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Collaboration towards value creation for end-of-life solar photovoltaic panel in Ghana

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ABSTRACT

This paper identifies value creation strategies and the role of stakeholders in advancing sustainable practices for end-of-life (henceforth EOL) solar photovoltaic panels (solar PV) in Ghana. This is preceded by an overview of the global outlook of sustainable practices for EOL solar PV as well as how these can be promoted in a developing country like Ghana. The framework discusses and promotes efficient collaboration towards value creation by stakeholders in advancing sustainable practices for end-of-life solar PV in Ghana. The methodology centers on an integrative review aimed at identifying the different aspects leading to a value creation framework for EOL solar PV. The paper discusses a hybrid public-private partnership (HPPP), which includes the types of synergy between different actors as well as their clear roles. The core options available to government, businesses and end-users in the value creation includes the provision of a technical solution, improved logistics and innovative business opportunities. The aforementioned options will achieve reduction, reuse, repair and/or recycling, targeted at promoting a unique collaboration between all relevant stakeholders. Furthermore, such options present an opportunity to promote awareness utilizing education in sustainability, thus promoting the need for extending the useful lifecycle of the products.

1. Introduction

Value creation is an essential concept and process that sets a business apart from its competitors, helps in securing long-term customers, and promotes branding. This paper looks at value creation from a new perspective, with a core relationship from the context of public-private partnership (PPP) and a well-designed framework of the roles of stakeholders in PV waste management. Value creation from a PPP perspective focuses on the role required from all stakeholders from government, businesses and households in any given economy (Regenfelder et al., 2017). Furthermore, value creation in this context should be measureable based on realistic targets linked to realistic objectives for a solution-focused action plan (Tsanakas et al., 2020). Value creation in this context does not focus on any short term profitability of the proposed framework to either reduce, reuse, recycle or repair a solar PV panel (Mahmoudi et al., 2019). Rather, value creation seeks to enhance awareness of what the consequence will be if the right proactive measures are not taken now to help mitigate any future e-waste and other supplementary derived waste from solar PV panels (Corwin, 2018; Regenfelder et al., 2017). Thus, the concept of value creation is on the basis of the role and responsibility of all stakeholders enshrined in a societal policy framework aimed at promoting awareness and enforcing the accountability of stakeholders in a way that helps to uphold the principles for the appropriate management of EOL solar PV panels (Mahmoudi et al., 2019; Tsanakas et al., 2020).

Solar PV power technology has been demonstrated to be a mature technology with a large potential market on a global scale (Song et al., 2020; Xu et al., 2018). The huge deployment of solar PV has contributed to the reduction of prices by around 50% since 2010 (Sharma et al., 2019). Currently, solar PV is adding more capacity than fossil fuels and is positioned as the third renewable energy technology after hydro and wind power (Chowdhury et al., 2020). One of the key factors of solar PV is its contribution to the energy transition towards cleaner and more sustainable energy systems (Domínguez and Geyer, 2019). "EOL" as a term is employed in end-of-life products descriptions, particularly from a supplier' perspective (Ndzibah et al., 2021). Generally, this term refers to the period of time beyond which a product does not officially receive any form of support or after-sales service, gradually making the product

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obsolete (Ndzibah et al., 2021; Salim et al., 2019a). Until recent years, EOL PV panels have been attracting more attention since the first PV installations have already reached the decommissioning stage. Moreover, the EOL of PV panels has become a phenomenon of public interest on a global scale, considering that the rapid spread of solar PV capacity is directly connected to the generation of PV waste (Chowdhury et al., 2020; Su et al., 2019). According to IRENA and IEA-PVPS (2016), PV waste could reach around 20 million tonnes by 2050. PV waste requires the attention of national governments and supply chain stakeholders due to its potential significance for the environment and human health (Corcelli et al., 2018; Guo et al., 2019). Furthermore, proper PV waste management brings considerable environmental benefits. Recycling 185 tons of PV panels affords savings of about 1480–2220 ton CO_2 equivalent (Cucchiella F, D'Adamo I, 2015; Ndzibah et al., 2021). In developing countries in Africa, Latin America and the Middle East, despite the high influx of solar PV installations, there are no apparent initiatives to deal with the phenomenon of EOL PV panels. As stated by Okoroigwe et al. (2020), unless strong action is taken in a timely manner, PV waste will be taken to commercial landfills and incinerators, or manual component removal practices will continue to be applied. Along the same lines, Hansen et al. (2021) argue that in the countries of sub-Saharan Africa electronic waste is taken to landfills, and there is a lack of adequate infrastructure and legislation for PV waste management in this regard. To this may be added the informal, poorly coordinated and decentralized nature of waste management schemes (Hansen et al., 2021). In developing economies, solar PV power and EOL solar PV waste are strongly linked to energy access strategies. The large gap between the supply of and demand for electricity services has driven the creation of innovative opportunities for the adoption of solar PV systems in rural and off-grid areas (Rehman et al., 2017; Sovacool, 2013). By 2014, African countries reached a cumulative solar PV capacity of 1344 MW (IRENA, 2014). According to the Africa Clean Energy Technical Assistance Facility and Coffey International Development Ltd (2019), the implementation of off-grid solar installations has benefited more than 100 million people with improved energy access. In these scenarios, energy access strategies should be implemented under a multidimensional approach, including EOL PV waste management. Since one of the central constraints in developing economies is their limited public budget, it is imperative that public and private actors join with efforts to provide innovative solutions to energy and environmental challenges (Pinilla-De La Cruz et al., 2020; UNU-INRA, 2019). Here, public-private partnerships (PPPs) appear as an alternative that can connect and complement resources and capacities among the different stakeholders (Pinilla-De La Cruz et al., 2021). In particular, in recent years, "hybrid" approaches to PPPs have emerged to enable a diversity of stakeholders to intervene in creating hybrid and innovative business models (Chaurey et al., 2012; Rehman et al., 2017). It is noteworthy that, despite the relevance of the EOL PV waste management phenomenon and its prevalence in developing economies, the literature presents few studies addressing this issue (Tsanakas et al., 2020). Therefore, the primary focus of our study is on value creation for EOL solar PV panels in developing countries through collaboration based on the conceptual framework proposed by Ndzibah et al. (2021). In so doing, we have followed the guidelines for integrative reviews proposed by Cronin and George (2020) in order to answer three research questions:

RQ 1. *How have sustainable practices for EOL PV panels been encouraged on a global scale and specifically in Ghana?*

RQ 2. *What are the value creation propositions for EOL PV panels from a public-private partnership perspective?*

RQ 3. *What are the roles of stakeholders in advancing sustainable practices for EOL PV panels in Ghana?*

Although there is no universal consensus classification of a developing country, according to the database of World Development Indicators provided by the World Bank and its member countries, Ghana is classified for the fiscal year 2022 as a lower-middle-income economy with a GNI per capita of between $ 1046 and $ 4095 (World Bank, 2021). Another factor which has influenced Ghana being recognized as a developing country is its high population growth of 2.21% per year (CIA, 2021), with high rates of unemployment (Manhart et al., 2019), high dependence on the primary sector, especially agriculture, and high dependence on exports of primary unprocessed commodities (Ingco et al., 2001; UN and FAO, 2017).

Ghana is selected here as a case study for two fundamental reasons: (i) its favorable solar radiation due its geographical conditions (average solar irradiation of 4–6.5 kWh/m^2/day: (EC Ghana and UNDP, 2015; IRENA, 2015) make it suitable for extensive development of solar PV projects, and (ii) according to the Ghanaian Energy Sector Strategy and Development Plan, the Government of Ghana will focus on "supporting *the use of decentralized off-grid alternative technologies (such as solar PV and wind) where they are competitive*" (EC Ghana and UNDP, 2015, p. 4). Approximately 30% of the Ghanaian population live in remote and often inaccessible locations where a suitable alternative to provide access to electricity would be isolated grids and mini grids. Currently, the government is testing various initiatives for the dissemination of solar energy systems, including the Solar Lantern Promotion Program (2 million lanterns in remote/off-grid locations), a photovoltaic solar energy installation with 715 kWp and 25 network-connected PV solar systems through private sector initiatives (EC Ghana and UNDP, 2015). Additionally, the Ghana Renewable Energy Master Plan (MoEn Ghana et al., 2019) established among its objectives for the year 2030 that approximately 20% of the electricity generation capacity from renewable energies will come from distributed generation (i.e. solar home systems, solar street lighting systems, mini-grids, etc.). Ghana represents developing economies with, on the one hand, high potential for solar PV capacity, and therefore for generating significant amounts of PV waste in the future, and, on the other hand, logistical challenges due to highly distributed PV installations (ACE TAF and Coffey International Development Ltd, 2019). The rest of the paper is organized as follows: Section 2 outlines the methodological approach. Section 3 details the results and discussion, which includes sustainable practices for PV panels on a global scale and the outlook for these in Ghana, and additionally the issue of value creation for EOL PV panels for Ghana is discussed. Section 4 presents the conclusions of the study.

2. Methodology

This study followed the guidelines for integrative reviews described by Cronin and George (2020) and Torraco (2005). The integrative review makes it possible to gather and synthesize knowledge across different communities of practice (Brown and Duguid, 1991; Cronin and George, 2020). The holistic triangulation of the data provides a better understanding of the phenomenon to produce unique insights and contributions. By following this methodological approach, it was possible to integrate the latest scientific articles exploring EOL PV panels, the data from international environmental agencies related to EOL PV, as well as official reports from public agencies in Ghana. In particular, Cronin and George (2020) recommend the following eight steps for conducting integrative reviews: (i) articulate the topic locally, (ii) find other communities of practices studying the same topic, (iii) bind d identifiable communities around a topic, (iv) refine primary findings from each community of practice, (v) abstract the findings into common themes, (vi) explore how the themes relate to each other, (vii) integrate themes into a coherent whole, and (viii) refine and refocus.

First, we identified the EOL solar PV power as the focus of our study. Subsequently, we captured the latest studies on the subject by conducting a systematic search in Elsevier Scopus and Web of Science electronic databases using the search string ((TITLE-ABS-KEY (("solar panel*" OR photovoltaic) AND ("end-of-life" OR "circular economy" OR "extended producer responsibility" OR "product stewardship"))) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"re") OR LIMIT-

TO (DOCTYPE,"English"))). We retrieved 379 records. After removing duplications, we obtained 335 hits. Those records were screened based on abstracts by assessing their relation to EOL solar PV panels, where 127 records were included in the analysis. Afterwards, given the relevance of collaboration in building a suitable scheme for EOL solar PV panels in developing economies, we conducted one additional systematic search in the Scopus database, using the search string ""hybrid partnership" OR "hybrid public private partnership" to look for articles in English. Here, we obtained 135 hits, including publications from 2001 to 2021. In the screening process, we found four articles that showed a relation to hybrid partnerships in sustainability and innovation. Given the relevance of the phenomenon in the energy, environmental and social dimensions, we included reports from international agencies in renewable energy and complemented the data set with official reports and information in websites published by African and Ghanaian public agencies. In total, our data set encompassed 131 academic studies from the systematic searches, five reports from international agencies, four official reports from public agencies in Africa and Ghana, and information from four websites. After the data set was defined, we proceeded to conduct a thematic synthesis through a holistic triangulation of the data. Initially, we identified constructs and later arranged the commonalities among the data into common themes in order to finally integrate all the findings into a comprehensive summary of global practices for EOL solar PV panels and a proposal for building value creation for EOL solar PV panels through a collaboration strategy for Ghana. In order to promote rigor in conducting this study (Yadav and Desai, 2016; Yadav et al., 2017), we followed the alternative principles for producing systematic reviews proposed by Denyer and Tranfield (2009). Fig. 1 summarizes the research outline.

3. Results and discussion

3.1. Sustainable practices for end-of-life photovoltaic panels on a global scale

Although solar PV panels are considered to be relatively reliable, failures may occur that affect their operation. According to Chowdhury et al. (2020), some manufacturing defects in design or light erosion can affect electricity generation (Chowdhury et al., 2020; Smith and Bogust, 2018). However, most failures occur during the productive stage (Chowdhury et al., 2020; Komoto et al., 2018). The most common failures involve cracks and microscopic failures. Furthermore, other factors that could affect the solar PV operational condition are the degradation of the ethylene vinyl acetate (EVA) anti-reflective layer on the glass, degradation by constant exposure to pollution or by changes in temperature, problems in the connections of both of the cells with other components of the system, and glass and frame breaks (Chowdhury et al., 2020; Cubukcu and Akanalci, 2020). Once PV panels reach the EOL stage, appropriate management is needed to avoid environmental and health impacts. Improper EOL PV waste disposal can lead to significant negative environmental effects from metals such as cadmium, amongst other materials (Corcelli et al., 2018; Deng et al., 2019). Some potential effects from long exposure to cadmium could be neural diseases, cancer, and kidney dysfunction (Cyrs et al., 2014). At the same time, it should be taken into account that some semiconductors in PV panels offer only a limited supply due to the geopolitical conditions of their reserves (Augustine et al., 2019). Therefore, recycling solar PV waste is a *sine qua non.*

3.1.1. Recycling process

Recycling practices can generate significant economic and environmental benefits by reducing the need for new materials and the cost of new products. When solar PV panels cannot be reused or repaired, they should be recycled (Ndzibah et al., 2021). Presently, different recycling techniques are applied, some with greater development and maturity than others, and the environmental impacts and financial costs can, in turn, have high variability. Commonly, these techniques encompass chemical, thermal, and mechanical processes for delamination and materials recovery (Maani et al., 2020; Song et al., 2020a). Some scholars have made focused their efforts on comparing the possible environmental impacts of various techniques for EOL PV waste management. In particular, the study conducted by Maani et al. (2020) analyzed the management of c-Si and CdTe. The authors found 10 different delamination techniques, of which six are applied to c-Si, and four to CdTe. When comparing the recycling techniques of c-Si with CdTe for delamination, quite similar results were found in relation to the use of thermal and mechanical treatments (Maani et al., 2020). In particular, the c-Si recycling process presented more significant impacts than those of CdTe, given the use of chemical treatments to separate the components (Maani et al., 2020). According to the above mentioned study, recycling methods should aim to recover the most expensive materials with the greatest impact on health and the environment such as tellurium, silicon, aluminium, silver, and copper (Maani et al., 2020). The economic sustainability of photovoltaic waste recycling programs faces important barriers due to high recycling costs and the lack of specific infrastructure for this type of waste (Cucchiella F, D'Adamo I, 2015; D'Adamo I, Miliacca M, Rosa P, 2017). According to Corcelli et al. (2018), based on Global Data. (2012), the value per watt of a recycled module will reach approximately 0.6 US dollars in 2025, with an increase of 1.21 per watt US dollars by 2035.

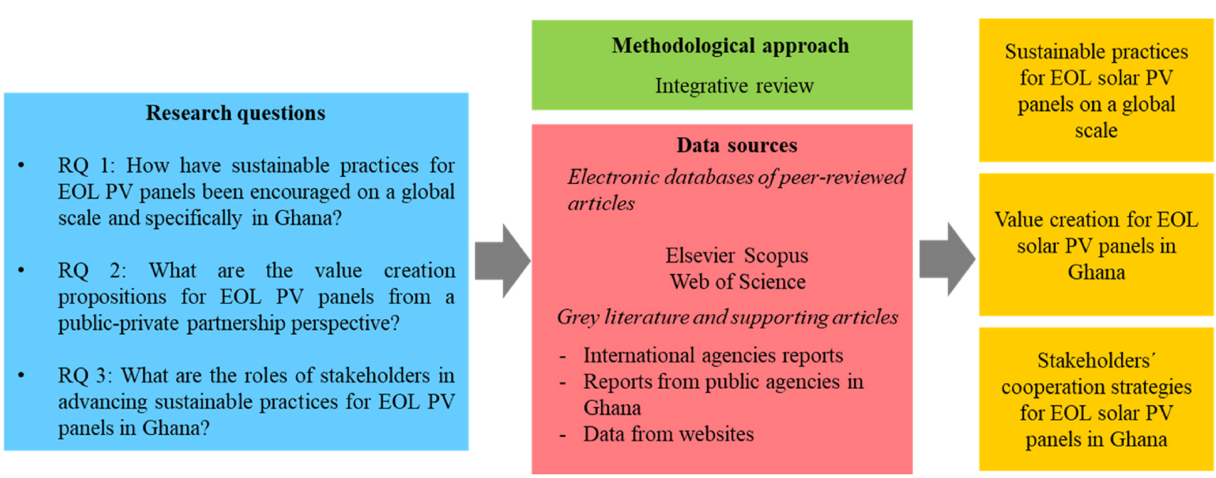

Fig. 1. Research outline.

Table 1
Value creation processes for end-of-life solar photovoltaic panels: reuse, refurbishment, recycling, and recommissioning

Value creation process	Contributions with references
Reusing	• Implementation of circular economy based reuse of PV cells (Brenner & Adamovic, 2017; CABRISS, 2021). • PV- waste as a source for raw materials and other valuable components (IRENA & IEA-PVPS, 2016; Tasnia et al., 2018). • The PV waste management focuses towards sustainability among different stakeholders (Azeumo et al., 2019; Mahmoudi et al., 2021). • Integrating social to techno-economic factors in a model provides a more realist scenarios of circularity potential of reusing and recycling PV panels (Walzberg et al., 2021). • At the end of life PV panels can be reuse as recycled materials (Chowdhury et al., 2020; Shin et al., 2017).
Repairing refurbishment	• The repair of PV panels can be managed efficiently by coordinating the stakeholders with respect to design, production, collection and recovery of the panels (Besiou & Wassenhove, 2015; Chowdhury et al., 2020). • Value creation goes beyond the economic dimension to involve environmental dimension. Remanufacturing and refurbishment of EOL solar PV panels are included in the sustainable innovation strategy (Regenfelder et al., 2017). • Identification of potential economic benefits of circularity in in different stages of the supply chain of EOL PV (Deng et al., 2020). • The repair and maintenance of end-of-life PV panels can be a useful aspect in the circular economy and can recommend research and development to reduce cost and environmental impact (Heath et al., 2020).
Recycling	• Recycle of PV panels after macro and micro analysis of crystalline silicon offers significant financial benefit (Shin et al., 2017). • Recycle of EOL PV modules focuses on the maximum recovery of materials to ensure the optimum benefit (Farrell et al., 2020) • The recycling of PV panels can be improved by the ease-of-disassembly of valuable components. It has significant impacts to reduce environmental impacts (Tao & Yu, 2015; Tasnia et al., 2018). • Challenges for creating value are the current high impact of energy consumption in mechanical treatment in the recycling of EOL photovoltaic panels. The energy resources used for recycling could be higher than the consumption of materials and energy used for construction (Del Pero et al., 2019). • PV wastes if appropriately recycled after decommissioned can bring substantial economic advantages to the renewable energy business (Mahmoudi et al., 2019). • Recycling and management of EOL PV panels as a "second mining" alternative from the consumer countries (Mahmoudi et al., 2019). • Advanced thermal treatment is explored to separate different materials from Silicon PV panels (Fiandra et al., 2019). • Value creation through the use of thermochemical process such as pyrolysis provides an alternative for recycling EOL c-Si PV modules (Farrell et al., 2021). • The value creation and value capture in EOL photovoltaic panels could be increased by maximizing the recovery of silver and copper, as well as recycling the aluminium frame and preserving the purity of the low Fe glass fraction. (Duflou et al., 2018). • Thermal delamination provides an alternative for removal of polymers crystalline silicon (c-Si) photovoltaic (PV) modules to facilitate materials recovering (Dobra et al., 2021). • Implementation of recycling policies and the use of technologies for data acquisition and treatment offers an alternative for the recycling of thin-film thermal process (Aravelli & Ramavathu, 2021). • Value creation and value capture from EOL PV panels could become a multi-billion USD industry. The challenge is to reduce recycling costs (Vargas et al., 2021). • The application of hexane offers an environmental alternative approach for expanding the lifespan of recycled PV panels (Tembo, 2021). • Value creation through the recovery of valuable materials resourced from waste crystalline-silicon PV module (Si, Ag, Cu, Sn) (W. Chen et al., 2021) . • Recycling EOL PV panels to recovery FTO coated glass substrate could be an alternative to take advantage of one of the most expensive components in PV panels (Chowdhury et al., 2021). • Value creation from recycling through the coarse tellurium extraction from photovoltaic waste (H. Chen et al., 2021). • Quantification of material flux recovery from recycling process using mechanical and manual dismantling techniques (Padoan et al., 2021). • A systematic analysis of different material alternatives to recycle dye solar cells (Miettunen & Santasalo-aarnio, 2021).
Recommissioning	• Recommissioning is an important decision to give a second-life to PV solar panels decommissioned but show functional conditions. This is one of the alternatives to maximize the benefits across the whole PV value chain (Tsanakas et al., 2020).

3.1.2. Global landscape of end-of-life photovoltaic waste

Currently, most countries do not have specific regulations for PV waste management, which generates inadequate disposal of this waste, with adverse effects on health and the environment (Mathur et al., 2020; Venkatachary et al., 2020). So far, the European Union and a few other countries have set up specific protocols for PV waste (Xu et al., 2018). The fast dissemination of solar PV technology has forced the European Union to create reactive policies to avoid possible impacts from waste generated at the EOL of PV panels (IRENA and IEA-PVPS, 2016; Sander, 2007). In 2012, the European Union issued the Waste Electrical and Electronic Equipment (WEEE) Directive, forcing manufacturers and suppliers of PV panels in the European market to cover the expenses of collection and recycling of EOL PV panels (Chowdhury et al., 2020; Sharma et al., 2019). The WEEE directive includes extended producer responsibility (EPR), whereby producers would collect and recycle at least 85% of their PV panels free of charge (ISE, 2018; Venkatachary et al., 2020). Along with the WEEE directive and national policies, voluntary initiatives to recycle photovoltaic panels have been established among different actors in the solar photovoltaic supply chain. The two most recognized waste recycling entities are First Solar and PV Cycle. First Solar offers recycling services, and uses almost 90% of the glass for reuse and 90% of the semiconductor materials for new modules (Sharma et al., 2019). PV Cycle is a public-private partnership integrated by stakeholders of the solar PV industry and European governments, which originated as a voluntary initiative for recovery and recycling (Sharma et al., 2019). At the moment, research efforts are shifting towards adopting sustainable strategies that broaden the scope of EOL solar PV panel management (Tsanakas et al., 2020). Here, different stakeholders can be involved to create value and business opportunities not only from recycling activities but also from reusing, repairing/-refurbishment, and recommissioning of solar PV panels. It is worth mentioning that although studies focusing on different forms of value creation from EOL have increased in recent years, the information is very diffuse (Tsanakas et al., 2020). In Table 1 we summarize the main studies focusing on value creation for EOL solar PV panels.

3.2. Outlook for end-of-life solar photovoltaic panels in Ghana

In the particular case of Ghana, the abundance of solar energy resources (in a range of 4–6.5 kWh/m^2/day) provides a suitable scenario for the emergence of new solar PV projects (EC Ghana and UNDP, 2015; IRENA, 2015). Ghana, like most countries in Africa, has a beneficial geographical situation, resulting in high solar radiation throughout the year (Aboagye et al., 2021). Notably, one of the key aspects of the expansion of solar PV technology in Ghana is the need to increase access to electricity (EC Ghana and UNDP, 2015). Currently, approximately 17% of the population have no access to electricity (US AID, 2020). Official information on the currently installed capacity of solar PV panels in Ghana is limited. In fact, there are significant differences regarding the solar PV installed capacity reported by different sources. For example, the Energy Commission reported the figure of 7.99 MW from solar PV by 2015 (EC Ghana and UNDP, 2015, p. 26), whilst non-official sources such as ESI Africa (2021) indicate a solar PV installed capacity of 64 MW. Regarding plans for new solar installations, information is provided by MoEn Ghana et al., (2019), which describes the new Ghana Renewable Energy Master Plan (REMP). The specific objectives of the REMP are enlarge the share of renewable energy in Ghana's energy mix to 1363 MW by 2030. In particular, the goal for solar PV is to reach around 692.5 MW of capacity by 2030 through three investment cycles that include utility scale, distributed PV, standalone PV, solar street lighting, and solar traffic signs, among other applications. Considering the difficulty of finding unified and official information on installed capacity, as well as the additions of new capacity every year since the first installations, estimation of the dismantling or dismantling projections of EOL photovoltaic solar panels is significantly complex. This would require an empirical approach in conjunction with the Government of Ghana and key stakeholders. At the moment, whenever it is possible to collect the data on annual capacities and on photovoltaic solar energy in the market, it is possible to use these in accordance with the model proposed in the IRENA and IEA-PVPS(2016). This model makes it possible to quantify the future flow of waste from photovoltaic panels using the conversion data and the probability of loss during the life cycle of the photovoltaic panel (IRENA and IEA-PVPS, 2016). The model uses two waste flow scenarios (regular loss and anticipated loss) using the Weibull function (IRENA and IEA-PVPS, 2016).

Although Ghana has adopted the Hazardous and Electronic Waste Control and Management Act of 2016, which includes provisions for the management and disposal of hazardous electrical and electronic waste and its related purposes, with guidelines and prohibitions on the import and export of hazardous and other wastes, it does not clearly include the country's informal e-waste sector in the process (Republic of Ghana, 2016, p. 3). Therefore, it is clear that Ghana and most other developing economies urgently need to define a clear 'roadmap' for PV waste management, even though the solar PV industry is relatively young in this particular country. According to the guidelines developed by the Africa Clean Energy Technical Assistance Facility and Coffey International Development Ltd (2019), the most important challenges for PV waste management in African countries are the entrenched informal sector, lack of stakeholder engagement, limited capacity (personal and technical), lack of enforcement, and insufficient data on electronic waste stocks and flows. Taking into account the relevance of cooperation between stakeholders, and the need to develop skills, knowledge and infrastructure, we have proposed a value creation option for EOL PV panels in developing economies like Ghana.

3.3. *Value creation from end-of-life solar photovoltaic panels in Ghana*

The strategy for the creation of value for EOL solar PV panels proposed for Ghana is derived from the conceptual framework developed by Ndzibah et al. (2021), which takes into account as key factors the technical solutions, logistics and innovative business models for activities, not only limited to recycling, but also including the reuse and repair of EOL solar PV panels. This conceptual framework is aligned with the global sustainability strategies for innovation supported by the environmental, economic and social pillars. The creation of value for EOL solar PV panels is not limited to a single side of the value chain, but integrates multiple associated actors in partnerships and business networks (Regenfelder et al., 2017). This strategy is detached from the traditional business models focused on a single product or service in the first phase of the life cycle, because, on the contrary, the creation of value emerges precisely from the exploration of all the possibilities of taking advantage of the product *per se*, and different components and all possible revenue streams. Therefore, technical-economic knowledge of the alternatives is essential for the development of value propositions, as well as the identification of the stakeholders at the different levels of the value chain. Furthermore, to ground a sustainable strategy for value creation, it is necessary to identify the skills needed for companies and for the people involved in different processes. Above all, it is crucial to customize the strategy to the reference context, considering the possible opportunities and limitations. Our study focuses on Ghana, a country that is emerging as a consumer of solar PV panels in the medium and long term.

In recent years, some African countries have been structuring policies for electronic waste management focused on preventing the impacts derived from hazardous materials (ACE TAF and Coffey International Development Ltd, 2019). However, most of these political frameworks are not oriented toward value creation from waste; moreover, the specific management of PV waste is not clearly laid out (ACE TAF and Coffey International Development Ltd, 2019; Hansen et al., 2021). Although value creation from EOL solar PV is particularly challenging in developing economies because of budget constraints, the lack of infrastructure for PV waste management, and the logistical complexity of transportation and collection in off-grid PV, it is undeniable that opportunities can be generated from reuse, repair/refurbishment and recycling (ACE TAF and Coffey International Development Ltd, 2019). The option of recycling solar panels after decommissioning activities would allow the unlocking of a wide stock of raw materials and other components (IRENA and IEA-PVPS, 2016; Ndzibah et al., 2021). PV waste can be a source of new revenue streams after appropriate recycling as well as reducing environmental and health impacts (Mahmoudi et al., 2019). In this sense, authors such as Sajjad Mahmoudi et al. (2019) have pointed out the potential of the recovery of materials as the "second mining industry" of the PV value chain. PV waste can lead to new products an opening a room on the global commodity markets. In a scenario of low PV penetration, the value creation and capture could reach around one US$ billion from the fabrication of approximately 50 million new solar PV panels from the recovered materials (Mahmoudi et al., 2019). However, three fundamental aspects must be taken into account to foster recycling in developing economies: (i) the logistics of collection, transport and transfer; (ii) the financial viability of implementing technical solutions for the recovery of materials; and (iii) the promotion of innovative business opportunities (ACE TAF and Coffey International Development Ltd, 2019; Augustine et al., 2019). Logistics is perhaps one of the most complex aspects to address (ACE TAF and Coffey International Development Ltd, 2019; Hansen et al., 2021; IRENA and IEA-PVPS, 2016). The high dispersion of solar PV installations and the proliferation of medium- and small-scale projects must be taken into account when planning EOL PV waste management (EC Ghana & UNDP, 2015; IRENA, 2015). Here, the costs of collection and transportation can dominate the overall costs of waste management (Augustine et al., 2019; Deng et al., 2019). At the same time, it will be crucial to bring in qualified workers (electricians and roofers), as well as personnel trained in collecting and transporting PV panels in the appropriate conditions (IRENA and IEA-PVPS, 2016). Furthermore, recycling infrastructure is fundamental to achieving the optimal recovery of materials (ACE TAF and Coffey International Development Ltd, 2019).

Currently, most PV waste recycling is carried out in conventional recycling plants, given the moderate amount of waste at the moment and the lack of economic incentives (IRENA and IEA-PVPS, 2016). However, it is desirable that recycling plants dedicated to PV waste be established in the long term, which could increase recovery capacity and maximize revenues, especially because the recycling industry in Ghana has a large proportion made up of the informal economy (ACE TAF and Coffey International Development Ltd, 2019; Manhart et al., 2019). As has been stated by Balde et al. (2017), electronic waste management in Africa is controlled by collectors and recyclers from the informal sector in most countries, recycling infrastructure are either non-existent or extremely limited. One of the examples cited in this report is the site known as "the Agbogbloshie" in Ghana, which has raised international concern.

Therefore, the implementation of synergies to formalize and qualify people and companies in the proper management of PV waste is relevant.

3.3.1. Second life of solar photovoltaic panels through recommissioning

One of the options that should be considered in developing countries like Ghana is the possibility of providing a 'second life' for PV panels by recommissioning, either by being replaced after 25–30 years of use by more efficient equipment, or by being repaired and returned to an operational state. Before any decommissioning process, there should be a testing and assessment of individual units to establish whether the PV panels can be reused, repaired or recycled. PV panels in operational conditions can be given a 'second life' as in new installations in rural communities, educational centers or other third parties. Equipment, the evaluation of which indicates that they are still in operational condition, even with efficiency reductions, will still be very useful to meet the needs of multiple communities to have access to energy services. In this regard, Tsanakas et al. (2020) argue that a significant number of solar PV panels are decommissioned even if they do not show operational failures for reasons related to insurance claims, or the overhauling of solar infrastructure, amongst other technical reasons. These solar PV panels or arrays of PV panels could be considered in the first instance to be recommissioned after a testing and labelling process is completed.

Currently, to our knowledge, no official estimates of PV waste quotas have been published for disposal, recycling or reuse/repair/retrofit/recommissioning. However, Ghana's Renewable Master Plan recognizes that along with increasing solar PV capacity, PV waste will also increase, requiring proper management. The plan considers that REMP resources will support the expansion of the recycling infrastructure and the construction of new locations for the appropriate use and disposal of photovoltaic waste (MoEn Ghana et al., 2019).

3.3.2. Reuse, repair and refurbishment

Similarly, EOL PV panels found in non-functional conditions should be subjected to a quality inspection to identify the origin of the failure and possible alternatives to fixing it (ACE TAF and Coffey International Development Ltd, 2019; IRENA and IEA-PVPS, 2016). Value creation in this case includes prolonging the value chain towards a circular economy business, where PV solar panels can be repaired or refurbished (Kazancoglu and Ozkan-Ozen, 2020; Regenfelder et al., 2017). Repaired PV panels can be sold at a price of about 70% of that of new panels (IRENA and IEA-PVPS, 2016). As an example, in countries like India, the reuse industry includes maintenance, repair, resale and refurbishment and reassembly, and the remanufacturing of electronic waste (Corwin, 2018, p. 19). The growing market for electronic waste for the above mentioned purposes has enhanced the development of industries specialized in different aspects of the process, producing significant positive impacts in the economy (Corwin, 2018). With the proliferation of PV installations, the market for second-hand PV panels and components is also increasing in developing economies. The second-hand market industry can provide a new eco-friendly variant for entrepreneurs in Ghana. To achieve a well-developed market for second-hand PV panels, it is necessary to establish technical tests and qualification to guarantee the operating conditions of the PV panels returning to the market (IRENA and IEA-PVPS, 2016; Tsanakas et al., 2020). At the moment, most repair or refurbishment activities of PV solar panels in developing countries are not performed under formalized or standardized schemes (Tsanakas et al., 2020). This aspect may hinder business opportunities at the medium and large-scale level. It is difficult to provide an economic estimation for implementing value creation strategies for EOL photovoltaic solar panels in Ghana due to the limited and unreliable information currently available. However, it is important to mention that the REMP contemplates an estimated investment of US $ 5.6 billion during the period 2019 to 2030. This amount includes investment in infrastructure for the recycling and disposal of photovoltaic waste. Under the plan, successful implementation could generate more than 200,000 jobs, including those related to recycling (MoEn Ghana et al., 2019).

3.3.3. Ghana as an importing country of solar photovoltaic panels

The phenomenon of EOL solar PV panels has been overlooked in consumer countries (Mahmoudi et al., 2019). To foster value creation from EOL PV waste management, it is imperative to take into account that countries such as Ghana are importers of PV panels (Hansen et al., 2021). Since the production of this equipment takes place outside the country, the recycling costs are, in practice, being assumed by the importing country. Furthermore, the recovered semiconductor materials do not have developed markets within the importing country. This is possibly one of the most complex aspects in promoting value creation from EOL PV panels in countries like Ghana. In addition to the costs of the logistics of collecting highly dispersed PV panels and their treatment, there is the barrier of the commercialization of the components recovered in recycling processes. Ghana, in its role as an importer of PV panels, will not develop a demand for materials that will achieve a positive balance between recycling costs and revenues from the marketing of materials (Hansen et al., 2021). Viable options for the recycling of EOL PV panels in Ghana would be the establishment of policies to extend responsibility for the costs of recycling and disposal of hazardous materials to the producer (ACE TAF and Coffey International Development Ltd, 2019; Hansen et al., 2021), whereby companies would be compelled to recycle PV panels after decommissioning. This would require the alignment of the solar PV value chain in Ghana so that the quantities of equipment on the market can be both controlled and the logistics of recovery ensured. Regardless of the strategy for creating and capturing value of EOL PV panels, alignment of the actors in the value chain is required. Regarding the value creation from second life through the recommissioning, reusing, repairing, refurbishment or recycling of EOL solar PV panels, it is imperative to build collaboration networks among stakeholders of the whole value chain (Regenfelder et al., 2017).

3.3.4. Public-private partnerships: stakeholders' collaboration strategies

Synergies among stakeholders from the solar PV industry and the waste management sector are crucial for an effective EOL PV waste management system (Hansen et al., 2021; IRENA and IEA-PVPS, 2016). Partnerships in the global landscape of PV waste management indicate some successful examples, such as PV CYCLE, but more evidence is needed related to the formation and consolidation of cooperation between the PV solar industry and waste management. Similarly, some recent studies present public-private partnerships as a possible alternative to encourage both the public and private sectors to assume and share responsibilities in the management of EOL photovoltaic solar panels and the creation of value (Khawaja et al., 2022). The first step in creating a collaborative strategy, for example public-private partnerships, is to identify groups of stakeholders in the solar PV industry. Information from official agencies in Ghana (EC Ghana and UNDP, 2015; MoEn Ghana et al., 2019) indicates five groups: (i) public agencies in energy issues, (ii) actors in the solar PV industry, (iii) financial institutions, (iv) end-users, and (v) research and educational institutions (Fig. 2). Since the guidelines for electronic waste in Ghana do not include specific norms for PV waste management (EPA, 2018), there are no visible synergies between the solar PV industry and the waste management sector.

Here it would be relevant to mention that the ownership of the major on-grid solar PV installations in 2015 are related to the Volta River Authority (2500 kW), Noguchi Memorial Institute for Medical Research (715 kW), Trade Works Company Ltd (10 kW) and the Energy Commission (4.25 kW) (EC Ghana and UNDP, 2015, p. 26). Additionally, there is also a significant presence of private companies in solar power installations: for example, in private office buildings and private residences, and also there are more than 90 installations in rural communities (EC Ghana and UNDP, 2015). Along with these stakeholders, there is also international coordination with financial institutions such as

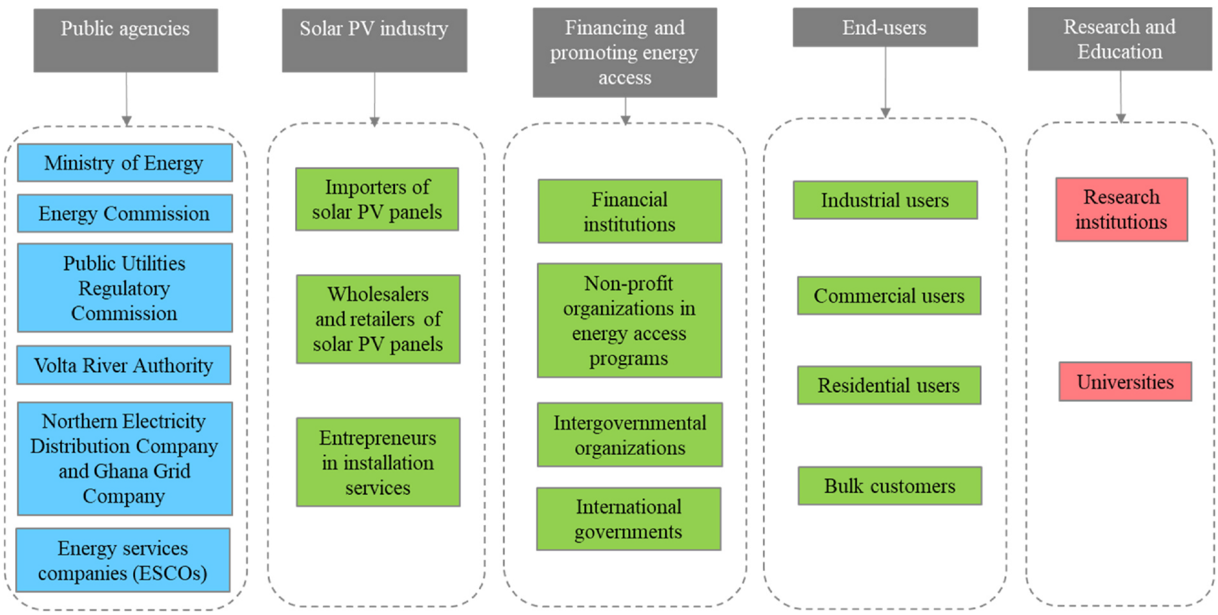

Fig. 2. Stakeholder map of the solar photovoltaic industry in Ghana.

multi-development banks, research institutions, non-profit organizations, intergovernmental organizations and international governments to support actions aimed at changing to renewable sources in Ghana. Some examples are the African Development Bank, World Bank, European Union, United Nations, Agence Française de Développement, Dutch Ministry of Foreign Affairs, German Federal Ministry for Economic Cooperation and Development, Norwegian Ministry of Foreign Affairs, Australian Agency for International Development, UK Department for International Development, and Swiss Agency for Development and Cooperation (EC Ghana and UNDP, 2015, p. 26).

To elucidate the path to building solid collaboration in PV waste management, we propose a new map of stakeholders based on a systemic approach (Fig. 3). Here, stakeholders are classified into three levels: (i) the strategic level, which includes policymakers, regulators and legislators in Ghana (IRENA, 2015; MoEn Ghana et al., 2019); (ii) the operational level, encompassing stakeholders such as those participating in current solar PV projects (upstream stakeholders), end-users, and those actors who create value from PV waste (downstream stakeholders); and finally, (iii) the supporting level, including institutions related to research and development and to education, as well as consultants and civil organizations. This map locates new actors that can intervene in the energy arena by offering services related to repair,

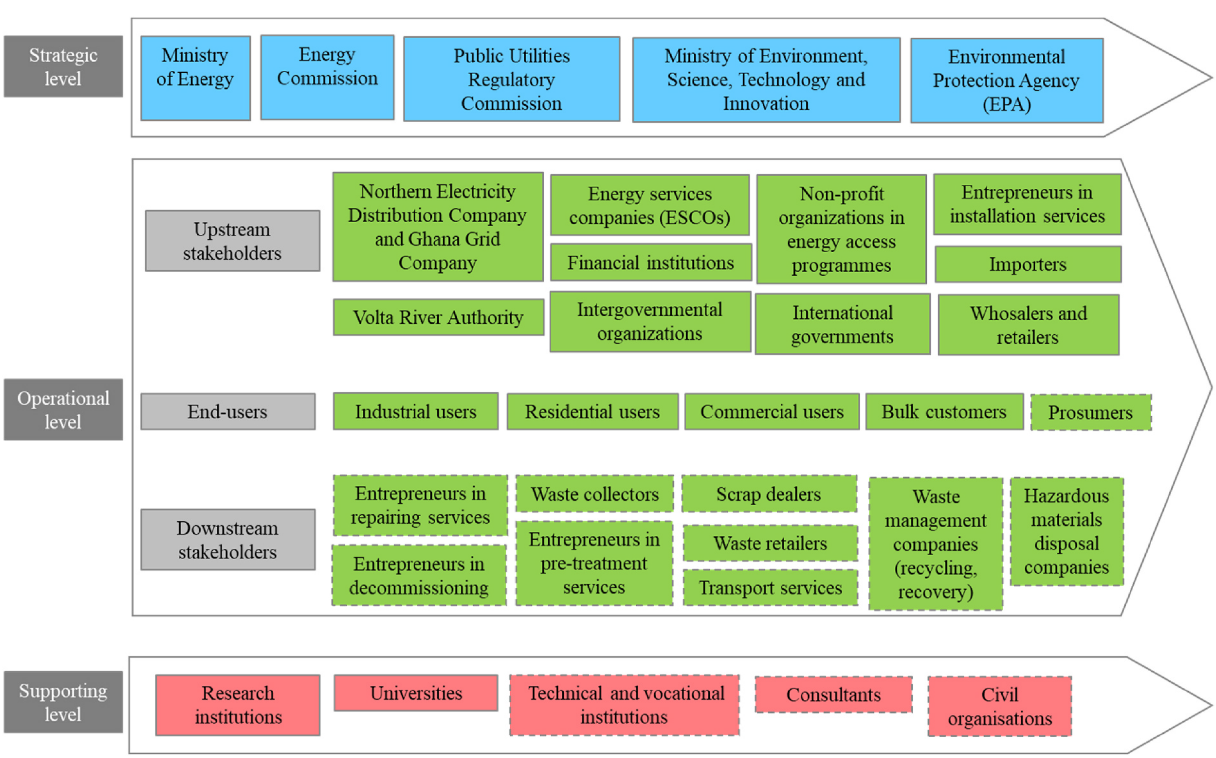

Fig. 3. Stakeholder map adapted to solar end-of-life solar photovoltaic panels management for Ghana.

installation, recycling, transport, storage, and consulting in EOL PV management, as well as users who can become "prosumers" in the medium term: that is, producers and consumers at the same time.

The collaboration strategy for the Ghanaian context should consider the possible barriers, drivers and enablers. Since 2011, the Ghana Ministry of Finance initiated a national policy on PPPs for the development of infrastructure and services projects (EC Ghana and UNDP, 2015; MoEn Ghana et al., 2019). At the moment, PPPs have proven to be a suitable option for thermal power plant projects in Ghana. At the same time, PV solar power in Ghana and in other developing economies is characterized by decentralized, off-grid, rural use, in large proportion in smaller-scale projects, where conventional cooperation approaches can be highly limiting (EC Ghana and UNDP, 2015; IRENA, 2015). In fact, PV systems and off-grid solar PV have very specific characteristics for cooperation initiatives in PV waste management, such as the great variety of stakeholders in the value chain (ACE TAF and Coffey International Development Ltd, 2019). Taking into account the complexity of addressing collaboration between cross-sectoral stakeholders for a 'meta-problem' such as the implementation of a sustainable innovation strategy and value creation for EOL solar PV panels, we found a basis in the application of the concept of 'hybrid public-private partnerships' (HPPPs) (Ungureanu et al., 2018; Vikkelsø et al., 2021). According to Ungureanu et al. (2018) and Zhu and Sun (2020), hybrid partnerships encompass a broad assortment of organizational arrangements between cross-sectoral stakeholders, combining resources for sustainable business. Hybrid partnerships should be designed according to the specific context because they comprise diverse goals, values and institutional logics (Nel, 2018; Vikkelsø et al., 2021). Based on a HPPP approach, we propose to build cooperation among stakeholders at the strategic level, the supporting level, and the operational level to achieve a suitable EOL PV waste management system. For instance, HPPPs can be built by public agencies with upstream stakeholders such as retailers, importers and ESCOs, and with downstream stakeholders such as entrepreneurs in repairing, decommissioning, pre-treatment, transport and waste management services. These HPPPs can assist in compliance with policies of extended producer/supplier responsibility to undertake PV waste management (ACE TAF and Coffey International Development Ltd, 2019; IRENA and IEA-PVPS, 2016). One of the most important challenges of the HPPPs for PV waste management will be financing the infrastructure and developing the technical and business competencies in the downstream stakeholders (Manhart et al., 2019). Overall, building new HPPPs should start with a clear definition of their possible revenue stream(s) and cost(s), identification of possible risks, and appropriate mechanisms for ensuring transparency, commitment and accountability. The financial viability of EOL PV waste management depends not only on the development of the national value chain (Hansen et al., 2021), but also on the interaction with international actors (Hansen et al., 2021). Therefore, simultaneously with the consolidation of HPPPs in the national value chain of Ghana, work should also be done in cooperation with international actors, such as PV panel producers, international dealers and suppliers in commodity markets, governments and other associated international organizations. Stakeholders at the strategic level of the Ghana national value chain should work on building HPPPs with international governments from where the PV panels are mainly imported. These alliances will help to make it easier for producers and suppliers to assume the extended responsibility of the producer in the collection and management of EOL PV waste. Furthermore, strengthening synergies with international actors could facilitate the transfer of knowledge to Ghana on emerging technologies to create value from recycling, repair, refurbishing, and recommissioning of EOL solar PV panels, as well as research and development and education and training activities.

3.3.5. *Collaboration in transferring knowledge: a platform for education in sustainability*

As mentioned before, one of the most important barriers in the implementation of a sustainable PV waste management system at a global level is the lack of technical and business capacities in PV waste management (IRENA & IEA-PVPS, 2016). According to Tsanakas et al. (2020), the activities related to reuse, repair and refurbishment of EOL solar PV panels are currently developed under informal or non-standardized procedures. The case of Ghana deserves particular attention due to its high potential in the solar industry, and, at the same time, informal economy in the waste management sector (ACE TAF and Coffey International Development Ltd, 2019; Hansen et al., 2021). Therefore, it is essential to create an educational platform for capacity-building. The role of this platform is documenting the needs in terms of technical competencies as well as business, management and marketing competencies, and developing suitable programs to support the EOL PV waste management system (EPA, 2018; Salim et al., 2019b) (Fig 5). The platform should provide certified programs to prepare citizens to meet the requirements of PV waste management in cooperation with stakeholders in the value chain (EC Ghana and UNDP, 2015; Salim et al., 2019b). To establish this platform requires the agreement between different stakeholders to determine the demand for people both in the upstream and downstream side and the skills required in each case (Fig. 4). It is necessary to liaise with the national government to determine the needs for skills and demand. The academy needs to prepare programs according to the needs of the upstream and downstream stakeholders in the value chain. The establishment of HPPPs between stakeholders will provide competent personnel to carry out activities aimed at value creation and the adequate disposal of EOL PV panels, and additionally, it will foster the expansion of the renewable energy industry in Ghana. Moreover, the consolidation of this platform will contribute to compliance with national policies and international normes in solar PV waste management, and also with the reduction of CO_2 emissions and acknowledgement of the significance of the environmental and health aspects associated with PV waste.

3.4. *Discussion of key insights from the research work*

This study offers an innovative proposal on value creation for EOL solar PV panels. Our research work integrates data from the most relevant and up-to-date studies and official reports. This phenomenon has been approached using three research questions. The first asks *how have sustainable practices for EOL PV panels been encouraged on a global scale, and specifically in Ghana?* At a global level, although there is concern about the need to deal with the PV waste problem, only the European Union has implemented a specific regulation for PV waste management. The European Union has incorporated PV waste in its Waste Electrical and Electronic Equipment (WEEE) Directive, which involves specific targets in terms of collection, recovery and recycling. This directive also introduces the principle of extended producer responsibility for PV panel producers participating in the EU market. The proper management of hazardous materials contained in PV waste is encouraged, as well as the exploitation of business opportunities from the recovery of valuable materials. Several voluntary initiatives of public-private partnerships have shown positive results in facilitating compliance with extended producer responsibility and material recovery. However, it is necessary to extend cooperation networks among stakeholders from the solar PV industry, public agencies and the waste management sector. Additionally, reliable data is required regarding the number of solar panels that enter the market at the level of each country, which would serve as the basis for designing adequate regulatory instruments (IRENA and IEA-PVPS, 2016). In particular, this is a barrier for developing economies, where it would be necessary to implement mechanisms to unify the data referring to PV panels that enter the market and to those that reach the decommissioning stage. The second part of the same question focuses on *how to encourage or promote sustainable practices for EOL PV panels in a developing economy like Ghana.* In Ghana, as in most developing economies, the challenge of implementing a robust sustainable PV waste management system is paramount. The proposal is

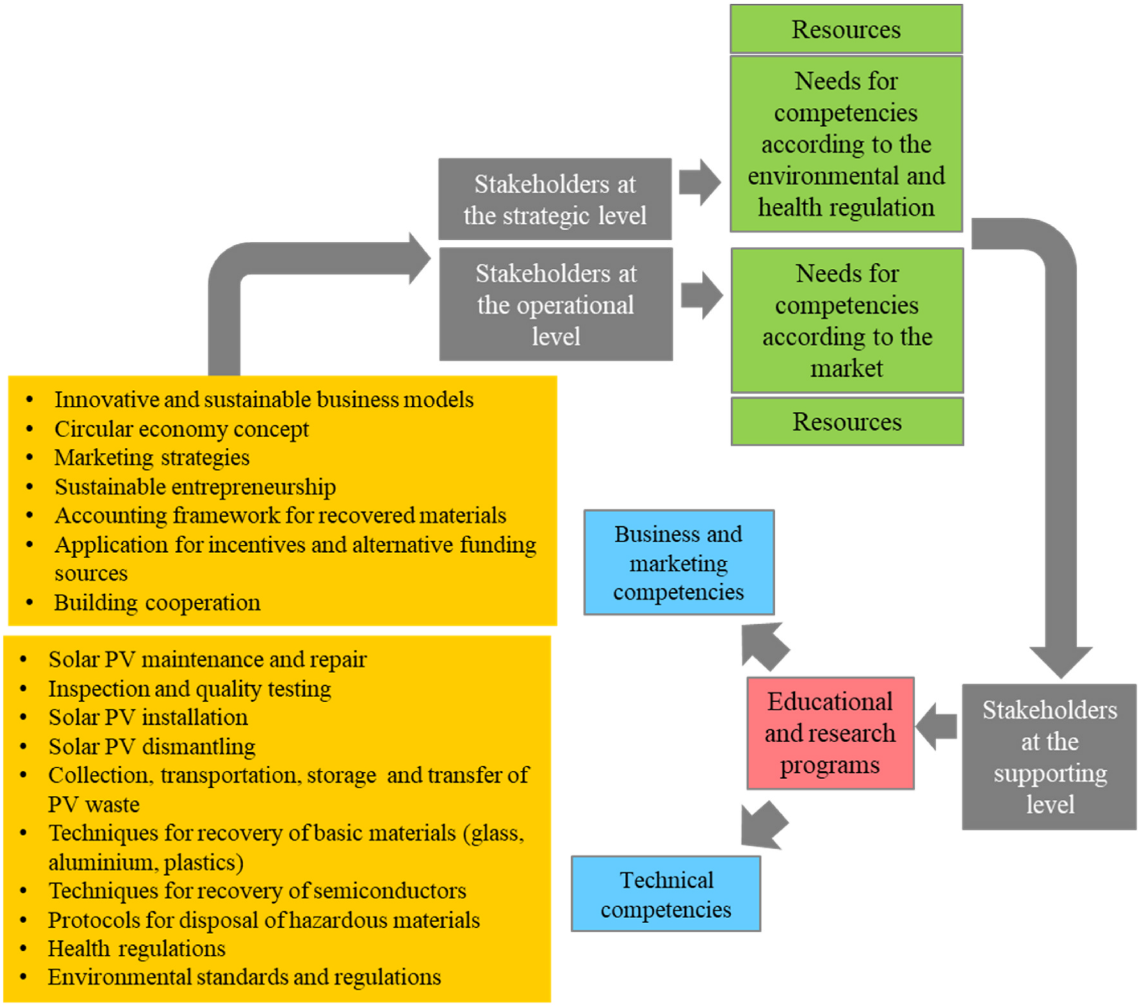

Fig. 4. Cyclical scheme of the technical, business and marketing competencies to address in a platform for education in sustainability and the stakeholders at the strategic, operational and supporting level.

based on three factors according the study conducted by Ndzibah et al. (2021): (i) exploration and strengthening the value creation from PV waste in terms of reuse, repair/refurbishment, recommissioning and recycling; (ii) building hybrid partnerships among stakeholders at the strategic, operational and supporting levels; and (iii) the creation of a platform for capacity-building. These factors must be supported by an adequate regulatory and financial framework. Therefore, it will be necessary to focus work at a strategic level not only on designing policies and regulation, but also on the appropriate incentives to motivate stakeholders to actively participate in PV waste management. Additionally, intensive work is needed to develop innovative business models, reducing the risk aversion of stakeholders in a nascent industry and ensuring the economic sustainability of the system. Building sustainable EOL PV waste management in developing economies also involves high up-front costs in infrastructure, personal training, and operation costs. Moreover, the emerging markets for PV by-products and second-hand PV panels may not provide the expected economic returns in the short and medium term. Governmental support is needed to address the challenge of applying the principle of extended producer responsibility (EPR) to leverage the cost of PV waste management. The second research question *discusses the value creation propositions for EOL PV panels from a public-private partnership perspective*, and the proposal involves identifying the stakeholders in the whole value chain, considering the complexity of HPPPs from their multiplicity of actors. Additionally, our study presents the relevant role of stakeholders in the strategic, operational and supporting levels of the value chain, where their core responsibilities are clearly beyond politicizing waste management. In addition, despite budget constraints, inadequate infrastructure, as well as an ongoing logistical complexities there are opportunities to promote the reuse, repair, recommissioning and recycling of EOL PV panels. Furthermore, in the context of developing countries and specifically Ghana, the basis of encouraging such value creation includes a clear protocol to ascertain: (i) the logistics of collection, transport and transfer; (ii) the financial viability of implementing technical solutions for the recovery of materials; and (iii) the promotion of innovative business opportunities. A constructive synergy among stakeholders from the solar PV industry and waste management sector will strengthen a better value creation process. The third research question related to *the roles of stakeholders in advancing sustainable practices for EOL PV panels in Ghana.* We present a map of current stakeholders of the PV industry as a baseline. Additionally, we propose a new map, where stakeholders are classified according to their role in the EOL PV waste management system. The creation of synergies among those stakeholders would be crucial for the success of PV waste management. However, cooperation depends largely on a solid institutional framework for ensuring the principles of transparency, accountability, power balance and commitment in hybrid partnerships. Once PV waste management is established, benefits can be obtained from the three dimensions of sustainability, namely the environmental, social and economic dimensions (Ndzibah et al., 2021; Salim et al., 2019a). The incorporation of the circular economy concept can help in reducing GHG emissions and the use of landfill for PV waste disposal as well to the proper disposal of hazardous materials (Ndzibah et al., 2021; Salim et al., 2019a). In the social sphere, there are relevant opportunities, such as the creation of new jobs, new sustainable entrepreneurships, and enhancing cooperation and participation of social actors in the EOL PV waste management system (Ndzibah et al., 2021; Salim et al., 2019a). Regarding economic benefits, the value creation from PV waste can stimulate the economy through new ventures, the development of new markets and technology transfer. It should be noted that this article does not intend to rule out the existence of uncertainty about the implementation of different strategies for the creation of value of EOL solar PV panels in Ghana (i.e. waste volume uncertainty, material uncertainty, demand for recovered material uncertainty, etc.) (Besiou and Wassenhove, 2015), but rather to expose the technical, logistical and social aspects involved. As mentioned above, international experience indicates the relevance of country-level strategies based on value chain alignment and collaboration among stakeholders, and strong policies related to the responsibility of producers, importers, and users among involved stakeholders. Additionally, support should be given for research and development to create internal infrastructure and to take advantage of the opportunities of EOL solar PV panels after decommissioning. Therefore, it is undeniable that one of the critical steps towards reducing risk will be the implementation of policies and associated regulation and incentives for managing EOL solar PV panels in Ghana.

4. Conclusions

This study provides a contemporary viewpoint on PV waste management on a global scale based on the most salient studies (Salim et al., 2019a; Song et al., 2020). But the central goal is to approach this phenomenon in developing economies, in particular in the context of Ghana. Our study puts emphasis on the value creation of EOL PV panels for developing economies, using Ghana as a practical example. The study thus offers a comprehensive outlook on EOL solar PV panels on three fronts, namely the exploration of value creation, building HPPPs among stakeholders, and collaboration strategy for knowledge transfer through an education platform. Particularly regarding building hybrid partnerships, this study provides a map of current stakeholders and a roadmap with all the stakeholders of the supply chain, organised at the strategic, operational and supporting levels. Furthermore, the paper provides information regarding the technical, business and marketing competencies needing to be addressed in a platform for education in sustainability. Finally, our study highlights the research area focus for further studies.

4.1. Future prospects

Efforts in future research work to structure and implement strategies oriented towards value creation and value capture through collaboration of EOL PV panels in developing countries should focus on:

- A review of results of international experiences in programs of extended producer responsibility, reverse logistics, emerging recycling technologies and public-private partnerships to structure strategies oriented to the closed cycle and the creation of value and the capture of value of EOL solar PV panels;
- Focusing research efforts on building extended producer responsibility schemes, in which the network of services and sales at different levels (national and international) is used to collect the EOL solar PV panels (Yu and Tong, 2021);
- Structuring of voluntary participation schemes in collaboration programs that generate synergy between the actors in the value chain, and whose results contribute to the development of adequate regulation and incentives (Besiou and Wassenhove, 2015);- Focusing research efforts on the potential market for equipment and materials recovered from EOL photovoltaic solar panels leading to reduced uncertainty for stakeholders;- Developing information systems related to photovoltaic solar panels in the market that provide realistic projections on the amounts of photovoltaic waste in Ghana;- Building an EOL PV waste management regulatory framework for developing economies that focuses on value creation from PV waste, builds cooperation networks and structures a platform for education in sustainability.- The creation of innovative business models that reduce the risk aversion of stakeholders in a nascent industry that guarantee the economic sustainability of the system.

4.2. Managerial implications

The present study is not limited to summarizing the existing literature. Compared to previous studies on EOL PV waste, in addition to providing an outlook on the world landscape of PV waste management, our study also proposes a value creation process for building EOL PV waste management systems in developing economies. The research outcomes of our work include (i) an identification of value creation strategies for Ghana, (ii) a stakeholder roadmap for building PV waste management partnerships in developing economies and specifically in Ghana, and (iii) information regarding the technical, business and marketing competencies needed to be addressed in a platform for education in sustainability.

Concerning the managerial implications and recommendations for policy-makers, our study provides a synthesis of the key factors in PV waste management in a global outlook and in the context of developing economies. Practitioners can find useful information regarding their possible participation and articulation in the construction of PV waste management, in addition to the possibilities of value creation from waste. Policy-makers will find a roadmap for working on strategic aspects such as the building of a regulatory framework aimed at promoting the attempt not only to reduce the environmental and health impacts of waste, but also to create value, promote cooperation, and energize the economy.

CRediT authorship contribution statement

Emmanuel Ndzibah: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Giovanna Andrea Pinilla-De La Cruz:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Data curation, Writing – review & editing. **Ahm Shamsuzzoha:** Conceptualization, Methodology, Writing – review & editing.

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.

Appendix 1

Table A1
Table of Abbreviations/Nomenclatures

Acronym	Full text
EOL	End-of-life
PV	Photovoltaic
HPPP	Hybrid public-private partnership
PPP	Public-private partnership
GNI	Gross national income
EVA	Ethylene vinyl acetate
c-Si	Crystalline silicon
CdTe	Cadmium telluride
WEEE	Waste Electrical and Electronic Equipment
EPR	Extended producer responsibility
REMP	Ghana Renewable Energy Master Plan
CO_2	Carbon dioxide
EU	European Union
GHG	Greenhouse gas
kW	Kilowatt
MW	Megawatt
UK	United Kingdom
kWp	Kilowatt Peak
ESCO	Energy service company

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