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RESEARCH ARTICLE

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Towards development of effective policies and regulations for sustainable off-grid solar electronic waste management systems in Kenya

Kariuki David Mugendi[1,2] | **Caleb Ombuor Mireri**[1] | **Martin Korch Enevoldsen**[3]

[1]Department of Spatial and Environmental Planning, Kenyatta University, Nairobi, Kenya

[2]Department of Environment and Natural Resource Management, Africa Nazarene University, Nairobi, Kenya

[3]Kobra Advice, Charlottenlund, Denmark

Correspondence
Kariuki David Mugendi, Department of Environment and Natural Resource Management, Africa Nazarene University, P.O. Box 53067, Nairobi 00200, Kenya.
Email: dmugendi82@gmail.com

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Abstract

Off-grid solar systems provide clean and affordable energy sources. Adoption of off-grid Solar energy is becoming increasingly popular in Kenya as a source of renewable energy, with an estimated 10 million people using off-grid solar power systems as of the end of year 2022. However, the rising off-grid solar systems technology uptake comes with a growing amount of solar e-waste, which can have harmful environmental and health effects if not managed properly. Current data on the exact amount of solar e-waste being generated in Kenya is unavailable and this amount will continue to rise with the expiry of many of these off-grid solar systems lifespans. This study through stakeholder's workshop and document review data collection and analysis approaches, established that Kenya just like many countries in the Global South has a robust general waste policy and regulation management framework. However, it lacks specific policies and regulations on off-grid-solar electronic waste management a challenge that many countries in the Global North have made considerate steps in addressing. In addition, there is a lack of awareness of the hazardous nature of off-grid solar systems' e-waste components to both consumers and institutions of governance. There is a lack of adequate infrastructure and sufficient systems for off-grid solar e-waste management in the country. Enforcement and implementation challenges of the existing general waste regulations due to limited resources and capacity and corruption culture are major impending factors. This calls for the development of effective policies and regulations to ensure sustainable off-grid solar e-waste management in Kenya against the backdrop of the rising uptake of off-grid solar systems.

KEYWORDS

collection, legislations, off-grid, policy, recycling, solar electronic waste, sustainable, systems

1 | INTRODUCTION

The main sources of e-waste from off-grid solar systems are batteries, solar panels, and appliances such as lamps. According to Shellenberger,[1] these components contain hazardous materials such as lead, Cadmium, Silicon, Aluminum, and Mercury that can leach into soil and water, or release toxic fumes when burned and this may cause environmental pollution posing great health hazards to human and other living things. Off-grid solar e-waste, if disposed in the environment will also lead to a loss of valuable resources that could be reused or recycled. In Kenya, the majority of solar panels and batteries are imported from other countries. According to Cross & Murray,[2] 71% of the imported home solar systems in Kenya are not regulated and find their way into the country through the black market have a short lifespan of less than 2 years, and the implication of this is that the turnaround time of product to e-waste will be extremely very high. Currently, there are no specific policies and regulations in place to govern the management of solar e-waste in Kenya and this portends environmental and health risks. According to a 2019 report by the International Renewable Energy Agency (IRENA), Kenya generates about 44,000 tonnes of general e-waste per year, of which only 15% is formally collected and recycled. This study examines the current state of off-grid solar e-waste management in Kenya and proposes recommendations for improving it.

2 | LITERATURE REVIEW

According to Bodies et al. photovoltaic (PV) modules are extremely efficient solar energy-generating devices with no greenhouse gas emissions, as they do not yield noise or utilize material resources. About 70% of the world's solar energy is produced by five countries in the world. These nations are China, Germany, Japan, the United States, and Italy. As the uptake of both on-grid and off-grid solar energy systems continues to increase globally, the production of solar electronic waste will continue to grow, hence the need for sustainable management approaches.[3] Different countries have grouped solar waste differently, in the European Union for example solar waste is classified as electronic waste and in addition, they are categorized as hazardous waste material.[4] According to Nieto et al.,[5] in the United States of America, different states classify solar waste differently, some categorize them as normal solid waste to be managed through landfills while other States have classified them as hazardous waste materials like in the case of European Union that calls for specialized approach in their management. In broad-spectrum solar waste falls under the electronic waste categories, but recent studies have shown that they are hazardous waste materials.[6]

Ockwell et al.[7] observes that, the world generated 53.6 metric tons of electronic waste in the year 2019 and this is projected to grow by 40% by the year 2030. About 80% of general electronic waste globally in developing countries is handled informally. The main units of off-grid solar products include photovoltaic (PV) solar modules, lamps which mainly are LED, batteries that could be lead or lithium–based, metal frames and fixtures, cables, and control units with a circuit board mounted electronic controls. According to Palkova,[8] photovoltaic modules for the longest time were not considered as electronic waste among the European Union members until 2012. Since the categorization of the materials as e-waste the various constituents of off-grid solar products are classified in line with their treatment and dismantling characteristics. The dismantled waste category is referred to as fractions. These fractions include metals, screws, glass, paper, cardboard, plastics, and cables.

The photovoltaic panels majorly are made up of panels consisting of mixed fractions of screws, metals and crystalline silicons, glass panels and aluminum silver and ethylene vinyl acetate (EVA). A classic crystalline silicon solar panel contains 10%–15% frame aluminum, 65%–75% glass, and 3%–5% silicon. They can also contain several harmful carcinogenic materials such as chromium, arsenic, and cadmium.[9] Management of off-grid end-of-life (EoL) of the photovoltaic waste modules cannot be effectively managed through landfills and this calls for technological strategies such as recycling as viable options.[10] Management approaches such as recycling immensely contribute to the virgin resource conservation of materials such as copper, semiconductor materials glass, silicon, and aluminum, among others. The functioning photovoltaic panels are laminated with glass and this makes them very safe but if the glass is broken the panels do get damaged and this can cause leakage of some substances that may be very toxic to the environment.[11]

According to Wang et al., the main fraction for the lead acid batteries which is a storage device for the solar energy is lead mixed with plastics and sulfuric acid. Graphite, aluminum, lithium, copper, and plastics forms the main fractions in Lithium Ion batteries. If a recycling approach is to be adopted in the management of these batteries, their components should remain unbroken and managed as a distinct fraction while being conveyed to their ultimate recycler for safety

purposes. The key fraction for control units are printed circuit boards and mixed electrical and electronic components in addition to plastic. The cables are mostly made up of plastic insulations and copper.

Cross & Murray[2] note that the solar lanterns fractions are photovoltaic panels, the light emitting diode, lithium battery plastics, and printed circuit boards and this implies that the fractions are a mixture of metals, glass, plastics, and mixed materials. Batteries according to the EU regulations are not included in e-waste regulations. They are classified under hazardous waste and managed under hazardous waste regulations. It is important to observe that different types of batteries are used with solar systems with Lead-acid batteries being very common for mini-grids while lithium Iron (Li-ion) batteries are found in smaller devices, such as solar lanterns and solar home systems. Lithium –Iron-Phosphate and Lithium-Manganese-Oxide are the most common off-grid batteries being used today. Lithium battery recycling requires advanced technology and a lot of resources and currently is done only in developed countries). These fractions from off-grid technology devices must be reclaimed from the environment. Failure to remove this waste leave the environment blemished by corroding batteries and solar panels.[12]

According to Hansen et al.,[13] there has been increased technological innovation in the area of off-grid solar systems for energy generation and access globally. However, this technological advancement comes with potential and unintended environmental consequences. This innovation has resulted to the rapid adoption of off-grid solar systems for energy access especially in developing countries this comes with increased generation of solar electronic waste. Solar panel waste is expected to reach 78 million metric tons by 2050. Equally, fractions from discarded off-grid solar devices still remain a major challenge since they are produced without the intention of their dismemberment even under extreme environmental Settings.[14] In addition, the materials are made by mixing valuable elements with those of less value hence retrieving the valuable materials is an expensive venture. Globally material scientists, waste handlers, and manufacturers are trying to find means of efficiently reclaiming off-grid solar device materials. However, most of these devices are yet to reach the end of their lives to make the recycling facilities worth investing in.

In developed economies, Investors dealing with off-grid solar systems play a very important role in the management of off-grid solar systems' electronic waste. In these Global North economies, the dealers of these solar systems have responsibilities beyond their initial investment, such as supporting sustainable end-of-life practices, recycling initiatives, or contributing to regulatory efforts for proper waste disposal.[13] There have been some solar e-waste management efforts also in some countries in the Global South. According to Samarakoon et al.[15] in Malawi, repair practices of solar systems have immensely contributed to the management of solar e-waste generated and its environmental impact. There have been local repair shops that utilize some of the materials from solar e-waste in their repair efforts. This repairing approach has been underscored by Munro et al.[16] in their work towards a repair research agenda for off-grid solar e-waste in the Global South. The study notes that improving repair practices for off-grid solar systems will enhance environmental sustainability. This is because the approach will prolong the lifespan of systems, reduce e-waste, and minimize the ecological footprint of solar technologies in the Global South. However, the challenge with this repairing approach is that the extended life span of the solar systems will eventually expire and therefore combining repair and another approach such as recycling will be very sustainable.

Kumar & and Turner[17] observe that end-of-life sustainable solar e-waste management approaches in Global South have immense impacts on the socio-economic characteristics of the locals. The waste materials can be sources of livelihood through making new products and at the same time avoid environmental pollution that may lead to serious health effects. However, according to Kinally et al.,[18] the off-grid solar waste management landscape is being faced with a plethora of challenges that have hindered sustainable solar e-management. The study observes the need to adopt initiatives such as recycling, component reuse, or creating incentives for proper disposal as in the case of Global North. This calls for a sustainable solar e-waste management strategy. This study aimed to review the current management practices, policy, and legal framework governing the management practices of off-grid solar electronic waste in Kenya and make recommendations on the areas of improvement to ensure sustainable management approaches not only in Kenya but the entire global South.

3 | METHODOLOGY

The study used a qualitative research approach and adopted a triangulation research design method by combining workshop prolonged engagement research design as explained by Orngreen and Levinson[19] and document review and analysis design. The study organized three workshops and all the participants were invited by the facilitators through purposive, criterion sampling so that they could provide data on off-grid solar e-waste management systems in Kenya.

The study used intense workshop engagement between the workshop facilitators and participants that led to the obtaining of thick and rich data in the course of the interaction. The engagement entailed the facilitator's engagement with the participants and the participants' engagement among themselves.

In addition to video recording the discussion sessions on solar e-waste management in Kenya field notes were taken by the workshop rapporteurs throughout the workshop sessions. A second workshop observer from the facilitating team was appointed and he checked on the style of the workshop was being conducted and intonation to help in ensuring both "participants' engagement" and "facilitator's engagement" by use of a scale of either high or low based on five types of engagement participation that is "complete," "active,"" moderate," "passive," and "nonparticipant" an approach borrowed from Lain.[20] The second observer played a critical role in establishing the credibility of the collected data using this approach. The engagement focused on the challenges facing solar e-electronic waste management in Kenya, existing policies, guidelines, and legal framework, and opines of the participants on how sustainable electronic solar-waste management policies and regulations can be realized.

There were 27 participants representing the various stakeholders relevant in the off-grid solar e-waste management industry represented in three of the organized workshops. Table 1 below shows the representatives of the various stakeholders in the off-grid solar electronic waste workshops recorded data was transcribed and summaries of the participant's views were made. In addition, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis which is a method for identifying and analyzing internal strengths and weaknesses and external opportunities and threats on the views of the participants on electronic waste management systems in Kenya with a keen focus on solar e-waste was carried out. See the footnote link below for the final workshop proceeding.

The collected and analyzed workshop data using SWOT analysis of the waste management system practices from the workshop was augmented with a review summaries of existing policy, legal and institutional framework relevant to off-grid solar electronic waste management in Kenya. The following documents were reviewed and analyzed *Constitution of Kenya 2010*, *EMCA CAP 387*, *Waste Management Regulations 2006*, *Public Procurement and Disposal Act 2015*, *E-waste Guidelines 2011(Developed by NEMA)*, *National E-waste Strategy 2019*, *Draft E-waste Regulations 2013*, *Sustainable Waste Management Act 2022* and *Draft EPR Regulations 2021*.

4 | RESULTS AND DISCUSSION

4.1 | Constitutional, policies, legislation and practices on off-grid solar e-waste management in Kenya

4.1.1 | Constitutional context

Kenya has made significant progress in creating structures for environmental protection. The right to a clean and healthy environment has found its way into the bills of rights as per Article 42 of the *Constitution of Kenya 2010*. Article 69 (1 g) obligates the government to eliminate any processes that degrade the environment. In addition, Article 1(6) states that any Convention that the Country has ratified becomes part of the national laws and a good example is the *Basel Convention* which prohibits the trans-boundary movement of any hazardous material. The *Constitution of Kenya 2010* is the overarching law in the country. Under this article 42, the Kenyans citizens have the right to hold the government into account for clean and healthy environment. The government of Kenya through the National Environmental Management Authority is supposed to develop regulations which has already been done as it has explained in Section 4.1.2. This calls for manufacturers, importers, retailers, and consumers to take individual and cooperate responsibility to keep the environment clean and healthy.

4.1.2 | Policy and legislation

This study established that Kenya has increasingly taken considerable strides in policy-making to protect its people from the consequences of poor e-waste management. However, like many of its African counterparts, Kenya lacks policy and legislation on the management of e-solar waste an area developed economies in the Global North such as European countries and USA have made considerate strides as reported by Vanessa et al.,[21] The absence of a definitive law on e-solar waste management is partly because solar PV power is a relatively new concept in the country. Solar PV panels use in

TABLE 1 Off-grid solar e-waste stakeholders workshops representative.

Category of stakeholders organization	Specific stakeholder organization	No. of representatives
National government of Kenya	• Ministry of Environment, Forestry and Climate Change • NEMA Kenya	2
The regional government of Kenya	• Directorate of Environment Kiambu County • Nema Kiambu County Chapter	2
Manufacturer/Wholesalers/Retailers/Dealers of OGSE products	• Davis and Shartlif • Solibrium Solar Company • Total Energies • Chloride Exide	4

Waste collection company	• Recycla
	• E-waste Initiative Kenya (Ewik)
	• Pure Planet Recyclers
	  ◦ Waste Electrical and Electronic Equipment Centre (WEEE Centre)
	  ◦ Enviroserve
		4

Waste recycling company	• WEEE Centre • Enviroserve • Sintmond Group	2
Environmental consultancy and management companies	• Greeniche Environmental Management Centre Ltd • Kobra Advice • Duke Waste Management	2
University or other academic institution	• Kenyatta University • University of Nairobi • Jomo Kenyatta University of Agriculture and Technology • Technical University of Denmark • Africa Nazarene University	5
Private sector	• Kenya Private Sector Association • Kenya Association of Manufacturers	2
Waste management associations and regulators	• Kenya Association of Waste Recyclers • GOGLA	2
Other representatives of interest	• Danish Embassy • United Nations Environmental Programme	2

Kenya has become popular in the last decade.[22] Notwithstanding its popularity, only few homes have solar PV panels due to the high cost of panels and installation. Lack of a specific policy and legislation on e-solar waste management is detrimental to the country's ability to address this type of waste.

It is important to note that Kenya has already put in place the *National Environmental Policy 2013*. The policy requires the country to provide clean and healthy environment (Section 6), hence poor disposal of electronic waste including solar e-waste is prohibited, however the policy is a general environmental policy and does not clearly provide a roadmap on management of electronic waste in the country leave alone solar e-waste. At the county governments levels, very few counties have developed e-waste management policies and legislations. Currently, only Machakos County has developed an e-waste regulation addressing diverse electronic waste, but it does not specifically address solar e-waste hence a gap in managing various fractions that constitute solar e-waste.

The most relevant policy that closely relates to solar e-waste in the country is the *National ICT Policy of 2006*. This policy requires electric and electronic equipment's dealers to demonstrate their readiness to contain the effects of their PV infrastructure on the environment to qualify for licenses from the Kenyan Authorities. The goal of this policy is to ensure that the companies producing solar electronic equipment take full responsibility for the solar e-waste generated at the end life. These producers should take responsibility to conserve and protect the environment. This legislation can help in containing malpractices of dumping of e-waste. However, because of its lack of specificity on solar PV, it has not addressed real issues in this sector. The other policy addressing electronic waste in general in Kenya includes *Kenya Vision 2030 (2008–2030)*. The Vision 2030 programme recognizes that Kenya cannot attain high economic and social development without prioritizing environmental management. Waste management including electronic waste is a priority flagship project in the policy. The policy prioritizes e-waste as an emerging waste category with an emphasis on support to Small and Medium Scale Enterprises (SME) to improve waste management.

Another instrument addressing management of electronic waste in Kenya is National E-Waste Guidelines 2010. *The National E-Waste Guidelines of 2010* in Kenya provide a strategic roadmap for addressing the challenges posed by electronic waste These guidelines serves as a crucial document to address the growing challenges associated with the increasing generation of electronic waste from various sources. The primary aim of these guidelines is to ensure the safe and environmentally sound handling, recycling, and disposal of e-waste, while also promoting sustainable practices. The guidelines provides clear definitions of what constitutes e-waste and categorize different types of electronic equipment that fall under its scope. In addition, the guidelines outline the roles and responsibilities of different stakeholders, including manufacturers, importers, consumers, and government bodies. The importance of this is to clarify who is accountable for proper waste management at various stages of the product lifecycle. Further, the guidelines emphasize the importance of establishing collection centers for e-waste and promoting recycling practices, safe disposal and awareness and education. The guidelines reference international best practices in e-waste management, drawing inspiration from established frameworks and experiences of other countries. However, the guidelines are for general electronic waste and there are no specific guidelines on solar e-waste and this may amber development of management strategies of specific fractions making up the solar e-waste. In addition lack of sufficient infrastructures for waste recycling and material recovery has also hindered the guidelines success.

In regard to legislations that are closely addressing solar e-waste in Kenya, the Government has enacted several laws and others are still being developed. However, there is no specific solar e-waste legislation in Kenya. The main legislation guiding e-waste management in Kenya is the *Environmental and Management Coordination Act (EMCA CAP 387) and Environmental Management and Cordination (Waste Management) Regulations of 2006*. The Act and the regulation play a pivotal role in guiding and shaping the sustainable management of waste within the country. The *Environmental Management and Coordination Act (EMCA CAP 387)* serves as a foundational piece of environmental management legislation. It provides the overarching framework for environmental protection and management in Kenya. Under EMCA, various regulations and guidelines are developed to address specific environmental issues, including electronic waste where the solar waste falls in. The act defines the role of relevant government agencies, industries, and other stakeholders in ensuring proper waste including e-waste category management where solar e-waste falls. The *Environmental Management and Coordination (Waste Management) Regulations of 2006* are a crucial subset of regulations under EMCA. These regulations specifically focus on waste management, including e-waste. The regulation outlines a detailed procedures, standards, and practices that should be followed for the collection, transportation, storage, treatment, recycling, and disposal of electronic waste. The regulations address safe handling of e-waste to prevent environmental contamination. The regulation defines electronic waste and categorize different types of electronic equipment that fall within the scope of e-waste management. In addition, the regulation stipulates the responsibilities of various stakeholders, including government bodies, manufacturers, importers, consumers, and waste management facilities. This ensures accountability at different stages of the e-waste lifecycle. Furthermore, the regulation details the procedures for establishing collection centers, recycling facilities, and treatment methods for e-waste. They might emphasize recycling and sustainable disposal practices. Finally, the regulations stipulate enforcement mechanisms to ensure that all stakeholders adhere to the prescribed e-waste management practices. Penalties for non-compliance are also outlined. Even though this regulation applies to general environmental waste and not specific to solar-e-waste, its enforcement would ensure sustainable electronic waste management where solar e-waste falls. However there is a need to develop solar e-waste specific regulations that would help in developing management strategies for various fractions in solar e-waste.

Another legislation relating to solar e-waste management is the *Public Procurement and Asset Disposal Act of 2015* that governs disposal of goods and services in public institutions. Under this law, the public institutions have to bind and invite competitive tenders for disposal of computers and other electronic waste as scrap in line with procurement procedures.

This Act will contribute in managing the solar e-waste among government institutions and offices only but will not address the private sector solar e-waste problem. In addition the general legislation is not specific to solar e-waste hence limited interms of different fractions. The Government of Kenya has developed the *Environmental Mamagement and Cordination (e-waste regulations) 2013*. This regulation signifies the government of Kenya's commitment to addressing the challenges posed by electronic waste. These regulations are expected to provide a structured framework for the proper management of e-waste, ensuring that it is handled in a way that safeguards the environment, promotes public health, and supports sustainable practices throughout the e-waste lifecycle. However like in the already addressed regulations it is not specific to solar-electronic waste hence it is limited in the sense that some elements constituting the solar e-waste fractions may not effectively be managed by a general e-waste regulation.

One of the most progressive environmental management Act that has been developed by the Kenyan government providing a more profound roadmap on the management of electronic waste in Kenya, is the *Sustainable Waste Management Act 2022* which has already been enacted and it is in its implementation and operationalization stage. It proposes a transition from linear to circular economy with increased recovery of value from waste material. In addition the Act calls for establishment of the Waste Management Council within a year of its operationalization. The council shall collaborate with other agencies at the international, national, and county government level with regard to Identifying sustainable waste prevention and management. The Act also calls for the promotion of inter-county (which is the devolved units of the 47 governments of Kenya government system) waste management partnerships in consultation with county governments. The Act therefore provides a collaborative approach to waste management including electronic waste where off-grid solar e-waste falls. Most importantly the Act in section 13(3) calls for development of the Extended Producer Responsibility Regulation. Luckily this regulation bill has already been developed and it is in its final stage of enactment. The Extended Producer Responsibility Regulation is similar to the regulations being used in industrialized economies. The *EPR Regulations Bill (2021) of Keny*a identifies e-waste as one of the products subject to extended producer responsibility. Upon its enactment all producers of electrical and electronic equipment's shall establish or join a Producer Responsibility Organization (PRO) as shareholders and operationalize an EPR Scheme collectively. This regulation is based on the principle that producers are solely responsible for what they produce. Enactment of this regulation within the 1 year stipulated by the *Sustainable Waste Management Act 2022* will immensely help in managing the electronic waste material where the off-grid solar e-waste falls. However, if the *Kenyan Extended Producer Responsibility Regulation (2021*) is enacted in its current form it may not solve the general electronic/solar electronic waste problem in the country. The regulation does not protect vulnerable groups such as waste pickers even though 80% of the electronic waste in Kenya is collected and managed by the informal sector. In addition there is a need for specific regulation on solar e-waste management that will provide the road map to PRO on how to manage the various constituents of the different solar e-waste fractions. To take care of the interest of the informal sector involved in collecting solar e-waste, the Producer Responsibility Organizations needs to allocate a proportion of fees paid by the dealers and producers to them to avoid locking them out of the e-waste management loop and this may introduce a socio-economic problem to this group of people and this could negatively affect the sustainability concept.

4.1.3 | Management practices

There is insufficient data on management and organization of solar energy products e-waste in Kenya. From the existing emphirical studies that has been done, it has emerged out that there is a wide range of substandard solar energy products from companies whose devices are not certified by the Global Lighting Quality Assurance programme, which requires a 12-month warranty for all products sold. From the GOGLA representative in the stakeholders workshop, all companies that are members of Global Off-Grid Lighting Association have set up standards that their solar energy products have to meet before they are sold to the market and the 12 months warranty has to be issued. The association was established in 2012 and currently has over 200 members. However, the products from GOGLA non-members are typically cheaper. Previously known as counterfeit products, these generic products represent an estimated 71% of pico-solar sales in Kenyan market according to the workshop participants. According to the GOGLA representative one fifth of these unregulated solar energy products in Kenya stop working within 18 months of purchase representing speedy entry into e-solar waste chain, which represents a serious threat to environmental sustainability. This finding shows that the turnaround period from the useful product to solar e-waste is extremely short and this means rapid generation of the off-grid solar e-waste, hence increased environmental pollution.

Workshop representatives from Kenyatta University who had participated in a research on how consumers are managing their off-grid solar electronic waste as shown in https://www.youtube.com/watch?v=wXG4NtELtvw indicated that 40% of the respondents kept the e-waste at home, while 38% would return it to the seller and 7% would dispose of the product. The 7% cent of respondents who said they would dispose of the product were further questioned to understand how they would go about waste disposal, 37% stated that they burn it, 9% bury it, 6% dispose it with trash, 3% dump it at handyman's place, 21% leave it outside somewhere, 21% take it to a scrap dealer and 3% would throw it away. These findings implies the lack of awareness and the danger this potends to the health of the people and environment. Knowledge on the constituents elements and their hazardous nature to the final consumers of the off-grid solar systems is very critical.

Through the stakeholders workshop, the study established that there are estimated 750,000 solar home systems in the country. Unfortunately, despite the various hazardous components found in solar electronic waste such as Chromium, Arsenic, Cadmium, Lithium, Silicon, among others. In most cases, the e-waste including solar e-waste in Kenya just like in many African countries ends up being mixed with ordinary waste in dumpsites and landfills this implies that even the nonhazardous waste gets contaminated by these hazardous elements and this poses great environmental hazards. This calls for waste segregation and adoption of sustainable off-grid solar e-waste management approaches such as repairing practices and recycling.

However the study established that, little recycling of electronic waste is done in the country. It emerged out that less than 0.1% e-waste gets recycled annually in Kenya and that electronic waste is mostly handled by the private sector. Most of the companies dealing with these types of waste are transfer stations because they lack capacity and infrastructures. Those engaged in recycling only handle certain fractions and ship the rest of the fractions to their partners overseas.

One of the key private companies handling e-waste in Kenya is WEEE Centre Limited, and the company happened to have a representative in the stakeholders workshop. The company provides electronic waste collection, dismantling and automated processing services. The dismantled materials are sold to local recycling facilities. The rest of the waste is shipped to partners abroad for further processing. Hazardous and non-valuable electronic waste fractions are mostly the ones that are shipped to the international recyclers and smelters. In addition, private organizations and companies drop the electronic waste to the companies' offices. The company in collaboration with a battery recycling firm called Aceleron is deploying a new battery technology to recycle, and upgrade lithium-ion batteries that are sold and used in the market. Moreover, the company has been creating awareness on general electronic waste in various parts of Kenya targeting individual households, but there is a need to have more emphasize on solar e-waste.

WEEE Centre Limited has also partnered with a local telecommunication company, Safaricom Kenya Limited a private company that in its efforts to contribute to environmental sustainability in Kenya has been actively participating in collection of electronic waste including home solar systems and used phones in Kenya offers transportation of the collected e-waste material to the WEEE centre company facility for management. In addition the telecom company has invested substantial funds and resources creating public awareness and runs collection drives to enhance safe disposal of e-waste in Kenya. However these are all private companies and the sustainability of their contribution to solar e-waste management is based on their profitability. There is a need as stipulated in the *Sustainable Waste Management Act 2022*, to harness on collaboration between the private sector and public sector in waste management to enhance sustainability.

Other private companies in Kenya involved in e-waste management in Kenya as established in the workshop include Sintmond Group, that is licensed to deal with advanced recycling electronic waste such as batteries, and computers, among others. Sinomet Kenya Limited, which specializes in e-waste d transportation, treatment/disposal and transboundary movement of e-waste. In addition, E-waste Initiative Kenya (Ewik) which is an NGO based in Kenya deals with electronic waste management in the informal sector, hence providing sustainable disposal option across the country through their networks. Another player in electronic waste in Kenya is Enviroserve Kenya. The company provides friendly and accredited e-waste recycling services. The company is part of the global Enviroerve Group, which is dedicated to electronic waste recycling. The enactment and implementation of Extended Producer Responsibility 2021 of Kenya regulation, provides a room for the county governments and Producer Organization responsibility to partner with such private firms for sustainable off-grid solar e-waste management approaches such as material recovery and recycling.

The workshop participants pointed out the setbacks facing electronic waste management in Kenya and the potential challenges for the rising amount of off-grid solar electronic waste. They in addition underscored the opportunities as well that could be harnessed to realize sustainable solar electronic waste management in Kenya against the backdrop of increasing off-grid solar systems uptake.

The study engaged the stakeholders and experts in the workshop in carrying out a SWOT analysis, based on their expertise and knowledge of the current management systems of electronic waste in Kenya, with a keen focus on solar

TABLE 2 SWOT analysis results for off-grid solar e-waste management systems in Kenya.

Strength	Weakness
• Established agencies for enforcement such as NEMA • Devolved government system with devolved waste management functions • Availability of experts and stakeholders to contribute towards a sustainable off grid solar e-waste management policies	• Lack of specific policy on off-grid solar e-waste • Lack of established e-waste collection, transportation and recycling infrastructures and limited resources • Poor coordination among the various stakeholders and lack of awareness • Lack of data on material flow and this is a major hindrance to effective policy development • Lack of sufficient resources to invest in e-waste management • Lack of standards and regulations for e-waste treatment and disposal • Industry is 80% carried out informally
Opportunities	**Threats**
• Extended Producer responsibility framework that emphasizes on the take back scheme • Enforcement and implementation of Sustainable Waste Management Act 2022 that calls for, circular economy, private public partnership, counties to set out waste collection, material recovery and recycling centers	• Corruption • Poor enforcement and implementation • Lack of awareness • High Poverty levels among the consumers

e-waste. In addition, the participants views were augmented with the researchers knowledge derived from the document reviews analysis. The findings of the SWOT analysis were presented in Table 2 below.

4.1.4 | SWOT analysis results of off-grid solar e-waste management systems in Kenya

The finding of this study shows that solar e-solar waste management represents a serious challenge in Kenya in the coming days if proper measures are not put in place. Failure to effectively manage solar e-solar waste is a threat to sustainable development in the face increasing uptake of solar energy. The study has also established that the little effort being made in managing electronic waste in Kenya is from private sector and the government has not put up physical infrastructures to manage the waste. In addition, there is insufficient data on solar e-waste stock, flows, and routes in Kenya. About 80% of the collection and handling of electronic waste/solar e-waste in Kenya is done by the informal sector. The study has also established that a small proportion of the electronic waste/solar e-waste is being recycled or shipped abroad for recycling by the private sector. Furthermore, there is limited awareness on the solar e-waste hazard at various levels – policymakers, government officials, developers, traders, and consumers. The study also observes that there has been insufficient stakeholder engagement in solar e-solar management leading to weak policies or prolonged policy preparation.

The study further established other challenges facing solar electronic waste management in Kenya such as poor waste collection infrastructure, lack of specific solar e-waste end of life policy and legal frameworks. Lack of enough capacity and resources by the enforcing agencies was also pointed out to be major challenge that needs to be addressed in addition to ensuring transparency and fighting of corruptions among the various stakeholders. The study also established that the general electronic waste legislations drafts awaiting enactment are not customized to the local needs, for example the Extended Producer Responsibility does not fully respond to the informality of electronic waste collectors/handlers in the country. Some stakeholders pointed out that the Kenyan Extended Producer Responsibility draft regulation was borrowed from the developed economies. The context in the industrialized economies is very different from that in the developing countries. Therefore, there is need for effective stakeholders' participation in policy making to take into consideration the local context in solar e-solar waste management. It is also important to underscore the challenges posed by increased counterfeit solar energy systems in the implementation of Extended Producer Responsibility regulation upon its passage. As the uptake of solar energy systems continues to grow, there is a need for an integrated participatory approach in the management of solar e-waste in Kenya and developing countries in general.

5 | CONCLUSION

With increased focus on the development of solar energy globally, investment in the subsector is bound to increase. Similarly, solar e-waste is bound to increase. Unfortunately, Kenya does not have explicit policies and legislations on solar e-waste making it difficult to create functioning structures and processes for effective management of solar e-waste. There is need for a policy and legislative framework that explicitly addresses solar e-waste management in the country. Such policy and legal instruments can either be stand alone or fused into existing policies and legislations. The policy and legal framework should among others focus on:

1. Extended producer responsibility
   Extended producer responsibility will ensure that the cost of solar e-waste management is internalized in the cost of the product. Also, the producer takes responsibility to collect and manage solar e-waste at the end of the product's life.
2. The policy and legislative framework will provide a mechanism for effective management of solar e-waste, specifically retrieval, collection, transportation, storage, repairing recycling, and safe disposal of residues. This will be important in safeguarding the environment from the adverse effects of solar energy development.
3. Recycling, repair, and reuse of solar e-waste can be staggered at different scales and locations, including source, volumes, and market chain of the fractions. This will create room for stakeholder engagement at all levels.
4. Active stakeholders' engagement is very critical in the effective management of solar e-waste, including networking, cost–benefit sharing, information sharing, skills transfer, and awareness–raising on the solar e-waste phenomenon. There are many actors in the production, distribution, and use of solar energy products as well as the management of e-waste. The actors also include policymakers, regulatory agencies, and enforcement agencies.
5. Research and data management of solar e-waste is very important for better response to emerging waste management challenges. At the moment, data on solar e-waste and its management is scanty. Further, the impact of solar e–waste on the environment is largely unknown. So, there is a need to promote research on this sub-sector for informed decision-making.

AUTHOR CONTRIBUTIONS

Kariuki David Mugendi: Data curation (equal); formal analysis (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Caleb Ombuor Mireri:** Supervision (equal); writing – review and editing (equal). **Martin Korch Enevoldsen**: Proof read the manuscript,edited and contributed in writting the policy recommendation section.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs.

ORCID

Kariuki David Mugendi https://orcid.org/0000-0002-4089-549X

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