherent hindrances to the sustainability of OGS and obstructs the implementation of waste management strategies that are effective in high income countries. Failing to acknowledge the established dynamics of SSA's OGS market risks the efficacy of waste management initiatives. Nonetheless, the dynamics of SSA's OGS market has received insufficient academic and institutional attention.

Market dynamics

The global off-grid solar (OGS) market is decentralised, complex, and predominantly unregulated (Lighting Global et al., 2020; Groenewoudt et al., 2020; Zalengera et al., 2020). In the regulated sector of the market, licenced companies sell OGS products that typically meet the Lighting Global quality certification standards and product sales are monitored by the Global Off-Grid Lighting Association (GOGLA) (Lighting Global et al., 2020). GOGLA is branded as the voice of the global industry, but the regulated sector only represents an estimated 28 % of global OGS product sales (Lighting Global et al., 2020). The remaining majority of sales are through the unregulated sector. In the unregulated sector, sales are not monitored, complex untraceable informal supply chains link unregulated international imports (primarily from China) to remote off-grid communities, where products are sold through unlicensed and informal vendors, making data difficult to collect (Groenewoudt et al., 2020; Samarakoon, 2020). There is a paucity of research on SSA's unregulated OGS sector, despite representing the majority of the OGS market. Only four of the 52 reviewed studies (Cross & Murray, 2018; Groenewoudt et al., 2020; Samarakoon, 2020; Samarakoon et al., 2021) provide a detailed insight into the dynamics of SSA's unregulated OGS sector, such as the supply chains, typical product composition, sales interactions, user satisfaction, and end of life practices. A comparison between the dynamics of the regulated and unregulated OGS market sectors is shown in Table 2.

Table 2
Comparison of the dynamics of the regulated and unregulated sectors of the off-grid solar market (Lighting Global et al., 2020; Groenewoudt et al., 2020; Samarakoon, 2020; Samarakoon et al., 2021; Kizilcec & Parikh, 2020; Barrie & Cruickshank, 2017; Wassie & Adaramola, 2021; Grimm & Peters, 2016; Bensch et al., 2016).

	Regulated market	Unregulated market
Global market share[a]	28 %	72 %
Industry affiliation	GOGLA	None
Quality certification	Lighting Global standards	None
Warranties	Minimum two years for SHS, one year for pico	None (vendor's discretion)
Payment method	PAYG, upfront	Upfront cash
Supply chain	Formal supply chains, branded shops and sales agents, sales are monitored by GOGLA	Chinese products imported through unmonitored supply chains to unlicenced vendors in SSA
Design	Pico (>11 Wp), pre-assembled plug and play (PnP) SHS, component based SHS	Pico (>11 Wp), component based SHS using whatever is locally available
Battery types used	Lithium-ion and lead-acid	Lead-acid
Installation	Trained professional	Informal technician or by users themselves
Availability	Available in developed regions and urban areas. Limited or no availability in less developed regions and rural areas.	Widely available, even in less developed regions and rural areas.

GOGLA = Global Off-Grid Lighting Association, SHS = solar home system, PAYG = pay as you go. SHS = solar home system.
[a] Global market share is based on GOGLA's 2020 market trends report (Lighting Global et al., 2020).

Considering the data available on the sale of regulated OGS products, SSA represents the majority of the global market and was responsible for 67 % of regulated sales during the second half of 2019 (c.2.95 million units) (GOGLA, 2019b). There is significant variation within SSA's OGS market. Local markets differ in their level of establishment, which type of technology is favoured, and the estimated share between regulated and unregulated sales. SSA's regulated OGS market is predominantly contained within hot spots in East Africa: Kenya, Rwanda, Tanzania, Uganda, and Mozambique (GOGLA, 2018). The development of local OGS markets is influenced by several economic, geographic, political and social factors such as wealth, the adequacy of transport infrastructure, the nature of existing supply chains, public incentives for the adoption of OGS, and the local social acceptance of the technology (Zalengera et al., 2020; Ondraczek, 2013; Opiyo, 2019; Ferrall et al., 2021; Carr-Wilson & Pai, 2018).

From an economic perspective, investments from private OGS suppliers into local OGS markets are dictated by financial viability. Regulated, quality certified OGS products are expensive and SSA's OGS market is inherently risky. Serving rural and remote energy-poor populations implies low densities of customers that have low ability to pay, and there is limited access to financing for both suppliers and customers (Kizilcec & Parikh, 2020; Wassie & Adaramola, 2021). In Uganda, the upfront cost of regulated 10 Wp SHSs was found to start from around 180 EUR, while unregulated SHSs of the same capacity were found for as low as 20 EUR (Groenewoudt et al., 2020). The improvised ‘do-it-yourself’ (DIY) approach of unregulated systems allows for such large cost savings, although cost cutting methods are associated with reduced product lifetimes (see *Product failures and durability*). With the prohibitively high upfront cost of regulated SHS, regulated SHS are almost exclusively purchased through the pay as you go (PAYG) financing model offered my regulated suppliers (Adwek et al., 2020). PAYG has been widely praised for breaking down the affordability barrier to regulated SHSs, enabling their competition with unregulated products (Lighting Global et al., 2020; Carr-Wilson & Pai, 2018). However, the financing model is economically challenging for suppliers: payback periods restrict cash flow, customers do not have credit ratings to evaluate their financial eligibility, and the rate of payments from customers is low (Kizilcec & Parikh, 2020). In this sense, delivering expensive, quality certified products to dispersed energy-poor populations poses an inherent economic challenge – profitability is an ongoing struggle for regulated OGS suppliers. Hence, the business of regulated suppliers is typically focused within more viable market hotspots in developed regions or urban areas where customers have higher ability to pay (Groenewoudt et al., 2020; Ondraczek, 2013). In less established markets and more remote areas, access to regulated products may be limited or unfeasible, while cheaper unregulated products are often more available (Samarakoon et al., 2021; Wassie & Adaramola, 2021; Grimm & Peters, 2016; Bensch et al., 2016). However, unregulated products are associated with lower quality (see *Product quality*) and shorter lifetimes (see *Product failures and durability*).

Waste drivers

This section outlines the key factors accelerating SSA's OGS waste flow. Firstly, concerns regarding OGS *Product quality* are discussed. Then, the *Product failures and durability* section describes how affordability constraints and the low local technical capacity in SSA typically result in short OGS product lifetimes. Finally, the restricted availability of *Repair* services and barriers to increasing the availability of repair services are discussed. Addressing these issues can increase the sustainability and lifetime of OGS products in SSA, slowing the waste flow and mitigating the environmental, human health and economic burdens associated with OGS waste in SSA. However, these issues restricting the technical sustainability of OGS products are rooted in the complex economic and social dynamics of SSA's OGS market.

Product quality

Lighting Global, the World Bank's program for sustainable growth of off-grid solar, describes product quality as an indication of the level of service provided, durability and truth in advertising (Lighting Global et al., 2020). In the regulated sector, products are typically quality certified and meet the Lighting Global standards, mandating good build quality and the provision of product warranties (see Table 2) (Samarakoon, 2020; Lighting Global, 2017; Lighting Global, 2018a). Whereas the unregulated sector, by its nature, is not subject to any quality certification. The narrative from within the regulated sector is that low-quality unregulated products are the main driver of solar e-waste, and that the unregulated sector risks consumer confidence in OGS technologies and ultimately poses a barrier to achieving SDG 7 (Bloomberg New Energy Finance and Lighting Global, 2016). However, studies comparing the quality of regulated and unregulated OGS products in SSA have yielded conflicting conclusions (Groenewoudt et al., 2020; Samarakoon, 2020; Wassie & Adaramola, 2021; Bensch et al., 2016; Lighting Global, 2018b).

A substantial range in the quality of unregulated OGS products has been recorded. Unregulated SHSs have a component-based design, so the overall quality of the systems depends on the quality of the individually selected components. High quality unregulated products have been reported, which can match the performance of their regulated counterparts and provide a stronger price to performance ratio due to their substantially lower price (Samarakoon, 2020; Bensch et al., 2016; Lighting Global, 2018b). However, the presence of low quality and non-fictional, fake products is an established theme in the unregulated market (Groenewoudt et al., 2020; Wassie & Adaramola, 2021; Lighting Global, 2018b). Planned obsolescence and fake products are symptoms of the rapidly growing, decentralised and predominantly unregulated OGS market. Low quality and fake unregulated products pose a risk to both OGS users and to the local vendors who may unwittingly purchase these products, resulting in short product lifetimes and risking the trust in OGS products – potentially hindering uptake. The quality of unregulated OGS products is reported to usually be reflected by their price (Groenewoudt et al., 2020). Although, the level of quality may not be easily discernible for customers (Groenewoudt et al., 2020; Samarakoon, 2020). Samarakoon (2020) emphasises that energy-poor customers characteristically have low levels of education and may not be aware of quality implications, making them vulnerable to exploitation from vendors. However, Wassie and Adaramola (2021) emphasise that quality concerns are not restricted to the unregulated sector and that there is a lack of accountability for either product quality or honouring guarantees within the regulated sector as well.

The reviewed studies show that product quality is a concern throughout the OGS market, particularly in the unregulated sector. However, the concept of quality dualism posed by the regulated sector is over simplistic and fails to acknowledge why low-quality products are so prominent. There is a basic need for the provision of electricity in SSA and energy-poor populations characteristically have low levels of income (Groenewoudt et al., 2020). The regulated OGS sector is unable to geographically reach or demographically cater to a substantial fraction of the energy-poor. Cheap, low-quality, short-lived products may either be an attractive alternative, the only available option, or the only affordable option to energy-poor OGS customers in SSA. The dominance of the unregulated market is expected to result in short OGS product lifetimes in SSA, accelerating the OGS waste flow. Although, there is a paucity of research describing the dynamics of the unregulated market and the performance of unregulated OGS products in SSA (see *Market dynamics*).

Product failures and durability

High failure rates and low technical sustainability of OGS products have been identified in nine of the reviewed articles (Cross & Murray, 2018; Groenewoudt et al., 2020; Samarakoon, 2020; Kizilcec & Parikh, 2020; Wassie & Adaramola, 2021; Dauenhauer et al., 2020; Crossland et al., 2015; Gebreslassie, 2020; Azimoh et al., 2014). A study in Kenya found one fifth of OGS solar products to breakdown within 18 months of purchase (Cross & Murray, 2018). These studies confirm short product lifetimes (low durability) to be an issue throughout the market, although more pronounced in the unregulated sector.

The short lifetimes of OGS products increases the volume of the OGS waste flow and the associated environmental burdens. Furthermore, frequent faults and failures also results in unreliable electricity services for customers and can reduce the trust in OGS technologies. Reliable energy is a defined criteria of SDG 7 ("affordable, reliable, sustainable and modern energy for all" (General Assembly & "Transforming our world: the 2030 Agenda for Sustainable Development", 2015)), and is hence recognised as an important quality for electricity services to promote sustainable development. Low product durability has also been cited as the greatest hindrance to the uptake of OGS products in some regions (Wassie & Adaramola, 2021).

Batteries have the shortest nominal lifetimes of all the OGS components (shown in Table 3) and restrict the expected lifetime of OGS products to just 4 years (Hansen et al., 2020). Batteries are vulnerable to deterioration from overuse. To achieve nominal lifetimes, a battery's state of charge must be maintained within sustainable bounds. Two main battery types are used in OGS: lead-acid and lithium-ion, the choice between which has significant cost, durability, environmental, and hazard implications (see *Environmental and health impacts of the current waste management practices*). Lead-acid batteries should not be allowed to discharge past 50 % of their capacity, whereas up to 80 % of the capacity of lithium-ion batteries can be used (Charles et al., 2019; Diouf & Avis, 2019). Discharging batteries beyond this point (deep discharge) results in degradation of the electrode materials. Repeated overuse results in rapid degradation, which has been identified as the primary underlying cause of OGS system breakdowns in SSA (Dauenhauer et al., 2020; Crossland et al., 2015; Azimoh et al., 2014).

Battery overuse can be a result of both technical and social factors, relating to how systems are designed and how they are used. The key factors that contribute to battery overuse and OGS breakdowns are well understood: product quality, technical skill in system design and installation, and usage habits (Magalini et al., 2016; Groenewoudt

Table 3
The lifetime and material composition of off-grid solar product components (Manhart et al., 2018; Diouf & Avis, 2019).

Component	Lifetime	Typical material composition
Photovoltaic (PV) panel	>10 years	Crystalline silicon, glass, aluminium, copper and trace elements (indium, tin and gallium).
Charge controller	5–15 years	Printed circuit board, solder paste, various electrical and electronic components, and plastics.
Batteries	2–6 years:	
Lead-acid	500 cycles (50 % discharge)	Lead, lead-oxide, sulphuric acid, plastics.
Lithium ion	2000 cycles (80 % discharge)	Graphite, various organic substances, copper, aluminium, lithium, plastics.
Cables	>10 years	Copper, plastic insulation.
Pico solar lamps	3–5 years	PV, panels, Li-ion battery, LEDs, printed circuit board, plastics.

LED = light emitting diode.

et al., 2020; Wassie & Adaramola, 2021; Azimoh et al., 2014). However, with the mixture of technical and social factors that can contribute to battery overuse and OGS deterioration, it may be difficult to diagnose the specific cause of a system breakdown.

Durability vs affordability. The design of component-based SHSs can be tailored by individually selecting components to meet the customers' needs and budget. In the regulated sector, component-based SHSs are typically designed by trained professionals only using expensive quality certified components (Groenewoudt et al., 2020). In the unregulated sector, SHS designs are more improvisational, utilising whatever is available in the local market: this typically includes unregulated components imported from China, second hand components, and often automotive batteries (Manhart et al., 2018). The upfront cost of unregulated SHSs can be substantially reduced by using cheaper components, designing systems only using the bare essentials, and by customers designing and installing systems themselves (Groenewoudt et al., 2020). However, cost cutting methods in SHS design are associated with reduced service lifetimes (Manhart et al., 2018; Groenewoudt et al., 2020; Samarakoon, 2020).

Batteries, the most vulnerable component, are also the most expensive (Kizilcec & Parikh, 2020). Lead-acid batteries are typically a fraction of the price of lithium-ion, but their expected lifetimes are less than a third and they are more susceptible to overuse (Charles et al., 2019). Regulated OGS products increasingly use lithium-ion batteries, whereas, the upfront cost of lithium-ion batteries is prohibitively expensive in the unregulated market and unregulated SHS almost exclusively rely on lead-acid batteries (Lighting Global et al., 2020; Diouf & Avis, 2019). Lead-acid automotive batteries are also sometimes used in improvised SHSs, although automotive batteries are not designed to supply continuous power and their application in OGS results in their breakdown within two years – half of the average product lifetime (4 years) (Manhart et al., 2018). Removing charge controllers (protects batteries from overuse and overcharging) from the SHS design is another significant source of cost reduction. The exclusion of charge controllers from the SHS design has been recorded to result in system breakdowns within 1–2 years (Groenewoudt et al., 2020). Customers designing and installing SHS themselves, saving the cost of employing a technician, can also significantly reduced the lifetime of SHS – the lack of skill and improper SHS design and installation is another key hindrance to OGS durability in SSA (see *Product failures and durability*).

These cost-cutting measures effectively make unregulated OGS products affordable for SSA's characteristically low-income energy poor, however, also significantly reduce the lifetime of OGS products, often to <2 years. Therefore, the short expected lifetimes of unregulated OGS products is also feature of the affordability constraints of energy-poor customers, rather than solely a criticism of unregulated OGS suppliers and the build quality of their products.

Low technical skill and improper usage habits. The improper design and installation of OGS systems is another key hindrance to the technical sustainability of OGS systems in SSA (Groenewoudt et al., 2020; Dauenhauer et al., 2020; Crossland et al., 2015). OGS systems in SSA are commonly found to be designed with PV panels and batteries that are undersized for their application, and PV panels are often improperly oriented (Dauenhauer et al., 2020; Crossland et al., 2015). Undersized or improperly oriented PV panels result in insufficient energy generation and chronically undercharged batteries. Both undercharged and undersized batteries are forced to discharge past their sustainable limit (overuse) to meet their user's energy demand, accelerating deterioration and significantly reducing the lifetime of batteries. The impact of the lack of technical expertise is expected to be more pronounced in the unregulated SHS sector as unregulated SHSs are typically installed by local informal technicians or by users themselves (Groenewoudt et al., 2020). Low technical skill in OGS design and installation can also be a feature of adorability constraints (see *Durability vs affordability*), for example by purchasing cheaper undersized components or avoiding the cost of employing a technician. Local technical skill is also required for the provision of maintenance and repair services, although this is also found to be lacking in SSA (see *Repair*).

Low user skill in the operation of OGS also substantially reduces the lifetimes of OGS systems in SSA (Crossland et al., 2015; Azimoh et al., 2014; Mgonja & Saidi, 2017). Socio-technical factors have been identified as a crucial but often overlooked cause of system breakdowns (Crossland et al., 2015; Azimoh et al., 2014). Low user skill and detrimental usage habits stem from a lack of understanding of OGS technologies. A survey carried out by Mgonja and Saidi (2017) in Tanzania found that 70 % of OGS users were not aware that the weather affected energy generation and the performance of their systems, revealing the general level of user understanding to be very low. A common example of a detrimental user behaviour that severely reduces system lifetimes is failing to clean PV panels (Gebreslassie, 2020). Soiled PV panels cannot efficiently generate energy, which results in batteries being chronically undercharged and overstrained. Dirt on PV panels can also cause ‘hot spots’, where the shading of solar cells results in electrical resistance and heat generation, degrading the PV module. Another common detrimental practice is the bridging of charge controllers (Manhart et al., 2018), which is when SHS users physically bypass their charge controllers with a conductor to gain extra capacity, at the cost of deep discharging and deteriorating their batteries. Although, detrimental usage habits do not solely result from technical ignorance. In South Africa, the rate of OGS theft is particularly high, and Azimoh et al. (2014) recorded safeguarding measures to significantly reduce SHS lifetimes. SHS users in South Africa were recorded to place their PV panels on the ground, rather than fixing panels to their roofs, so that the panels could be stored inside at night. Laying panels flat, a sub-optimal angle for energy generation in South Africa, caused batteries to be chronically undercharged and overstrained, and was recorded to approximately half the lifetimes of SHSs (Azimoh et al., 2014). Finally, overuse can also stem from inflated user expectations. Vendors overpromising the level of service that their products can provide may encourage users to overstrain their systems, which has been recorded as a significant issue in both established and undeveloped markets in SSA (Groenewoudt et al., 2020; Samarakoon et al., 2021).

The reviewed studies show that the lifetime of OGS products is significantly restricted by the low technical capacity in SSA, which commonly manifests in improper OGS design, installation, and operation. The low technical capacity is a relevant concern for both the regulated and unregulated market sectors, as the use of expensive, quality certified components cannot mitigate the socio-technical hindrances to OGS sustainability.

Repair

With the high rate of failures in all OGS product categories, the provision of maintenance and repair services has been acknowledged as vital for the sustainability of the OGS market (Kizilcec & Parikh, 2020). In urban areas and more established markets, repair services may be readily available, either through formal repair centres or within established informal repair economies (Cross & Murray, 2018; Groenewoudt et al., 2020). Whereas in less developed solar markets and rural areas, repair services can be difficult to access or even unavailable – OGS users often resort to attempting to repair their systems themselves through experimentation (Samarakoon, 2020; Dauenhauer et al., 2020; Lai et al., 2020). The limited access to repair and maintenance services has been recognised as a key hindrance to the uptake of OGS products in SSA, restricting the market's growth (Samarakoon, 2020; Wassie & Adaramola, 2021).

In the regulated market, where available, formal repair services are often included within warranty periods and PAYG contracts, and repairs are carried out by trained professionals only using branded quality certified components (Groenewoudt et al., 2020). Although, providing repair services to low densities of remote customers is expensive and the geographical and demographical reach of the regulated sector is limited (see *Market dynamics*). Informal repair economies are well established across SSA, which support local OGS markets but are also economic hubs and a significant source of livelihoods. However, the level of technical expertise within the informal repair sector is often criticised, particularly by members of the regulated OGS sector (Cross & Murray, 2018; Samarakoon, 2020; Wassie & Adaramola, 2021). Unregulated SHSs tend to have a simple modular design comprised of generic and locally available components. Notwithstanding the criticism of informal repair services, simple OGS faults such as broken switches, wires or electrical contacts can be inexpensively repaired without the need for skilled experts (Groenewoudt et al., 2020; Gebreslassie, 2020). The only detailed analysis of informal OGS repair in SSA has been carried out by Cross and Murray (2018), investigating OGS repair in Nairobi. These authors found technical skill to be abundant in Nairobi's informal repair economy. Repairs were often improvisational, but customers were happy to make compromises on how products were used if it enabled them to regain some level of functionality (Cross & Murray, 2018). Furthermore, Cross and Murray (2018) emphasise the importance of the informal repair economy for supporting out of warranty regulated products, as regulated product warranties are typically capped at two years (half of the average OGS product lifetime). Although, the informal repair economy is often framed by regulated suppliers as a risk to their brand image and intellectual property (Murray & Corbyn, 2018). Suppliers are concerned that their branded products will be poorly repaired or refurbished, damaging their reputation. Accordingly, regulated PnP SHSs typically have a sealed design to prevent informal technicians or users from accessing the enclosed electrical components, aimed at ensuring that products meet their warranty times (Murray & Corbyn, 2018). However, as warranty times are short (typically 2 years, half of the average product lifetime), faults are common, and the sealed design compromises repairability, the sealed design can in-fact restrict the lifetimes of PnP SHSs (Cross & Murray, 2018; Groenewoudt et al., 2020). This segregation between foreign owned regulated OGS businesses and local OGS markets within SSA also prevents knowledge transfer, obstructing the development of local technical skill – a crucial hindrance to the sustainability of OGS in SSA (see *Low technical skill and improper usage habits*) (Groenewoudt et al., 2020; Gebreslassie, 2021).

Despite the criticisms of the level of expertise within the informal repair sector, informal repair services are the only available option for many OGS users. When repair services are unavailable, broken OGS products are a sunk cost. Hence, even if informal repairs have limited success, informal repairs are an additional opportunity to extend the lifetime and utility of OGS devices. Furthermore, the segregation between the regulated and unregulated sectors significantly reduces the durability of OGS products, restricting repair services and obstructing the development of local technical skill – two critical barriers to the sustainability of OGS and the growth of the OGS market in SSA. Hence, OGS suppliers should be encouraged to integrate into the existing dynamics of local OGS markets, discussed in *Circular economy solutions*.

Environmental and health impacts of the current waste management practices

When faults cannot be repaired, OGS products reach the end of their service life and become waste. In the EU, e-waste is formally managed through sophisticated logistics and recycling infrastructure, enforced by effective legislation. The EU WEEE Directive was introduced in 2004, which is now considered to be a reference model for emerging policy (Magalini et al., 2016; Corbyn et al., 2019a; European Union, 2012). As a result, >95 % of waste lead-acid batteries in the EU are formally recycled, and an amendment in 2012 mandates the collection of at least 85 % of waste solar panels (European Union, 2012; Seban & Nowak, 2020). Whereas in SSA, there is a general absence of formal e-waste management. In most countries across SSA, the legislative (see *Waste management legislation and policy*), operational and physical infrastructure for the management of e-waste is inadequate. Consequently, the improper management of e-waste is a well-established issue in SSA – Ghana is home to the world's largest e-waste dumpsite: Agbogbloshie (Corbyn et al., 2019b). OGS waste is commonly disposed of alongside municipal solid waste: in landfills, dumped in nature, or burnt (Hansen et al., 2020). Although similar to other forms of e-waste in SSA, OGS waste is often directed into a complex system of informal waste management, where rudimentary techniques are used to recover some valuable materials (Manhart et al., 2018; Magalini et al., 2016; Hansen et al., 2020; Groenewoudt et al., 2020; Charles et al., 2019). However, the informal treatment of e-waste is associated with low material recovery rates and severe environmental and socioeconomic consequences (Manhart et al., 2018; Rees & Fuller, 2020). Informal e-waste recycling is often carried out in densely populated communities, exposing large populations to toxic pollution, and is recognised as a serious threat to public health in SSA (Orisakwe et al., 2020).

Lead-acid batteries are typically the shortest lived OGS component and hence occupy a relatively large fraction of the waste flow (Hansen et al., 2020). Used lead-acid batteries are the most valuable OGS waste fraction (see *Waste treatment*) and often reach the informal recycling sector, but are also the most toxic waste fraction (Charles et al., 2019; Antonanzas-Torres et al., 2021). Approximately 65 % of the weight of a lead-acid battery consists of lead (and lead oxide) (Manhart et al., 2018). Lead is a cumulative neurotoxin, known to impact human brain function and development at low levels of exposure, and is lethal in high concentrations (Rees & Fuller, 2020). Whilst other significant lead exposure pathways exist, the informal recycling of lead-acid batteries has been recognised as the world's largest source of toxic pollution that directly affects human health (Manhart et al., 2016). Although, the symptoms of lead poisoning are mostly unspecific and the general awareness of lead toxicity is low across SSA, so poisoning often remains undetected (Manhart et al., 2016). The informal recycling process typically involves manually disassembling batteries by breaking them open with axes or machetes and melting lead battery cells over open fires. This process releases toxic lead dust and vapours into the surrounding environment (Manhart et al., 2016). The poisoning of informal lead-acid battery recycling workers is very common. Toxicity is also spread through cross-contamination (often into household products) and environmental contamination, endangering surrounding communities (Manhart et al., 2016).

Whilst lead exposure has been dramatically reduced in high-income countries, there is a paucity of research relating to lead toxicity in low and middle-income countries (Rees & Fuller, 2020). It is estimated that there are between 1150 and 7200 informal lead-acid battery recycling sites in SSA, which directly exposes between 670,800–4,149,880 people to lead poisoning (Ericson et al., 2016). However, few studies (Haefliger et al., 2009; Lomotey, 2010; Etiang', 2018) have measured the health impacts that informal lead recycling operations have on their surrounding communities. Each of these studies (Haefliger et al., 2009; Lomotey, 2010; Etiang', 2018) has attributed either mortality or life-threatening blood lead levels to nearby informal lead smelters. Notably, the (previously misdiagnosed) death of 18 children was attributed a single informal lead-acid battery recycling site in Senegal (Haefliger et al., 2009). Furthermore, hazardous practices are not confined to the informal sector and have been reported as common in industrial formal lead smelters in SSA as well, showing the general lack of awareness and regulation surrounding lead toxicity (Manhart et al., 2016). A few sophisticated and properly regulated formal lead-acid battery recycling companies do exist in SSA, such as Associated Battery Manufacturers in Kenya and First National Battery in South Africa, but these exceptions have a very limited capacity in respect to SSA's volume of lead-acid battery waste.

If lead-acid batteries are not collected and recycled, other disposal practices (landfill, dumped in nature or burnt) also releases lead pollution (Hansen et al., 2020). Burning batteries releases lead fumes and slag, and in landfill, lead is known to leach from e-waste when it comes into contact with water (UNEP, 2004; Yang et al., 2020; Tsydenova & Bengtsson, 2011). Therefore, in the general absence of properly regulated lead-acid battery recycling, all of the common disposal practices for lead-acid batteries in SSA result in environmental lead pollution. Such environmental lead pollution can contaminate water and soil and accumulate in food chains, which effectively spreads toxicity and makes the full extent of the damages caused by polluting activities difficult to measure (Cesaro et al., 2017).

Whilst adequate data does not exist to reliably quantify the toxic pollution from improper lead-acid battery disposal in SSA, the health impacts of lead poisoning are well understood and extremely severe. Globally, 800 million children are estimated to have a blood lead level that is known to affect brain development (>5 μg/dL), this population is almost exclusively contained within Africa and Asia (Rees & Fuller, 2020). This widespread lead exposure is estimated to cost Africa $134.7 billion (international dollars) every year, equivalent to 4 % of its GDP (PPP), in the form of the loss of economic productivity solely from the impairment of child brain development (Rees & Fuller, 2020; Attina & Trasande, 2013). The majority of SSA's lead-acid battery waste is currently from vehicles (Tur et al., 2016), although the ambitious targets for the deployment of OGS products (to reach hundreds of millions of people by 2030 (Climatescope, 2018)) threatens to exacerbate the unabated waste flow and its associated socioeconomic and environmental impacts.

Aside from lead, the informal recycling and improper disposal of lead-acid batteries are also associated with the release of sulphuric acid into the environment, hazardous due to its corrosive nature and its toxicity to aquatic life – a food staple in SSA (Hansen et al., 2020; World Fish Centre, 2004). The lithium-ion battery chemistries that are used in OGS applications (lithium manganese oxide and lithium iron phosphate) are considered to have a low toxic potential. However, unlike lead-acid batteries, lithium-ion batteries contain critical raw materials: lithium and graphite, categorised as having critical economic importance whilst also facing supply risks (Commission, 2020). Although, lithium-ion battery recycling is still in its infancy, and the lithium-ion batteries typically used in OGS currently have a low (or even negative) recycling value (Manhart et al., 2018). As a result, these lithium-ion batteries are more often disposed of in landfill or nature, contributing to the depletion of these finite critical materials (Charles et al., 2019). Lithium-ion batteries are also associated with fire risks, making improper handling and storage particularly dangerous (Manhart et al., 2018). Of the other components, printed circuit boards are often treated by backyard hydrometallurgical processes, poorly handling very hazardous chemicals such as cyanide and mercury to recover low yields of copper or gold (Manhart et al., 2018). Copper can also be recovered from electrical cables, accessed by burning off plastic cable insulation, releasing carcinogenic furan and dioxin gasses into the surrounding environment. Finally, compact fluorescent lamps (CFL), often used in OGS applications, contain mercury, another potent neurotoxin, that can both vaporise or leach from broken bulbs or landfill sites (Tsydenova & Bengtsson, 2011). Despite the life threatening impacts of these practices, the systematic exposure pathways of toxic pollution and the wider societal and environmental costs associated with the mismanagement of e-waste are not well understood (Manhart et al., 2016).

Barriers to waste management

This section outlines the key themes obstructing the implementation of OGS waste management in SSA. Firstly the *Waste management legislation and policy* is described as inadequate. Then, the challenges facing the reverse logistics of *Waste collection* are discussed. Finally, *Waste treatment* is discussed, considering the absence of physical recycling infrastructure in SSA and the economic burden of recycling OGS waste. These institutional, infrastructural, technological and geographical challenges must be considered and navigated for waste management initiatives to be effective.

Waste management legislation and policy

The issue of the improper management of toxic waste in low-income countries has long received attention. In 1992 an international treaty was adopted to create a framework for the proper management of hazardous waste – the Basel convention (The Basel convention on the control of transboundary movements of hazardous wastes and their disposal, 1989). Many countries in SSA (including all of the OGS hotspots: Kenya, Rwanda, Tanzania, Uganda and Mozambique) have ratified the Basel Convention, some since before 2000, but few have implemented the principles into national legislation (Magalini et al., 2016). It is not clear if the Basel convention is effectively enforced anywhere in SSA (UNEP, 2011). Moreover, no single country in SSA has an enforced and organised waste management policy for e-waste similar to Europe's WEEE Directive (a reference model for emerging policy) (Magalini et al., 2016; Corbyn et al., 2019a).

The lack of formal waste management infrastructure, the prevalence of the informal recycling sector, and the general lack of awareness surrounding the socioeconomic and environmental costs of improper e-waste management pose barriers to implementing effective e-waste management policy in SSA (ACE, 2019). Findings from the *E*-waste Africa Programme (UNEP, 2011) show that regional and international efforts have been made to enforce the Basel Convention and address e-waste, but laws typically lack uniformity and coordination, resulting in ambiguities and contradictions. This lack of legislative clarity makes monitoring the movement of e-waste, regulating recycling practices, and enforcing laws very challenging (UNEP, 2011). Furthermore, OGS waste management policy faces a fundamental economic challenge; the cost of collecting and processing OGS waste exceeds the market value of the materials that can be recovered through established recycling processes (negative recycling value, see *Waste treatment*) (Magalini et al., 2016). This opens the question of who is to bear the financial burden of waste management.

The most common approach to financing e-waste management, both in high and low-income countries, is based on the principle of Extended Producer Responsibility (EPR) (Corbyn et al., 2019b; European Union, 2012). EPR states that the producers of waste must take financial and operational responsibility for the management of the waste that they create (European Union, 2012). Although, ambiguities exist within the enforcement of EPR as to how the 'producer' is defined, what responsibilities they have, and what technologies are included within the scope of e-waste. Between the drafted and published e-waste legislation across SSA, there is ambiguity and no consistency as to if OGS products and their components are specifically included within the scope of e-waste (Magalini et al., 2016; Corbyn et al., 2019a). Table 4 describes the e-waste legislation in SSA's OGS hotspots (Kenya, Rwanda, Tanzania, Uganda and Mozambique), showing that only Kenya

Table 4
E-waste legislation in sub-Saharan Africa's off-grid solar market hotspots (Magalini et al., 2016; Corbyn et al., 2019a). OGS = off-grid solar, N.A. = not applicable, EPR = extended producer responsibility.

Country	e-Waste legislation	Financing mechanism	OGS specified in scope	Batteries in scope	Ratified Basel convention
Kenya	Drafted	EPR	Unclear	Yes	2000
Rwanda	Published	EPR	Unclear – being discussed	Yes	2003
Tanzania	Draft pending	N.A.	N.A.	N.A.	1993
Uganda	None	N.A.	N.A.	N.A.	1999
Mozambique	None	N.A.	N.A.	N.A.	1997

OGS = off-grid solar, N.A. = not applicable, EPR = extended producer responsibility.

(drafted) and Rwanda have a legislative framework for e-waste management, both founded on EPR, and both containing ambiguities relating to OGS (Corbyn et al., 2019a). If the drafted and published e-waste legislation across SSA were effectively enforced in their current state, it would create an uneven OGS market landscape across SSA. Such inconsistent legislation, that imposes additional financial burdens onto OGS suppliers in some counties and not in others, may incentivise suppliers to focus on more favourable markets, and potentially discourage them from supplying OGS products to countries that are taking a more proactive approach to e-waste management (by implementing EPR). Furthermore, Cross and Murray (2018) raise the concern that, depending on how the “producer” is defined, EPR legislation could endanger the informal repair sector. For example, Kenya's drafted e-waste management bill (Draft E-waste Regulations, 2013) defines informal repairers as producers of waste and would impose disproportionate obligations and threaten jail time for non-compliance (Cross & Murray, 2018). By penalising informal repairers, this legislation risks both a vital support mechanism for the OGS market and a local economic hub (see *Repair*). An exception to the general EPR trend is Ghana's recently implemented “eco-levy”, a different form of producer financing (Corbyn et al., 2019a). The eco-levy obliges OGS suppliers with a fixed cost for importing products into Ghana ($1.5 for pico solar lanterns and $8 for SHSs), which then relieves them of any operational responsibilities for the collection and treatment of their products when they reach the end of their service life (Corbyn et al., 2019a).

Despite the absence of meaningful legislation, the regulated OGS industry has acknowledged the issue of OGS waste, and in 2014, GOGLA members adopted an industry wide position based on EPR (Corbyn et al., 2019a). In adopting EPR, regulated OGS suppliers have committed to taking responsibility of their products when they reach their end of life. However, GOGLA's 2014 initiative was agreed on a voluntary basis, without a reporting structure or consequences for non-compliance (Hansen et al., 2020). Before 2019, some small but pioneering waste management efforts had been made within market hotspots by companies such as BBOXX, who had set up 25 repair and waste collection sites in Rwanda, and Mobisol, who had established a network of recycling facilities across East Africa (Hansen et al., 2020; GOGLA, 2019d). In 2019, the Global LEAP Awards Solar *E*-Waste Challenge was launched by the Efficiency for Access Coalition (Blair et al., 2021). Eight companies were awarded grants (totalling $1 million) to trail pilot OGS waste management projects throughout the year. As a result of the challenge, 415 new waste collection points were established, over 250 tonnes of waste were collected and 72.5 tonnes were treated (Blair et al., 2021). These efforts show a clear commitment from within the regulated OGS industry to tackle the emerging waste problem. However, these isolated initiatives relied on external funding and have had a narrow reach in respect of the estimated 12,000 tonnes of OGS waste generated in SSA in 2020 (Magalini et al., 2016; Hansen et al., 2020). So, it is still unclear how the industry's general commitment is going to be put into practice across SSA.

In the meantime, the issue of OGS waste is gaining visibility and the regulated OGS industry is coming under increasing pressure to manage its waste flow. Particularly because the industry is heavily dependent on foreign investment which is largely driven by environmental, social and governance criteria, and is subject to accountability constraints (Murray & Corbyn, 2018). Although, the financial landscape of SSA's OGS market is harsh and profitability is an ongoing struggle for regulated suppliers (see *Market dynamics*) (Corbyn et al., 2019b). Hence, while the enforcement of EPR is still uncertain, regulated OGS suppliers may be discouraged from implementing proactive waste management strategies which may overburden them with costs. Also, inevitably transferring the additional costs of waste management onto customers would further widen the price gap between regulated and unregulated products, increasing the dominance of the unregulated sector (Murray & Corbyn, 2018). In this sense, private companies have a limited capacity to compensate for the lack of centralised waste management infrastructure. Addressing the negative value OGS waste flow, without hindering the electrification efforts of the regulated OGS sector, will require more involvement from governments and smart private-public partnerships (see *Circular economy solutions*). To pursue this, and obtain legislation that fairly shares and clearly allocates the costs of proper waste management, GOGLA has initiated discussions with policymakers in priority countries, such as Kenya and Ghana (Corbyn et al., 2019a).

The emerging consensus on managing SSA's OGS waste, from both the industry body and legislation across SSA, is founded on the principle of EPR – an end of life waste management financing mechanism. Concerningly, the emerging focus on EPR fails to recognise that the majority of SSA's OGS waste flow is from unregulated products. The sale of unregulated products is unmonitored and through complex untraceable informal supply chains (Samarakoon, 2020). In this sense, unregulated products have no formal producers, making it impossible to enforce EPR. Hence, while an effectively implemented EPR scheme would satisfy the corporate responsibility of regulated suppliers, it would only treat a small fraction of the waste flow (c.72 % of global OGS sales are unregulated (Lighting Global et al., 2020)). It would be unfeasible to expect regulated suppliers to accept the financial burden of managing unregulated OGS waste. Moreover, this burden would restrict the capacity of the regulated sector to expand, restricting the availability of quality certified OGS products. The current reach of the regulated OGS sector is already limited, and the role of the unregulated sector in achieving SDG 7 must not be overlooked (see *Market dynamics*). Therefore, to mitigate hazardous pollution from OGS waste without hindering the prospects of achieving SDG 7, waste management strategies need to address the market comprehensively – implementation described in *Circular economy solutions*.

Waste collection

The decentralised and distributed nature of the OGS market, which makes waste collection complicated and expensive, poses a significantly barrier to centralised OGS waste management and formal recycling. With the lack of existing formal e-waste management infrastructure, new logistical chains need to be established, rather than being able to integrate OGS waste collection into existing systems.

Accessing waste from waste holders has been identified as the crux of OGS waste management (Corbyn et al., 2019b). OGS waste holders are often unwilling to part with their waste without financial compensation, because they believe their broken products still hold value (Cross & Murray, 2018). This perception stems from the entrepreneurial nature of the informal sector, in which waste collectors will purchase e-waste from households to then sell on to repairers or recyclers at a higher price. Waste pickers have been reported to travel long distances to purchase e-waste, even to remote rural areas with low population densities (Samarakoon, 2020). Aside from a few isolated efforts from regulated producers in establishing take back schemes (see *Waste management legislation and policy*), informal collectors are the only existing channel of OGS waste collection in SSA (Hansen et al., 2020; Groenewoudt et al., 2020).

The existing informal waste management system rivals the implementation of formal centralised waste collection. The purchase price of waste is typically determined by informal repairers, who can often afford to pay more than recyclers to access waste (Magalini et al., 2016). This is because the utility of broken products to repair activities can outweigh the market value of the materials that can be recovered through recycling. This reflects the established concept that repair is a higher value process than recycling in the circular economy, retaining more of the economic value embedded within the original product (Ellen MacArthur Foundation, 2013). Informal recyclers also have a general economic advantage over formal recycling operations as they simply discard the negative value and hazardous waste fractions that formal recyclers are burdened with. However, informal recycling practices suffer from low material recovery rates. For some valuable waste fractions, particularly lead-acid batteries, the higher material recovery rates achieved by formal recycling process can make formal recycling economically favourable (Manhart et al., 2018).

Mitigating the severe environmental and human health impacts of OGS waste requires altering the existing informal waste collection chain, to divert the waste flow away from toxic informal recycling practices and towards regulated formal recycling industries. However, to feasibly achieve effective waste collection, collaboration with the existing network of decentralised informal waste collectors is recognised as essential (Magalini et al., 2016; Murray & Corbyn, 2018; Corbyn et al., 2019b). Appropriate incentives will have to be developed to engage informal waste collectors (and users) to divert the existing waste flow to central collection points. Although, GOGLA want to challenge the public perception that e-waste is valuable, and advise suppliers to pursue non-cash incentives for customers to return waste, such as offering merchandise, discounts on new products, or entry into raffles (Corbyn et al., 2019b). However, the viability of central waste management depends on altering existing behaviours. It seems unrealistic to gain participation from waste collectors and OGS users without being able to provide them with the same level of remuneration that they would otherwise receive through their existing habits. Energy-poor OGS users or informal waste collectors (characteristically low-income groups) cannot be expected to willingly disadvantage themselves. Educational campaigns should not be expected to prevail over existing markets for valuable waste materials. As a decentralised, distributed and predominantly unregulated market, there is limited capacity to enforce new measures. Therefore, in order to change behaviours, there must be adequate incentives to encourage participation. The development of such incentives for OGS users and informal waste collectors is the key to effective waste collection, and hence waste management altogether (implementation discussed in *Establish reverse logistics systems and local recycling infrastructure*) (Magalini et al., 2016).

Various incentives for waste collection were trialled in the 2019 Global LEAP Awards Solar E-Waste Challenge (Blair et al., 2021). Public awareness of waste collection initiatives was raised via activities such as TV and radio adverts and community engagement. Among OGS users, the most popular incentive for returning waste was found to be discounts on new products, as users were keen to replace their broken sources of electricity. Whereas cash incentives were found to effectively engage local scrap dealers to deliver large volumes of waste. Brand agnostic collection schemes were also trailed, offering discounts on quality verified products in exchange for users returning broken unregulated products, with the hope of strengthening the reputations of regulated suppliers and increasing local trust in OGS technologies. More than 250 tonnes of OGS waste was collected as a result of the challenge and data was collected to develop OGS waste management strategies (Blair et al., 2021). However, these pilot collection schemes were all facilitated by the grants awarded by the challenge organisers, and it is still unclear how OGS suppliers could feasibility implement these initiatives at scale without external financial support (see *Waste management legislation and policy*).

Waste treatment

Many OGS components (e.g. lithium-ion batteries, PV panels, printed circuit boards, lighting sources and brominated plastics) require specific recycling processes using infrastructure that does not exist in SSA (Magalini et al., 2017). Hence, recycling these components currently requires them to be exported to developed counties where the necessary infrastructure does exist. Formal infrastructure for the recycling of other OGS components (e.g. lead-acid batteries, metals and some plastics) does exist in SSA, but experience competition from informal recycling practices (Manhart et al., 2018; Charles et al., 2019).

To address the absence of recycling infrastructure, the UK's Department for International Development's (DFID) published a report outlining a strategy to manage SSA's OGS waste (Magalini et al., 2016). The DFID report (Magalini et al., 2016) outlines a waste management strategy based on the “best-of-2-worlds” global e-waste management philosophy (Magalini et al., 2016). The best-of-2-worlds philosophy defines a strategy where e-waste from low-income countries is manually disassembled domestically, and then exported to high-income countries to be processed in state-of-the-art facilities (Wang et al., 2012). This is framed as a pragmatic solution that acknowledges the limitations of low-income counties, whilst ensuring that waste is recycled efficiently and that hazardous materials are treated properly. In this sense, DFID's OGS waste management model is based on disassembling end of life OGS products in SSA and exporting the majority of the waste fractions to Europe to be recycled, shown in Fig. 2.

DFID estimated the recycling values of different OGS waste fractions, averaged across SSA (Magalini et al., 2016). In their model, significant transport costs are incurred by transporting the majority of the waste flow to Europe. DFID's results show a substantial variation in the recycling values between different waste fractions, highlighting that the choice of what components are used in the design of OGS products substantially influences the overall recycling value of the product. The design of OGS products varies significantly within and between product categories, and hence their recycling values vary significantly as well. Recycling lead-acid batteries and copper wires (used in SHSs) are the most profitable activities in OGS recycling. Whereas recycling lithium iron phosphate (LFP) batteries (the most common lithium-ion battery chemistry used in OGS products) represents the greatest economic burden (Magalini et al., 2016). GOGLA adopted the DFID model to estimate the overall recycling value of common OGS products, shown in Table 5. Their estimates show pico and smaller SHSs, using LFP batteries, to have a negative recycling value, while larger SHSs using lead-acid batteries have a positive recycling value (Magalini et al., 2016; Corbyn et al., 2019b; Magalini et al., 2017).

DFID extrapolated their recycling value calculations and estimated the total cost of recycling the approximate 3600 tonnes of OGS waste produced in SSA in 2017 to be between 9.3 and 11.4 million EUR (Magalini et al., 2016). Since 2017, SSA's OGS waste flow is estimated to have more than tippled to 12,000 tonnes (2020) (Magalini et al., 2016). However, DFID used unclear assumptions for the material composition of the waste flow to calculate this overall recycling cost. For example, DFID assumed that SHSs only used LFP batteries, representing a substantial economic burden. When in fact SHSs in SSA are known to primarily use lead-acid batteries (Diouf & Avis, 2019; Antonanzas-Torres et al., 2021), representing a substantial potential revenue from recycling. Therefore, the costs of recycling SSA's OGS waste flow may be substantially lower than estimated by DFID. Moreover, reliable data for the volume and material composition of SSA's OGS waste flow does not exist as the market is predominantly unregulated (see

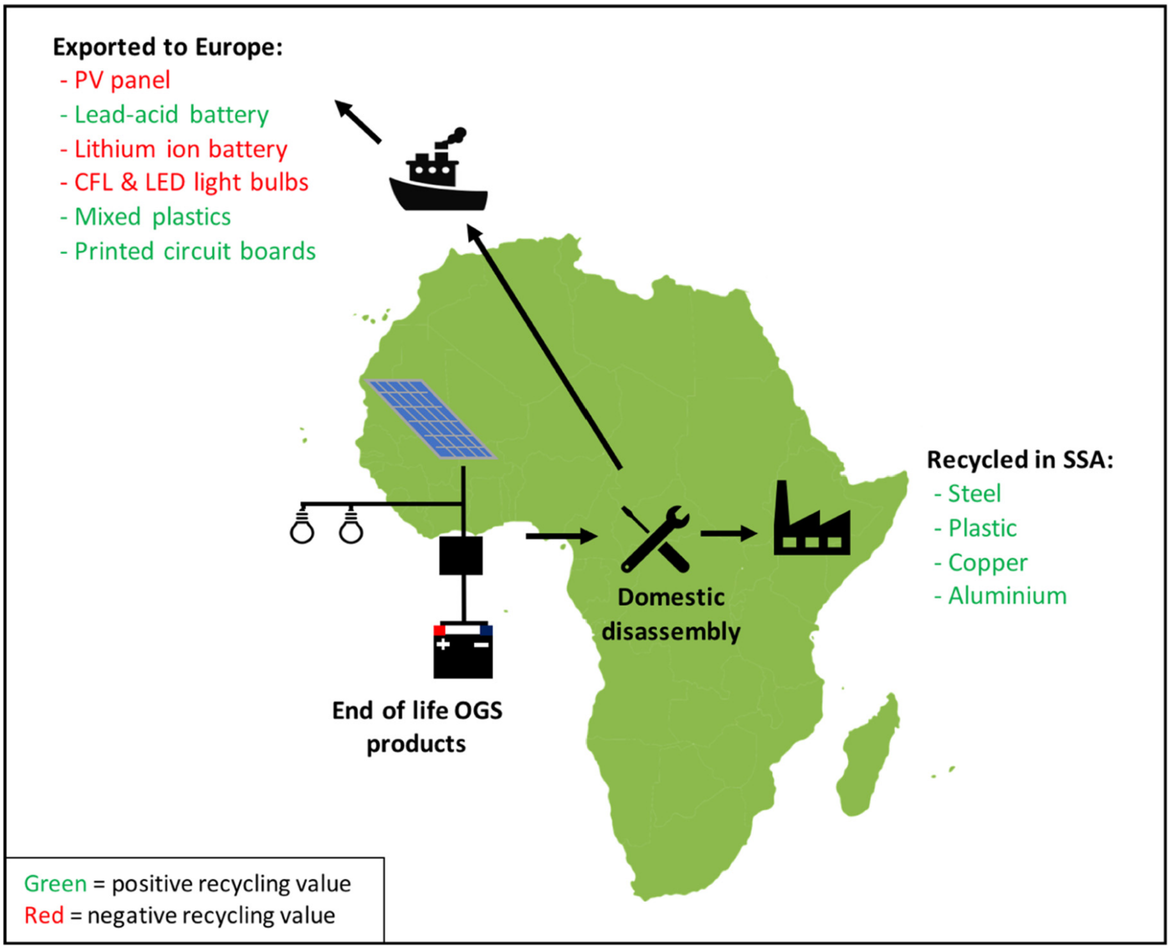

Fig. 2. Positive and negative recycling value waste fractions from the UK's Department for International Development's model for recycling sub-Saharan Africa's off-grid solar (OGS) waste. PV = photovoltaic, CFL = compact fluorescent lamps, LED = light-emitting diode.

Market dynamics), and hence, the economic burden of recycling SSA's OGS waste is still uncertain.

Under the best-of-2-worlds approach, the valuable activity of lead-acid battery recycling is exported to Europe despite the existence of formal recycling infrastructure within SSA. Aside from toxicity concerns, an economic justification for exporting lead waste is that, to be viable, recycling processes also need a market for the recovered materials. Industrial lead smelters in SSA typically yield low quality secondary lead, for which there are few domestic applications and a potentially saturated market (Manhart et al., 2016). Consequently, lead recycled in SSA is commonly exported to Europe or Asia to be refined (Manhart et al., 2016). As 80 % of the global demand for lead is used to manufacture lead-acid batteries, it is likely that used lead-acid batteries exported from SSA will be recycled, remanufactured, and then sold back into SSA to meet the domestic battery demand (International Lead Association, 2016). Therefore, lead recycling, refining and battery manufacture are examples of value-added activities that are being exported out of SSA, which may otherwise be retained if the appropriate infrastructure existed.

This exportation of value out of low-income countries into high-income under the best-of-2-worlds philosophy is criticised by Lepawsky et al. (2017), who highlight that doing so reproduces existing inequalities between high and low-income countries. In this sense, prioritising OGS recycling (based on international export) over local resource conservation activities such as repair, exports value out of SSA while also undermining both the environmental and domestic socioeconomic gains from local resource conservation activities (such as employment) (Lepawsky et al., 2017). This criticism is complemented by Cross and Murray (2018), who emphasise that prioritising recycling over repair diverts responsibility away from producers to design sustainable products and depends on infrastructure that does not exist in Africa. Instead, Cross and Murray (2018) argue that the OGS industry should focus on integrating into the dynamics of the existing waste management system, rather than attempting to finance the centralised waste management of an inherently decentralised market. These authors state that the use of materials that cannot be processed within the existing informal waste management systems is a result of product design.

The findings of this article support Lepawsky et al. (2017) and Cross and Murray's criticism of prioritising recycling over repair. The lack of maintenance and repair services greatly restricts the lifetime of OGS product in SSA, resulting in high waste volumes (see *Repair*).

Table 5
Recycling value of typical off-grid solar products calculated by the UK's Department for International development and the Global Off-grid Lighting Association (GOGLA) (Magalini et al., 2016; Corbyn et al., 2019b; Magalini et al., 2017).

Technology	Pico	Small SHS	Large SHS
Battery type	Lithium-ion (LFP)	Lithium-ion (LFP)	Lead-acid
Other components	Steel, PV panel, mixed plastic, CFL or LED bulb	Copper, PV, mixed plastic, PWB, CFL or LED bulb	Steel, copper, PV, mixed plastics, PCB
Total weight	0.9 kg	2.5 kg	20 kg
Recycling value (EUR per device)	−0.8 to −1.1	−0.12 to −1.07	1.8 to 2.3

SHS = solar home system, LFP = lithium iron phosphate, PV = photovoltaic, CFL = compact fluorescent lamps, LED = light-emitting diode, PCB = printed circuit board.

Additionally, this section has shown that the negative recycling value of OGS waste is a feature of product design. Therefore, prioritising recycling over repair (failing to address low product durability), and diverting responsibility away from producers in product design, results in high volumes of negative recycling value waste. In this sense, by following DFID's model, GOGLA is focusing on how to finance an expensive approach to waste management, rather than utilising available measures to reduce the economic burden. However, Cross and Murray's (2018) suggestion, for the regulated OGS industry to integrate into SSA's existing informal waste management system, fails to address the high toxicity of informal recycling practices. Moreover, recycling infrastructure for core OGS components, such as PV panels and printed circuit boards, does not exist in SSA (Magalini et al., 2017). While resource conservation activities can extend the life of OGS products, safely treating OGS products when they inevitably reach the end of their usable life currently requires certain components to be exported to countries in which the necessary recycling infrastructure exists. This will remain the case unless sophisticated recycling infrastructure is developed within SSA (implementation discussed in *Establish reverse logistics systems and local recycling infrastructure*).

Circular economy solutions

This review has described the environmental burdens posed by OGS waste and the barriers to implementing waste management. Although, these environmental burdens and hindrances to sustainability are not specific to OGS waste and should be viewed within the broader context of SSA's e-waste issue. E-waste is the world's largest source of waste (European Commission, 2015). While e-waste is effectively managed in high income countries, mitigating the environmental burdens of e-waste in SSA requires societal wide transformations from developing physical infrastructure to enforcing legislation and changing social practices (Heyes et al., 2018). OGS products currently only contribute a small percentage to SSA's total e-waste flow: 7 % in Kenya in 2020 (SSA's largest OGS hotspot) (Magalini et al., 2016; Forti et al., 2020). Therefore, OGS suppliers should not be expected to bear the full costs of introducing e-waste management infrastructure to SSA. Moreover, in establishing waste management legislation, governments should acknowledge the role of the OGS market in providing electricity access and compensating for the lack of centralised electricity infrastructure. Governments should consider how new waste management legislation may impact their electrification and sustainable development targets and subsidise the OGS market in areas where its financial capacity is limited.

The unregulated sector represents the majority of the OGS market and plays a core role in OGS contributing to the realisation of SDG 7 (see *Market dynamics*). However, the emerging consensus on how to manage SSA's OGS waste does not address the unregulated waste flow (see *Waste management legislation and policy*). To mitigate the environmental burdens of OGS waste in SSA, waste management strategies need to address the market comprehensively. Fortunately, within the existing market dynamics, there are accessible and low-cost opportunities for increasing OGS sustainability, as well as strong economic opportunities that may be capitalised on with the investment in domestic infrastructure. Domestically capitalising on value generating activities in the OGS value chain is a key driver for the development of local markets (Ondraczek, 2013). Failing to do so represents missed opportunities for sustainable development and increases the reliance on other countries in achieving SDG 7 (Gebreslassie, 2021).

To comprehensively address the OGS waste flow, while encouraging electrification efforts, the level of expertise in the unregulated sector needs to be progressed, toxic practices need to be mitigated, and the growth of the regulated sectors needs to be encouraged. The following sections describe how this can be realised through circular economy solutions by: i) increasing the accessibility of regulated products and implementing ecodesign; ii) promoting local resource conservation; and iii) establishing reverse logistics systems and local recycling infrastructure.

Access to durable regulated products and implementation of ecodesign

Durable regulated products need to be made more accessible to mitigate the hindrance to OGS durability posed by low quality and fake products without penalising the unregulated sector and making electricity less accessible. The geographical and demographical reach of regulated suppliers is restricted by profitability, and customers' access to quality certified products is restricted by affordability (see*Market dynamics* and *Durability vs affordability*). In this sense, publicly financed end-user subsidies can help to make durable OGS products more accessible to the energy-poor, help the regulated market expand, and promote electrification. Providing electricity access is a means of enabling modern economic activity and promoting sustainable development, which in turn can increase government revenue. Hence, the regulated OGS market is an effective area for public subsidisation.

Sustainable design or ecodesign is a well-established concept that can help to increase the circularity and environmental sustainability of products (Mendoza et al., 2019; Peña et al., 2021). Generally, 80 % of the environmental impacts of consumer products can be mitigated at the design stage (CIRAIG, 2015). The environmental burdens of OGS waste can be mitigated by considering aspects such as product durability, reparability and recyclability at the design stage. For example, the lifetime of OGS products may be extended by designing products to be easily repairable. The warranty periods of regulated OGS products are typically capped at two years (half of the expected lifetime), product failures are common, and the capacity of the regulated OGS sector to provide repair services is limited (see *Repair*). Therefore, regulated OGS producers should design their products to be easily repairable within the existing informal repair network. For example, producers should avoid 'black boxing' the design of their products, avoid the use of proprietary screws, and use locally available components where possible. The business case for regulated suppliers to increase the repairability of their products is given in the following section. However, it may be unfeasible to enforce design standards within the unregulated sector due to its informal nature.

Furthermore, the economic barrier to OGS recycling can be mitigated by considering the end of life process and maximising the recycling value of products at the design stage. Examples of this can be increasing the ease of product disassembly and prioritising the use of locally recyclable and positive recycling value materials. In this sense, developing easily repairable products is already one of the four key principles of GOGLA's voluntary EPR initiative (Corbyn et al., 2019a). Additional principles, such as eliminating the use of unrecyclable materials or reducing the use of negative recycling value materials could also be instated. Although similar to the existing principles, these should be actively enforced to have a more significant impact.

Promote local resource conservation

The emerging consensus on how to manage SSA's OGS waste prioritises recycling over repair (Magalini et al., 2016; Corbyn et al., 2019a; Corbyn et al., 2019b). However, this fails to address the short lifetimes (low durability) of OGS products and results in high volumes of negative recycling value waste. The regulated industry's reluctance to pursue repair may be explained by the concerns over intellectual property and the level of expertise in the informal repair sector. However, low product durability is also a key hindrance to the uptake of OGS products and hence the market's growth. As such, prioritising repair over recycling would increase the longevity of OGS products, increase trust and uptake (expanding the market), reduce the economic burden of the waste flow, and improve the prospects of achieving SDG 7. For OGS suppliers, resource conservation activities such as maintenance and repair can reduce their overhead costs and improve their relationships with customers (Spear et al., 2020). Whilst for local communities, these resource conservation activities provide significant socioeconomic benefits through employment (Lepawsky et al., 2017).

The widespread provision of maintenance and repair services by regulated suppliers may not be financially feasible. Therefore, the regulated OGS market should be encouraged to integrate into the existing local informal repair network. To address the concerns over the level of expertise in locally available (informal) repair services, training programs should be made available to local technicians. Resource conservation activities provide local socioeconomic benefits through employment and waste management and, hence, are an effective area for public subsidisation. For example, technical training programs could be publicly financed or facilitated by NGOs. Where already available, such training programs are actively sought after by informal technicians (Groenewoudt et al., 2020).

Similarly, low user understanding and detrimental usage habits may also be addressed through user training initiatives. Mandating user training programs with OGS product sales would impose a restrictive financial burden on OGS suppliers, although the provision of information sheets or user manuals is very feasible. End user training is also possible through existing educational institutions and with promotion from NGOs. A good example of a user training initiative is the smartphone app developed by SolarAid, which acts as a guide for users to diagnose and repair common faults with their branded products (SolarAid, 2021).

Establish reverse logistics systems and local recycling infrastructure

Mitigating the environmental burdens associated with OGS waste requires central waste collection to divert waste away from toxic incumbent informal recycling and waste disposal practices. With ineffective e-waste legislation across SSA, and the limited capacity to enforce new practices in the decentralised and predominantly unregulated OGS market, adequate incentives need to be developed to change existing practices. Effective incentives are needed to persuade holders to part with their waste and to mobilise the existing informal waste collection network to direct waste to centralised collection points. At collection points, waste products can be disassembled, and the resulting waste fractions exported to respective recycling industries. The popular PAYG financing model offers a good foundation to establish such reverse supply chains. In particular, the continuous relationship between suppliers and customers can facilitate the provision of incentives for customers to return waste, and existing networks of regional distributor agents may be utilised for waste collection. Incentives for the collection of regulated OGS waste products can be financed through regulated OGS suppliers honouring their EPR commitments. However, because it may not be possible to enforce EPR in the unregulated sector, collecting unregulated waste will require external funding, possibly from public subsidisation.

Harnessing the OGS waste flow through reverse logistics can facilitate the development of domestic recycling infrastructure. Regarding the treatment of hazardous waste, lead-acid batteries are the most damaging waste fraction. Phasing out lead-acid batteries for lithium-ion is currently too expensive to be feasible in the unregulated sector, and the capacity of governments to enforce such a measure is limited. Therefore, lead-acid batteries are expected to continue to play a fundamental role in off-grid electrification, and the adequate management of lead waste should be one of the highest priorities in any waste management strategy. Moreover, lead-acid batteries are also the most valuable waste fraction and there is a strong economic case for investing in sophisticated lead-acid battery recycling infrastructure within SSA. Lead-acid battery recycling is very profitable. Sophisticated lead-acid battery recycling would also secure a supply of high quality lead, which can enable domestic lead-acid battery manufacturing, closing the material loop within SSA. Hence, closing the lead-acid battery material loop within SSA is a means of domestically capitalising on the most profitable opportunities in the OGS waste chain, which would otherwise be exported to high-income countries.

Furthermore, investing in sophisticated domestic lead-acid battery recycling infrastructure is also a measure for preventing lead exposure. When appraising the feasibility of establishing sophisticated lead-acid battery recycling infrastructure in SSA, the external economic costs of failing to adequately manage lead waste should be considered. In particular, the cost of the loss of economic productivity due to childhood lead exposure that results from the informal recycling of lead-acid batteries should be considered. It has been estimated that Africa loses 4 % of its GDP a year from lead poisoning (Attina & Trasande, 2013). Therefore, with the potential for such substantial societal gains, developing sophisticated domestic lead-acid battery recycling infrastructure should be a priority area for public subsidisation.

Public-private partnerships can be an effective tool for establishing sophisticated domestic recycling infrastructure. For example, the only e-waste recycling plant in East Africa that is capable of treating OGS waste is Enviroserve Rwanda, which is a result of a partnership between the government of Rwanda (through the Rwanda Green Fund) and Enviroserve – an established e-waste business based in Dubai (Enviroserve Rwanda Green Park, n.d.). Enviroserve has facilitated OGS companies (such as BBOXX) in honouring their EPR commitment in Rwanda, and the public-private partnership is a case study of how well-defined policy can de-risk private investment. Similar public-private partnerships can facilitate the development of lead-acid battery recycling and manufacturing infrastructure to close the lead-acid battery material loop in SSA.

Gaps and areas for future research

This review has found the transparency of the environmental burdens posed by OGS waste in SSA to be low, and undoubtedly unclear for policymakers. Hence, increasing the transparency of the costs and benefits associated with addressing SSA's OGS waste is imperative, to encourage policymakers to define strategies, attract investment, and identify necessary synergies in cases where the costs and benefits are not shared by the same parties. Research studies such as cost-benefit analyses, value chain analyses, and life cycle health impact assessments are effective tools to quantify the economic, environmental and wider societal costs and benefits associated with addressing SSA's OGS waste with circular economy solutions.

Specifically, there is a paucity of data relating to the dynamics of the unregulated OGS market and the environmental impacts of informal waste management practices. The unregulated OGS sector represents (c.72 %) of the global OGS market (Lighting Global et al., 2020), yet only 4 of the 52 reviewed studies (Cross & Murray, 2018; Groenewoudt et al., 2020; Samarakoon, 2020; Samarakoon et al., 2021) address the unregulated sector. Hence, the dynamics of SSA's OGS market, such as the supply chains, the material composition and lifecycle of products, user satisfaction, and end of life disposal practices are still poorly understood. A better understanding of the existing dynamics of SSA's OGS market is necessary to gain participation from key local stakeholders in waste management initiatives. Formal e-waste management is generally absent across SSA, while the informal recycling of lead-acid batteries has been cited as the world's largest source of toxic pollution that directly affects human health (Manhart et al., 2016). However, quantitative studies have not been carried out to assess the impact that informal e-waste management practices have on the environment and the health of the surrounding communities. Research studies such as life cycle assessment, health studies, value chain analysis, and cost-benefit analyses can be utilised to quantify the economic, environmental and wider societal costs and benefits associated with addressing SSA's OGS waste with circular economy solutions.

Finally, with the increasing uptake of OGS products, there is an emerging market of high-efficiency devices that can be powered by SHSs (e.g. TVs, fans, and fridges). The waste volumes from these appliances are expected to exceed the volumes from SHSs themselves (Magalini et al., 2016). Currently, there is no testing or reporting structure for the quality of these products, and such data is limited (Lai et al., 2020). Increasing the transparency on the durability of these products, addressing their waste flow, and investigating the impacts that these products may have on the public trust in OGS technologies and hence the prospects of achieving SDG 7, are all important areas for future research.

Conclusion

This review examined 52 papers to assess the potential for circular economy solutions to address the growing volume of waste from off-grid solar (OGS) products in sub-Saharan Africa (SSA). The dynamics of SSA's OGS market were described, the factors accelerating the waste flow were identified, the environmental and human health implications of the waste flow were described, the barriers to implementing waste management were discussed, and potential circular economy solutions were proposed to address the OGS waste flow.

The landscape of SSA's private OGS market is found to be complex, divided between the regulated and unregulated sectors. Furthermore, there is significant regional variation as the market is predominantly contained within hotspots in East Africa (Kenya, Rwanda, Tanzania, Uganda, and Mozambique). The geographical and demographical reach of the regulated sector is restricted by profitability and the inherent economic challenge of delivering expensive high quality products to a dispersed energy-poor customer base that have a low ability to pay. Hence, the majority of OGS products in SSA are assumed to be from the unregulated sector, in which cheaper lower quality products are disseminated through unlicensed vendors, yet there is a paucity of data to describe the sector's dynamics.

The OGS waste flow is accelerated by the short lifetime of OGS products in SSA. High rates of failures and short expected lifetimes are reported in all product categories, although more pronounced in the unregulated sector. The leading hindrances to product durability are identified as: i) poor product quality, ii) affordability constraints; iii) the low level of local technical expertise in system design and installation; iv) low user understanding and detrimental usage habits; and v) low access to maintenance and repair services. Most of these factors typically manifest as overstrained batteries which rapidly degrade and can substantially limit the lifetime of OGS products to less than two years.

In the general absence of formal e-waste management, the current waste management practices for OGS products in SSA are found to have severe environmental and human health implications. Valuable waste fractions are often informally recycled with extremely severe environmental consequences. Most concerningly, the informal recycling of lead-acid batteries is a primary driver of lead exposure in SSA and is cited as the world's largest source of toxic pollution that directly affects human health. These severe environmental and socioeconomic burdens risk being exacerbated by the targets to provide OGS products to millions of people by 2030 in line with SDG 7.

However, implementing effective waste management faces significant challenges: i) competition with incumbent informal recycling practices; ii) inadequate legislation; iii) the complexity of reverse logistics; iv) the negative recycling value of some OGS products; and v) the absence of sophisticated formal recycling infrastructure. Furthermore, the emerging consensus on how to address SSA's OGS waste, from the industry's body and legislation across SSA, is based on Extended Producer Responsibility and fails to address the unregulated waste flow, which is the majority of SSA's OGS waste flow.

In light of these challenges, solutions based on the theory of the circular economy are suggested to address SSA's OGS waste flow. Increasing the durability and repairability of products should be a priority before recycling. This can be achieved through increasing the accessibility of regulated quality certified products, implementing ecodesign, and promoting local resource conservation actives such as maintenance and repair. Reverse logistics systems should be established by collaborating with the existing informal waste collection network to enable the formal recycling of products that cannot be repaired. Furthermore, establishing sophisticated lead-acid battery recycling should be pursued through public-private partnerships due to the potential for such wide societal gains in mitigating lead exposure. Sophisticated lead-acid battery recycling would also enable domestic battery manufacturing, closing the material loop of lead-acid batteries within SSA and domestically capitalising on the most profitable activities in the OGS waste chain. Finally, the main research gaps have been identified. In particular, the transparency of the economic costs and the socioeconomic and environmental benefits associated with addressing OGS waste is currently low, undoubtedly unclear for policymakers.

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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