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Life cycle assessment of solar home system informal waste management practices in Malawi

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HIGHLIGHTS

- First quantification of lead pollution from informal recycling of solar batteries.
- Equivalent of 100 lethal oral lead doses released to environment from one battery.
- Environmental impacts amplified by user practices that restrict battery lifetimes.
- Environmental impacts of solar home systems can exceed diesel generators.
- Holistic solutions needed for off-grid solar technologies to be safe and low-carbon.

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ABSTRACT

This study performs the first life cycle assessment of solar home systems (SHSs) to use data quantifying lead pollution from informal lead-acid battery recycling. The typical life cycle of SHSs in off-grid communities surrounding Malawi's capital of Lilongwe is assessed, considering affordable components imported from China, lead-acid battery lifetimes of one year, the collection of materials through the informal scrap market, the open dumping and burning of waste, and informal lead-acid battery recycling (remanufacturing). Lead-acid batteries are highlighted as the most damaging SHS component, occupying 54–99% of each impact category, caused by the burdens of lead mining and the high assembly energy of batteries, amplified by short battery lifetimes – subject to detrimental user practices. The amount of electricity delivered to users is significantly restricted by the low efficiency of affordable SHS components. Meanwhile, the informal remanufacturing of a single lead-acid battery is recorded to release over 100 times the lethal oral dose of lead for an adult into densely populated communities, resulting in a terrestrial ecotoxicity potential of 200–386 kg 1,4-DCB eq. per kWh delivered. Proposed formal recycling solutions are found to successfully mitigate the toxicity of informal waste management but incur significant burdens: substituting toxic but resource-efficient informal remanufacture with safe but energy-intensive formal battery production. Furthermore, the short one-year lifetimes of lead-acid batteries can cause the environmental impacts of SHS to exceed the impacts of diesel generators in most impact categories, resulting in a global warming potential of up to 1.4 kg CO_2/kWh. Hence, both extended battery lifetimes of three

Abbreviations: SSA, sub-Saharan Africa; SHS, solar home system; SDG, sustainable development goal; OGS, off-grid solar; LCA, life cycle assessment; PV, photovoltaic; AC, alternating current; DC, direct current; PWM, pulse width modulation charge controller; CN, China; PVC, polyvinyl chloride; EVA, ethylene vinyl acetate; PET, polyethylene terephthalate; PE, polyethylene; BAU, business as usual; REC, formal recycling; REC + EXT, formal recycling and extended battery lifetimes of three years; PCB, printed circuit board; LCI, life cycle inventory; GWP, global warming potential; SODP, stratospheric ozone depletion potential; IRP, ionizing radiation potential; OF-HHP, ozone formation-human health potential; PMP, fine particulate matter formation potential; OF-TEP, ozone formation-terrestrial ecosystems potential; TAP, terrestrial acidification potential; FEUP, freshwater eutrophication potential; MEUP, marine eutrophication potential; TEP, terrestrial ecotoxicity potential; FEP, freshwater ecotoxicity potential; MEP, marine ecotoxicity potential; HCTP, human carcinogenic toxicity potential; HNCTP, human non-carcinogenic toxicity potential; LUP, land use potential; MRSP, mineral resource scarcity potential; FRSP, fossil resource scarcity potential; WCP, water consumption potential.

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years and formal recycling are found to be necessary for SHSs to be considered as a safe and low-carbon technology – requiring holistic interventions.

1. Introduction

In line with the United Nations' 7th Sustainable Development Goal (SDG 7) of universal electricity access by 2030, the sale of household scale off-grid solar (OGS) technologies (solar home systems and pico solar lamps) through the private OGS market has become an increasingly popular electrification strategy across sub-Saharan Africa (SSA) [1–3]. These OGS technologies are considered a particularly effective solution to provide electricity access to areas that cannot be easily reached by national grids. Furthermore, gaining electricity access with OGS technologies has also been shown to facilitate several other SDGs, promoting poverty alleviation, education, health and climate action [4]. Accordingly, the private (OGS) market has become embedded into national electrification strategies. Notably, the Malawi Government have defined the target that 45% of its population will have purchased OGS technologies by 2030 (approximately 11.2 million people), necessitating the import of millions of solar home systems (SHS) [5,6].

This privatisation of electricity access through the OGS market has left low-income energy-poor households responsible for providing their own electricity infrastructure. Meanwhile, SSA's OGS market is predominantly unregulated, depending on bottom of the pyramid markets for affordable products, and suffers from a general lack of supplier accountability: substandard, short-lived and counterfeit OGS products are common [7,8–10]. Low user understanding in SHS design, installation and operation has also been highlighted to result in frequent SHS failures and short product lifetimes [10]. Furthermore, similar to other countries across SSA, Malawi currently has no physical or legislative infrastructure for the management of electrical and electronic waste (e-waste) [11,12]. Donor OGS electricity access projects also do not typically include plans or budgets for end of life waste management. With this lack of formal infrastructure, the current informal waste management practices for OGS products have been found to present significant environmental and human health risks, particularly due to the potential release of lead – a potent neurotoxin regarded as the most hazardous material in e-waste [7,13–16]. Concerningly, Kinally et al. [16] have reported informal recyclers in Malawi remanufacturing lead-acid batteries from SHSs within densely populated off-grid communities, potentially releasing significant quantities of lead pollution into their surrounding environments. Meanwhile, the informal recycling of lead-acid batteries is recognised as a primary vector for lead exposure in SSA and has been cited as the world's largest source of toxic pollution that directly affects human health [17–20]. However, despite these severe risks, there is still a lack of research describing or quantifying the environmental impacts of informal OGS waste and e-waste disposal practices across low- and middle-income countries.

Previous studies assessing the environmental impacts of SHSs in developing countries have navigated the lack of transparency of the current waste disposal practices by instead using the available data for waste management processes in the Global North. The first life cycle assessment (LCA) by Alsema [21] in 2000, assumed that SHSs in developing countries were recycled following European standards – despite the lack of recycling infrastructure. Nonetheless, Alsema found lead-acid batteries to account for 50–90% of the environmental impacts of SHSs. Meanwhile, Bilich et al. [22] assumed lead-acid batteries to have a lifetime of 13 years in OGS systems in Kenya, and considered that end of life waste was disposed of in sanitary landfills. However, lead-acid batteries have been recorded to have a typical lifetime of only one year in SHS in off-grid communities in Malawi, and sanitary landfills are unavailable across many countries within SSA [7,10]. Other literature praises lithium-ion batteries as a viable alternative for SHSs, with higher technical performance and avoiding the toxicity concerns of lead-acid batteries [23–25]. However, lithium-ion batteries remain prohibitively expensive for energy-poor consumers and SHS in SSA predominantly rely on more affordable and widely available lead-acid batteries [10,24]. Furthermore, Mukoro et al. [26] have highlighted that LCAs on solar technologies in SSA often fail to consider the impact categories of human toxicity and ecotoxicity, overlooking these risks altogether. Hence, these prior studies fail to reflect the current life cycle of SHS in SSA and potentially underestimate the impact of informal waste management practices. Only one LCA study, by Antonanzas-Torres et al. [27], has acknowledged and considered the impacts of the informal recycling of lead-acid batteries. However, Antonanzas-Torres et al. [27] emphasized the lack of quantitative data and made the assumption that lead pollution from informal recycling was between 10 and 100 times greater than that from formal recycling. Therefore, the transparency of the environmental impacts of the implementation of SHS in SSA is still low.

To address this disparity between the theoretical and actual environmental impacts of SHSs in developing countries, this study evaluates the environmental impacts of the typical life cycle of SHSs in off-grid communities surrounding Malawi's capital of Lilongwe recorded by Kinally et al. [10]. This is for the purpose of highlighting the magnitude of the environmental risks associated with the current informal SHS waste management practices, justifying the need for further research and waste management interventions. Reflecting the recorded SHS life cycle, the LCA considers affordable components (with low electrical efficiencies) imported from China, short lead-acid battery lifetimes of one year, the collection of materials through the informal scrap market, the open dumping and burning of waste, and informal lead-acid battery recycling. Specifically, the first data to quantify lead pollution from the informal recycling of lead-acid SHS batteries is manually collected. Meanwhile, justified assumptions are used to model the leaching of lead from e-waste dumped in nature. The hotspots for environmental impacts in the current SHS life cycle are identified and the potential to mitigate environmental burdens with proposed waste management solutions is assessed. Finally, the environmental performance of SHSs is compared with diesel generators – the only readily available alternative for off-grid household electricity access in Malawi.

Considering the structure of this paper, Section 2 describes the methodology, including the data collection and the assumptions and datasets used to complete the environmental impact assessment. Section 3 presents the results, first identifying the environmental hotspots in the current SHS life cycle, then evaluating the potential to mitigate the environmental burdens of SHS with proposed formal recycling solutions, and finally, comparing the environmental performance of SHSs with home generators. Section 4 then discusses the implications of these findings for OGS electrification strategies, and also describes the limitations of the study and makes recommendations for future research. Finally, Section 5 presents the conclusions.

2. Methodology

The environmental impacts of SHSs in Malawi have been evaluated by performing a life cycle analysis following the ISO 14040 and ISO 14044 standards [28,29]. The study followed the four defined stages of: i) goal and scope definition; ii) inventory analysis; iii) impact assessment and iv) interpretation of the results, described in the following sections.

2.1. Goal and scope of the study

The goals of the study are to i) evaluate the environmental impacts of a typical SHS in Malawi and identify the most damaging aspects of their life cycle (environmental hotspots), ii) to compare the environmental impacts of the current SHS waste management practices with scenarios for potential waste management solutions, and iii) to compare the environmental performance of SHSs with home generators.

The analysed SHS has been designed to reflect a typical SHS in Malawi based on surveys with SHS users in peri-urban villages surrounding Lilongwe [10]. The SHS is composed of a 150 Wp poly-crystalline silicon photovoltaic panel, an 80 Ah lead-acid battery, a 300 W Solar Africa (generic) inverter, a pulse width modulation (PWM) charge controller, and 6 m of insulated copper wire, shown in Fig. 1. Appliances that utilise the electricity generated by SHSs (such as light bulbs, phones and radios) are not included in the assessment. A functional unit of 1 kWh of AC electricity is considered to allow for a representative comparison with other options for electricity access. Specifically, a typical 5 kW home diesel generator is selected as a comparison for the SHS. The system boundaries considered are from 'cradle to grave', including the production of materials, manufacturing, transportation, use, and end of life waste management, as shown in Fig. 2.

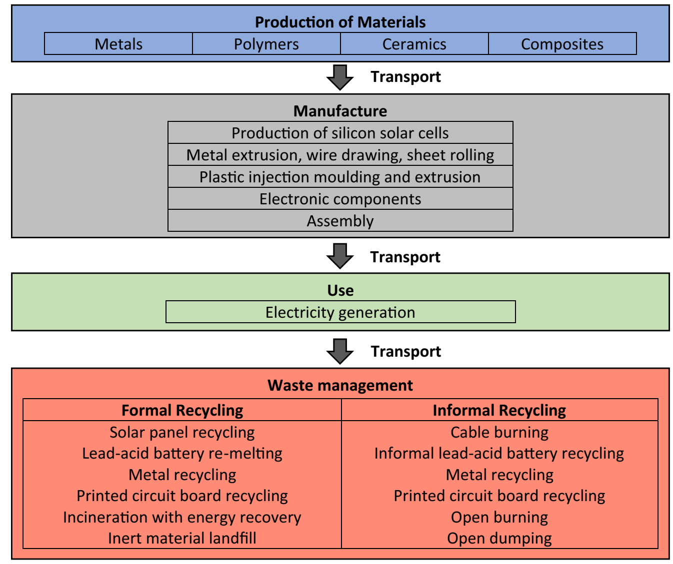

Fig. 2. System boundaries.

2.2. Life cycle inventory

Background data from the Ecoinvent database v3.9.1 was used for the production of materials, the production of multi-crystalline solar cells, transport, and some waste management practices. Due to gaps in the Ecoinvent database, data was also manually collected and taken from literature, described in the following sections. Specifically, material inventory data for the controller and inverter was manually collected, and the flow of materials through the informal lead-acid battery recycling process was recorded in the field.

2.2.1. Production of materials and manufacture

The material inventory for the SHS is summarised in Table 1. The data used for the material composition of a poly-crystalline solar panel reflects a typical 150 W/m^2 poly-crystalline solar panel produced in China in 2013 [30], although, more recent data was used for the production of a photovoltaic cell from the Ecoinvent database v3.9.1. Inventory data for a typical lead-acid battery was obtained from the EU sustainable batteries report [31,32] (shown in S1), and the 80 Ah battery was assumed to weigh 22 kg. The material inventory data for the Solar Africa 300 W inverter and pulse width modulation (PWM) charge controller was manually collected by disassembling and weighing the components of these products (full inventories shown in S1). The inventory for 6 m of insulated copper wire was taken from Ecoinvent on [33,34], assuming 2.5mm^2 diameter wire, weighing 0.04 kg/m^2. Finally, the inventory data for the 5 kW home generator is taken from prior literature that considers data sheets for common home generators used in Thailand [35], shown in Table S3.

The SHS is analysed over a 25-year period, reflecting the expected lifetime of the solar PV panel [21]. The shorter-lived components are disposed of and replaced during the SHS lifetime. Insulated copper wires are assumed to have a 10-year lifetime, inverters a 3-year lifetime, and PWM charge controllers a 2-year lifetime. The lifetime of lead-acid batteries in peri-urban villages in Malawi has been recorded to vary substantially between 3 months and 3 years [10]. This is because lead-acid batteries are inherently vulnerable to rapid deterioration with detrimental usage practices and poor SHS design, particularly from regular deep-discharging and overcharging [36,37]. For the purpose of this study, the average reported lead-acid battery lifetime of one year in SHS in off-grid communities surrounding Lilongwe is considered [10].

2.2.2. Operation and electricity generation

Considering SHS installation, solar panels are often placed flat on roofs without any fixings or leant against objects during the day so that they can be stored inside and protected at night [10]. Meanwhile,

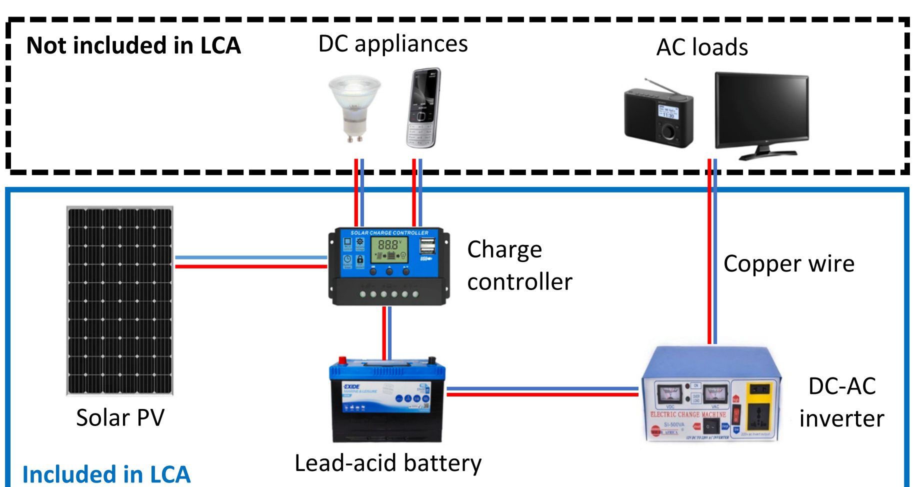

Fig. 1. Typical solar home system design, showing the core components included in the life cycle assessment. AC = alternating current, DC = direct current, PV = photovoltaic.

Table 1
Life cycle inventory for the charge controller, inverter and insulated wire solar home system components.

Component	Material	Value	Unit
Polycrystalline PV panel (per 150 W unit) [30]			
PV cell	Photovoltaic cell, multi-Si wafer	0.90	m^2
Assembly	Aluminium alloy	1.86	Kg
	Tin (solder)	23.60	g
	Copper, cathode	94.40	g
	Tempering, flat glass	5.41	Kg
	ethylene vinyl acetate foil	0.80	Kg
	Polyvinyl fluoride, film	0.10	Kg
	Polyethylene terephthalate, granulate	0.34	Kg
Assembly energy	Medium voltage (CN)	7.12	kWh
Lead-acid battery (per 22 kg unit) [31]			
Electrodes	Lead	13.41	kg
	Oxygen	0.50	kg
Electrode grid alloys	Antimony	156.20	g
	Arsenic	6.60	g
	Copper	2.20	g
Electrolyte	Sulphuric acid	2.27	Kg
	Water	3.72	Kg
Plate separators	Polyethylene	402.60	g
	Glass	44.00	g
Case	Polypropylene	1.48	kg
Assembly energy	Medium voltage (CN)	65.45	kWh
Charge controller (per unit)			
Assembly	Polyamide, injection moulded	41.70	g
	Low alloyed Steel	35.58	g
	Stainless steel	2.61	g
	Insulation tape (PVC)	0.49	g
Electronic components	* full inventory in S1	50.16	g
Processes	Sheet rolling, wire drawing * full inventory in S1		
Inverter (300 W, per unit)			
Assembly	Low-alloyed steel	1158.83	g
	Stainless steel	22.58	g
	Polyamide, injection moulded	25.58	g
	Insulated wire	39.51	g
	Copper cathode	161.81	g
Electronic components	* full inventory in S1	18.98	g
Processes	Sheet rolling, wire drawing * full inventory in S1		
Insulated wire (per kg) [33]			
Copper wire	Copper	385.00	g
Plastic insulation	PVC	407.70	g
	Polyethylene	191.90	g
	Copper	15.38	g
Process	Wire drawing, copper	400.38	g
Processes	Extrusion, plastic pipes	599.60	g

PV = Photovoltaic, CN = China, PVC = polyvinyl chloride, EVA = ethylene vinyl acetate, PET = Polyethylene terephthalate, PE = Polyethylene.
[*] Full inventory for disassembled components provided in table S1 in the supporting information.

Table 2
Solar home system performance.

Orientation	North	East	South	West	Average
Yearly in-plane irradiation (kWh/m^2)	2165.56	2082.22	1950.60	2046.38	2061.19
PV losses %	20.36%	20.14%	20.33%	20.50%	20.33%
25-year PV generation (kWh DC)	5803.14	5594.31	5228.96	5474.70	5525.25
25-year available electricity (kWh AC)	2089.75	2014.55	1882.98	1971.48	1989.68

In-plane irradiation and PV losses (angle of incidence, spectral effects, temperature, low irradiance losses, and soiling) taken from PVGIS for Lilongwe [38].

maintenance practices often only consist of cleaning solar panels with water or a cloth [ibid]. Hence, SHS installation, operation and maintenance are assumed to have negligible environmental impacts.

The electricity generated from the 150 Wp PV panel depends on its orientation (azimuth and tilt angles) and is also subject to user-dependent factors, particularly the cleaning schedule. The orientation of solar panels in SHSs in peri-urban Lilongwe was found to generally reflect the orientation of the user's front facing roof pitch, rather than the technical optimum [10]. Hence, an average yearly in-plane solar irradiation of 2061.19 kWh/m^2 was selected, based on the average irradiation of different azimuth angles (0^o, 90^o, 180^o, 270^o) at a 13^o pitch (average recorded roof pitch) calculated for Lilongwe with PVGIS, shown in Table 2 [38]. Losses in the PV electricity generation from the angle of incidence, spectral effects, temperature and low irradiance losses were calculated in PVGIS [38], taking an average value (for the four azimuth angles) of 15.33% for the modelled SHS. Notably, as PV panels are typically mounted on sheet metal roofs (with high thermal conductivity) and PV panels are vulnerable to efficiency losses with heat, thermal losses could potentially exceed 15% in practice [39]. However, these potential thermal losses from sheet metal roof conductivity are not considered in the study. Soiling losses of 5% are considered, typical for SSA, although soiling losses vary substantially depending on panel cleaning schedules [40]. In regions with long dry seasons near the Sahara Desert, cleaning PV panels at least every two weeks has been found to maintain soiling losses below 1%, however, insufficient cleaning can cause soiling losses to exceed 50% [41–43]. Shading losses were considered to be negligible as multi-storey structures are uncommon in peri-urban settlements in Lilongwe. Finally, a typical annual efficiency loss of 1% from PV degradation is considered [44]. These assumptions result in a generation of 248.69 kWh (DC) in the SHS's first year of operation, and a total of 5525.25 kWh (DC) over the 25-year lifetime. The electricity generation is expected to increase or decrease by 5% from this calculated average value depending on if the PV panel faces North (optimal) or South, respectively.

The fraction of the electricity available to the SHS user from the inverter (AC) was calculated considering the efficiency of each component in the SHS, assuming a typical evening-peak energy demand curve – drawing electricity from the battery [45]. Losses from the DC cabling and AC cabling were both considered to be 2% [46]. The PWM charge controller is assumed to have a 71.42% efficiency [47], the lead-acid battery a 70% efficiency [48], and the modified sine wave DC-AC inverter a 75% efficiency [49]. The combined losses from each component result in only 36% of the electricity generated by the PV being available to the user: 1989.68 kWh (AC) over the 25-year SHS lifetime. Notably, substantially higher SHS efficiencies can be achieved with high end components such as maximum power point tracking charge controllers, lithium-ion batteries, and pure sine wave inverters (all >95% efficient) [50,51]. However, these high-end components are prohibitively expensive for typical energy-poor households [10].

Considering the electricity generation from the diesel generator, small 5 kW home generators are significantly more powerful than typical SHSs, although, the electricity generation is dependent on fuel use – restricted by the affordability constraints of energy-poor households. To account for the influence of the level of utilisation, two operational scenarios are considered for the generator: i) low fuel use: matching the level of service from the SHS over 25 years, and ii) high fuel use: satisfying the expected 15,000-h operational generator lifetime over 25 years. The burn rate of the generator is considered to be 0.39 L/kW (AC) at a load of 2 L/h. Matching the level of electricity service from the SHS by only generating 1989.68 kWh (AC) represents a substantial underutilisation of the generator, requiring only 388 h of operation over the 25-year period. Whereas, achieving the expected 15,000-h expected operational lifetime of the generator yields 76,923.08 kWh (AC) over the 25-year period.

2.2.3. End of life waste management

Three end of life waste disposal practices are compared: i) the current informal waste management (business as usual (BAU)) and two potential waste management solutions: ii) formal recycling (REC), and iii) formal recycling with extended battery lifetimes of three years (REC + EXT). The informal waste management reflects typical SHS waste management practices that have been described in off-grid communities surrounding Lilongwe [10]. The informal waste management practices considered include the informal remanufacturing of lead-acid batteries, the collection and export of materials through the informal scrap market, open burning (plastics and glass), and burying in waste pits (open dump) (metals, plastics, glass, PCBs, solar PV cells), summarised in Table 3 and explained in the following section. These current informal waste management practices are also considered for the diesel generator. Whereas the formal recycling scenarios reflect proposed waste management solutions where all of the SHS waste materials are collected, exported to South Africa and recycled, considering the available data on established recycling and waste management processes in Europe. The collection and formal recycling of SHSs has been shown to be profitable, particularly driven by the significant value of recovering lead from lead-acid batteries [52,53]. However, a more detailed economic analysis of the proposed waste management is beyond the scope of this study. South Africa is selected for the proposed waste management solution because regulated lead-acid battery recycling is well developed (such as the First National Battery recycling plant), and there is an already well-established bilateral trading relationship with Malawi [54]. A complete list of the assumptions and datasets used to model each waste management process is shown in Table S4 in the supporting information.

In the end of life modelling, the environmental impacts are allocated to the product's initial life. The burdens of the recycling processes are considered, but the materials recovered by the recycling processes are credited as avoiding the production of primary materials. Following the net-scrap approach, the avoided product is considered as the fraction of a material that is recovered by a recycling process minus the fraction of the recycled content of the feedstock material used in production [55–57].

2.2.3.1. Informal waste management. The informal scrap market is an established source of livelihood in Malawi and scrap dealers efficiently aggregate valuable material from surrounding communities [10]. However, there is a lack of data to quantify the amount of materials collected. For the purpose of this study, informal scrap collectors are assumed to collect 80% of the steel, aluminium, copper and 50% of the printed circuit board (PCB) waste, and the remaining fractions of these materials are assumed to be openly dumped in nature. The aluminium, copper and steel collected by the scrap dealers are assumed to be sold and transported to recyclers in China while the PCBs are exported to recyclers in South Africa [10]. The recycling of these materials (steel, aluminium, copper and PCBs) is modelled using the available data for formal recycling processed in the Ecoinvent database. The dumping of these metals (steel, aluminium and copper) and PCBs in nature is modelled as the open dumping of municipal solid waste due to the lack of specific data.

Dumping e-waste such as PCBs and silicon-metal solar cells in landfills has been found to result in the leaching of lead into soil [15,58]. However, there is currently a lack of data to reliably predict the long-term environmental impacts of dumping electronic waste in either sanitary landfills or unregulated open dumping. The solubility and mobility of lead in soil is pH-dependent and substantially increases in acidic conditions [59]. When exposed to acidic conditions, between 13 and 90% of the lead content of a crystalline silicon PV panel has been recorded to leach to soil (approximately 0.08–0.52 g of lead per kg of PV panel) [60]. Unregulated acid draining is commonly practiced at scrap dealing sites and informal electronics repair shops within peri-urban villages in Malawi (expected to increase soil pH) and therefore the lead leaching from e-waste is expected to be significant at these sites [10]. Due to the lack of existing datasets for the dumping of e-waste, the dumping of solar PV panels and PCBs is modelled with the open dumping of municipal solid waste dataset (Ecoinvent v3.9.1) with the added assumption that 40% of the lead content of solar PV panels and PCBs being leached to the soil. The lead content of PCBs (including components mounted to the substrate) is considered to be 2.5% [61], hence the lead leaching is assumed to be 0.23 g/kg of solar PV panel and 10 g/kg of PCB. Notably, whilst the use of lead in solder, circuit boards and electronic components is being effectively phased out in the Global North, such advances cannot be taken for granted in the off-grid solar market in the Global South due to its predominately unregulated nature and the lack of supplier accountability [10].

The process of informal lead-acid battery remanufacturing uses rudimentary techniques and readily available tools to fabricate functioning batteries from used battery scrap, pictured in Fig. 3. The battery remanufacturing process is unstandardized, although follows the same general steps: melting lead scrap, crushing positive battery plates, and fabricating improvised cells, meanwhile unusable materials are discarded into the local environment [10]. The informal recycling of lead-acid batteries was modelled by collecting data from the observation of informal recyclers within peri-urban villages surrounding Lilongwe. The flow of materials through the informal lead-acid battery recycling process was recorded with two different recyclers in separate villages, both following the recycling of a 50 Ah battery, shown in Figs. S6 and S11 and described in the supporting information. The two recorded recycling processes differed significantly due to the condition of the battery being recycled and the recycler's preferred approach (discussed by [10]). For the purpose of this study, an average value was taken between each of the two recycling methods for each material input and output per kilogram of lead-acid battery recycled, shown in Fig. 4. This material flow per kg of battery recycled was then adapted to model the informal recycling of a slightly larger 80 Ah battery for the purpose of this study.

A significant amount of lead was lost to the environment as dust or shrapnel from the moment that the degraded lead cells were removed from the battery casing and throughout every stage in the recycling process. The lead lost during each individual step of the process could not be accurately recorded. Instead, the total amount of lead lost to the environment over the recycling process was calculated. The mass of each material that was purposefully added to or removed from the battery during each stage of the recycling process was recorded using portable scales. Then the total mass of lead accidentally lost to the environment was considered as the deficit between the weight of the materials used to

Table 3
Summary of informal waste management assumptions.

Component	Informal recycling assumptions
Lead-acid battery	Informal remanufacture, recovering approximately half of the lead battery cells. LCI summarised in Fig. 4. Remanufacturing avoids the production and transport of half a battery. 0.312 kg lead released to environment per kg of battery: 90–95% lead lost to soil, 5–10% lead lost to air. Sulphuric acid and plate grid alloys released to soil
Solar PV panel	Glass and plastic: 50% burnt, 50% buried Aluminium: 80% collected, exported to China and re-melted; 20% in municipal solid waste open dump Cell: modelled as municipal solid waste with 0.23 g of lead leaching to soil per kg of solar PV
Inverter and charge controller	PCB: 50% collected exported to South Africa and recycled, 50% modelled as municipal solid waste open dump with 10 g of lead per kg PCB leaching to soil. Plastics: 50% burnt; 50% buried Steel: 80% collected, exported to China and recycled, 20% in municipal solid waste open dump Copper: 80% collected, exported to China and recycled; 20% in municipal solid waste open dump
Insulated wires	80% collected and openly burnt to remove insulation, copper exported to China and recycled; 20% in municipal solid waste open dump
Generator	Steel, aluminium and copper: 80% collected, exported to China and recycled; 20% in municipal solid waste open dump Plastic: 50% burnt, 50% buried

PV = photovoltaic, LCI = life cycle inventory, PCB = printed circuit board.

Fig. 3. Fabricated lead grids being coated in lead oxide paste and dried over a charcoal cooking stove during the informal lead-acid battery recycling process, described in detail in the supporting information.

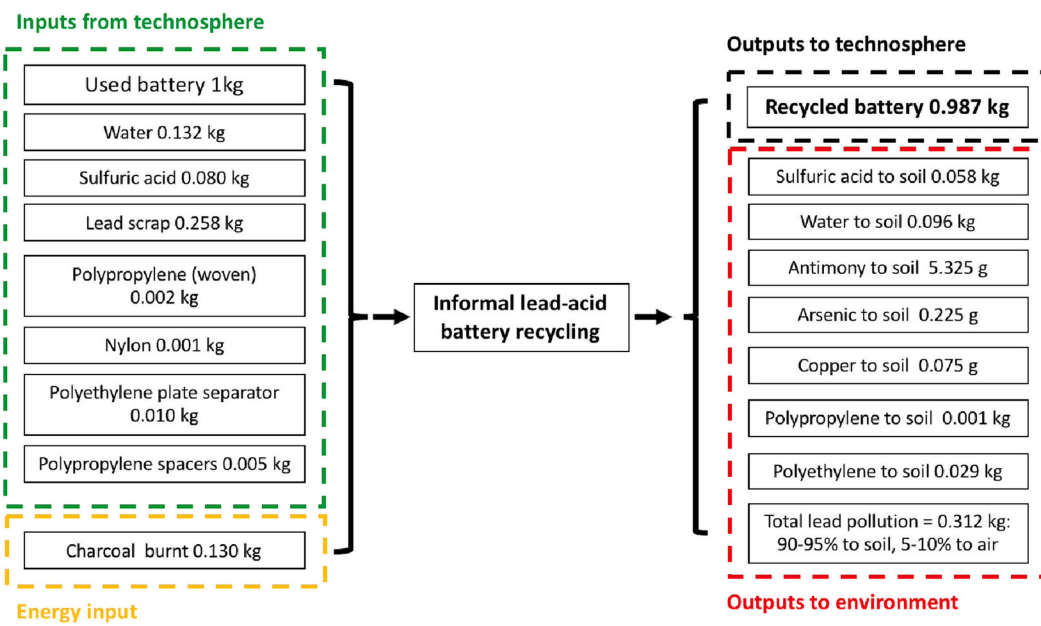

Fig. 4. Informal lead-acid battery recycling material flow analysis. Values have been taken as an average of the two recorded recycling processes shown in Figs. S6 and S11 in the supporting information per kilogram of lead-acid battery recycled. Battery acid concentration is assumed as 37.89% [31].

fabricate the recycled battery and the weight of the final battery itself. A significant amount of lead is believed to have been lost to the air as lead vapours from melting lead and as lead dust. However, these lead air emissions were not quantified. The industrial smelting of lead scrap in a blast furnace (1600 °C) has been recorded to release between 30 and 140 g of lead air emissions per kg of secondary lead produced (before emissions controls) [62]. However, with the lower temperature of charcoal stoves, a lower fraction of lead is expected to be lost as vapour from lead melting. Furthermore, the handling and crushing of degraded lead plates into powder is expected to release a significant amount of lead dust into the surrounding environment. Meanwhile, the informal lead-acid battery recycling process was practiced openly on busy market streets. Therefore, lead dust that settles on topsoil is expected to be kicked back up into the air by foot traffic and by the windy climate. With this uncertainty of the amount of lead pollution released into the air, a sensitivity analysis is performed assuming that the lead air emissions are between 5 and 10% of the total amount of lead lost throughout the recycling process.

In the observed recycling processes, lead scrap was taken from two used batteries to produce one remanufactured battery. And during the recycling process, the equivalent of approximately half (48%) of the lead content of a battery was lost to the environment. Hence, the informal recycling of one battery is assigned the credit of avoiding the production and transport of half of a new battery. Meanwhile, the materials taken from other used batteries during the recycling process are considered as burden free.

2.2.4. *Transport*

All of the SHS components and the home generator are considered to be delivered from Shanghai, China to Lilongwe, via Maputo port, Mozambique. A distance of 15,200 km by container ship was considered to ship the components from Shanghai port to Maputo port. Then a distance of 2000 km by lorry (16–32 metric ton, EURO3) was considered to deliver the components from the Maputo port to Lilongwe. For the end of life scenarios, the same journey (15,200 km by container ship and 2000 km by lorry) was considered for the scrap materials returned to China (aluminium, copper and steel). Whereas, the waste materials delivered to be recycled in South Africa were considered to be transported 2000 km by lorry (16–32 metric ton, EURO3) from Lilongwe to Benoni, South Africa. Transport was not considered for the informal collection of scrap, informal lead-acid battery recycling or dumping of waste in nature, as waste is often transported by foot. The transport considered for each process is shown in Table S1 in the supporting information.

2.3. *Life cycle impact assessment*

The ReCiPe 2016 midpoint method [63] was used considering a default hierarchist perspective to calculate eighteen impact categories: global warming potential (GWP), stratospheric ozone depletion potential (SODP), ionizing radiation potential (IRP), ozone formation-human health potential (OF-HHP), fine particulate matter formation potential (PMP), ozone formation-terrestrial ecosystems potential (OF-TEP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEUP), marine eutrophication potential (MEUP), terrestrial ecotoxicity potential (TEP), freshwater ecotoxicity potential (FEP), marine ecotoxicity potential (MEP), human carcinogenic toxicity potential (HCTP), human non-carcinogenic toxicity potential (HNCTP), land use potential (LUP), mineral resource scarcity potential (MRSP), fossil resource scarcity potential (FRSP), and water consumption potential (WCP). The ReCiPe 2016 method is selected because it is the most recent impact assessment methodology (following the advised best practice [64]). Furthermore, the ReCiPe 2016 midpoint method is commonly used to assess the impacts of power plants and electrification technologies [22,27,56], hence, enabling comparison between SHSs and other technologies and mitigating variation between the impact assessment characterisation factors. All of the available impact categories are considered to enable a comprehensive comparison between SHSs and other technologies.

3. Results

This section presents the results of the life cycle impact assessment. Firstly, Section 3.1 presents the environmental impacts of the current SHS life cycle, considering informal waste management practices. Then, Section 3.2 compares the current life cycle impacts with scenarios for two proposed waste management solutions: i) formal recycling, and ii) formal recycling with an extended battery lifetime of three years. Finally, Section 3.3 compares the impacts of the solar home system life cycle with typical home generators.

3.1. *Current practices: informal waste management*

The environmental impacts of the current SHS life cycle (BAU) in off-grid communities surrounding Lilongwe are shown in Fig. 5, showing the impacts of the SHS per kWh of electricity available to the user over the 25-year lifetime. Considering each of the SHS components, lead-acid batteries are found to be responsible for the majority of the environmental burdens, in line with prior studies [21,27]. Lead-acid batteries occupy 77–99% of all of the impact categories except IRP, MEUP and WCP, where the occupation falls to 54–61%. Specifically, the production of lead-acid batteries contributes to >80% of all of the impact categories

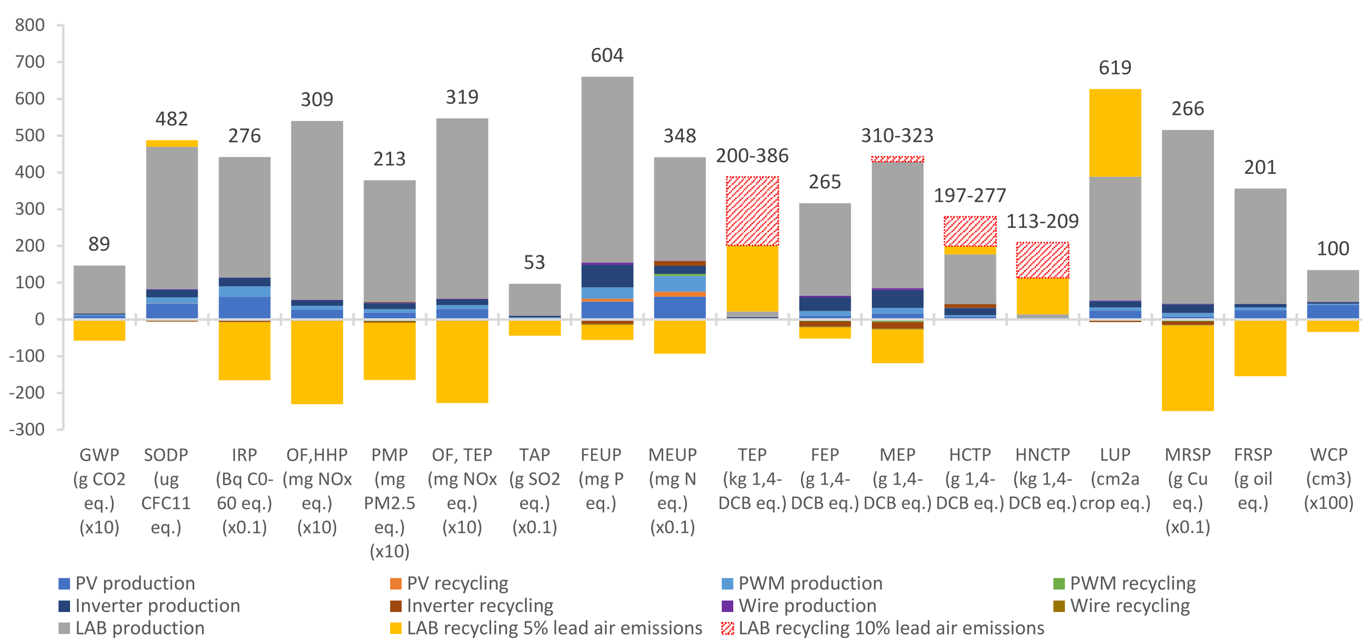

Fig. 5. The environmental impacts of solar home systems in Lilongwe per kW (AC), considering the current informal waste management practices (BAU). For the impacts, multiply by the factor shown in brackets for each unit to yield the actual value. PV = photovoltaic, PWM = pulse width modulation charge controller, LAB = lead-acid battery GWP = global warming potential, SODP = stratospheric ozone depletion potential, IRP = ionizing radiation potential, OF-HHP = ozone formation-human health potential, PMP = fine particulate matter formation potential, OF-TEP ozone formation-terrestrial ecosystems potential, TAP = terrestrial acidification potential, FEUP = freshwater eutrophication potential, MEUP = marine eutrophication potential, TEP = terrestrial ecotoxicity potential, FEP = freshwater ecotoxicity potential, MEP = marine ecotoxicity potential, HCTP = human carcinogenic toxicity potential, HNCTP = human non-carcinogenic toxicity potential, LUP = land use potential, MRSP = mineral resource scarcity potential, FRSP = fossil resource scarcity potential, WCP = water consumption potential.

apart from TEP, HCTP, HNCTP and LUP. The environmental burdens from lead-acid battery production predominantly result from the mining and production of lead (TAP, TEP, FEP, MEP, HCTP, HNCTP, MRSP and WCP), and the high energy demand of battery production being met by China's coal dependent grid (GWP, SODP, OF-HHP, PMP, OF-TEP, FEUP, MEUP and FRSP). Tailings from lead mining and slag from lead smelting contribute to the majority of the HCTP and HNCTP, FEP and MEP impacts of battery production. Lead mining also has significant MRSP impacts from the loss of silver, zinc and magnesium, as lead is often extracted as a by-product from the mining of these materials. Spoil from coal mining also causes significant burdens, responsible for the FEUP and MEUP impacts and also makes a significant contribution to the HCTP. The high battery assembly electricity demand is also responsible for the majority of the IRP impacts, caused by mining uranium to fuel the approximate 5% contribution of nuclear power in China's electricity generation [65].

Meanwhile, informal lead-acid battery recycling presents substantial toxicity burdens, contributing to 90–95% of the TEP, 11–37% of the HCTP and 88–94% of the NHCTP impacts. These toxicity burdens result from the significant quantity of lead pollution released during the battery remanufacturing process. The informal lead-acid battery remanufacturing process was recorded to release approximately 48% of a battery's lead content into the surrounding environment: 3.5–4.7 kg of lead pollution was recorded from the remanufacturing 50 Ah batteries (Figs. S6 and S11) – representing >100 times the lethal oral lead dose for a 70 kg adult (31.5 g: 450 mg per kg of body weight [66]). Hence, the informal remanufacturing of an 80 Ah battery (modelled in the SHS) is expected to release 6.4 kg of lead pollution – >200 times the lethal oral lead dose for an adult. The TEP, HCTP and HNCTP impacts of this lead pollution are found to significantly increase depending on the fraction of the lead pollution that is released into the air. However, aside from the substantial toxicity burdens, informal battery remanufacturing provides significant benefits as a highly resource-efficient process of remanufacturing batteries from scrap materials, mitigating the energy-intensive formal production of new batteries. Notably, the GWP impact from burning charcoal, and FEP and MEP impacts from releasing antimony, sulphuric acid and lead pollution into soil during the informal battery manufacturing process are outweighed by the benefits of avoiding the energy-intensive process of formal battery production.

Aside from lead-acid batteries, the production of the PV panel has significant impacts despite its long 25-year lifetime compared to the other SHS components that are replaced multiple times during the SHS life cycle. Producing electronics grade silicon has a substantial water demand, responsible for the PV panel's 39% contribution to the WCP impacts. Both the production of electronics grade silicon and silicon solar cells also have substantial electricity demands. This electricity demand is responsible for the majority of the PV panel's contribution to the FRSP (13%), GWP (11%), and MEUP (18%) impacts from burning coal, and the IRP contribution (22%) from nuclear power generation. The DC-AC inverter makes the most significant contribution to HCTP (15%), associated with the inverter's high steel content (toroidal transformer core) and the toxicity of electric arc furnace slag from steel production and recycling. The inverter also makes a significant contribution to the FEP (9%) and MEP (10%), as a result of the inverter's high copper content (toroidal transformer coils) and the high toxicity of copper water emissions from copper mining. The PWM charge controller makes a significant contribution to the MEUP impacts (14%), predominately attributed to the production of the LCD screen, to the IRP impacts (9%) from nuclear energy production, and FEUP (5%) from mining coal and copper. Otherwise, the PWM charge controller contributes to <5% of the remaining impact categories. Finally, the insulated copper wire contributes <3% to all of the impact categories, despite the open burning of wire insulation.

Considering the overall end of life waste management impacts of the SHS, aside from the toxicity of informal battery recycling and arc furnace slag from steel recycling, the only significant contributions (>1%) are MEUP impacts associated with the open dumping of plastics and municipal solid waste. The collection and recycling of metals (copper, aluminium and steel) and PCBs through the informal scrap market provide significant environmental benefits.

3.2. Potential waste management solutions

Fig. 6 shows the environmental impacts of the proposed formal recycling (REC) scenario, showing the contributions from each SHS component to the impacts of the SHS, per kWh of electricity available to the user over the 25-year. Fig. 7 then compares the environmental impacts of the current SHS lifecycle (BAU) with i) formal recycling (REC), and ii) formal recycling with an extended battery lifetime of three years (REC + EXT).

3.2.1. Formal recycling

Considering the formal recycling of end of life SHS waste with the current 1-year average battery lifetime (REC), formal recycling successfully mitigates the substantial toxicity of the current informal recycling practices. Compared to the current (BAU) waste disposal practices, formal recycling (REC) reduces the TEP by 95–97%, FEP by 72%, MEP by 69%, HCTP by 55–68% and HNCTP by 98–99% (depending on the % of lead emissions released to the air during informal battery recycling). However, the formal recycling scenario has higher environmental impacts than the current SHS life cycle in GWP, IRP, OF-HHP, OF-TEP, TAP and FRSP, as a result of the increased reliance on formal lead-acid battery production. Informal battery recycling recovers half of the battery's lead materials (half lost to the surrounding environment) and remanufactures batteries from scrap materials while consuming negligible resources. Whereas, formal recycling effectively recovers all of the battery's lead (mitigating the substantial lead pollution from informal recycling), however, incurs a significant electricity demand from remelting battery scrap into pure lead and then formally manufacturing a replacement battery. In this sense, toxic but resource-efficient informal battery remanufacture is replaced with safe but energy-intensive formal battery manufacture. Meanwhile, lead-acid battery production is responsible for the majority of the environmental impacts of the SHS – contributing to at least 87% of every impact category in the formal recycling scenario.

Aside from the lead acid battery and the HCTP burden from steel recycling (electric arc furnace slag), the formal end of life waste management for all of the remaining SHS components provides an environmental credit in every impact category from the materials recovered, from mitigating the impacts of production. The formal recycling scenario benefits from the 20% increase rate of recovery steel, copper and aluminium, compared to informal waste management, and the additional recovery of glass, nickel, copper (from circuit boards) and precious metals (silver, gold and palladium), and silicon [67,68]. There is also a significant benefit from avoiding the lead leaching from dumping PCBs and solar cells, which contributes to the reduction of the FEP and MEP of PV panels, inverters and charge controllers by 28–73% compared to the informal disposal scenario. Finally, the formal recycling scenario also provides significant benefits from mitigating the current significant MEUP impacts from the open dumping of plastics and municipal solid waste.

3.2.2. Formal recycling with extended battery lifetimes

The lifetime of lead-acid batteries in SHSs in Malawi is currently significantly hindered by improper SHS design, installation and usage practices, resulting in a typical battery lifetime of 1 year – far shorter than the 3 to 5-year expected battery lifetime [10]. Hence, measures to achieve nominal battery lifetimes offer significant potential to reduce the number of battery replacements required over the SHS lifetime. Fig. 7 shows formal recycling and achieving a three-year battery lifetime (REC + EXT) to reduce the burdens in every impact category by 29–99% compared to the current informal waste disposal practices (BAU) and

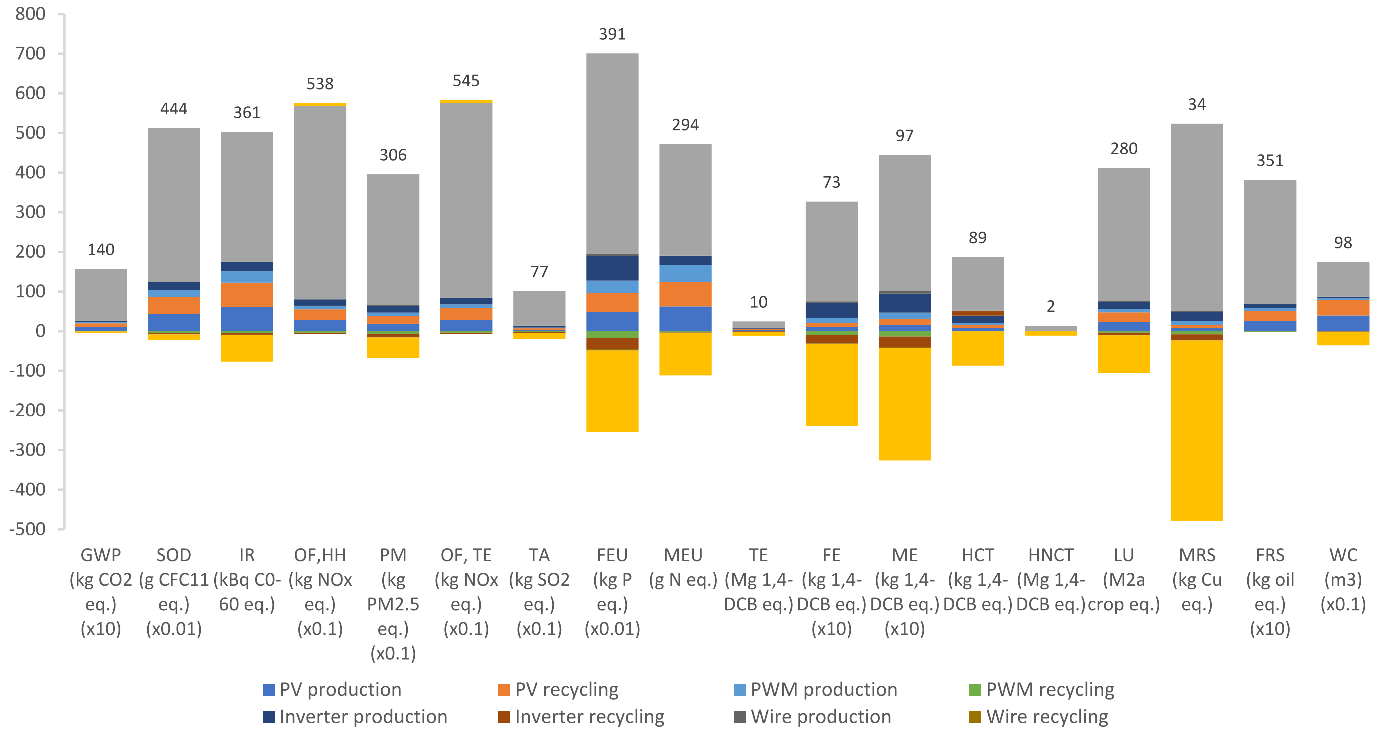

Fig. 6. The environmental impacts of solar home systems in Lilongwe per kW (AC), considering the formal recycling (REC). For the impacts, multiply by the factor shown in brackets for each unit to yield the actual value. PV = photovoltaic, PWM = pulse width modulation charge controller, LAB = lead-acid battery. For the nomenclature for impacts categories see Fig. 5.

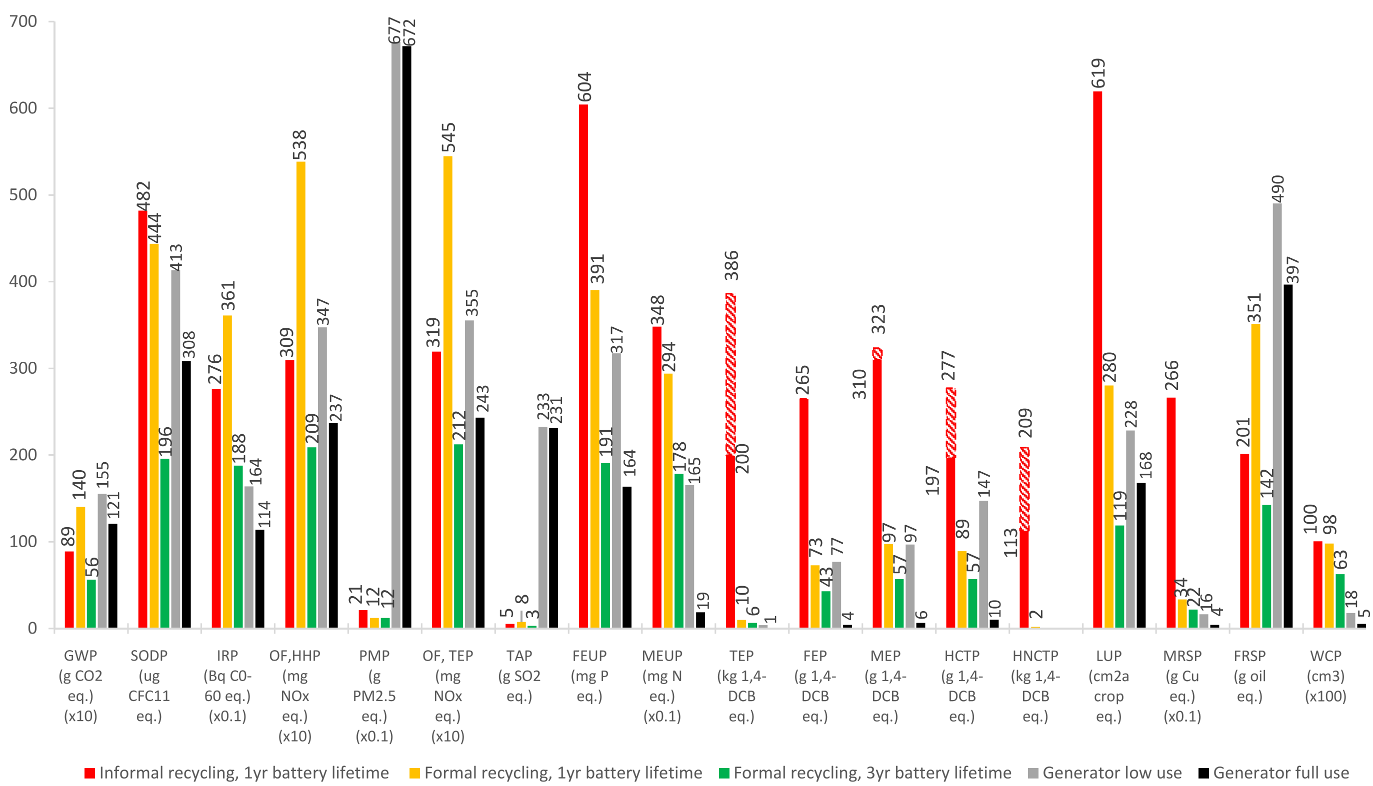

Fig. 7. The environmental impacts of solar home systems over the 25-year SHS lifetime, comparing the current informal waste management practices with formal recycling and formal recycling with extended lead-acid battery lifetimes of three years. Multiply by the factor shown in brackets for each unit to yield the actual value. For the nomenclature for impacts categories see Fig. 5.

35–62% compared to the formal recycling scenario (REC), presenting the lowest burdens in every impact category. In this sense, formal waste management combined with increasing the operational lifetime of batteries (REC + EXT) effectively mitigates both the substantial toxicity of the current informal waste management practices and the significant burdens from lead-acid battery production.

3.3. Comparison with generators

Fig. 7 shows the environmental impacts of SHS per unit of electricity available to the user (kWh AC) compared to a typical home diesel generator, considering both low and high fuel use scenarios. The generator fuel use scenarios show that the impacts relating to the production of the generator (IRP, TAP, MEUP, TEP, FEP, MEP, HCTP, HNCTP, MRS, WCP – driven by the manufacturing electricity demand, and the production and recycling of copper and steel) are proportionally reduced (per unit of energy generated) with higher utilisation of the generator. Whereas, the environmental impacts relating to the generator's use, diesel production (SODP, FEUP, LUP, FRSP) and diesel burning (GWP, OF-HHP, PMP, OF-TEP, TAP), are more equivalent for the two fuel use scenarios because the environmental impacts are shown per unit of electricity generated, rather than the total impacts over the generator's lifetime.

The current SHS life cycle (informal waste management, BAU) is found to have higher environmental impacts (predominantly driven by the impacts of producing lead-acid batteries) than generators in 12 of the 18 impact categories, irrespective of the level of generator utilisation. The MEUP, TEP, FEP, MEP, HCTP, NHCTP, MRSP, and WCP of the current SHS life cycle (BAU) are all at least 18 times greater than home generators (high fuel use). Most significantly, the SHS's HNCTP is up to 2473 times greater (with 10% lead emissions to air) than the diesel generator (high fuel use), and the TEP is up to 562 times greater, as a result of the substantial lead pollution from informal lead-acid battery recycling. Whereas, the formal recycling scenario with the current 1-year average battery lifetime (REC) increases the GWP of SHSs in line with diesel generators (substituting toxic but resource-efficient informal battery remanufacture with safe but energy-intensive formal battery manufacture). Formal recycling and extending the lifetime of lead-acid batteries to three years (REC + EXT) reduces the GWP, SODP, OF-HHP, OF-TEP and LUP of SHSs below the level of diesel generators, although, the IRP, FEUP, MEUP, TEP, FEP, MEP, HCTP, NHCTP, MRS and WCP still significantly exceed the impacts of fully utilised diesel generators (high fuel use). However, the SHS formal recycling and extending the lifetime of lead-acid batteries to three years (REC + EXT) scenario has lower environmental impacts than the low fuel use diesel generator in most (12/18) of the impact categories (all except IRP, MEUP, TEP, HNCPT, MRSP and WCP – driven by battery production). In this sense, significantly extending the lifetimes of lead-acid batteries in SHS beyond the current one-year average is necessary for the environmental impacts of SHS to be considered lower than the impacts of diesel generators.

4. Discussion

This section compares the results of the life cycle impact assessment with prior studies and literature. Then the implications of the results for off-grid solar electrification strategies are discussed, outlining key themes to mitigate the health and environmental hazards of the application of SHSs in SSA. Finally, the limitations of the study are disclosed and impactful areas for future research are outlined.

4.1. Comparison with literature

The environmental impacts of the modelled SHS per unit of electricity (kWh AC) available to the user are shown in Table 4. Considering the few prior life cycle assessment studies on OGS technologies in SSA with comparable impact categories, the environmental impacts are found to be greater than estimated by Mukoro et al. [56] for SHSs in Kenya by a factor of at least 3.8 in every impact category. This is particularly because Mukoro et al. [ibid] considered the units of electricity generated by a DC plug and play SHS as a function unit (kWh DC), not accounting for the low fraction of the generated electricity that is available to the user to power standard electrical appliances in AC. Most significantly, the data collected on the informal lead-acid battery refurbishing practices are found to substantially increase the toxicity impacts of SHSs compared to previously modelled waste management practices. The TEP and HNCTP impacts are found to be greater by factors of 140–270 and 900–1670, respectively (depending on the fraction of lead emissions that are lost to the air during informal battery recycling), than reported for SHS in Kenya where end of life lead-acid batteries are disposed of in open dumpsites [56]. Furthermore, the TEP impacts are greater by a factor of 2,500,000-4,900,000 than reported for PV microgrids using lead-acid batteries in Kenya by Bilich et al. [22], who assumed that batteries were disposed of in sanitary landfills – ignoring

Table 4
Solar home system environmental impacts per kWh (AC) generated over the 25-year operational lifetime.

	Informal recycling (5–10% lead air emissions) (BAU)	Formal recycling, 1 yr battery lifetime (REC)	Formal recycling, 3 yr battery lifetime (REC + EXT)	Generator low fuel use	Generator high fuel use
GWP (kg CO2 eq.)	0.888	1.40	0.563	1.55	1.21
SODP (mg CFC11 eq.)	0.482	0.444	0.196	0.413	0.308
IRP (Bq C0–60 eq.)	27.6	36.1	18.8	16.4	11.4
OF,HHP (g No_x eq.)	3.09	5.38	2.09	3.47	2.37
PMP (g PM2.5 eq.)	2.14	3.06	1.21	67.7	67.2
OF, TEP (g NO_x eq.)	3.19	5.45	2.12	3.56	2.43
TAP (g SO2 eq.)	5.28	7.66	2.89	233	231
FEUP (g P eq.)	0.604	0.39	0.191	0.317	0.164
MEUP (mg N eq.)	34.8	29.4	17.8	16.5	1.88
TEP (kg 1,4-DCB eq.)	200–386	9.97	6.46	3.78	0.687
FEP (g 1,4-DCB eq.)	265	73.0	42.9	76.8	4.28
MEP (g 1,4-DCB eq.)	310–323	97.4	57.1	97.0	6.36
HCTP (g 1,4-DCB eq.)	197–277	89.2	56.9	147	10.2
HNCTP (kg 1,4-DCB eq.)	113–209	1.96	0.965	0.668	0.0840
LUP (M^2a crop eq.) (x10^{-3})	61.9	28.0	11.9	22.8	16.8
MRSP (g Cu eq.)	26.6	3.35	2.18	1.65	0.406
FRSP (kg oil eq.)	0.201	0.351	0.142	0.490	0.397
WCP (cm^3) (x100)	100	97.9	62.7	17.7	5.32

lead pollution from informal recycling practices.

Whilst SHSs are branded as a low-carbon technology [69], the current GWP of SHSs in Malawi is found to be 0.888 $kgCO_2/kWh$ (BAU), and is further increased with formal waste management. Hence, the emission factor for SHSs in Malawi is found to exceed Malawi's current national grid emission factor of 0.489 $kgCO_2/kWh$ (predominantly based on hydroelectricity) [70] and the estimated average grid emission factor across Africa of 0.709 $kgCO_2/kWh$. However, these grid emission factors do not consider the scope three emissions from construction and waste management of the national grid and electricity generation infrastructure (following the IFI greenhouse gas accounting approach [71]), unlike the emission factors reported for the SHS and diesel generator. Furthermore, the calculated emission factor for SHSs in Malawi is greater by a factor of 11.3 and 8.4 than reported by Mukoro et al. [56] and Bilich et al. [22] for OGS systems in Kenya, respectively. Notably, both Mukoro et al. [56] and Bilich et al. [22] assumed lead-acid batteries to have lifetimes of 10–13 years in off-grid solar systems in Kenya. Whereas, the typical lifetime lead-acid batteries in SHSs in peri-urban villages in Malawi has been recorded to be one year [10]. Meanwhile, lead-acid batteries are found to currently be responsible for 83% of the GWP of SHSs in Malawi, and 54–99% of the remaining impact categories. However, the calculated emission factor for SHSs in Malawi is in line with Antonanzas-Torres et al. [27], who found the GWP of SHSs in SSA to range between 0.4 and 1.2 $kgCO_2/kWh$ (considering the 36% AC/DC kWh conversion calculated in Section 2.2.2), depending on the lifetime of lead-acid batteries (2–4 years) and operational losses.

The formal recycling of lead-acid batteries following European recycling standards is found to successfully mitigate the high toxicity of informal battery refurbishment. However, this formal recycling has significant environmental impacts from the increased reliance on formal battery manufacture (substituting toxic but resource-efficient informal battery remanufacture with safe but energy-intensive formal battery manufacture) significantly increasing the GWP, IRP, OF-HHP, OF-TEP, TAP and FRSP of SHSs. Specifically, formally recycling the SHS waste flow considering the currently one-year average lifetime of lead-acid batteries results in a GWP of 1.40 $kgCO_2/kWh$ – in line with diesel generators. Hence, to mitigate both the high toxic potential of SHSs and to achieve greenhouse gas mitigation (compared to the average grid emission factor across Africa), both extended battery lifetimes and formal battery recycling are necessary. The proposed waste management solution considering both a three-year lead-acid battery lifetime and formal recycling (REC + EXT) shows a GWP 0.563 $kgCO_2/kWh$. This is in agreement with the GWP reported for SHS in developing countries by Alsema in 2000 [21], who assumed that SHS waste management followed European recycling and disposal practices. Notably, while the manufacturing of solar PV panels has experienced significant efficiency improvement since Alsema's study [21] in 2000, the impacts of PV manufacturing are far outweighed by the impacts of lead-acid battery production over the SHS lifetime. However, due to the high electricity demand, the impacts of lead-acid battery production are significantly influenced by China's electricity grid, which has reduced in carbon intensity by 20% since 2000 and is expected to continue to reform in line with China's ambition to achieve carbon neutrality by 2060 [72,73].

4.2. Implications for electrification strategies

The inventory data collected for the informal recycling of lead-acid batteries from SHSs finds potentially lethal quantities of lead pollution: an equivalent of >100 times the lethal oral dose of lead was recorded to be released to the surrounding environment from the informal recycling of a single SHS battery. However, the direct health impacts are still uncertain as the amount of this environmental lead pollution that is ingested by humans has not yet been quantified. Nonetheless, the few health studies [74–77] that have previously investigated the health impacts associated with informal lead-acid battery recycling practices have confirmed elevated blood lead levels, neurological defects and even child fatalities within the surrounding communities. The small-scale informal battery recycling operations recorded in this study have been shown to be common on the streets of densely populated off-grid communities in Malawi, often presented as "battery repair shops" [10]. Up to five battery repair shops have been found within individual off-grid communities surrounding Lilongwe, and battery repair shops have also been found within the proximity of nursery schools and community water wells [10]. Therefore, the health impacts of the recorded lead pollution from the informal recycling of SHS batteries are expected to be severe, potentially transcending generations [19,78–81]. Meanwhile, these alarming risks threaten to be exacerbated by the target to import millions of OGS products in the absence of safe waste management infrastructure [6,10]. Formal waste management solutions are urgently needed for SHSs to be considered as a safe technology.

The environmental impacts calculated in the LCA suggest that nominal lead-acid battery lifetimes (3–5 years) should be achieved for SHSs to be considered as a low-carbon technology. However, lead-acid batteries have an inherent technical vulnerability to overcharging and over discharging. In particular, using batteries beyond 50% of their storage capacity (deep discharging) causes irreversible damage, reducing their operational lifetimes. This technical vulnerability is exploited by the lack of technical expertise in SHS design, installation, and operation, and regular overcharging and deep-discharging causes rapid battery deterioration – identified as a primary cause for OGS system failures in SSA [7,10]. Although these factors (related to SHS design and use) hindering the sustainability of SHSs can be attributed to the user, these practices reflect the demographic of energy-poor communities that characteristically have low levels of income and education [8]. Furthermore, theoretically, there is potential to reduce the environmental impacts (particularly the GWP) by manufacturing SHSs in other counties. For example, manufacturing the SHS components in Europe [27] – mitigating the current significant impacts associated with China's coal dependent grid. However, such a change in production may not be feasible within the current dynamics of SSA's OGS market, which is predominantly unregulated, relying on affordable components delivered from China [7,10]. Meanwhile, there is a lack of financing mechanisms to make durable, high-efficiency and non-toxic components affordable (such as lithium-ion batteries), and a lack of legislative capacity to regulate the quality of products imported [10]. Therefore, the severe toxicity and high environmental impacts of SHSs should be seen as a symptom of the current lack of the legislative, economic and waste management infrastructure necessary to support a sustainable OGS market.

Mitigating the current high environmental burdens and health risks of SHS by achieving extended battery lifetimes and facilitating formal recycling requires a holistic approach. Potentially effective initiatives include: i) public education campaigns on SHS design, operation and waste hazards; ii) incentivising the existing informal waste collection network to redirect toxic waste to Environmental Health and Safety (EHS) compliant waste management infrastructure; and iii) effective legislation controlling the disposal and transboundary movement of hazardous waste, as outlined by Kinally et al. [7,10].

4.3. Limitations and areas for future research

This study highlights that current informal SHS waste disposal practices pose significant environmental risks. Previous studies have overlooked informal waste management practices due to the lack of data, instead making invalid assumptions and considering the available data for formal disposal and recycling processes established in Europe – substantially under-reporting the environmental impacts of OGS technologies. Whereas, this study attempts to compensate for the lack of available data by collecting field data and disclosing justified assumptions (see Section 2.2.3), potentially limiting the accuracy of the results but highlighting the magnitude of the environmental risks associated with the current life cycle of SHSs and highlighting the need for further research. Notably, there is a lack of transparency and data to quantify the collection rates, fate and recycling processes of the materials collected through the informal scrap market. The efficiency of electricity generation from SHS is also dependent on user practices, such as solar panel orientation and cleaning schedules, significantly influencing the environmental impacts per unit of electricity delivered to the user. Moreover, there is a general lack of geographic representation of SSA in life cycle databases and in environmental impact assessment methodologies, particularly limiting the accuracy of local environmental impacts [26]. Hence, developing life cycle databases that represent the Global South should be a priority. This study collects the first data to assess the life cycle impacts of informal lead-acid battery recycling, however, collecting small samples of data to record an unstandardized process that varies significantly depending on the recycler's available resources and level of expertise. Alarming quantities of lead pollution are identified from the informal recycling of lead-acid SHS batteries. Notably, the fraction of lead that is released into the air is highlighted to have a significant impact on terrestrial ecotoxicity and human toxicity. However, the fate of this lead pollution and the subsequent health impacts are still uncertain. Further environmental and health studies are urgently needed to investigate lead exposure pathways and to quantify the amount of lead pollution that is ingested by humans to expose the health impacts that informal recycling practices are imposing on the surrounding communities. Furthermore, there is also a lack of data describing and quantifying the impacts of other informal e-waste management practices in SSA. For example, the informal recycling of PCBs by backyard hydrometallurgical leaching has been reported to include the open handling of highly toxic and hazardous chemicals such as mercury and cyanide [23,67,82]. The burning of lead-acid batteries, solar panels and electronic waste has also been reported as common [10,83]. Therefore, the impacts of these practices may be underestimated in this study and are important areas for future research.

5. Conclusions

This study uses Malawi as a case study to addresses the disparity between the theoretical and actual environmental performance of solar home systems (SHSs) in the Global South. Based on the description of the life cycle of SHSs in off-grid communities surrounding Malawi's capital of Lilongwe, the first life cycle assessment of SHSs to consider typical informal waste disposal practices is performed – collecting data to quantify lead pollution from informal lead-acid battery recycling.

Lead-acid batteries are highlighted as the most damaging SHS component, contributing 54–99% of each impact category associated with the current SHS life cycle. The significant burdens from lead mining and the high assembly energy of batteries are exacerbated by the short lifetime of batteries in SHSs in Lilongwe (ten times shorter than in literature) and China's coal dependent grid. Accordingly, the global warming potential (GWP) of the current SHS life cycle (0.888 $kgCO_2$/kWh) is found to be up to 11 times greater than previously estimated within sub-Saharan Africa. Meanwhile, the informal remanufacture of lead-acid batteries is recorded to release life-threatening quantities of lead (over 100 times the lethal oral dose for an adult from a typical battery) into densely populated communities, presenting severe localised health risks. Further studies are urgently recommended to investigate the health impacts that informal lead-acid battery recycling operations have on their surrounding communities.

Formally recycling the current SHS waste flow is found to successfully mitigate the toxicity of the current informal waste management practices. However, formally recycling the current waste flow, substituting toxic but resource-efficient informal battery remanufacture with safe but energy-intensive formal battery manufacture, results in significant additional burdens in other impact categories, increasing the GWP of SHSs to 1.40 $kgCO_2$/kWh – in line with diesel generators. Finally, achieving extended battery lifetimes of three years combined with formal recycling is found to both mitigate the toxicity of the current waste management practices and avoid excessive greenhouse gas emissions.

However, a holistic perspective including significant social, economic and legislative interventions is required to achieve these waste management solutions and for SHSs to be considered as a safe, low-carbon technology in Malawi. Furthermore, the severe environmental risks quantified from toxic informal lead-acid battery recycling practices are relevant across SSA and threaten to be exacerbated by the ambitious targets for the adoption of off-grid solar technologies in the lack of adequate legislative and physical e-waste management infrastructure [7]. These risks of informal lead-acid battery waste management practices are also relevant to the automotive industry – responsible for the majority of SSA's lead-acid battery demand. Finally, by manually collecting data and disclosing justified assumptions to confront overlooked data gaps relating to informal waste management practices, this study is subject to a significant level of uncertainty. Nonetheless, this study highlights the magnitude of the severe risks associated with the current SHS life cycle practices and further research is urged to continue to increase the transparency of the environmental and health impacts of off-grid solar technologies in SSA.

CRediT authorship contribution statement

Christopher Kinally: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. **Fernando Antonanzas-Torres:** Supervision, Writing – review & editing. **Frank Podd:** Funding acquisition, Supervision, Writing – review & editing. **Alejandro Gallego-Schmid:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization, Funding acquisition.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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