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Preparing for future e-waste from photovoltaic modules: a circular economy approach

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Abstract:

The increasing adoption rate of photovoltaic power generation shows that renewable energies have a bright future. Yet, this could be overshadowed by the unintended consequence of increased generation of Waste of Electric and Electronic Equipment (WEEE) at the installations' End-of-Life (EoL) stage. As countries find themselves dealing with the increasing WEEE issue, they may adopt different practices which, if wrongly implemented, could potentially backfire, creating additional issues especially among vulnerable social groups. This work proposes improving the WEEE management system by including the Informal Recyclers in the equation, benefitting social groups and material recovery through by delivering materials along different streams in the closed-loop supply chain. The proposed model intends to support the circular economy approach on waste management systems.

Key words:

Recycling, WEEE management model, informal recyclers, photovoltaic panels.

1. Introduction

Through the past decades, world's population has rapidly increased and, if current trends continue, is predicted to reach 9.7 billion by 2050, and peak at 11 billion by 2100 (United Nations, 2019). With a global trend of ageing population, an aggravated food waste problem, surging demands in energy consumption, as well as an increasing demand of new products from customers' side (Lofthouse & Prendeville, 2018), is evident that our current traditional linear manufacturing model calls for action and urgent change. The Circular Economy (CE) business model seems to provide a much needed answer to this change by implementing different approaches, such as the 10R strategies (Reike et al., 2018).

The concept of CE embodies an alternate method aiming to alter the linear consumption pattern (i.e., take-make-dispose) and make it more sustainable, creating "a production-distribution-consumption model that is regenerative and restorative by design" (Hidalgo-Carvajal et al., 2021). This concept has gained relevant traction recently among scholars and practitioners, evolving around different disciplines and approaches. However, as the concept is transversal and common to different disciplines, and each of them has its own version of the definition (van Loon et al., 2021), this creates a discrepancy between the widespread consensus received by the objectives and means of the CE and the difficulty of defining what it is (Korhonen et al., 2018). Additionally, up to date, most of the advanced analyses from academics and practitioners has been mainly focused on two of the dimensions: environmental and economic.

Moreover, the social aspects of the CE have been largely ignored, sometimes only being considered as

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side-effects, "peripherally and sporadically integrated into the circular economy concept" (Geissdoerfer et al., 2017), even when these have been mentioned by organizations as part of their policies (Bubicz et al., 2021). As can be seen, the benefits related to an appropriate implementation of the CE framework will help countries and governments "to meet the objectives of the 2030 Agenda for Sustainable Development" (European Commission, 2018) from all different perspectives.

World's current linear manufacturing model continues to overlook all dimensions of sustainability (Chuang & Lin, 2015) along the whole supply chain. Among the gradually rising manufacturing of new products and the consequent resulting waste after their End-of-Life (EOL), Electric and Electronic Equipment (EEE) take a key place. As highlighted by Guzzo et al. (2021), EEE "plays a central role in society as it facilitates day-to-day tasks, improves living conditions and work environments, and facilitates communication". Furthermore, obsolescence plays a fundamental part in the amount of waste (WEEE) generated per year, with approximately 53.6 million tons generated during last year (Forti et al., 2020), consisting of both, the absolute obsolescence and the relative obsolescence (Shittu et al., 2021).

Amongst the rapidly increasing manufacturing of EEE, one stands out due to its potential: photovoltaic (PV) modules, with all its components. As an important fact, there were more solar installations in 2019 than fossil fuel and nuclear power additions combined, which occurred for the fifth year in a row (REN21, 2020), following a trend led by major greenhouse gas emitters like China, the United States, and India (Harrington, 2017). This has been also supported by the decreasing cost of solar PV which has globally plummeted by 99 percent in over the last decades, reaching a point of cost competitiveness with conventional generation technologies (fossil fuels), even without government subsidies (Lazard, 2019). Yet, an unexpected outcome of having access to cheaper technology, will be an increase in the waste generation from PV installations at their end-of-life stage in the near future.

The International Renewable Energy Agency (IRENA) predicts that between 1.7 and 8 million tons of PV waste will be generated in 2030 and between 60 and 78 million tons in 2050 (IRENA & IEA-PVPS, 2016). The later implies that PV modules' waste could exceed by 10% the total amount of electronic waste generated by other devices. This could be translated in an increase in the economic value associated with the recoverable raw materials through recycling, with a rough estimate of USD 450 million in 2030 and USD 15 billion in 2050 (IRENA & IEA-PVPS, 2016).

With proper WEEE management many benefits can be obtained, ranging from avoiding wrong chemical disposal of elements and substances dangerous to human health and environment, to recovering tons of materials that can be reused or reintroduced in the manufacturing processes. According to the most recent data, merely 17.4% of the total WEEE is correctly recycled (Forti et al., 2020), whereas the rest finds a secondary market in less-developed countries (Wang et al., 2016), or is "misplaced" either on their way to the recycling facilities or during the sorting and recycling process (Bigum et al., 2017; Pekarkova et al., 2021). One of the strongly recommended suggestions to improve waste management (WM) is to include "the long tradition and experience available in the informal sector" (Agamuthu, 2010) and complement it with the regulations and working conditions (hygiene, safety and fair payment) provided by a formal sector (Asim et al., 2012). Furthermore, incorporating the Informal Recycling Sector (IRS) into WM proves to serve as a facilitator for CE implementation, by including the often forgotten aspects of the social dimension in the equation (Awasthi et al., 2019; Mies & Gold, 2021), and lastly, supporting accomplishing the Sustainable Development Goals (SDGs) (Valencia, 2019).

As the informal systems continue to exist and thrive side-by-side with the formal system (Oteng-Ababio et al., 2013), it becomes necessary to propose a model that combines them both and generates value through the CE approach. Thus, the goal of this study is to answer the following question: How do the informal recycling sector can be integrated in the waste management systems to support achieving the SDGs?

The main objective of this document is to draw a picture on the potential benefits in waste reduction derived from including IRS along WEEE management systems of PV modules. Through the review of academic and grey literature, diverse impacts (good and bad) from implementing different practices in WEEE management were identified. Also, areas where IRS could be included along the reverse supply chain process for WEEE have been suggested.

2. Methods

To complete this exploration, the authors followed a qualitative research methodology, suggested by multivocal literature reviews (Yasin & Hasnain, 2012), consisting of reviewing academic and grey literature, to identify a wide range of relevant documents to the discussion. In the academic area, two main databases were used given their larger subject and pertinent journal range: Scopus and Web of Science. Additionally, to complement the search for grey literature, Google Scholar was used.

For this purpose, the research considered academic documents in the period of 1992-2021, using the following search strings in the literature review: ("WEEE" OR "photovoltaic module" OR "PV panel") AND ("recycl*" OR "circular economy" OR "closed loop supply chain"), retrieving a total of 1,915 unique academic articles, from which 36 were included in the final sample. The research design and selection process can be seen in Figure 1.

It was found that most academic documents were peer-reviewed articles (60%), followed by conference papers (23%), literature reviews (8%) and book chapters (7%). And the publications can be allocated to the following subjects: Environmental Sciences, Engineering, Energy, Material Sciences, Business Management, and other areas.

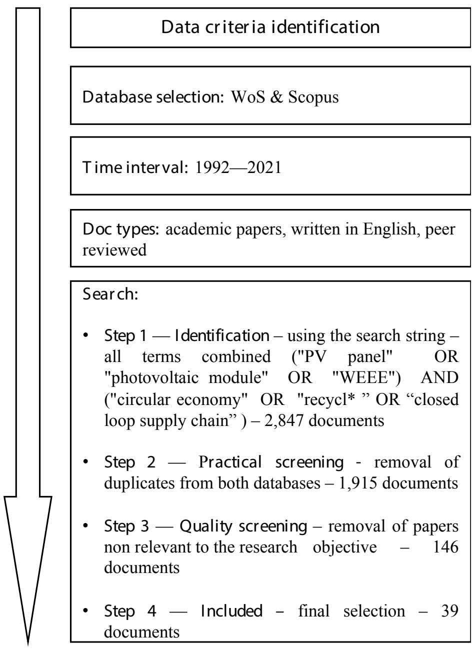

Figure 1. Research design.

3. Results

Although the hypothesis is that as the WEEE continues to growth, its management improves along with it; however, through the literature review, was possible to identify that this is not always the case. Additionally, considering that waste from PV modules will increase in the future, is necessary to complement the current PV module recycling system, making sure that WEEE management practices are properly adopted.

3.1. PV modules recycling

After completing the literature review on PV recycling processes, we identified that the module availability on today's market is split in two main categories: silicon-based panel (c-Si) and non-silicon based materials such as cadmium telluride (CdTe), and copper indium gallium (di) selenide (CIGS)) (Chowdhury et al., 2020). Presently, most of the recycling efforts are focused on c-Si PV type (Chowdhury et al., 2020), counting with three specific recycling types: mechanical, thermal and chemicals (Kang et al., 2012). A special case, which is still under discussion, are the solar thermal modules, which have a different material composition than PVs; however, for this study, only PV modules have been considered.

Additionally, as mentioned by Besiou & Van Wassenhove (2016), given the long life cycle of the PV waste and the existence of precious/rare materials (silver, indium, gallium and germanium) in it, a new approach to properly manage this waste becomes necessary. Moreover, with a growing interest around PV module' recycling worldwide, steps need to be taken. Right on this track, Europe has carried most of the development on this area. Companies and research institutions have worked together into more efficient ways to develop PV from recycled materials (Solar World AG, First Solar, PV CYCLE), innovating recycling processes (Saperatec, Fraunhofer ISE, RECYCLIA, Screlec), increasing the life cycle of components (AUO) and generating collaborative knowledge (IEA-PVPS). In addition, legislation has been developed at regional level in the European Union (WEEE directive), which helps individual countries to adapt it into their own legislations (Sousa et al., 2018).

3.2. WEEE practices

On one hand, cases on which companies carried socially and environmentally responsible practices were clustered in "good case practices". Some companies and countries have created E-waste policies and proposed WEEE management strategies (Delgado et al., 2006), while others have focused on creating social enterprises and services around WEEE (Lixandru et al., 2017), and a few have invested in education programs for their citizens and research around the issue (Awasthi et al., 2019). While most of the initiatives focus on dealing with the WEEE once it is generated by improving the collection system (cleanSpot, Relight, C-SERVEES) and the recycling process (C-SERVEES, GateC, Inventorization, CFC3-recycling), a key element for successful WEEE management systems is reducing the generation of waste (Matsushida Electric, Siemens/Fujitsu), and generating enterprises focused on sustainable WEEE recycling (Social Market Economy).

Good practices have been largely and consistently allocated in developed markets (Li et al., 2013: Richter & Koppejan, 2016; Sousa et al., 2018), as these have investing resources, and more detailed management plans to deal with WEEE (Dieste et al., 2017). Plenty of good practices have been developed in specific areas, such as education (Morris & Metternicht, 2016; Nikoloudakis & Rangoussi, 2019), policy making and implementation (Yu et al., 2010; Pariatamby & Victor, 2013; Daum et al., 2017), use of diverse set of technologies (Stejskal, 2016; Wang & Wang, 2019; Coughlan & Fitzpatrick, 2020), improve sorting practices (Picon et al., 2010; Barletta et al., 2015), inventorying practices (Yumoto & Shiratori, 2009), logistics and network design (Gamberini et al., 2010; Mar-Ortiz et al., 2011; Kilic et al., 2015; Islam & Huda, 2018; Nowakowski & Mrówczyńska, 2018), and creating enterprises with social impact (Papaoikonomou et al., 2009; González et al., 2017). In Table 1, the identified good practices, per region, can be found.

Although it is reassuring to see plenty of these initiatives spreading around the world, is important to highlight that only one of these initiatives proposes the inclusion of IRS as part of the waste management systems (WMS), specifically in the Asian region.

On the other hand, "bad practices" present unintended consequences, and refer to cases on which practices are preceded by poor management of WEEE residues,

Table 1. Identified good practices per region.

Location / Practice	Europe	Asia	Latin America	Africa	Arab States region
Automated processing	x	x			
E-waste policy	x	x			
Transportation of WEEE	x				
WEEE management	x	x	x	x	x
ICT Tools	x		x		
Social Enterprises	x		x		
Consulting services	x				
Inventorying		x	x		
Education	x	x	x		x

and are not aligned with the SDGs (Goodship et al., 2019). Evidence of bad experience can be located all around the world; however, it was found that most of these unsafe practices frequently occur on developing countries (Ongondo et al., 2011), where a lack of regulation allows for different failures in the system (Honda et al., 2016; Mihai et al., 2019). Poor storage, wrong transportation and sorting practices are some of the key issues that countries currently face on this matter (Shinkuma & Huong, 2009; de Souza et al., 2016; Singhal et al., 2019). A summary of the identified bad practices, per region, can be found in Table 2.

Furthermore, two main direct consequences of the poor management remain latent: environmental impact and social impact. Among the environmental impacts, key issues are derived from inadequate management of hazardous materials (Zhang et al., 2017), open burning (Cesaro et al., 2019), improvised metallurgical processing (Li et al., 2015), and/or misplaced waste (Bigum et al., 2017; Pekarkova et al., 2021), creating conditions for further contamination.

On the social impact side, the long-term impacts on health (Mihai, 2020) and working conditions (Lima et al., 2016) of the informal recyclers are the key issue. According to (Marke et al., 2020), an easy way to solve both issues is through improving regulations on the topic. Nevertheless, regulating informal recyclers is the most difficult part given the essential role they play on the delicate waste management ecosystem (Williams, 2016).

Although the WEEE generation continues to increase yearly, the amount of bad practices seems to increase with it (Althaf et al., 2019) as there exist either insufficient control or a lack of it over the waste flows (Rochman et al., 2017).

Table 2. Identified bad practices per region.

Practice \ Location	Europe	Asia	Latin America	Africa
Unregulated system	x	x	x	x
Informal sector	x	x	x	
Open burning		x		x
Poor storage system		x	x	x
Poor transportation		x	x	
Poor sorting		x		x
Unsafe handling	x			
Nonexistent legislation			x	
"Misplaced" WEEE	x			
Stolen materials	x			

Additionally, on the other extreme of the supply chain, extraction of raw materials also identifies several bad practices, mostly related to the social impacts, largely on working conditions (labor exploitation, numerous accidents and deaths, air poorly breathable and stiffing heat), hygiene problems and diseases, including cancer (Santillán-Saldivar et al., 2021). Therefore, the "bad practices" issue calls for attention from the EEE manufacturers and all parties along the entire supply chain.

3.3. The IRS in the WEEE management

Based on the examples of good and bad practices, the role and importance of the informal sector on the solid WM, especially for WEEE, becomes critical, considering also that these need to be positioned and aligned with CE principles (Ranjbari et al., 2021). Inclusion of the informal recyclers in the system provides significant economic benefits to those working under these systems, despite the related health and social issues (Wilson et al., 2006). Moreover, IRS is heavily composed by social groups which are mostly poor and marginalized. Despite this fact, the informal sector is usually considered by governments as a sector that needs to be either eradicated or formalized, as they are unregulated, unlicensed and, in addition, they do not pay taxes (Andrianisa et al., 2016).

Under this assumption the authors propose including the IRS in the PV circular supply chain cycle, taking advantage of their extended experience as waste pre-collectors (WPC) and waste segregation experts. Considering the fact that IRS is a common practice around the globe, frequently in areas of emerging markets (Chi et al., 2011; Umair et al., 2016; Hai et al., 2017; Ghisolfi et al., 2017; Echegaray & Hansstein, 2017; Parajuly et al., 2018; Asibey et al., 2020), the impact that including IRS in the waste

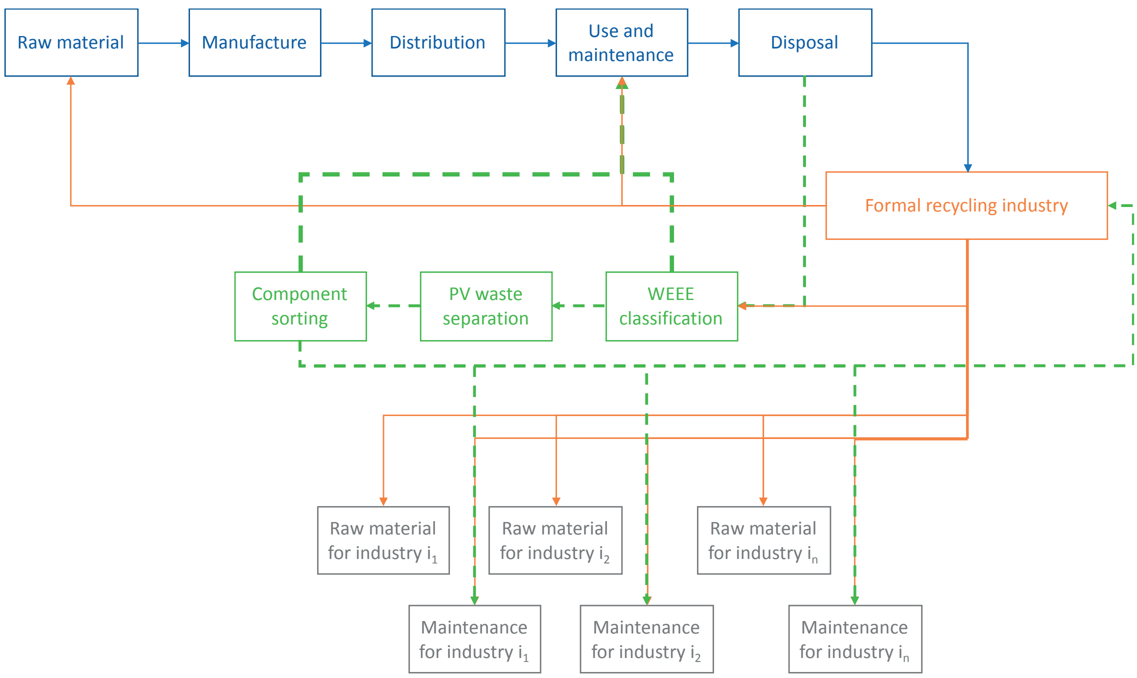

Figure 2. Including the Informal Recycling Sector in the Circular Economy Supply Chain model (own development).

management system could have is vast and positive for these populations and economic sectors.

The model presented in Figure 2 proposes a WMS for WEEE on which IRS becomes a "visible" part of the system. The traditional linear supply chain is represented in blue, showing the extraction to waste model.

When the waste is properly disposed, Formal Recycling Industry (FRI), in orange, receives it and transform it into materials that can be used for maintenance (as spare parts) or recycled to be sold as raw materials for the same industry or to another industry (i_1 ... i_n), as can be seen in grey.

However, due to mismanagement, not all WEEE is properly collected by the FRI, and it ends up in the hands of the IRS upon being disposed in collection points or landfills. As shown in green, WEEE classification by IRS generates a stream of material for reuse (own usage and second-hand market), sale to repair shops (within the same or another industry) and supply of materials to FRI.

Additionally, by including both, the FRI, and the IRS in the WEEE management, as the recovered number of critical materials increases, it would reduce drastically the need for extraction of critical raw materials (CRM), which are key for the industrial value chain of different sectors such as new technologies and medical sector, as well as for energy and environment sectors (for renewable energy technologies), in this specific case, the PV modules. As mentioned by Santillán-Saldivar et al. (2021), maximizing the recovering and recycling of materials would also mean reinserting these materials into the domestic economy, having a long-lasting impact.

The proposed model complements a gap in the research where only improvements to the FRI have been discussed, by establishing a formal collaboration between the FRI and the IRS in the WEEE management. Moreover, this model supports the implementation of circular economy in three fronts: First, recovering a greater amount of materials directly impacts the economic part by reducing the cost of production as the need for virgin raw materials is reduced. Second, given the reduction of need for raw materials and the avoidance of inadequate disposal of WEEE in landfills, it directly reduces the environmental impact. Finally, a social positive impact is reached by generating job opportunities and social inclusion of the IRS in the WM. Moreover, this model could be used not only for WEEE, but could also be considered as a tool to improve current urban WMS.

This model follows the work proposed by Wilson et al. (2006) and Valencia (2019), and includes the role of IRS into WEEE management from a circular economy perspective, which would, potentially, benefit many different industries and social groups.

4. Main contribution

The performed literature review shows a need to tackle the WEEE issue from different fronts: first, a need for a review of the different WEEE flows; second, a demand for identification of current WEEE management practices; third, a need for linking together the informal and formal recycling sectors under the WMS. Despite the growing amount of different EEE (i.e., mobile phones, computers, internet-enabled devices, renewable energy assemblies, among others), there seems to be a lack of preparedness for the future management of this waste once the EEE become obsolete and is discarded at its EoL. Additionally, this work contributes to the literature by providing a model which complements the Reduction, Reuse and Recycle (3R) practices currently in place.

Furthermore, the proposed model aims to integrate a usually excluded social group that could help solve the growing issue of the WEEE management by being integrated into the WMS. This would have a positive influence in the following key areas: firstly, reducing the environmental impact of this waste; secondly, increasing the economic value of the recovered material and improving the domestic economy; thirdly, and more importantly, providing a beneficial social effect for this social group, increasing their own economic conditions, and directly benefitting their health and working conditions.

5. Conclusions

Waste management systems are confronted with the reality of increasing e-waste. This has been partially driven by the decrease of prices, increase of living standards, and consumption of goods and services. Moreover, some technologies have become more affordable, due to continued government support and cumulative innovation. Among these, adoption of solar technologies leads the trend as they added more installations in 2019 than fossil fuel and nuclear power combined. However, a future unintended effect is an increase in the generation of WEEE at the EoL of those installations.

To deal with this future effect, several initiatives have been conducted around the world to either advance in the materials and manufacturing processes or improve current recycling practices. Reviewing the experiences with general WEEE management, it was possible to identify good and bad practices on the topic. Unfortunately, bad practices are largely present in developing countries. Moreover, these bad practices are related to poor and marginalized social groups, as they rely on waste generation to generate income. This informal sector is usually considered by governments as a sector that needs to be either eradicated or formalized, as they are unregulated, even though they play a key role on waste management. Moreover, the IRS continues to exist and thrive side-by-side with the FRI, which, if both were bound to work together, would improve the waste management through an improved closed-loop supply chain.

To potentiate the impact that IRS could have in the WEEE management, we propose an improved closed-loop supply chain model which incorporates IRS and represents how they are able to supplement FRI's work, and directly contribute to Circular Economy principles and development of SDGs.

As a future path of research, the development of specific indicators that combine the contribution from IRS and FRI is needed. This invites for a multidisciplinary involvement around the topic through a more systemic view, reviewing the impacts they have on each other. Additionally, considering the increased development of solar thermal technologies, research on the proper waste management of these materials is needed.

This study is relevant for academics and decision makers working on the topic, as it proposes a supply chain integrating outcast social groups, creating long lasting impacts at economic, social, and environmental levels.

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