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Bringing light, connectivity and waste to local communities: A study of the post-consumption value chain for off-grid solar devices in Kenya

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ABSTRACT

In areas with low penetration of grid-based electricity, off-grid solar (OGS) devices have for the last decade played an important role of providing light and access to communications. However, this has come at a cost in terms of creation of streams of electronic waste. To shed light on this issue, this paper explores how broken-down OGS are handled by post-consumption value-chain actors, and which factors are essential for reducing the amount of OGS-derived waste. The study is based on a household survey and interviews with value-chain actors. The Global Value Chain Framework was used for analysis. The empirical findings reveal that broken devices do not follow a linear trajectory from consumer to end destination, but rather move back and forth between repair and consumer, and even between different repair options, and that devices might hibernate at all these nodes, until they find an end-destination. Broken devices stored at home comprised 72 % while only 8 % were disposed of. Repair rates were high for devices brought to firm and informal repair shops alike, but the latter mainly did simple repairs due to a lack of skills, 'black-box engineering' and limited access to spare parts. Unlike other countries in the region, the vast majority of the broken devices are provided by larger international companies which, through their warranty and take-back schemes, could collect a significant percentage of the waste stream and repair or redirect it into established schemes for the recycling. In spite of recent attempts of regulation, this still has to materialize.

1. Introduction

In areas in the Global South with low penetration of grid-based electricity, off-grid solar (OGS) devices have for the last decade played an increasingly important role of providing light and access to communications by charging mobile phones and through radios and TV sets. Since 2010 on the African continent, Kenya has been a frontrunner in this development, followed by other East African countries, such as Ethiopia, Tanzania, Uganda, Rwanda and Zambia [1,2]. This has had important impacts on the well-being of rural dwellers, but it has also come at a cost of creating streams of e-waste in rural areas with poor or no infrastructure to deal with this increasing problem [3].

The prospect of providing electricity to rural dwellers based on solar PV at an unforeseen speed attracted much positive attention from researchers and practitioners working in the field of rural electrification (see e.g. Nygaard et al. [4]), but it has recently also led to increasingly critical research on the effects of this development [5]. The first strand of literature addresses the energy justice implications of the adoption of OGS devices. For example, Samarakoon and Samarakoon et al. [6,7] draw attention to the equity consequences and point out that OGS devices are prone to reproducing structural forms of injustice and do not always represent a sustainable solution to energy poverty in the Global South. Cross and Neumark [8] show how the high interest rates of PAYG businesses model and the practice of repossessing devices from defaulting customers leads to resistance among the poor to OGS companies, which they believe earn excessive profits. Groenewoudt and Romijn [9] take this further and argue that business models that address the bottom of the pyramid have not been shown able to make a profit while at the same time delivering affordable services to the poor. Accordingly, they call for a more pluralistic route, with greater roles for local, non-affiliated entrepreneurs and non-profits, and they also suggest that the public sector is negotiating the trade-offs as much as possible.

The second strand of literature addresses the environmental implications of the adoption of OGS devices and focuses on broader issue of

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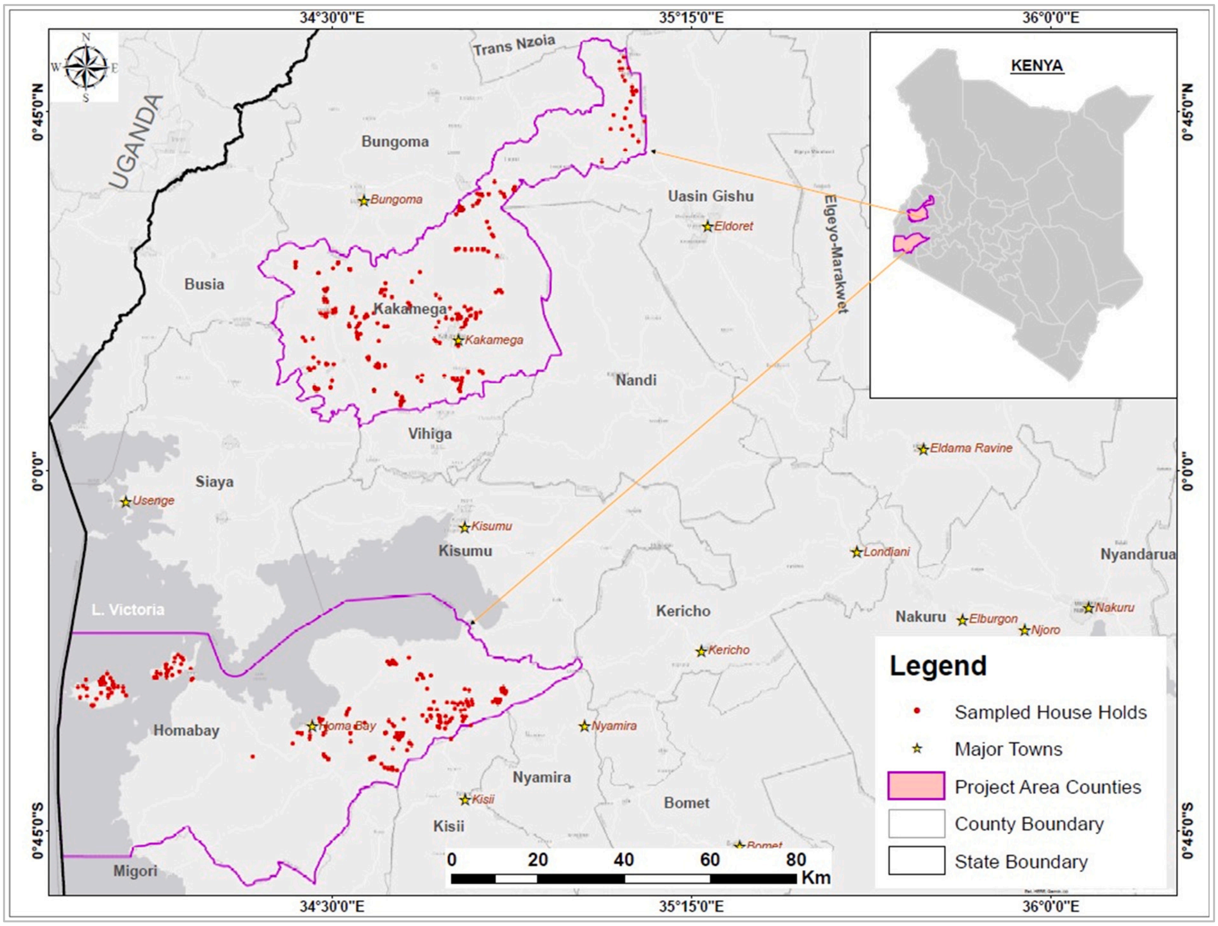

Fig. 1. Map of Kenya on the northeast end of the figure and the two counties where the study was conducted.

'practices' in the chain from consumers to repair shops, scrap-dealers, deposits or recycling, which in this paper we refer to as the post-consumption value chain. Within this body of literature, Hansen et al. [10] have developed the building blocks of a conceptual framework for studying governance systems for the OGS life-cycle with the aim of identifying suitable solar e-waste (SEW) collection, handling and recycling strategies. In another recent study, Hansen et al. [11] find that, while management engages in discussions of potential take-back schemes for OGS waste, the investors behind the OGS companies are still more concerned about reputational risk than the actual activities on the ground.

A specific focus on repair was introduced by Cross and Murray [12] in their seminal ethnographic account of the informal repair of OGS devices in Kenya, in which they highlighted the importance of informal repair shops, so-called *fundis*, as a means of reducing OGS waste. The repair focus was taken to a higher level in a perspective paper in *Nature Energy* that introduced the concept of 'the right to repair' to the context of the Global South, pointing out a number of issues hindering repair and providing a research agenda. This was described and unfolded further in two comprehensive national studies by Samarakoon et al. [13] in Malawi and by Munro et al. [14] in Zambia, in which they provide a thorough description of practices among post-consumption value-chain actors, emphasizing how strengthening the social and material infrastructures of repair are vital to extending the lifespans of off-grid solar devices. In parallel, Harrington and Wambugu [15], in their research based on focus-group interviews in Kenya, challenge the strong international focus on standards and suggest that more efforts should be made to create a sustainable ecosystem of on-the-ground solar services, including training *fundis* and providing access to spare parts.

However, with respect to broader survey-based information on waste-handling in Kenya, we have to turn to the grey literature, such as the UK-AID financed study of how 500 M-Kopa customers managed their waste, which provides important insights into the management of waste, albeit from just one company [16], and the Lighting Global-financed national study on quality and consumer experiences with OGS devices based on 4195 telephone interviews. The latter provides detailed information about consumer perceptions of quality, but it only touches slightly on issues of repair and waste-handling [17].

This paper contributes to this emerging literature on repair and broader value-chain practices by providing rich empirical insights into the practices of handling 'broken' OGS devices in Kenya, based on a survey of 525 households with broken devices, combined with interviews with value-chain actors. More specifically, it explores how broken-down OGS are handled by post-consumption value-chain actors in two counties in Kenya, and which factors determine the amount of OGS-derived waste.

The paper is structured as follows. Section two describes the conceptual framework for the analysis, and section three outlines the methodology. Section 4.1 provides the context for the diffusion of OGS devices in Kenya. Sections 4.2 to 4.5 present the current practices of actors in the post-consumption value chain, which is followed by a discussion of the findings in Section 5 and conclusions in Section 6.

2. Conceptual framework

In this paper, we made use of the global value chain (GVC) perspective to structure the analysis of practices along the post-consumption value chain for OGS waste in Kenya.

The global value chain (GVC) approach provides a perspective for analyzing the full range of activities involved in bringing a product or service from its initial conception and production to its end use [18]. GVC research usually involves an analysis of the flow of materials and the interaction between actors along a delimited value chain, beginning with the material input suppliers, and ending with the final product consumers.

The GVC perspective was used to explore the various dynamics along the PV value chain in Kenya. Hansen et al. [19] studied the business strategies that local firms adopt in their efforts to upgrade within the PV sector; Davy et al. [20] explored the challenges in localizing and upgrading the assembly of PV modules in Kenya; and Lema et al. [21] explored the value-chain linkages and interactive learning within the PV value chain in Kenya. The GVC perspective has thus proved useful in terms of directing attention towards the key actors, processes and mechanisms involved along the solar value chain in a systematic manner.

The GVC perspective operates with **four main analytical dimensions**, which are used to characterize a given value chain and to identify opportunities for the insertion of local developing-country firms at various points in the value chain [22]. The first dimension involves the **input-output structure**, which includes the flow of materials, goods and services across various segments along a value chain. The input-output structure typically involves analyzing the specific linkages connecting actors and activities in the value chain from the upstream raw-material suppliers via the producers to the final end-consumers. A second dimension is **governance** of the value chain, including analysis of the role of so-called 'lead firms', powerful actors that control (or 'govern') the flows of information and resources, and the functional division of labor in the value chain [23]. The decisions and activities of lead firms form the governance structure of value chains, which have repercussions throughout the entire value chain, including whether and how production activities 'touch down' in specific geographical localities. A third dimension is devoted to the **geographical aspects**, which includes considerations regarding the localization of the specific segments of the value chain, including production activities and end-markets. Geographic scales included in the analysis may range from local (subnational) to national to regional value chains depending on the value chain in question. Finally, the GVC perspective focuses on the **institutional context,** which may include the economic and political framework conditions, public and private regulations, physical infrastructure, supporting industries and resource endowments surrounding value-chain actors and activities [24]. Accordingly, each segment in the value chain, from the upstream and production nodes to the downstream consumption and post-consumption nodes, are embedded within certain institutional structures and framework conditions that are external to the value chain.

Here, we used the four dimensions to structure our analyses of current practices in the post-consumption value chain.

3. Methodology

Kenya was selected as a relevant case for studying an emerging OGS e-waste challenge because it was a frontrunner in terms of the penetration of OGS devices in rural areas in SSA and even globally, while at the same time having a poor infrastructure for the collection of E-waste. The study was carried out within two counties, Kakamega and Homabay (see Fig. 1), both in the west of the country. The two counties were selected because of high numbers of solar (device) users according to the Census report of 2019 [25]. In Kakamega and Homabay, 36.7 % and 52.5 % of households use solar for lighting (including communication) compared to National average of 19.3 %. The findings from these two counties may therefore not necessarily reflect the situation in other counties in Kenya.

The study adopted a cross-sectional design in which data were collected one-off by administering household questionnaires (See Appendix A.1 and A.2) to identify end-users (consumers) and their practices, as well as follow-up interviews among a few households to probe on certain practices. Interviews were also held with repair-shop technicians, junkshop owners, waste collectors and other actors to understand their main practices concerning broken solar devices. The study also sought to analyze the influencing factors, including socio-economic conditions, the lifespan and quality of products and their repairability and recyclability.

The data-collection tools, that is, the household questionnaires and interview schedules, were pre-tested on fifteen households on either site, retail-shop technicians, junkshop owners and waste collectors in the two counties. They were then adjusted appropriately to address the reliability and validity of the measurements. The pre-test was conducted in October 2021, and the survey was carried out in December 2021 and August 2022.

Households that participated in the survey were purposively selected. A total of 525 households were captured in the survey (299 and 226 households in Kakamega and Homabay respectively). The introductory section of the data-collection tool screened the households to capture only those users who i) had a broken system at the time of the survey, ii) had a broken system in the past that had been repaired and was still in use, or iii) had a broken system in the past which was not fixed or repaired.

Two focus-group discussions were held, whose participants included consumers in different locations. This helped to corroborate the findings from the household survey. Thirty-two interviews were held with representatives from households, formal and informal repair shops and scrap-dealers.

Waste collectors, both formally registered and those operating informally, in both counties were included in the survey to understand the practices of end-users as far as disposal is concerned, that is, whether broken OGS devices are found in the municipal waste collection, and whether households sell the broken devices to these waste collectors. Waste-pickers therefore formed part of the survey to establish what kind of solar e-waste they collect and where they take it. Interviews were also conducted with national and county officials within relevant departments to understand the institutional framework and to corroborate some of the data given by the other actors within the survey. Details of the interviews are presented in Appendix B.1.

Survey data was entered into an Excel database and analyzed using descriptive statistics. Interviews were in a few cases written up as summaries based on field notes, while in most cases they were recorded and transcribed. Interview data were coded based on pre-selected themes and concepts.

4. Analyzing the OGS post-consumption value chain

4.1. OGS value-chain development globally and in Kenya

'Off-grid solar devices' is a term covering a range of products, including i) solar-powered lanterns; ii) smaller solar home systems (SHS) with a PV panel, battery, a USB connection for telephone charging and two to three LED bulbs for lighting; and iii) larger SHS including more appliances such as torches, radios and TV sets. These devices are mostly acquired by consumers in non-electrified rural areas and to a lesser extent by consumers in electrified areas to serve as a back-up to an unstable electricity supply or to be used in a complementary fashion in cases where users are trying to reduce their electricity bills. They are mainly sold as integrated plug and play systems (kits) and in most cases are acquired by consumers on a hire-purchase basis, which has been coined as 'Pay As You Go' (PAYG). This business model allows the consumer to pay 3–15 % of the value upon purchase and to pay back the remaining balance during a period of one to two years [2]. In Kenya most of these devices are quality-certified by the World Bank-supported GOGLA institution,[1] and for GOGLA-affiliated lead firms, products are

[1] The certification scheme has recently been taken over by Verasol, managed by CLASP.

normally covered by a two-year warranty period.

In contrast to these 'GOGLA-affiliated' certified plug and play systems under warranty, there is a smaller share of non-certified products and systems, including non-branded products, counterfeit products and component-based systems.

Until 2010 on the African continent, Kenya was a frontrunner in sales of SHS to private consumers, and by 2010 it was estimated to having installed up to 320,000 SHS [26]. This position was mainly due to a low rural electrification rate, a relatively large middle class in rural areas being able to afford individual SHS, a Kenyan battery manufacturer, local champions and support from various donor organizations [27].

Based on this early mover position and Kenya leading in the implementation of mobile payment systems (M-PESA), a couple of innovators from the banking and telecom industries invented the PAYG business model, allowing payments in installments via mobile pay. Due to intelligence built into the devices, they only deliver services if the payment balance is positive. This business model broke the barrier of the high up-front cost for PV products and created a step increase in sales, starting in Kenya, and later spreading to other countries on the African continent and worldwide, such as India [27]. M-Kopa, which was one of the pioneers, started operations in 2012, and already by 2015 it had managed to sell >300,000 systems, or the same amount installed by 2012 [4]. The Kenyan market expanded considerably and peaked in 2019 with almost two million OGS devices sold annually. As the market is now considered 'mature', annual sales fell slightly to about 1.8 Million in 2021 [2].

The larger companies operating on the PAYG market today include Greenlight Planet (SunKing), M-Kopa d.light, Bboxx, Azuri Technologies, MySol (former Mobisol) and Zola Electric [11]. These companies have emerged since 2011, and to sustain their dramatic growth, they have been dependent on substantial inflows of foreign capital. Interestingly, in spite of their success in terms of sales, the profitability of the OGS business model addressing the bottom of the pyramid has come under pressure [9]. Most prominently this was illustrated when one of the largest companies, the German owned Mobisol, filed for bankruptcy in 2019 [8], later being taken over by ENGIE Energy Access and rebranded as MySol [28].

From a global value-chain perspective, these OGS companies are lead firms that assemble subcomponents and package them into plug and play kits, including panels, control and battery units, LED lights, radios, TVs, mobile phones and torches. Subcomponents are mainly sourced from Tier 1 suppliers abroad, mainly from China, but some companies, including M-Kopa [29], Mobisol [30] and Fosera [31], have sourced panels from the Kenyan panel assembly company Solinc [20].

Within Kenya, these companies are operating through branches in the major towns. These branches have a shop with an exhibition of products, and in most cases, they also have a local repair shop. Some companies, such as M-Kopa, only deal with repairs from a central repair shop in Nairobi. In addition to direct sales, most companies also operate through sales agents, who access potential customers in rural areas and are paid on a commission basis. In some cases, these sales agents are also responsible for continuous contact with the consumers, for example, in cases of defaulting payments or broken devices.

The lead firms, the upstream and downstream actors, and the flows of products and waste are illustrated in Fig. 2, which has a focus on the post-consumption part of the chain. Products flow from lead firms to consumers, and in the post-consumption chain, broken devices flow to either a lead firm's repair shop or to an informal repair shop, a so-called '*fundi*'. When devices can be repaired, they will be returned to the consumer, if not, they will either be returned to the consumer for further consideration, be stored at the repair shop to be used for spare parts, or move on to a scrap dealer, and to some extent be recycled. However, it should be noted that a fair amount of waste product from consumers, repair shops and recyclers will end up being deposited on the ground, in lakes or latrines, or will end up in formal and informal dumpsites.

The value chain for counterfeit products and component-based systems is also illustrated in Fig. 2. Compared to the chain described above, mainly comprising GOGLA affiliated brands, there are no lead firms taking care of after sales services. These products are bought from small independent shops and in markets and will only be repaired by *fundis*.

It should be noted that Fig. 2 describes two ideal cases. There are also examples of companies not affiliated to GOGLA selling plug and play systems and component-based systems with a warranty and provide after-sales services.

4.2. Input-output structure

4.2.1. Lead firms

The lead-firm suppliers of OGS products in the two counties were mixed in terms of those we would categorize as affiliated, non-affiliated and others. From our survey, focusing on repaired and broken-down OGS devices, we found that the share of GOGLA-affiliated products is 83 % and that 7 % are non-affiliated known brands. About 10 % are unbranded or unknown brands. We estimate that more than half of the non-affiliated brands are component-based systems (5 % of total). The affiliated brands in the study sites include M-Kopa, Bboxx, SunKing, Mobisol, Solar-Panda and Azuri, with SunKing taking the largest share at 40 % (Fig. 3). These firms' large presence in the study sites is also a reflection of the potentially large sources of OGS e-waste.

Clearly, the affiliated devices are more popular, which also reflects the device population of functional and non-repaired devices. There are several reasons for the high percentage from the 'affiliate' companies, including the payment mode, which allows users with low incomes to access the devices by paying relatively affordable daily amounts in installments (ranging from Kshs. 20 to 150) for otherwise expensive devices. The sales agents of affiliated firms have also infiltrated most of the areas and increased the sales of the OGS devices and a smaller amount are distributed through Non-Governmental Organizations (NGOs), Saving and Credit Cooperative Societies (SACCOs) and private sales offices. Other than that, it was observed that a household's purchase and use could influence that of a neighbor, so it was commonplace to find a whole neighborhood with one type or brand of OGS.

While affiliate companies sell their products as a 'system' or 'package', for the non-affiliate companies (Component based system), individual components, such as the solar photovoltaic (PV) modules, batteries, lights, inverters, wiring and appliances, are sourced and assembled independently by either a product aggregator or an individual for their own household, sometimes even piecemeal over a long period of time. This is evident in the higher solar-energy systems, where most are component-based and cannot be traced to any specific brand or represent a mixture of brands.

Of all the OGS products purchased, 95 % were new, and 5 % were second hand or refurbished. Seventy-eight percent (78) % of the OGS products we surveyed were bought under warranty: 81 % and 30 % of new OGS products and secondhand OGS products respectively. Of the total of 78 %, 89 % had warranty periods lasting one or two years. While the non-affiliates may have had agents and warranties just like the affiliates, the fact that they are not necessarily stationed in one location where a client can trace after-sales services may contribute to the lower numbers.

4.2.2. Consumers

A majority, (54 %) of the households captured in the survey had three to six persons. Household size was on average 5.4 persons per household, which is relatively large household sizes compared to the national average household size of 3.8 persons. For both counties, the average household size according to the 2019 census was 4.3 persons. Seventy-eight percent (78 %) stated monthly incomes of Kshs. 15,000 and below, with more than half (43 %) earning less than Kshs. 5000 which is way below the national basic minimum wage of Kshs. 15,201 for the non-skilled worker [32]. As explained under Section 3, all households targeted for the survey had OGS devices. However, 19.8 %, 1.0 % and 3.5 % of households also used main grid, mini-grid and

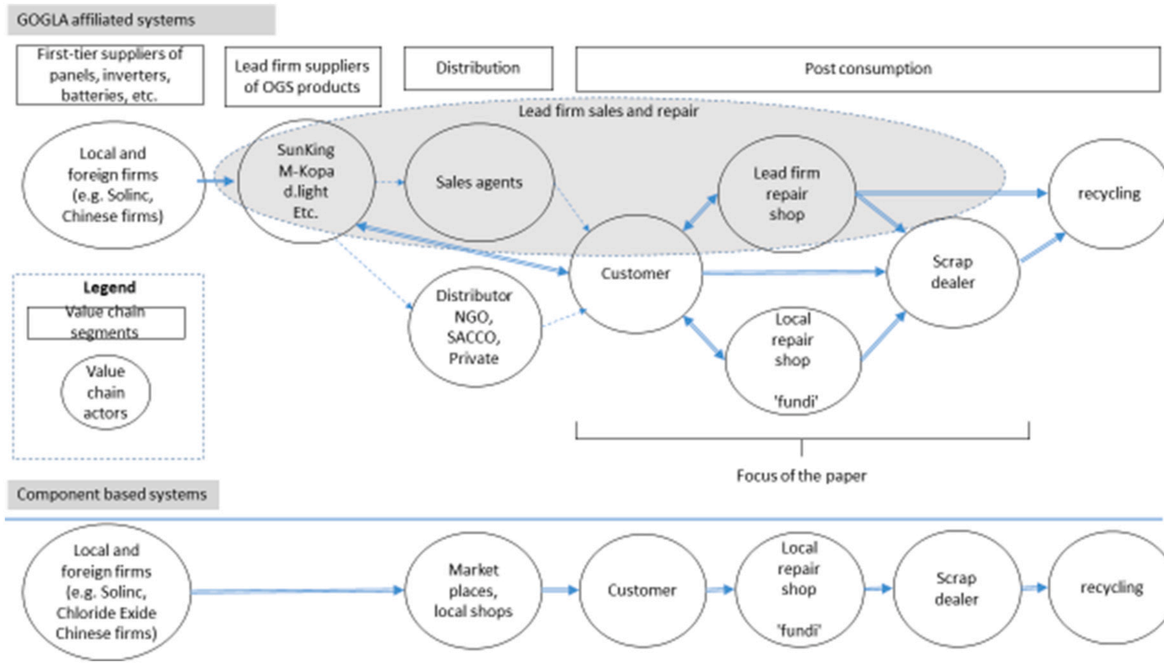

Fig. 2. Global value chain for off-grid solar products.

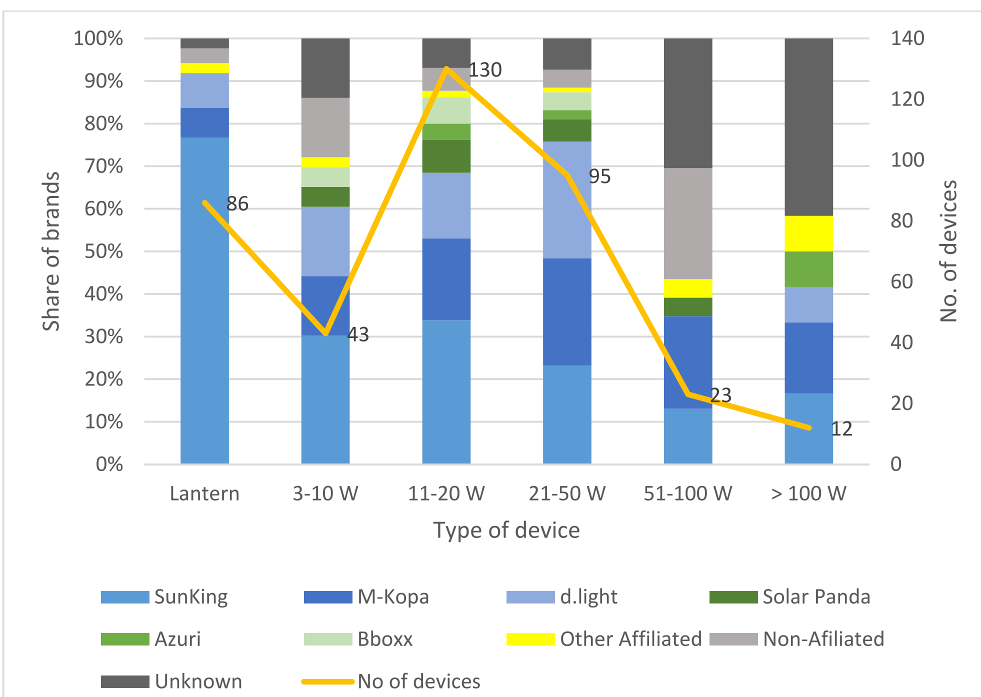

Fig. 3. Percentage of broken down or repaired OGS devices surveyed categorized in Product Type and Brand for households with one device only (n = 389).

batteries as other sources of electricity respectively.

Overall, a high (31 %) percentage of households included in the survey acquired OGS devices in the form of solar lanterns to provide light. Seventeen percent (17 %) acquired devices with multiple light and a charging system (3–10 W). Thirty-seven percent (37 %) had a system with 3–4 lights, phone charging and radio (11-20 W), followed by 30 % with a basic SHS, including a television set for entertainment purposes (21–50 W). Only 15 % had more powerful SHS systems above 50 W, which can power more appliances. These percentages do not add up to a 100 % as about 26 % of the household had more than one device. The idea behind the introduction of OGS was essentially to light up areas not connected to the electricity grid and therefore to make OGS an essential support to the lives of those living in these specific areas. Once a household acquires the lighting equipment, the next practical move for them has been to upgrade to a system that provides entertainment. These systems are relatively expensive, given that most respondents have low incomes, with the cheapest device being a solar lantern single unit retailing at about Kshs. 500 to larger SHS containing multiple lights, TV and other appliances retailing at prices close to Kshs. 100,000. Members of a focus-group discussion in Kakamega pointed out that acquisition of these devices is akin to making an investment. Users attach great value to the devices given their costs. It is this frame of mind that ultimately contributes to the decision to repair a broken device, discard it as waste or keep it at home. Furthermore, to a greater extent, consumers seem to source high-energy systems from brands that are not necessarily affiliated to GOGLA (Fig. 3), most of whose incomes range from Kshs. 15,000 and above (Fig. 4).

All the households we surveyed had broken or repaired devices. The breakages varied from dysfunctional control systems to wires separating and broken screens. The firms' repair shops attributed the breakages to mishandling by clients, whereas the local *fundis* link most breakages to the poor quality of the products. Most broken devices had a lifespan of up to three years before they broke down: 85 % for affiliated products and 76 % for non-affiliated products. Fig. 5 shows that the devices that broke down between one and three years after they had been acquired constituted 44,2 %, 41,9 %, 56,9 %, 54,7 %, 52,2 %, 41,7 % for the six different types of systems ranging from lanterns to SHS > 100 W.

4.2.3. *Flow of broken and repaired devices*

Certain consumers and households had more than one device, so the households had a total of 683 devices. To examine critically the flow of broken and repaired devices, we looked at the 'first' device in each household, the total of which came to 525 devices (see Fig. 6 and Appendix C.1 for more details,).

When OGS devices break down, the consumer can take the product either to the firm's repair shop or to a local *fundi*. We found that 129 of the 525 devices have been repaired and are now functional. Of these, 82 had been repaired at a firm's repair shop, 32 by a local *fundi*, and 15 by others, often by a family member. Only 30 devices or 8 % were disposed.

In the survey, consumers could only provide the final destination of the device when it broke down, so Fig. 6 does not reflect the complicated path that a device may have taken, e.g. being brought for repair at the firm's repair shop more than once, before finally being stored at home when it broke down again. In this case it would be included as 'stored at home'.

In the next section, we provide more details of the flow and practices at each of the end destinations.

a) **Stored at home**

From our survey, we realized that of the 525 devices included in the survey, 396 were non-functional at the time of the survey, 284, or 72 %, being stored at home. A high percentage of consumers (45 %) had kept the broken devices at home because they did not know what to do with them, while 19 % and 18 % indicated economic reasons and other reasons respectively (Fig. 7). These broad categories of answers reveal a variety of economic and symbolic considerations, which we have described in detail in another paper. However, this indicates a lack of awareness on how to handle broken OGS products at the household level or a reflection of perceived value of these items even after their end of life.

b) **Firm's repair shop**

Broken devices from affiliated companies are most often repaired at the firm's repair shop. A broken device caused by the manufacturer's fault and still within the warranty period is repaired for free, but those found to have been caused by the client are charged. Some lead firms have introduced a small service fee in addition to the cost of repair, which is also minimized, to induce clients to bring broken devices out of warranty for repair. Repair fees are then added on to the product loan and paid in installments.

We asked respondents 'what happened when you took your device to the seller's repair-shop?' We therefore know that at least 166 consumers took their device to the firm's repair shop once, although only 130 consumers indicated the 'firm's repair shop' as the end destination for their broken device. The remaining 33 devices were at the time of the survey being stored at home after they had broken down again. As also shown in Appendix C.1, of the 130 devices with the firm's repair shop as their end destination, 82 were repaired and 48 were handled by the repair shop in the sense of harvesting spare parts, disposal, sending to a scrap-dealer or recycling. It is possible that part or all of the 48 devices may end up as waste.

The flow of waste passing through a firm's repair shop is illustrated in Fig. 8.

All the firms said that broken devices are brought to the firm's repair shop and not to the local *fundi*. It is assumed that the local *fundis* have no knowledge or skills to repair the devices and is likely to cause them more damage. However, one *fundi* we interviewed indicated that a firm used his expertise in their repair shop, and that he was not allowed to leave the repair site with any spare part or drawings. There are instances where consumers tamper with the products before completion of payments, for instance, by connecting the batteries directly to the electricity charging system or having a local *fundi* break the device open to repair

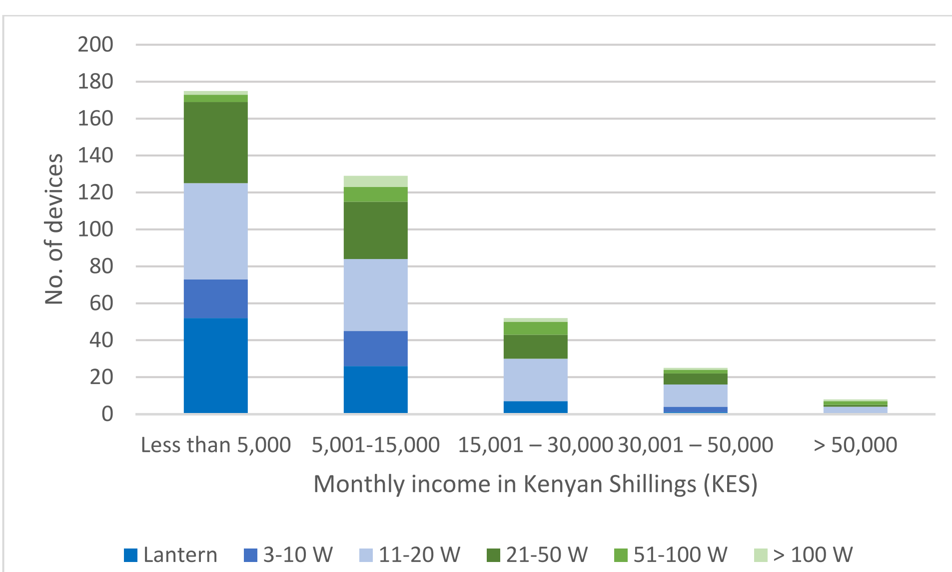

Fig. 4. *Income* vs *OGS Product owned* for households with one device only (n = 389).

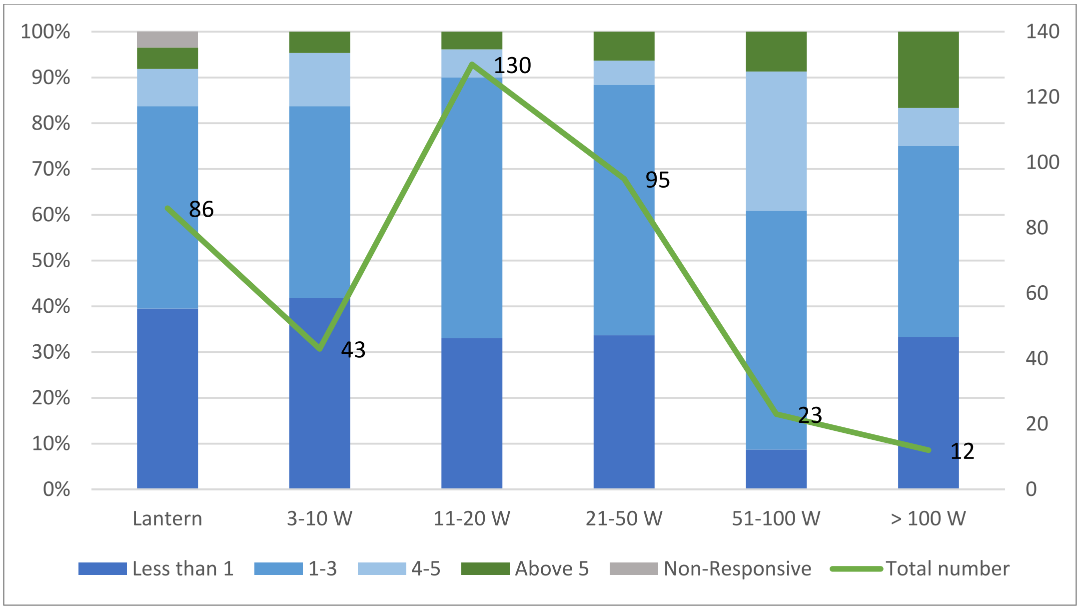

Fig. 5. Durability of broken OGS products in the survey for households with one device only (n = 389).

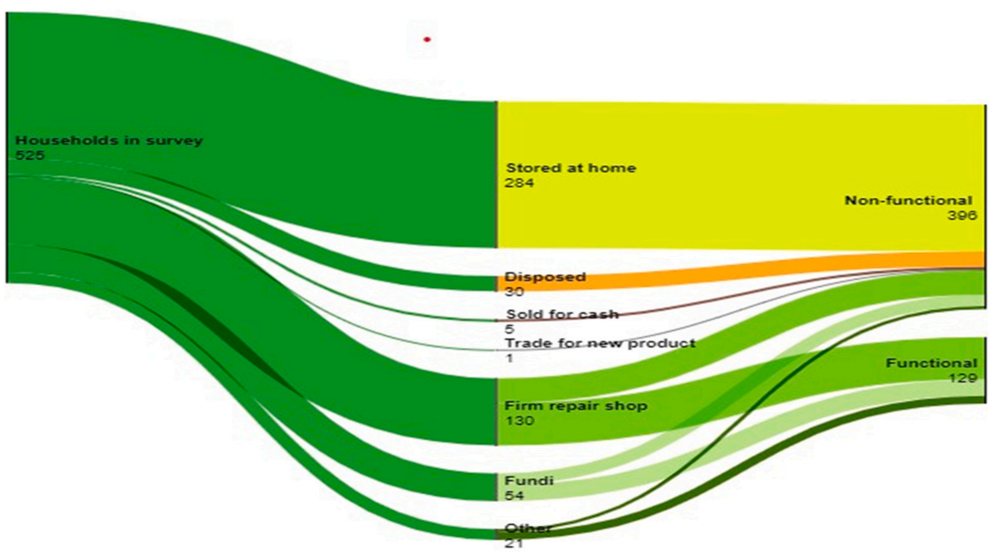

Fig. 6. Sankey diagram of end destination of the first device when it broke down (see Appendix B.1 for more details).

it. In such cases, the firms repossess their devices.

It is also important to note that in some cases, the cost of repair was reported to be higher than the deposit one could make to acquire another new product from another firm or brand. Some consumers thus convert this situation into an opportunity and acquire a new device from a different firm by making commensurate deposit payments. It meant that, for certain households, one would find same products or mixed components of a system from different firms with older broken products having not been paid for in full. This contributes to default payments and increases in waste from the unrepaired broken device. We also observed the practice of swapping products to give clients new gadgets in place of broken ones, especially with firms that do not do repairs on site. Their clients can also knowingly purchase low-priced refurbished products.

c) **The local *fundi***

The local *fundis* we interviewed repair all types of electronics and solar devices and are just one of the streams of electronics that are repaired. From the interviews, we learned that the *fundis* have no specialized training in repairing OGS but instead have acquired knowledge and skills by learning from each other in what is a form of apprenticeship. They receive more affiliated firms' products for repair, though they report that it is a challenge to repair these products, as they lack the spare parts, and some have special security features. Devices that are beyond repair are returned to or bought from the client. Non-repairable devices acquired from clients are broken up and the useful parts 'harvested' or 'cannibalized' for other repairs.

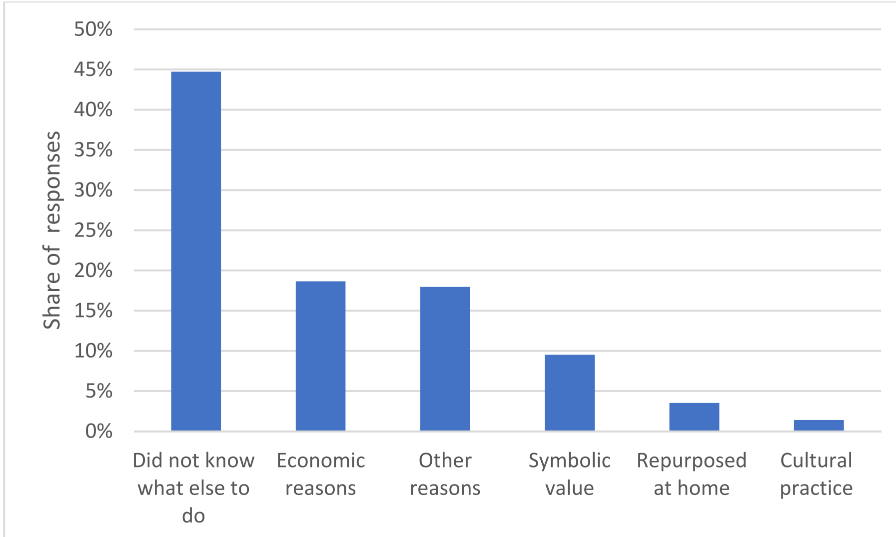

Fig. 7. Reasons for households holding on to broken devices (n = 272).

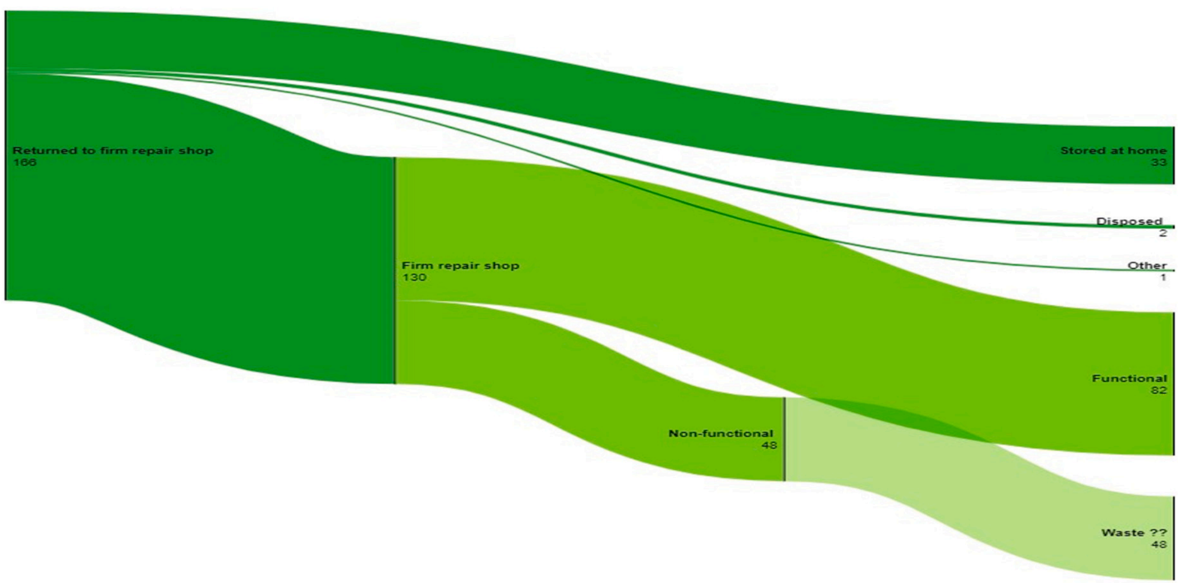

Fig. 8. Sankey diagram of end destination and 'condition' for devices brought to firms' repair shops.

From the survey, we know that, on their way to their final destination, at least 115 devices were taken for repair to the local *fundi*. As we see from Fig. 9, 39 of those later became non-functional and were stored at home, five were disposed by the consumer, while one was placed in the 'other' category. In the survey, consumers had noted that the final destination for 54 devices was the *fundi*, and of those 32 were repaired and made functional, while 22 ended up as non-functional and handled by the *fundi* (Appendix C.1). The survey also reveals that sixteen of the devices taken for repair to the *fundi* later ended up with the firm's repair shop, of which nine were repaired and seven were handled by the latter (already included in Fig. 8).

Interestingly, none of the devices taken to the firm's repair shop end up with the *fundi* at a later stage. Reasons which border on 'trust' are that local *fundi* may tamper with their devices or 'harvest' spare parts from them. This indicates that those who do not trust *fundis* rely on the firm's shop alone, while those trusting the *fundis* seem to go to them first, though in some cases ending up with the firm's repair shops.

Looking further at repairs, Fig. 10 shows problems like broken wires are to a large extent repaired by the family members as 'others' or by *fundis*, while only 40 % are repaired by firms' repair shops. In contrast, only 11 % of the failures in the control unit are repaired by *fundis.*

The type of breakage of the device is also important for its reparability. In Fig. 11 we see that a frequent problem, such as 'broken wires', is repaired in about 40 % of cases, while broken appliances and control-unit failures are only repaired in about 20 % of cases. This should be compared to 25 % of all broken devices which were repaired and functional at the time of the survey. The main reason for this low overall rate is that devices are not taken for repair.

Further, analysis of survey data in 2 shows us that the share of devices taken for repair to the firm's repair shops and *fundis* increases with

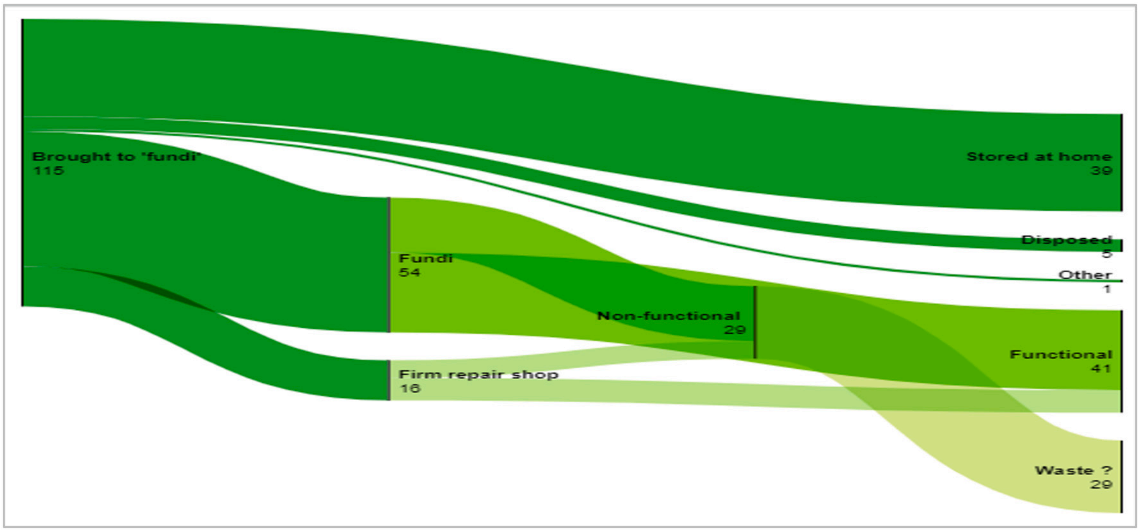

Fig. 9. Sankey diagram of end destination and 'condition' for devices brought to local fundis.

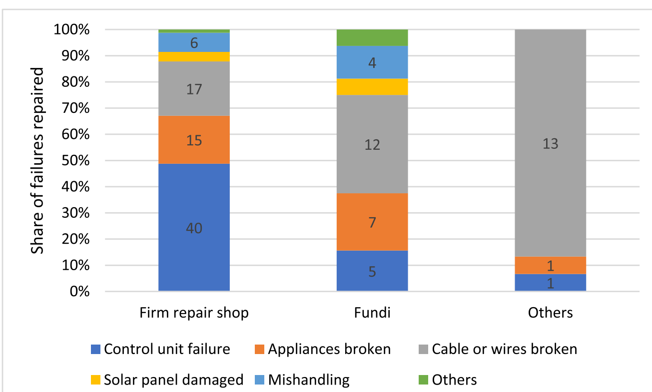

Fig. 10. Various types of breakages repaired by firms' repair shops, fundis and others (n = 129).

increasing income from 30 % to 56 %, but at the same time the repair rate increases with increasing income level, from about 50 % to 100 %. The net result of these two phenomena is that the share of repaired devices increases from 17 to 55 % of the total devices with increasing income (Fig. 12).

d) **Scrap-dealers**

Depending on the extent of the damage, some consumers resort to giving away or selling the broken devices directly to scrap dealers or junkshop owners. The firms' repair shops and local *fundis* also sell or give the broken parts that cannot be used any more to the scrap dealers by the kilogram. In our interviews with scrap-dealers, we were able to trace minimal OGS products to their shops. There are various reasons for this, one being that broken OGS devices are valuable and have thus been salvaged already by repair-shop owners and end-users. The other reason is that it is not possible to single out and identify OGS devices per se because at this point they have been broken down into lengths of cable, glass, aluminum frames, plastics and 'used' batteries. The dealers buy these pieces of 'waste' because they still have economic value. They get supplies weekly from places as far as 45 kms away. They buy in

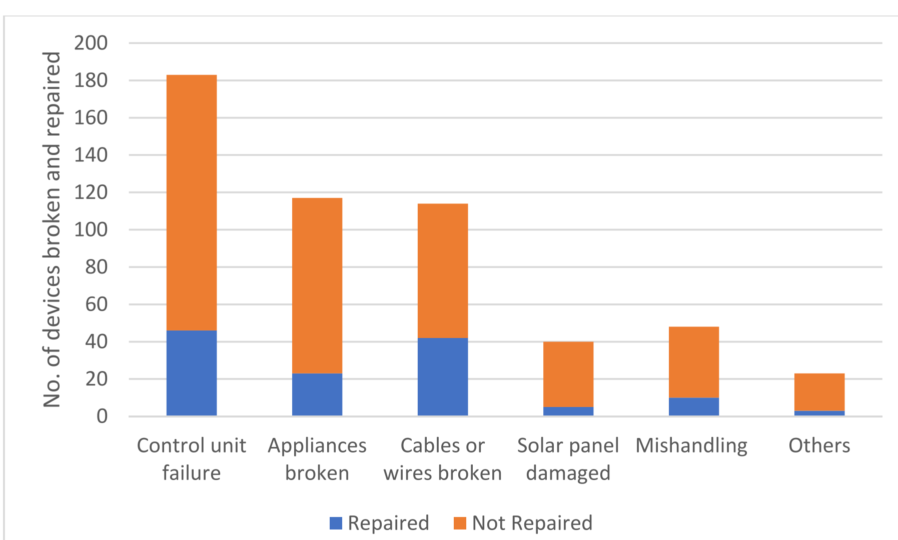

Fig. 11. Frequency and repair rate for different types of breakdowns (repair n = 129, total n = 525).

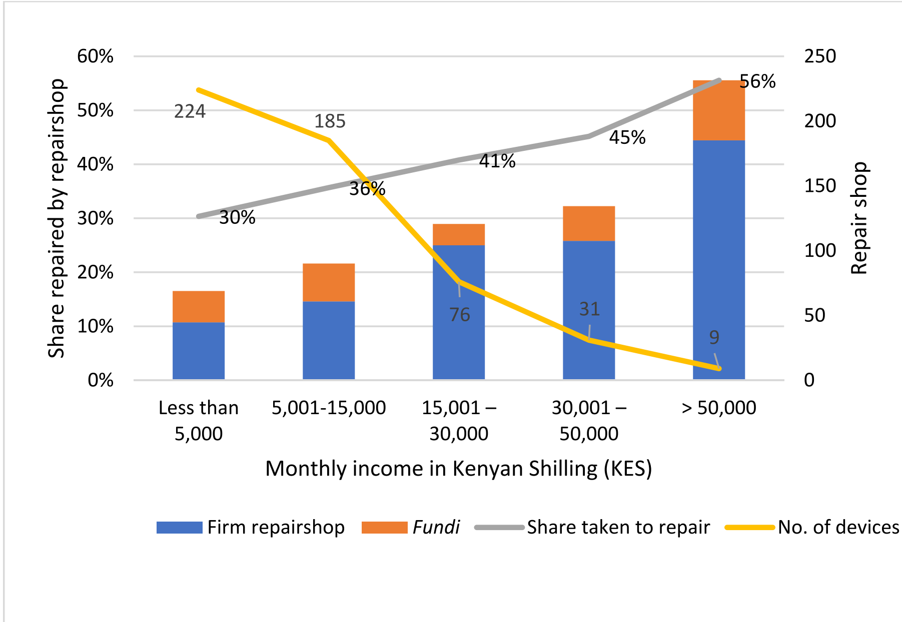

Fig. 12. Income level and share of devices taken to repair, and repaired by firm repair shops and *fundis* (n = 525).

kilograms at costs ranging from Kshs. 20 per kilogram of light metal to Kshs. 700 per kilogram for soft aluminum. 'Waste' batteries are bought for between Kshs. 40 and 50 per kilogram. The Dealers sell to companies like Chloride Exide,[2] agents from other companies and specialized collectors from within Kenya and neighboring countries.

4.3. Governance

As regards governance, we examined how power relations between the various actors in the post-consumption value chain influence the practices of waste-handling and waste reduction along the chain. Lead firms mainly exercise control over the post-consumption value chain through three different but interlinked ways of operating, namely i) the PAYG business model linking the consumers to the lead firms during the payback period, ii) the warranty on the products, which under certain conditions ensures the free repair of broken devices by the lead firm, and iii) the black-box engineering of the OGS kits and the control of spare parts, making repairs by companies outside the control of the lead firms difficult.

PAYG is the model used by most firms. A customer must make an upfront payment of up to about 10 % of the cost of the device and make the rest of the payment by 'little' regular installments. Installments are usually made via mobile money, though alternative methods include scratch cards, mobile airtime and cash. Some firms use the Global System for Mobile Communication and can remotely track usage of their products, which gives them more control over their clients. Other lead firms use agents to track payments and usage of their products. According to one firm's representative, this has allowed them to have one-on-one access with their clients.

While this system presents a friendly and flexible mode of payment, it comes at a cost to the consumer. This is not only in terms of the high interest rates that are paid for the credit over up to 9–12 months and the higher production cost of systems that include control systems; it also applies to giving lead firms access to their consumer data in terms of user and payment patterns, default rates, etc., which can later to be a valuable asset for the lead firms when diversifying into new commodities.

Warranties are attached to each product, and while the warranty periods given by the lead firms vary, they mostly range from one to two years. For most of the lead firms, payments for products are structured in such a way that they should lapse before the warranty expires. The practice, though, is that several defaulting clients make payments way after the warranty period ends. All the companies interviewed reported cases of default payments by clients. Some devices break down while still within the warranty, and for these, the firms take responsibility or ask the consumers to pay some money for repairs. Those cases that fall out of warranty are considered the responsibility of the consumers. As to whether such devices are repaired or end up as waste, that is a decision made by the consumer. Each firm has designed their own mechanism for tackling defaulters, but when there seems to be no meaningful progress, they repossess their devices and therefore have to handle the 'waste' products.

A small share of devices from established lead firms are distributed through NGOs, SACCOS and private distributors. These intermediaries are responsible for consumer relations, including payment, credit and warranty schemes. We observed that this extra link between lead firm and the consumer in several cases reduced the access to warranty and formal repair.

Lead firms' control of spare parts and so-called black-box engineering designs make it difficult for non-authorized repair shops, the *fundis*, to deal with the repair of OGS devices. The argument from the firms' repair shops is that it will reduce the brand's perception of quality if 'non-authorized' repairs are allowed, but the real reason might rather be that widespread repair of 'affiliated' products by *fundis*, will increase the risk of tampering with devices that have not yet been paid for and thus increasing the defaults in payments. Skilled repairers will go in and out as employees of 'authorized' repair shops, so despite the black-box engineering, it will be difficult to 'ring-fence' knowledge of how to repair. So, the only way to reduce repair handling by local *fundis* is by controlling the access to spare parts. Skills are transferable but spare parts are not. Local *fundis* thus have to rely on broken devices or local markets to get spare parts.

[2] Chloride Exide is the sales, marketing and distribution unit of the Kenyan conglomerate Associated Battery Manufacturers (ABM), which also owns Solinc, the only Kenyan PV panel assembly factory. Chloride Exide, import panels, distribute Solinc panels, distribute batteries and collect batteries for recycling [20].

4.4. Geographical scope

As regards geographical scope, we examined how location-specific factors influence practices in the post-consumption value chain. The post-consumption value chain for OGS devices includes the flow of devices from lead firms located in urban centers to consumers in the most isolated rural areas without access to the electricity grid, to proper road or waste-handling infrastructure, thus reducing the flow of broken products and waste back to the lead firms in the urban centers. The fact that this value chain is so geographically widespread has some important implications for the organization and governance of the chain, the rate of repair, the generation of waste and how waste is handled.

The lead firms are medium to large enterprises affiliated to donors and investors abroad with local headquarters in Nairobi, Kisumu and other similar large urban centers. These firms have established retail outlets in the 'smaller' urban centers and rural areas, including Homabay and Kakamega where our data were collected. It is from these shops that a lot of transactions take place between the end-users and the companies. Consumers can make purchases directly from the retail shops or through the firms' sales agents, who operate as small entrepreneurs in the rural settings.

The sales agents handle the marketing of products, sales and the installation of systems in clients' homes, ensure consumers complete payments for products purchased and provide after-sale services. The sales agents are key players in the chain because for some end-users they are their only connection to the lead firm. Some consumers do not even know where the lead firm's retails shops are located. This connection through sale agents has had a 'significant' impact on whether the consumers complete payment for products purchased or default on payment and on whether they repair their gadgets when broken or keep them unrepaired in the house.

When devices break down, consumers can take them to the local branch of the lead firm for repair, or as described above, they can take them to the local *fundi*. Some lead firms operate repair shops at the local branches, while other firms interviewed have chosen to transport the broken devices to their headquarters (Nairobi, Kisumu) for repairs, and some local branches also actively use the sales agents to transport broken devices from the consumers to the repair centers and back again.

We expected to find a correlation between the level of repair and the distance to lead firms' local branches, but we were not able to do so. On the other hand, we found significant differences in repair by *fundis'* and firms' repair across sub-counties, which indicates that the skills and practices of *fundis* and repair shops are more important than the actual distance to these shops. In Fig. 13, the shortest average distance to a firm's repair shop is 7.2 km in Lurambi and 62.5 km in Likuyani, while the largest rate of devices returned to the firm's shop is in Malava and Khwisero, in which customers were on average 23.3 km and 18.6 km from the firm's repair shop.

4.5. Institutional context

Rural electrification rates in Kenya has increased significantly from 25.7 % in 2011 to 68.2 % in 2021 [33]. This development has been driven by: i) ambitious goals set by the government, ii) support and finance from donors, such as the 'last mile' grid expansion project and the KOSAP mini-grid project funded by the world bank, and not least iii) by a supportive regulation, which has facilitated and regulated the marked for private companies to provide mini-grids and off-grid systems to rural communities [34].

In spite of this, until very recently, legislation addressing e-waste in Kenya has been non-existent. The National Energy Policy, for instance, provides for the promotion of widespread use of solar energy, with target set units of solar PV home systems by the year 2022. The policy is silent on measures to address e-waste emanating from increased solar usage. According to Mugendi et al. [35], however, there are a few new pieces of legislation that are relevant for solar e-waste management. The latest one is the *Sustainable Waste Management Act of 2022*, which provides among other things for the establishment of a new governance framework for waste management that would include a Waste Management Council (with representation from the private sector and manufacturing sector) and Extended Producer Responsibility Schemes. It also prescribes the need to establish Material Recovery Facilities.

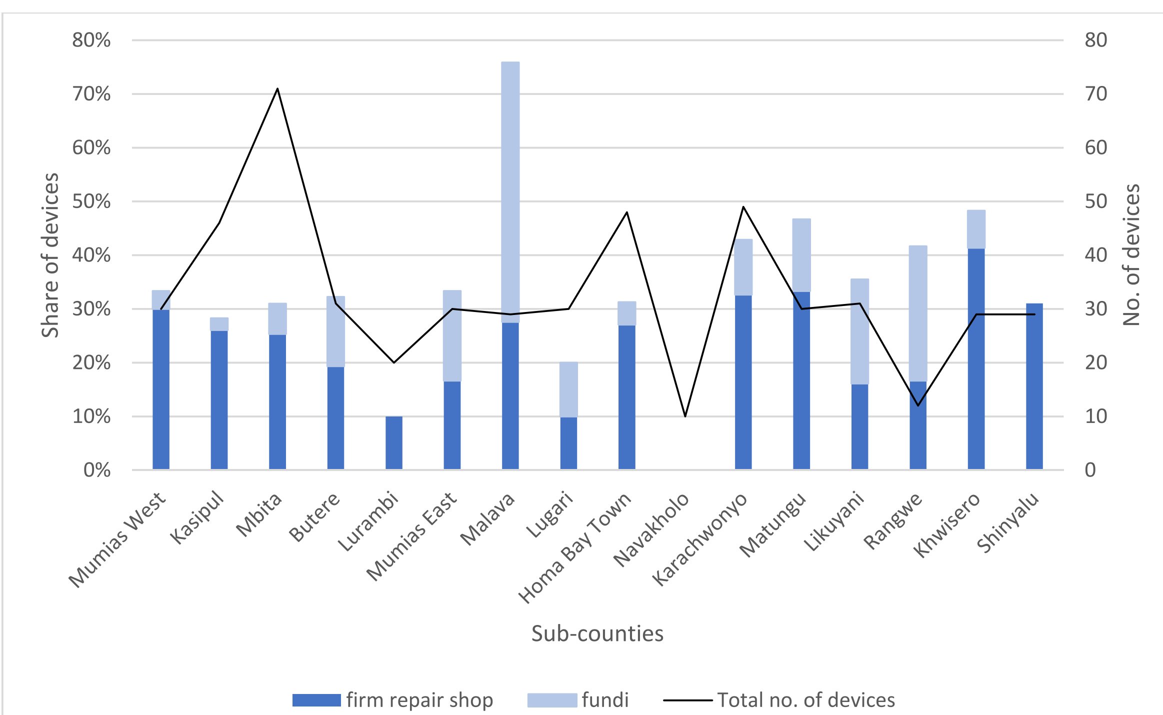

Fig. 13. Share of broken devices taken for repair per sub-county (n = 525).

There is also the Extended Producer Responsibility regulation of 2023, which calls for producers to coalesce together to establish a Producer Responsibility Organization. In this regulation, producers are expected to be responsible for the post-consumer disposal of e-waste. These would be very supportive legal provisions as far as solar e-waste is concerned, assuming they are effectively implemented.

The infrastructure for the collection, handling and recycling of e-waste in Kenya is not adequate. A few organizations are making an effort to recycle, including WEEE center, ENVIROSERVE and W*E*-Hub in the near future. As a result, most e-waste that is not 'hibernating' in homes, in firms' repair shops or with *fundis* is at risk of being disposed of in landfills, placed in temporary storage or deposited in nature or around people's houses. This is more the case in rural set-ups where municipal solid waste management systems are not as pronounced as those in urban set-ups. Kakamega and Homabay counties have clearly defined departments within the county structures that are responsible for waste management, but perhaps due to the small quantities today, not much has been dedicated to electronics or solar waste.

However, the large percentage of GOGLA-affiliated brands in the study sites points to a situation of established brands that can be called upon to exercise Extended Producer Responsibility with respect to the recovery of E-waste from OGS devices.

5. Discussion

In our surveys from Kakamega and Homabay, we found that 72 % of broken devices are stored at home, also referred to as 'hibernation', and that only 8 % have been disposed of by the consumers. The remaining 20 % are dealt with by firms' repair shops and the *fundis*. So far, we have only limited knowledge of the flow of broken devices downstream from these nodes in the chain.

Hibernation is a well-known phenomenon in the e-waste literature, and although difficult to compare across technologies, cultures and economic capabilities, it is of interest to mention that the most recent studies of mobile phones in Europe find hibernation rates of 61 % in the Netherlands and 54 % in the UK [36,37]. Our findings show higher figures compared to mobile phones in EU, but also high compared to the 40 % found in a report analyzing data from 500 M-Kopa customers in Kenya [16]. It is a bit lower than the 89 % found in a recent study in Zambia [38], but the figures in the Zambian study is not fully comparable. The 72 % in our study speaks of the first broken device. The high hibernation rate found in this study shows that 'hibernation' becomes a temporary 'option' for waste management, as does repair or recycling, and that what is to be considered as 'waste' still retains a potential economic, symbolic or emotional value for users.

Our survey revealed that 83 % of the broken lanterns and SHSs were provided as kits by companies affiliated to the GOGLA certification scheme, while the component-based systems only constituted 5 %. This was a surprise, as, based on a large body of literature, we started off with the pre-conception that about 30 % were GOGLA-affiliated and the rest were non-affiliated which we understood as mainly component-based systems when it came to SHS. Seemingly, though, our findings are in tandem with Harrington and Wambugu [15], who show that sales were more or less constantly 65 % affiliated and 35 % non-affiliated in the period from 2015 to 2020. The non-affiliated firms can consist of a 'branded' high-quality product from a larger company (in Tanzania, e.g., PROSOL), but without an interest in being affiliated with GOGLA, or they can be no-names, copycats and counterfeits and also (in the case of SHS), component-based systems. The latter is apparently very common in Malawi [6,7,13], and Zambia [38] while we found only a few percent in Kenya, as also noted by [15].

In fact, 83 % of the broken devices were provided by GOGLA-affiliated companies characterized by PAYG business models, warranty periods, black-box engineering and control of spare parts, rather than dominated by poor quality, often counterfeit products being sold in market places without any after sales services, as we have learned from the literature [3,6,7,9,13,39]. This implies that the technical and organizational options for lead firms to be part of the solution to this tinkering waste problem in Kenya is much larger than anticipated. The PAYG model of payment coupled with firms' sales agents forms a strong relational governance between firms and consumers. They permit 'personalized interactions' and help encourage repairs in cases when broken devices might otherwise have been stored at home. Such consumer relations also provide avenues for traceability and quality control, as well as an option for the collection of waste.

At the same time, lead firms' current practices of governance through the black-box engineering of the systems and the control of spare parts limit the options for *fundis* to do repairs. While black-box engineering reduces risk of copying, the control of spare parts makes it difficult for *fundis* to repair, which means that the share of broken devices repaired will be smaller and more waste will be generated. To counter this, Spear et al. [40]; and Munro et al. [38], argue that firms should instead strive to increase repairability. This could create opportunities for firms to continue relationships with customers through their visits to the company repair shop, and these relationships could lead to sales of additional products and services. Increased repairability along with access to spare parts would also increase the options for informal repair, which is especially important in remote areas far from firm repair shops. As noted by Munro et al. [38], if properly equipped and trained, *fundis* would be more versatile in such remote set-ups because they are would be able to repair devices from different firms. Yet Baraille and Jaglin [41] posit that even repairs by *fundis* within an urban economy today are compromised because first, dominant businesses sideline the *fundis*, secondly, repair holds a very marginal place in these companies' business models thus hindering any form of innovation towards repair and third, there is an increasing integration of disposable micro-electronic components in the solar equipment.

The geographical focus of the OGS market in remote rural areas with low-income dwellers, poor roads, and no proper waste infrastructure raises several specific concerns regarding the sustainability of the current business model, both economically and in terms of the collection and recycling of the waste products. Lead firms mobilized funding with a target to serve those at the base of the pyramid based on so-called innovative business models and succeeded in increasing sales and expanding markets. As highlighted by Groenewoudt and Romijn [9], the markets have proved to be less profitable than anticipated, and after years of losses, firms and their investors are increasingly focused on financial sustainability [42]. Interviews with lead firms and consumers alike revealed high default rates in payments among end-users, and a lead-firm representative noted this as one of the contributing factors to changes within the solar market. We observe not only that lead firms are picking the low hanging fruit by focusing on the most densely populated areas without grid access [43], but also that at least one firm is now considering changing its business strategy away from OGS (and the bottom of the pyramid), thus capitalizing on data harvests of 'reliable' consumers, and moving into other product categories, such as mobile phones, insurance and e-mobility. Other firms, however, have maintained and even increased their focus on the OGS market and show signs of developing strategies to meet customers' demands, for instance, allowing repairs on credit. This trade-off between the higher focus on profitability and the lower focus on the 'environmental' reputations of investors and shareholders, as revealed by Hansen et al. [11], may influence lead firm's willingness to invest in voluntary take-back schemes for broken OGS devices.

Although various regulations on waste-handling, including EPR, were drafted in 2022, lead firms are currently not incentivized by the government to take back broken devices. The EPR regulation is inspired by similar regulations in, for example, the EU, which has proven costly and difficult to operationalize in a way that reduces waste by increasing life-time and reparability, but rather focuses on collection and recycling [44]. However, negotiations on the operationalization and implementation of the EPR are ongoing, and we are waiting to see how and to what extent regulation in this rather unregulated sector can reduce the streams of OGS waste in Kenya.

6. Conclusion

This paper has set out to contribute to the emerging literature on practices of handling SEW by exploring the question of how broken-down OGS are handled by post-consumption value-chain actors in two counties in Kenya, and which factors are determining the amount of OGS-derived waste.

The empirical findings set out in this paper reveal that the broken devices do not follow a linear trajectory from consumer to end destination, but rather move back and forth between repair and consumer, and even between different repair options, and that devices might hibernate at all these nodes for shorter and longer periods, until they find an end destination in a waste deposit, or at a recycling facility.

Most importantly, we find that the current stream of electronic waste from broken OGS devices deposited by households at landfill and in non-authorized disposals is only 8 % and much lower than expected due the fact that 72 % of the broken devices are left hibernating in homes for a period, and therefore postponing the recycling challenge.

We find that there is significant waste reduction potential in increasing access to formal and informal repair and support from government, NGOs and lead firms in establishing training, access to tools and spare parts for *fundis,* would be one of the options for reducing this 'postponed' waste challenge.

Interestingly and unlike in other countries in the region, the vast majority (83 %) of the broken devices are provided by larger international companies affiliated to the GOGLA certification scheme, which, through their warranty and take-back schemes, could collect a large percentage of the waste stream and redirect it into established schemes for the recycling of electronic waste.

Alternatively, and although difficult to manage within existing business models, there is also a significant waste-reduction potential in lead firms developing products that can easily be reassembled and repaired, as well as having spare parts available for informal repairs of solar devices. Both alternatives should be considered in operationalizing the new Sustainable Waste Management Act, as well as in the Extended Producer Responsibility Regulation, which could take the country a step further as far as its management of electronic waste is concerned. In either case, parallel avenues to strengthen formal and informal repair should be strengthened.

Theoretically, we have found that the GVC framework, with its focus on input-output structure, governance, geographical scope and institutional context, has been useful for analysis of the empirical observations in the post-consumption value chain and for structuring this paper. Besides the valuable focus on value-chain governance, the value-chain approach has been useful in shedding light on the non-linear trajectory of the broken devices from consumer to end destination, which is a specific characteristic of post-consumption value chains compared to traditional upstream value chains.

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CRediT authorship contribution statement

Christine Majale: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Godwin Opinde:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ivan Nygaard:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103516.

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