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Towards a repair research agenda for off-grid solar e-waste in the Global South

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There has been a boom in the sale of small-scale off-grid solar products across the Global South over the past decade. A substantial portion of this boom has been driven by international investment in off-grid solar start-up companies, and a formalized off-grid solar sector has been established, with the Global Off-Grid Lighting Association acting as a key representative body. Although this boom has aided in extending electricity access to many energy-poor households and businesses, an emerging concern is the short (three to four years) working life that these off-grid solar products typically have. This has led to a growing issue of solar e-waste. Here we examine how the structure of the off-grid solar sector results in substantial barriers to addressing solar e-waste in the Global South. We consider how practices of repair might contribute to addressing the issue, and set out a research agenda to facilitate new approaches to the issues of solar e-waste.

The sale of off-grid solar (OGS) products—in the forms of solar lanterns and small solar home systems (SHSs)—has experienced an unprecedented boom in the Global South over the past decade. In 2019 alone, more than 35 million solar products were sold (equating to around US$1.75 billion in sales), a precipitous rise from the 200,000 products sold in 2010 (Fig. 1)[1]. In part, this boom has been driven by the rapid and substantial decrease in the price of components for these systems, which has led to the establishment of an OGS private-sector industry in the Global South[2], and the emergence of an OGS industry that has attracted more than US$2 billion in investment (equity and debt) since 2010[3,4].

Established predominantly in East Africa, a range of OGS start-up companies in this sector are increasingly expanding their operations to other regions in the Global South experiencing energy poverty, including broader sub-Saharan Africa, South Asia, South-East Asia, the South Pacific and Latin America[5,6]. These companies tend to use a range of financial and technology innovations to facilitate the 'last-mile distribution' of solar products across the Global South. Solar lanterns initially dominated sales in this sector (comprising an estimated 160 million of the 200 million OGS products sold since 2010); however, pre-packaged SHSs are becoming increasingly prominent (40 million sold since 2010)[7]. Early on, these SHSs were basic—comprising a few lights and a plug for mobile phone charging. Since 2016, however, they have become more sophisticated and often include radios, television sets and fans.

A striking dimension of what Munro terms the private-sector-driven 'photovoltaic turn' in the Global South[8] is the way in which OGS is celebrated as a key means to address the overlapping challenges of energy poverty as encoded by the United Nation's Sustainable Development Goal 7 (SDG7) alongside adaptation to climate change and decarbonization[9]. As Paterson and Stripple argue, in the case of carbon offset markets, the virtuous qualities of 'green' technologies have been critical in the construction of novel environmental markets[10]. In a similar way, solar technologies generally, and OGS technologies more specifically, are often encoded as unambiguously morally good[11]. However, in the wake of this triumphalist story of off-grid electricity roll-out and access, the altogether murkier story of solar waste has become apparent[11,12]. As Cross and Murray note[12], an overlooked socio-cultural and political dimension of the OGS market in Africa in recent years is the question of what happens to these solar technologies when they break down.

Accentuating this issue is that many, perhaps even the majority, of solar products sold in the Global South are described as being 'generic, copycat and counterfeit (photovoltaic) products'[13], and often only have working lives of a couple of years. Even branded, small-scale solar products usually only have one-year warranties, with an expected working life of three to four years[12,14]. Thus, the expected increase in the disposal of off-grid solar e-waste (SEW) in the Global South 'is potentially the dark side of a promising innovation'[2], a problem that was predicted several years ago[15].

In the shadow of the 200 million products (and associated appliances) sold since 2010, is a wave of waste that much of the Global South is poorly equipped to deal with due to the decentralized nature of OGS products[16]. Although solar suppliers and investors in the Global North have only recently started to take action on managing e-waste, they tend to sell much larger and more expensive solar systems with working lives of about 25 years, and operate in contexts with comparatively stronger regulatory frameworks, including quality standards and waste management infrastructure. OGS products sold in the Global South, including photovoltaics (PV), batteries (lead-acid and lithium) and lights, contain 'various hazardous materials, such as lead, cadmium, mercury and sulfuric acid, which may cause serious adverse effects to humans and the environment'[2]. Given that hazardous waste geographies disproportionately affect poor and marginalized communities[17], if solar waste issues are left unaddressed, they could play a role in undermining SDG10 (reducing inequality) and SDG12 (responsible consumption), as well as goals relating to health and water.

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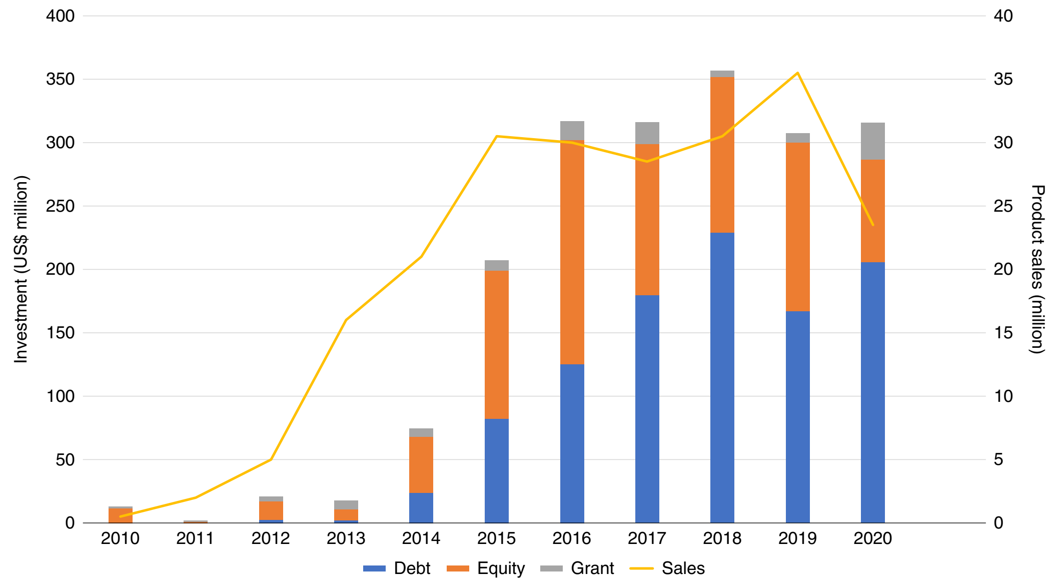

Fig. 1 | OGS investment and sales in in the Global South from 2010 to 2020. The yellow line shows the number of sales of off-grid products. The bars show investment in the sector, divided between debt investments (blue), equity investments (orange) and grants (grey). Data sourced from Lighting Africa[55–59], Lighting Global[1,60,61] and GOGLA Reports[5–7,13,62–69], covering regions across sub-Saharan Africa, the Asia-Pacific and Latin America. These organizations, however, do not collect data from China. The COVID-19 pandemic had an impact on the sale of solar lanterns in 2020. Initial data from 2021 indicate a modest recovery in system sales[7].

In this Perspective we analyse the dynamics of the OGS sector in the Global South and its implications for SEW. In particular, we focus on the political economy that shapes how the sector operates, and the structural challenges that this ultimately presents in efforts to address solar waste.

Structural challenges in the OGS market

A key player in the Global South OGS industry is the Global Off-Grid Lighting Association (GOGLA), which operates as an independent, not-for-profit industry association. GOGLA was established in 2012 and has over 180 members, for whom it provides advice and support. In partnership with the World Bank, GOGLA also hosts the Global Off-Grid Solar Forum and Expo. The 2020 forum and expo in Nairobi attracted more than 1,500 participants.

GOGLA broadly classifies Global South OGS products as either being affiliated or unaffiliated[1,18,19]. Affiliated solar products, which make up an estimated 30% of the market[1,14], tend to be clearly branded products (that is, selling a brand name) that are usually certified by peak industry bodies (for example, Verasol) and are sold by private-sector companies that have sophisticated websites promoting and marketing their operations, usually with rhetoric around green technology and solving energy poverty. Beyond product development, these start-up companies are also often engaged in strategies to finance and facilitate their distribution, and their overall operations are usually supported by international investment[4,20]. They tend to frame their work as being social enterprises: market-based initiatives that are solving social (for example, energy poverty) and environmental (for example, climate change) issues[11,21–23]. These companies have attracted more than US$2 billion in international investment, predominantly from impact investors. Nevertheless, the industry is still nascent. Very few of the companies distributing OGS projects in the Global South are profitable; rather, current operations tend to be financed by debt and equity investments, making long-term financial sustainability an acute challenge across the sector[4,24]. The company Mobisol is emblematic of this challenge. It was heralded by many as an early success story, selling OGS products in East Africa[25], and was framed as one of the stars of the sector of for-profit enterprises[26]. Mobisol filed for insolvency in 2019[4].

In parallel with this investor-backed PV industry has been the emergence of another solar market in the Global South. This market comprises the sale of what GOGLA and Lighting Global describe as unaffiliated products[1]. These unbranded products have proliferated alongside the affiliated solar product distribution chains and are sold by hardware stores, street vendors and informal purveyors[27–30]. Often deriving their designs from affiliated solar products, they are sold at cheaper price points, with their quality being more ambiguous[23]. Their presence is immense. Although the nature of their trading networks is rather inscrutable, the size of this unaffiliated solar market may be as large 72% of solar products sold, according to industry estimates[1]. Furthermore, as discussed below, their movement across Global South markets is distinct, creating additional challenges for addressing solar e-waste. The Global South OGS sector is thus complex, multifaceted and geographically dispersed.

Given this challenge, it is notable that current efforts to address SEW in the Global South have predominantly focused on the initiation of recycling schemes, rather than the potential repairability of these devices. As the issues associated with SEW have generated increasing public, non-governmental organization (NGO) and critical scrutiny[31], the key industry players have responded by instituting a range of recycling and product stewardship schemes. Examples include the work of the waste management companies Enviroserve in Rwanda and Hinkley recycling in Nigeria, each collecting around 85 tonnes of solar e-waste in 2019 as a part of the Global LEAP Awards Solar E-Waste Challenge[32].

These are important responses to SEW, but research suggests that they do not go far enough, as their reach is limited and, ultimately, they rely on relatively expensive infrastructure and logistical operations for waste collection. Importantly, these recycling projects also largely centre and rely on established solar distributors to conduct product returns. Indeed, recent research on extended producer responsibility in the electronics sector has shown how these top–down approaches can sometimes marginalize, and render illegal, successful and more localized informal repair and refurbishing economies[33,34]. In comparison, as we detail below, repair is a more salient approach for addressing solar e-waste, as it addresses e-waste much earlier on in the stream, it can provide economic benefits to the communities who do the repairing, and it can operate with more decentralized infrastructure and investment, making it a potentially scalable solution to the larger problem.

Recent international efforts to improve the repairability and interoperability of consumer electronic devices in general, and off-grid appliances specifically, have been the focus of sustained activism and advocacy that has culminated in the adoption of 'right to repair' provisions in intellectual property and consumer law[31]. However, it is notable that the adoption of right to repair provisions is unevenly distributed globally[35]. At the same time, recent scholarship has highlighted that enactment of right to repair provisions, common in the Global North, may have the effect of overshadowing locally coordinated cultures of repair and reuse that are common across Africa[36]. This work suggests that realization of a Global South 'right to repair', particularly in the context of SEW, requires a critical understanding of how political and economic dynamics shape OGS markets.

In the following sections, we attend to four structural challenges in the OGS market that have direct implications for SEW in the Global South. The first centres on the waste implications of competition between affiliated and unaffiliated OGS products. The second and third challenges centre on the SEW implications of manufacturers' black-boxing technologies and the promotion of closed proprietary hardware ecosystems, respectively. The fourth challenge underscores the distributional challenges that characterize last-mile distribution in the OGS market and what this means for the issue of SEW.

Affiliated versus unaffiliated competition. The competition between affiliated and unaffiliated solar products is a central dynamic of the OGS market and is a key driver of SEW in the Global South. Although the production costs of solar panels and batteries have plummeted over the past decade, unaffiliated products still dominate most OGS markets[1]. For energy-poor households, unaffiliated solar products offer distinct advantages, being regarded as offering greater value relative to their costlier counterparts[18,27,28]. This has substantial implications for the burgeoning issue of SEW. In general, OGS-sector companies selling affiliated solar products have been somewhat active in implementing voluntary solar waste initiatives, with support from GOGLA[37]. As distributors of affiliated products tend to position themselves as social enterprises, these efforts are probably driven by a range of ethical and reputational obligations—to consumers, financiers and partners[11]—and they therefore have engaged in nascent attempts to address SEW[38]. In contrast, unaffiliated products, which tend to be sold through diffused networks of third-party distributors, have no direct involvement in SEW initiatives. Given that they constitute the majority of OGS products sold, the question of who bears responsibility for the resultant SEW looms large.

The proliferation of SEW is concentrated in nations of the Global South that lack the infrastructure and institutional capacity to tackle electronic waste, suggesting that the problem is not likely to be addressed by local regulatory bodies[39]. This is particularly the case given the dominance of unaffiliated OGS products, which often fail to meet current regulatory quality standards and minimum warranty requirements, highlighting the limited capacity for regulatory enforcement. Given the ubiquity of unaffiliated solar products, there are also concerns among affiliated companies that poorly designed regulatory frameworks might result in their businesses facing unfair competition from non-compliant distributors or bearing the costs of managing the waste of unaffiliated products, forcing them to raise their prices and thereby reduce their competitiveness[1]. These dynamics highlight the limitations of relying on market forces or government policies to address SEW.

Black-boxed technologies. The black-boxing of technology is a common practice in the OGS industry, particularly among affiliated manufacturers[4]. OGS products tend to rely on design techniques common in consumer electronic devices more generally, including the use of proprietary screws and tamper-proof design layouts that are intended to limit third-party access and repair. In addition, many OGS products utilize parts that are difficult to source locally. These design strategies are commonly rationalized in terms of ensuring quality and the preservation of product warranties. However, perhaps a more important factor in the inflexible design of OGS products is the way in which these devices are integrated with pay-as-you-go (PAYG) technologies, which are increasingly used in affiliated products[40–42]. At the heart of PAYG technology is the ability for distributors to remotely enable or disable their systems based on the user's payment status. Understandably, affiliated producers and distributors see protecting interference with this remote locking technology as paramount[43]. It is increasingly the linchpin upon which their ability to lower the cost of operations and better compete with unaffiliated products rests. Thus, the limited repairability of affiliated products has direct implications for SEW, particularly as informal repair is widespread in the Global South[14,44]. This could also explain why unaffiliated solar products can be seen as offering greater value for money. Although unaffiliated solar products may—though not always[27,28]—be of lesser quality and durability, they tend to be easier to repair or upgrade in the informal repair markets on which energy-poor households tend to rely[14]. However, poor product quality, along with the limited skills and experience among informal technicians in repairing OGS products with closed/black-boxed designs, means that large volumes of unaffiliated products can end up as SEW.

There are signs that the affiliated tier of the OGS market recognizes the importance of improving repairability and extending the life of their products. The Global LEAP Awards has provided recognition and grant funding to firms looking to improve repairability, upcycle or recycle solar components. One example is Acceleron, which seeks to advance a circular economy for lithium-ion batteries by upcycling end-of-life batteries into new low-cost ones[37]. In parallel, there are products such as those offered by SolarWhat?! and Kuyere! that are seeking to disrupt industry norms. SolarWhat?! describes itself as 'pro-solar, anti-waste' and produces solar systems using open-source hardware that are repairable, reusable and recyclable[45]. Meanwhile, Kuyere!'s emphasis is on creating battery-free OGS systems. The use of capacitors, Kuyere! claims, allows for lower cost and reduced SEW while also providing economic empowerment through more localized assembly[46]. However, these approaches are still regarded as radical initiatives and are not reflective of the broader dynamics of the industry.

Closed proprietary hardware ecosystem. Allied to the black-boxing of technology within the OGS industry are closed proprietary hardware ecosystems. The majority of affiliated OGS systems distinguish themselves by offering all-inclusive plug-and-play systems. These systems are offered to consumers as integrated systems that require little technical knowledge to install. This compares favourably with unaffiliated solar products, which tend to be sold as discrete components (for example, a solar panel or battery) and require a technician (or semblance of technical skill) to install. However, these affiliated plug-and-play systems also have limited interoperability[47]. This means that cables and appliances that can be used with such a solar system tend to be brand- or manufacturer-specific. A combination of hardware (ports and cables) and software (digital handshakes) allows affiliated manufacturers and distributors to foster closed-hardware

Table 1 | A research agenda for repairability in the OGS sector

	Affiliated versus unaffiliated competition	Black-boxed technologies	Closed proprietary hardware ecosystem	Distribution geographies
What is the geography of SEW products in the Global South?	How does the distribution of affiliated and non-affiliated differ across space and socioeconomic groups?			Where do OGS products end up when they cease to function?
What are the barriers in preventing the OGS sector engaging in repairable design?		What opportunities are there to move to open-source product designs?	Are there opportunities for increased interoperability between affiliated solar products?	
What is the current capacity and challenges of local (and informal) SEW repair?	In what way do strategies for repair differ between affiliated and unaffiliated solar products?	How do black-boxed designs hinder local repair opportunities?	How do closed proprietary hardware systems affect the availability of spare parts and appliances?	What is the current geography of repairer capacity?

ecosystems[48]. This is justified in terms of ensuring quality and reliability, such as preventing the use of inferior-quality or incompatible products with their systems. However, it could also be argued that these measures ensure a brand ecosystem that allows distributors and manufacturers to profit from upselling parts and appliances (for example, televisions, fridges and fans). This practice greatly limits consumer choice, results in wasteful duplication, and constrains the establishment of second-hand markets for solar goods, especially for solar appliances[48]. In contrast, unaffiliated solar products tend to afford users the flexibility to use a wide range of components or appliances. Once again, we see how the affiliated versus unaffiliated dynamic in the industry presents various implications for SEW in the Global South.

Distribution geographies. Last-mile distribution is a major focus for producers, distributors and financiers of affiliated solar products. Although the tier's social enterprise credentials appear to rest on its ability to electrify rural households, it is also widely acknowledged that they are the most expensive and challenging to reach[1]. Over the past decade, considerable resources have been invested in addressing the geographic and logistical challenges posed by OGS markets in the Global South[4]. This includes grants and supplier-side subsidies to absorb the costs of last-mile distribution[49]. Given these costs, the financial viability of collecting SEW from last-mile locations is questionable. These costs are exacerbated by the tendency for SEW to be thinly distributed across a growing spread of rural households and villages—it is seldom found in large quantities at a single location[16,50]. These distribution geographies also highlight the likelihood that the rural poor will disproportionately bear the negative social and ecological impacts of SEW.

We return to the question of who bears responsibility for the SEW generated through the consumption of unaffiliated solar products. Although cascades of importers and vendors ensure that unaffiliated products have superior reach at the last mile in large volumes, this also has the effect of obscuring and diffusing responsibility. Given the intense price competition from unaffiliated companies and the costs of last-mile reach, affiliated solar firms are unlikely to have an appetite for collecting unaffiliated SEW unless considerable financial support or incentives are in place[12,32]. With meagre state waste management systems and a lack of local recycling facilities for SEW, affiliated distributors would need to absorb the costs of collection, warehousing and transporting SEW overseas for processing—costs that would ultimately be reflected in higher consumer prices, further reducing the competitiveness of affiliated products, or appeals to investors and creditors for more funding.

Future directions in OGS repairability

Although there are notable differences between the affiliated and unaffiliated tiers of the OGS market, our analysis gives emphasis to the common structural challenges that drive the issue of SEW. At its core, these challenges are endemic to market-based approaches, which rely on accelerating circuits of consumption to be profitable. In this paradigm, short product lifespans, black-boxing technologies, closed-hardware ecosystems and limited stewardship of products at end of life are normalized means to achieving a competitive advantage. In effect, even social enterprise start-ups have their choices to address SEW circumscribed by their financial bottom line—or that of their suppliers. This is particularly acute as, for the most part, affiliated companies are not yet profitable; indeed, they finance their operations through debt and equity. Thus, we argue that voluntary industry-led initiatives to address SEW are unlikely to enact major structural change.

More broadly, the issue of SEW is indicative of the harmful consequences of an energy policy that places heavy reliance on the purchase of OGS products as a means to address energy poverty. This is particularly the case in Global South contexts that are ill-equipped to manage the resultant influx of SEW. Although these products do indeed provide the energy poor with access to (limited) electricity, the shadow cast by the millions of short-lived products necessitated to do so needs critical attention. Overall, with poor praxis around SEW, the green credentials of the Global South OGS sector are highly questionable—the truncated life spaces of these off-grid products (one to four years) means that their waste impacts, as well as the energy used in manufacturing and distribution, undermine environmentally beneficial claims linked to their renewable energy status.

Given this situation, more critical research is needed on the potential repair dimensions related to SEW in the Global South. We identify three critical areas where future research needs to be focused to help facilitate greater focus on repair as a means to extend the lives of OGS products. Table 1 provides a breakdown in terms of how the questions relate to and address the four challenges of SEW in the off-grid sector that we identify above.

First, what is the geography of SEW products in the Global South? Apart from some notable exceptions[12,51], detailed studies on what actually happens to OGS products in their afterlives are conspicuously absent. Some of the data—in particular for the ~30% of the market that comprises affiliated solar products—is probably known or recorded by off-grid start-up companies in the sector, who often track their products with fintech software as a part of repayment mechanisms[52]. Beyond this, however, more detailed on-the-ground ethnographic studies are needed, in particular to understand how the materiality of SEW flows is entangled with a range of social and economic geographies. As Cross and Murray observe[12], off-grid products, when they stop working, reveal a 'range of social, cultural and economic activity around disposal, storage, retrieval, repair and reworking'. The where and the what of SEW ultimately has implications for the how of addressing SEW. There is also a critical justice dimension—who gets access to what types of solar product (for example, affiliated, unaffiliated) under what financial regimes (for example, PAYG finance, cash sales), and with what kinds of consumer rights (for example, warranties)? Until a more nuanced picture emerges, any policy initiatives to address SEW are likely to be misguided or inefficient.

Second, what are the barriers in preventing the off-grid solar sector from engaging in repairable design? The widespread use of black-boxed technologies and closed proprietary hardware ecosystems by OGS companies selling affiliated solar products, as we argue above, are antithetical to repairability. Promisingly, GOGLA recently released a white paper on interoperability in the sector, in recognition of the problems posed by closed proprietary hardware ecosystems, with a range of suggestions on how greater standardization for connectors, electrical components and firmware could occur within the OGS sector[53]. However, the paper is notably cautious—due to GOGLA's role as an industry representative (rather than advocacy) body—twice stating that GOGLA does 'not advocate or expect all companies in the OGS (off-grid solar) ecosystem to specialize and become interoperable'.[53] GOGLA is cognizant that many OGS solar companies may be reluctant to change their praxis around product design. As such, considerable research needs to be conducted on the upstream of OGS products, to understand current barriers to, and potential avenues towards, greater repairable design in the sector—research that directly engages with people working in OGS companies, as well as their financial backers. This should include a focus on how they rationalize their resistance to repairable design, which is in conflict with the 'moral good' narratives in which they contextualize their operations.

Finally, what is the current capacity and what are the challenges of local (and informal) SEW repair? Preliminary research indicates that local and informal repair geographies have emerged in response to the rise of SEW[12,14,54]. Local repairers—who often have existing business in electronic repair (for example, car batteries, radios and so on)—are often extending their work to include solar repair. However, the extent, distribution, capacity and current impact of local repairers in the context of SEW is largely unknown. What kinds of OGS product are ending up at local repair shops and how? What products can local repairers easily fix? What products do they struggle with and why? What gaps are there in terms of knowledge, tools and spare parts that curtail the potential expansion of local repair as a means to address SEW? Localized repair solutions to SEW evidently exist in some form in the Global South, but research is needed to understand the opportunities to augment and extend these repair geographies, networks and practices.

Conclusions

In this Perspective, we have detailed how the rapid rise of the sale and use of small-scale OGS products in the Global South is ultimately leaving in its wake a critical SEW issue that many nations are poorly equipped to address. Furthermore, we have examined how the political economy of the OGS industry—with indebted start-ups, tensions between affiliated and unaffiliated products, poor repairable design practices (for example, black-boxing, closed propriety technologies) and a sparse distribution geography of OGS—creates a series of structural issues for addressing SEW within the industry. Thus, we argue that voluntary industry-led initiatives to address SEW are unlikely to enact major structural change to waste issues. Subsequently, we have shown that a potential means for reducing SEW flows lies within local cultures of repair that already exist across the Global South. Nevertheless, for these to have a greater impact, more targeted research is needed to better understand the upstream issue of repairable design barriers in the OGS sector, as well as downstream issues relating to the geographical distribution of SEW in the Global South and the current capacities and challenges that shape local SEW repair capabilities.

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