

End of life analysis of solar photovoltaic panel: roadmap for developing economies

Solar
photovoltaic
panel

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Abstract

Purpose – The purpose of this paper is to propose a conceptual framework for handling end of life (henceforth EoL) scenarios of solar photovoltaic (solar PV) panels, which includes different options available to businesses and end-users, as well as promoting the collaboration between government and all relevant stakeholders.

Design/methodology/approach – This paper adopts purposeful sampling, secondary data and content analysis to develop an appropriate conceptual framework that helps to create awareness of the appropriate options for dealing with the EoL cases of solar PV panels.

Findings – From the data analysis, it is revealed that reuse, repair and recycling of solar PV panels can ensure value creation, public-private partnership and a solution for education in sustainability, and thus, prolonging the useful life cycle of the products.

Research limitations/implications – This paper limits the analysis on developing economies and the use of selected literature based on the recycling of solar PV panels.

Originality/value – This paper is an initial attempt to create an awareness by identifying, analyzing and educating the stakeholders to handle appropriately any EoL scenario of solar PV panels.

Keywords Surveys, Energy production, Environmental damages, Energy sector, Waste-based, Energy transformation, Mail questionnaires, Interviews, Online surveys, Stakeholder meetings, Wind-PV, Solar panels, End of life (EoL), Developing economies, Recycling, Reusing, Value creation, Ghana, Public-private partnerships

Paper type Case study

1. Introduction

Due to the finitude of the fossil fuels, the energy crisis is increasing day-by-day and it is considering a common problem globally (Leal *et al.*, 2018; Rani *et al.*, 2020). Fossil fuels are also responsible for environmental hazards and to keep the environment sustainable, it is necessary to look for the use of new sources of clean and renewable energies. Renewable energies contribute toward the environmental, social and economic development of countries (Poudyal *et al.*, 2019; Can and Korkmaz, 2019). There are various sources of clean and renewable energy sources such as solar (Shukla *et al.*, 2018), biomass (Kumar *et al.*,



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2015), wind (Thapar *et al.*, 2018), hydrogen (Askari *et al.*, 2018a), fuel cell (Askari *et al.*, 2018b, 2019; Salarizadeh *et al.*, 2019), nanocomposite (Salarizadeh *et al.*, 2020a, 2020b) and supercapacitors (Salarizadeh *et al.*, 2020a, 2020b). Each of the energy sources are suitable for specific geographical locations and can suit from region to region.

Solar photovoltaic (solar PV) is one of the most commercially viable renewable energy with many advantages. It is environmentally friendly and flexible to scale based on preferred capacity (Bakhiyi *et al.*, 2014). The installation of solar PV has scaled year after year from an estimated total of 1 gigawatt (GW) in 2004 to some 470 GWs as at 2017 an estimated annual growth rate of more than 20% (SolarPower Europe, 2018). It is obvious that PV power will be a leader in future energy development (Luo *et al.*, 2008; Winneker, 2013; Xu *et al.*, 2018).

Furthermore, in developing countries, the huge fragmentary phenomenon concerning demand and supply of electricity has created new innovative opportunities including the adoption of solar PV systems and its peripheral components. Individual, corporate and institutional installed capacity keeps growing and initially, all seem to be great. Solar PV technology provides important advantages over other low-carbon technologies for developing economies, including the possibility to implement in any scale; however, there is relevant environmental issues to take into consideration related to the disposal process of Solar PV panels, as parts of the components are considered as hazardous waste (Xu *et al.*, 2018). Currently, PV panel disposal is becoming a “hot topic” in developed countries because the “first batch” of decommissioned panels requires adequate waste management (Aman *et al.*, 2015; Xu *et al.*, 2018). Environmental issues derived from the inappropriate disposal process after decommissioning are the leaching of cadmium and lead, and losses of rare metals such as indium, gallium and germanium (Xu *et al.*, 2018). According to International renewable energy agency (IRENA) and IEA-PVPS, (2016), the amount of global PV waste reached around 250,000 metric tons and by 2050, it is expected to reach around 6 million metric tons.

Although solar PV contributes heavily toward mitigation of global energy demand but its proper disposal is critical to protect our costly environment. Solar PV can be recycled and reused because of its valuable materials after the end of life (EoL) (Aryan *et al.*, 2018; Ardente *et al.*, 2019; Vargas and Chesney, 2021). In such a perspective, an appropriate waste management strategy can be adopted to handle the waste generated from PV panels and recovered valuable materials from them rather than disposed to the landfills that create environmental hazards (Franz and Piringer, 2020; Mahmoudi *et al.*, 2021). The demand for electricity is growing exponentially worldwide, especially in developing countries, where there is also a gradual shift toward renewable sources of energies to fulfill such demand. In this study, an analysis is done based on the overall status of the global PV market and demonstrated the possible consequences of the generated PV wastes. In addition, this study also discussed the necessity of PV waste management and recycling and provided a methodology for implementing required policies and regulations. Nonetheless, an inherent issue needs to be resolved before it is too late. Considering such concern related to PV waste, this study identifies three research questions (RQs), which are answered during the scope of this research study. Identified three RQs can be stated as follows:

RQ1. What are the environmental consequences of the expired solar panels globally?

RQ2. How to manage the wastes as created from the expired solar panels for environmental sustainability?

RQ3. What are the roles of various stakeholders to make the solar panels beneficial with respect environment, economic and socially?

The term Solar PV panel describes the configuration of solar cells that use light energy (photons) to generate electricity (Ndzibah, 2003; Ndzibah, 2013). It is noteworthy that, components from the panel can be recycled. The term “EoL” is used in the description of products that are at the end of its useful life especially from the vendors’ point of view. Although this does not mean the end of the use of any given product, usually the term could refer to the time frame for which a product does not officially receive any form of support or after-sales service thus, gradually rendering the product obsolete (Salim *et al.*, 2018; Amo-Asamoah *et al.*, 2020).

Developing economies or developing countries are such countries considered to exhibit high-risk tendencies to international business, limited in both economic and technological innovations, as well as having a high percentage of the populace with low purchasing power potential. Nevertheless, many of such economies as an advantage have high-quality natural resources and unexploited market, which provides prospects for investment (Ndzibah, 2013).

The main purpose of recycling is to recover valuable material from the waste to use as a raw material for new products (De Oliveira *et al.*, 2017). Recycling is becoming a priority in waste management. According to the Directive 2008/98/EC (European Parliament, 2008), recycling is relevant because of its contribution to the reduction in waste generation. On the other hand, re-using practices provide the opportunity to give a “second life” to products and allow it to re-enter the market (Zacho *et al.*, 2018). Recycling and re-using practices usually aim to “create value” from waste, and thus, prolonging the life cycle of products. Therefore, value creation promotes the utilization of waste as a valuable product. Value creation has several advantages, for example, the reduction of waste disposal, reduction of negative impacts derived from waste, new business opportunities, etc. (Peltola and Viana, 2016).

Ghana is used for this paper as the basis for a practical example of a developing economy. Ghana has about 28 million people with a growth rate of approximately 1.9% per annum (Ndzibah, 2013). The existing power generation capacity as of 2017 is about 4,398.5MW. In that same year, solar PV power generation constituted some 22.5MW (Beijing Xiaocheng Company Solar Corporation generated 20MW of the total and Volta River Authority generated some 2.5MW). The aforementioned total capacity excludes embedded or captive back-up generation. It is noteworthy, that this installed capacity does not include the smaller installations by households and some businesses. However, the estimates of all smaller installations by registered vendors in 2017 amounted to a cumulative lifetime total of 5 MW with over 85% of such installation in grid-connected areas (IRENA and IEA-PVPS, 2016; Energy Commission Ghana, 2018; IRENA, 2018). The percentage share of solar PV installation to the total generated electricity is significantly low, yet these add up quickly over the lifetime of such installed capacity.

The rest of the article is organized as follows: Section 2 outlines various relevant works from past to present days on PV panels and its life cycle. The study methodology is highlighted in Section 3, while, overall study results are analyzed and discussed in Section 4. Most specific issues associated to PV panels are discussed in Section 5 and the study findings are concluded in Section 6.

2. Literature review

There is a growing trend of using solar PV globally to meet up energy crisis and to protect the costly environment. PV ensures clean and renewable of sources of energy, which is critical for a sustainable society. Although, the use of PV is beneficial to the humanity but it

creates environmental hazards when its useful life is expired. It is, therefore, essential to manage such wastes carefully in an economic way (Ludin *et al.*, 2018; Mahmoudi *et al.*, 2019; Nain and Kumar, 2020a, 2020b). Such waste management can be a source of financial gain if it is reused or recycled properly. It is estimated that the technical potential of materials recovered from end-of-life solar PV panels could exceed \$15bn by 2050 (Weckend *et al.*, 2016).

Decommissioning of solar panels can open a pathway to represent a significant untapped business opportunity. It is projected that recycling or repurposing solar PV panels at the end of their roughly 30-year lifetime can unlock a large stock of raw materials and other valuable components (Weckend *et al.*, 2016). The waste from PV panels, which is mostly glass and potential material influx could contribute to the economy after recycling. Those wastes can be reused by producing new panels or be sold into global commodity markets. This strategy can also contribute to increasing the security of future PV supply or other raw material-dependent products.

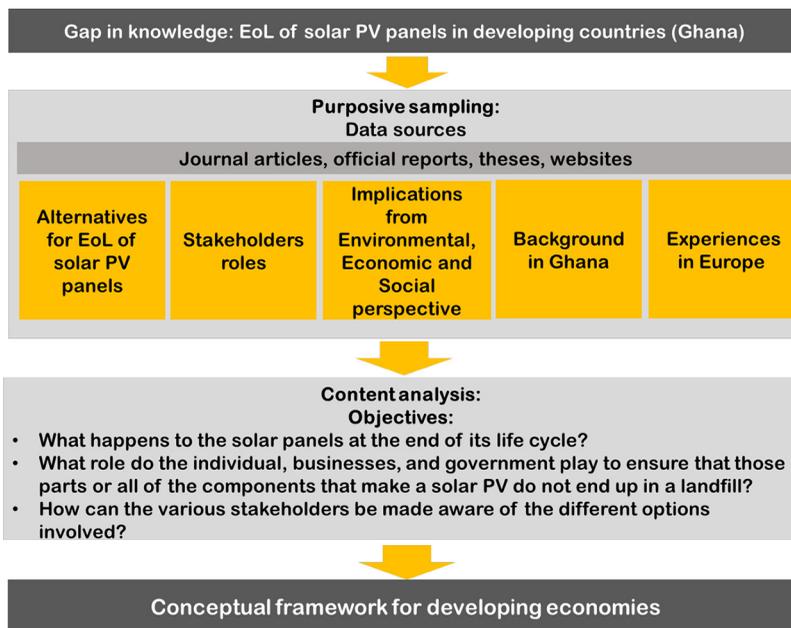
It is, however, needed to mention that the companies responsible to decommissioning of PV panels need to the adoption of effective PV-specific waste regulation to expand their waste management infrastructure with necessary innovation to waste management (Pandey *et al.*, 2016; Salim *et al.*, 2019). In general, most of the countries globally consider waste from PV panels, as “general waste” but the European Union (EU) was the first to adopt PV-specific waste regulations, which include PV-specific collection, recovery and recycling targets (Malandrino *et al.*, 2017; IEA and IRENA, 2016).

It is studied that PV panels’ waste management has considerable environmental benefits. Cucchiella *et al.* (2015) studied that recycling 185 ton of PV panels with an installed capacity to develop 2.46 MW allows savings of about 1,480–2,220 ton CO₂ equivalent. With respect to controlling such CO₂ emissions, it is essential to consider the combined environmental and socio-economic benefits of raw material recovery. Because of the potential increase of rare and valuable raw materials prices, the economics of recycling PV wastes will improve further in the future (Sica *et al.*, 2018). Proper waste management technique of PV panels also reduces the trends of their use as landfills, which contributes the reduction of landfill footprint and contributes to the reclamation of landfill volume for reuse (Padoan *et al.*, 2019; Nain and Kumar, 2020a, 2020b).

Decommissioning of PV panels can be executed through the circular economy concept, where waste management approaches require changes throughout value chains, from production, consumption and disposal of products to new business and market models, from new ways of turning waste into a resource to new modes of consumer behavior (Sica *et al.*, 2018; Heath *et al.*, 2020; Gautam *et al.*, 2021). Such a waste management approach represents unique opportunities to create value by enhancing regional businesses and jobs, and thus, opens up new economic avenues. It is essential to establish cooperation between stakeholders to maintain an uninterrupted supply of raw materials and overcome related challenges to guarantee the acceptance of future PV panel waste management systems (Huang *et al.*, 2017; Malandrino *et al.*, 2017).

3. Study methodology

For the methodology, this paper has considered the gap in knowledge as in EoL of solar PV panels in developing economies, adopts a purposive sampling technique by using expert samples from secondary data, which includes the selection of journal articles, official reports, thesis and authenticated website. The process then followed a careful content analysis based on the core objectives of the study for which the available data was analyzed and triangulated to develop a conceptual framework for developing economies. The analysis



Solar photovoltaic panel

Figure 1.
Research approach

Source: Authors

of the secondary data brought about the identification of specific processes for dealing with both hazardous and non-hazardous waste. Figure 1 below describes the process and parameters used to arrive at the conceptual framework.

4. Results analysis

As trends indicate, the Solar PV industry will continue with exponential growth, and costs will continue to fall. Therefore, access to this technology will become easily reached. One of the reasons for this phenomenon is the important advantages of solar PV technology over other low carbon technologies: On one hand, it is suitable to be applied at any scale, from the household level to large solar farms. Additionally, it does not require major maintenance, and the installation of a solar PV unit does not require complex infrastructure for its operation. Nevertheless, there are some notable disadvantages, for example, related to the relatively low efficiency of the current panels compared to the efficiencies achieved with other technologies (hydropower, thermal conventional technologies, etc.), as well as the variation in energy production because of the dependence to the solar irradiation on the location, time of year and weather conditions.

In the particular case of Ghana, the deployment of Solar PV technology will increase during the next few years. This technology is useful as a solution for the migration from fossil fuels to low carbon technologies, thus bridging the gap between the current demand and supply of electricity, as well as an alternate for the creation of decentralized energy systems for off-grid regions in the country. It is notable that one of the main drivers for the near diffusion of solar PV technology in the country is the fact that approximately 20% of

the population in Ghana does not have access to electric power, which is equivalent to more than 5 million people.

The production and export of solar PV panels are currently concentrated in countries such as China, Hong Kong, South Korea, Canada and the USA (SunShot initiative, 2018). The development of solar PV technology in those countries is extensive compared to other locations, for different reasons (government policies, a large investment in research and technology development, advanced learning curve, etc.). Therefore, the role of countries such as Ghana can be positioned as “consumers” of technology rather than producers. With the predictable massive entry of Solar PV technology to Ghana in the short term, it is also necessary to structure a series of policies and programs, with the aim of avoiding potential environmental, health, social and spatial impacts. According to the IRENA (IRENA and IEA-PVPS, 2016), the amount of PV panel waste has already reached close to 250,000 metric tonnes in 2016 and it is expected to reach about 5 million metric tonnes by 2050. These figures have forced the rapid implementation of policies to establish the proper PV waste management.

In the particular case of Ghana, which accounts for approximately 22.5 MW of cumulative solar PV power in 2017, it is possible to estimate that the amount of PV waste for that specific capacity in 25 to 30 years’ time will reach approximately 2140 metric tonnes (with the assumption that waste generated from solar PV panels produced after 2010 is approximately 95 tonnes per MW) (Sander and Al, 2007; IRENA and IEA-PVPS, 2016). The aforementioned numbers do not include the projections of new installations after 2017. The rapid deployment of Solar PV technology forced the EU to create policies “on the way” to avoid catastrophic impacts of waste generated at the EoL of PV panels (Sander and Al, 2007). In 2012, the EU issued the EU Waste Electrical and Electronic Equipment Directive, which among other purposes, forces producers and suppliers of PV panels who supply products to the European Market, to cover the costs of collection and recycling of EoL PV panels. So far, only the EU has established specific protocols related to PV waste (Xu *et al.*, 2018).

In developing economies such as Ghana, it is necessary to take preventive measures, and define a clear “roadmap” to guarantee the proper use of the advantages of solar PV technology. The measures will help to increase the accessibility to electricity, without causing greater negative impacts in the future when the panels reach the EoL. Figure 2 provides a conceptual framework for the EoL solar PVs in developing economies such as Ghana.

First, it is significant to bear in mind that diverse opinions are generated about the useful life of solar PV panels. Generally, producers suggest that the useful life of a solar panel is approximately 25 to 30 years. On the other hand, according to some studies, the useful life of the panel can be longer (Kadro and Hagfeldt, 2017). However, after 20 years of operation, the rate of electricity output reduces significantly and the probability of system failure occurring. An accurate definition of when the useful life of a solar panel ends is complex given that the market is still young (the first commercial installations started in the late 70s) and the technological development has been enormous in the past decades, especially with the “boom” of the solar PV industry that was generated from the year 2000.

4.1 Reusing: “photovoltaic panels second life”

The global need for reducing carbon emissions by adopting renewable technologies is forcing countries such as Ghana, to implement important projects by the government and also private companies. These projects will increase the production quota thus, reducing the

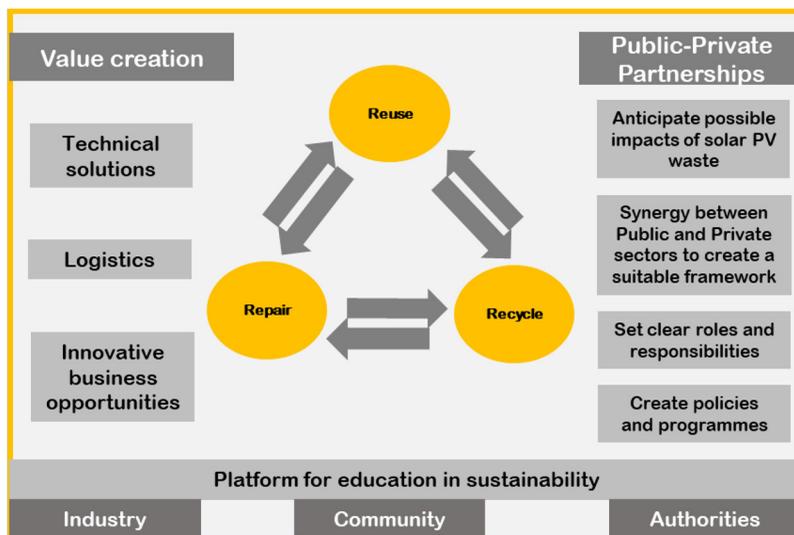


Figure 2. End-of-life solar PVs: conceptual framework in developing economies

Source: Authors

gap between the demand and supply of electricity. Nevertheless, after 25–30 years many of such installed units will be discarded and replaced by new infrastructure.

Before the decommissioning process, an evaluation of the individual units should be made to ascertain, which of such units can be salvaged for reuse, repair or recycle. If the panels are still in operational conditions, they can become a great alternate for installations in off-grid areas without access to electricity. A panel of 25 to 30 years could continue producing electricity for approximately 5 to 10 more years in a scenario in which there are no failures in the device and or proper maintenance is performed.

To make efficient use of resources and increase the coverage of access to electric power service, governments of developing economies should structure protocols to define the management of solar PV panels before their total disposal. Rural areas, schools or other institutions could benefit greatly from these measures.

4.2 Repairing

For the option of repairing, panels that are not in operative condition must be evaluated to define the failure, and identify if it can be fixed. For example, according to IRENA (IRENA and IEA-PVPS, 2016), 19% of the faults presented by solar PV panels correspond to J-box and cables, which may possibly be replaced in the country of use. The repair service industry could also specialize so that other types of failures can be addressed.

4.3 Recycling

Recycling practices generate important benefits such as the reduction of natural resources extraction and reduction in the cost of new product manufacturing [5]. In the case of such solar PV panels that cannot be reused or repaired, they can be recycled. Solar PV panels

contain valuable materials that can be recovered [23]. According to IRENA (IRENA and IEA-PVPS, 2016; Pagnanelli *et al.*, 2017; PV Cycle, 2018; Santos, 2018), more than 95% of the components of a first-generation solar PV panel (c-Si monocrystalline or polycrystalline) can be recycled and classified as non-hazardous materials. Additionally, there are components such as glass, which covers around 76% of the surface of the c-Si panels. More so, materials such as aluminium, constitute roughly 8% of the panel while polymer, which covers the back of the panel and its encapsulant (10%).

The aforementioned materials have the potential to be used as inputs for the manufacture of various products (Wambach *et al.*, 2006; Sander and Al, 2007). The percentage of remaining mass requires special treatment, as it contains silicon, silver and small amounts of tin and lead. Regarding the second generation panels or Thin-film, only 2% of the mass of the panel would be classified as hazardous waste. The third generation is related to concentrator photovoltaics organic cells, hybrid panels and dry-sensitized solar cells (Xu *et al.*, 2018; Padoan *et al.*, 2019).

Some aspects to take into account in the implementation of solar panel recycling practices are the logistics required for the collection, transportation, disassembly of the panels and subsequent treatment and disposal of hazardous waste (IRENA and IEA-PVPS, 2016). During the past years, research and development related to recycling techniques are increasing. Currently, there are available several techniques with pros and cons in terms of the complexity of the process, recycling costs, etc. The principal techniques are classified according to the material to recover or module fractioning (Fthenakis, 2000; Xu *et al.*, 2018). Figure 3 below gives a summary outlook of the principal recycling techniques used for solar PV panels.

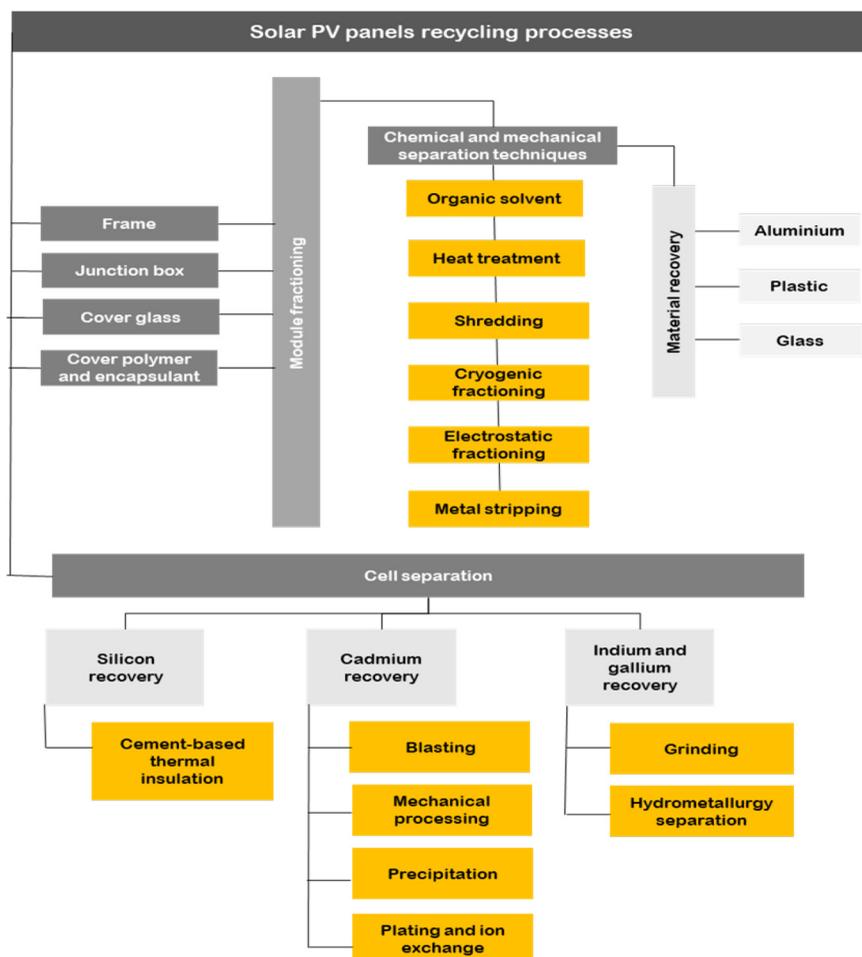
4.4 Reduce

Ghana is not currently producing solar panels, rather they act as importers of this type of technology. Therefore, it is crucial to define requirements regarding the selection of supplier companies in accordance with the policies to implement measures aimed at reducing PV waste. Recycling is a strong driver to promote waste reduction in solar PV panels' production. According to Kadro and Hagfeldt (2017), the re-integration of recycled materials from PV panels has several advantages such as the reduction of energy consumption from energy-intensive components, reduction in environmental impacts from solar PV panels and reduction of "energy payback time" (EPBT) of solar PV panels.

4.5 Value creation

EoL of solar PV panels should not be considered as merely the process of final disposal, given that the EoL is also an opportunity to create value and capture value from a different perspective (Kadro and Hagfeldt, 2017). For example:

- New business opportunities can be created from solar PV panels decommissioning, as well as maintenance and repair activities (Kadro and Hagfeldt, 2017).
- The creation of specialized logistics services for panel collection, transportation, evaluation of operating conditions and storage.
- Recycling is another opportunity to generate new jobs in the disassembling process of devices and subsequent materials' treatments (for example, homogenization by mechanical or thermal treatments).
- Finally, the creation of a business opportunity for specialized treatment of hazardous waste and its final disposal.



Source: Adapted from Sasala *et al.* (1996), Fthenakis (2000), Doi *et al.* (2001), Berger *et al.* (2010), Fernández *et al.* (2011), Dong (2014), Granata *et al.* (2016) and Xu *et al.* (2018).

Figure 3.
Principal recycling techniques

4.6 Public-private partnerships

One of the key actions for a successful strategy of creating value from EoL solar PV panels would be the structuring of a value chain for stakeholders. In this case, public-private partnerships (PPPs) could play a relevant role in achieving this objective based on the synergy and complementarity of the resources and competencies of the public and private sectors to advance the energy transition (Sambrani, 2014; Pinilla-De La Cruz *et al.*, 2020a, 2020b). In particular, PPPs between government, industry and societal groups could help to achieve the following actions:

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- Policies, protocols and programs related to roles and responsibilities in EoL solar PV panels.
 - Policies on setting the criteria for solar panel suppliers focused on the reduction of PV waste.
 - Protocols for reporting quantities of PV solar panels in the national market to estimate the PV waste in the future and the integration of databases of imports and sales.
 - Protocols for the assessment of operating conditions of solar PV panels and the definition of the corresponding actions.
 - Protocols to avoid and prevent the trading of solar PV waste to and from the country.
 - Adoption of a suitable logistic chain to guarantee the appropriate management after decommissioning. Nonetheless, solar PV panels can be reused or intended for recycling (IRENA and IEA-PVPS, 2016).
 - Definition of criteria to use decommissioned solar PV panels in off-grid locations (second life of solar PV panels).

Additionally, the roles and responsibilities of parties involving should be defined about the following activities:

- Responsibilities of producers in solar PV panels repair, recycling and final disposal management. For example, in Germany, the principle of “cost responsibility” is applied in these activities (IRENA and IEA-PVPS, 2016).
- Responsibilities of consumers and buyers for adequate management of solar PV panels after decommissioning.
- Definition of technical requirements of companies or individuals to carry out the assessment of operational conditions of solar PV panels and decommissioning. It includes repair, collection, transport, storage, recycling of non-hazardous materials and disposal of hazardous waste.
- Responsibilities in the definitions of technical competences and the corresponding educational programs.

4.7 Platform for education in sustainability

Education and training is a fundamental factor in the construction of a sustainable system for the proper management of the EoL solar PV panels. As solar PV technology has been deployed in countries such as Ghana for a few years, it is necessary to train people to carry out activities related to reuse, repair, recycling and final disposal of solar PV panels. This process must be designed according to country specific needs. A well-grounded platform will produce benefits such as:

- Decrease in environmental, spatial and health impacts associated to solar PV waste.
- Compliance with international standards in solar PV waste management.
- Increased efficiency in the use of resources in improving solar PV technology.
- Developing countries improved adaptation to new technologies and its transition to low carbon energies.
- Greater citizen awareness about the importance of responsible management of EoL solar PV panels.

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- Improved business and employment opportunities from innovative services around the EoL solar PV panels.

5. Discussions

The ongoing analysis of key parameters that makes up the design and implementation of appropriate protocols at this EoL analysis clearly hinges on three core drivers, namely, economic, social and environmental. For instance, the economic drivers advocate the conservation and recirculation of rare materials. More so, when the right parameters are placed, all stakeholders will be able to aggregate the cost of saving from reuse and recycling. In addition, the aforementioned factors help to add value and prolong the lifecycle of the installed system. Furthermore, the economic driver also enhances the competitiveness of producers by helping them adhere to strict international standards that promote quality and sustainability (Salim *et al.*, 2018).

The setup of a policy framework concerning EoL analysis will encourage producers to adhere to international standards throughout their supply chain process. Likewise, developing countries will create and implement policies to weed out the importation of sub-standard solar PV panels promoting such healthy competition among producers. For social drivers, the conceptual framework will set up a clear precedent in designing and facilitating opportunities for job creation, reduction of human health risk and achieve stakeholder expectations. The social drivers also will promote job diversity, as new technical skills will be developed and trained in educational setups to add value to the skilled labor market in developing countries (Salim *et al.*, 2018).

The environmental drivers have the potential to reduce greenhouse gas emissions and reduce EPBT of solar panels. Finally, the environmental drivers will ensure appropriate EoL management through evidence of the product and material impact. Figure 4 below is well-documented in the aforementioned discussion.

The aforementioned derivatives from the core drivers identified are reasonable; nevertheless, the main issue in Ghana, which could delimit the implementation among others is the type of labor policies, current educational curriculum and bureaucracy in public institutions that hinder economic progress. On the other hand, recent policies proposed by the Energy Commission (EC) (a public institution empowered to design and propose energy-related directives for consideration and implementation by the energy ministry of Ghana) has made it possible for the government to give incentive and subsidies to individuals and businesses able and willing to install solar PV. Nevertheless, the EC could collaborate more often with the private sector and notable stakeholders in the renewable energy industry, by means of seminars and workshops to understand the actual concerns of these stakeholders.

Moreover, the educational institutions could collaborate with current stakeholders in the solar business to develop a suitable curriculum that addresses conservation, responsible energy use and sustainability, as well as proper disposal of EoL solar PV panels. Finally, the promotion and set up of regional training centers will help address the training process of experts in solving the issues of reusing, repairing and recycling. More so, the process will add value to the diffusion of solar PV as a main or alternate source of electricity supply in the country. Current bureaucracy in public institutions such as the customs agency and standard board could be reduced by promoting transparency in the clearing process of renewable energy products. The customs and standard board should collaborate with the EC, as well as all registered renewable energy businesses in identifying and promoting international suppliers that adhere to the standards of production. The customs unit should recognize all registered stakeholders and help policymakers by enforcing decisions made.

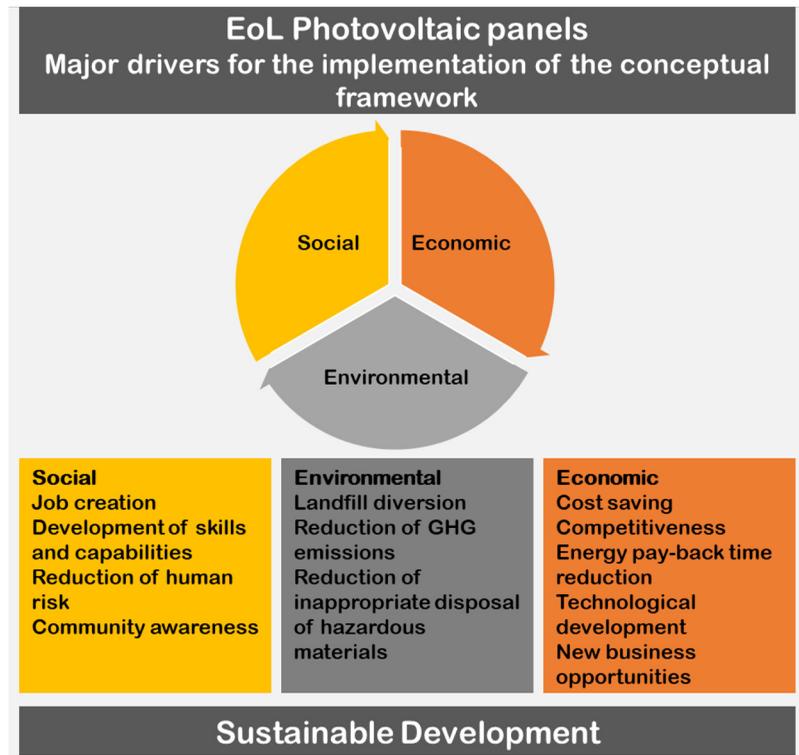


Figure 4.
Major drivers for the implementation of the conceptual framework of EoL solar PV panels in developing economies

Source: Adapted from Salim *et al.* (2018)

Finally, the support in the prevention of illegal trade is an important issue that the public institutions can promote.

This research work uses purposeful sampling in a diverse approach to help augment various opinions and actual strategic framework of the Government of Ghana in issues pertaining to recycling implementation plans for the future. The inclusion of an actual government representative in the focus group study helped address a critical issue of contemporary activities of how PV panels and its related components are managed. This research work also moves from the classic approach of merely identifying a problem and talking at length on the parameters covering the problem recognition. The paper rather goes further in identifying plausible and tentative solutions including, for instance, giving the panels a second life as in its potential for reuse after decommissioning of especially large-scale solar PV farms.

Furthermore, some options such as repairing and recycling made it possible to conceptualize a principal framework of reduction, value creation and the clear path and integration of PPPs right from the early stages of adoption or diffusion of solar PV systems in these developing countries. A suggestion of a platform for education in sustainability helps to address the classic barriers of inadequate management tactics prevalent in a lot of developing economies thus, helping the younger generation to plan in managing the potential fall out of EoL scenarios of solar PV panels.

6. Conclusions

The proposed framework answers the core RQs set for this paper. For instance, in the context of What are the environmental consequences of the expired solar panels globally? The proposed options include the ability to reuse the unit, especially if proper maintenance protocol is followed during the products' life cycle of 20–25 years. Furthermore, the solar PV panels could easily be repaired, as, for example, the broken component, such as the junction box or its peripheral components can easily be obtained and replaced by a qualified technician. Finally, in some cases, the solar PV panel could be recycled if for some reason the unit is broken beyond repair. The recovered components can be reintegrated into new products.

In answering the second RQ, which is considered how to manage the wastes as created from the expired solar panels for environmental sustainability?, the conceptual framework proposes policy decisions. Additionally, the framework suggested the collaboration among stakeholders in setting local and international standards to establish the types of panels that can be imported. The set objective can promote transparency in the customs regulation, processes and the proper involvement of the standard board, as well as other regulated public sectors.

The third objective, which asks what are the roles of various stakeholders to make the solar panels beneficial with respect environment, economic and socially?, includes awareness creation based on collaboration and promotion of policy decision in education in the form of new curriculum development, workshops and seminars. The set objective will, thus sensitize the stakeholders about the validity and applicability of the policy, creating more job opportunities and new knowledge skills. This research study goes beyond the technical description of the technological processes for the use of EoL solar PV panels. This study also aims to pay the reader's attention to the phenomenon by describing the problems at a global level and the challenges for developing economies, as is the case of Ghana. Indeed, this study, in addition to informing, proposes a roadmap to act proactively to reduce possible environmental impacts and maximize economic opportunities and improvement of the quality of life. From the study findings, a conceptual framework is developed that made up of three fundamental elements, namely, the creation of value from waste in economic, logistical and technical terms, building PPPs, which is an integrating element of the different social actors in the establishment and implementation of strategies, roles and actions aimed at taking advantage of the EoL PV alternates and structuring of a platform for sustainability education oriented toward the formation of technical competences and greater awareness of the phenomenon.

This study also considered that the proposed conceptual framework might have contributions both at the managerial and policy levels. From this conceptual framework, further studies can make significant contributions by focusing on each of its fundamental elements. In particular, exploration value propositions from waste, as one of the pillars of the circular economy, must be a concept to be integrated into the energy transition in developing economies. On the other hand, PPPs will be a *sine qua non* in the energy transition process, taking into account the strength of this cooperation scheme based on the complementarity of resources and skills addressing a social goal.

References

- Aman, M.M., Solangi, K.H., Hossain, M.S., Badarudin, A., Jasmon, G.B., Mokhlis, H., Bakar, A.H.A. and Kazi, S.N. (2015), "A review of safety, health and environmental (SHE) issues of solar energy system", *Renewable and Sustainable Energy Reviews*, Vol. 41, pp. 1190-1204.

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- Amo-Asamoah, E., Owusu-Manu, D.G., Asumadu, G., Ghansah, F.A. and Edwards, D.J. (2020), "Potential for waste to energy generation of municipal solid waste (MSW) in the Kumasi metropolis of Ghana", *International Journal of Energy Sector Management*, Vol. 14 No. 6, pp. 1315-1331.
- Ardente, F., Latunussa, C.E.L. and Blengini, G.A. (2019), "Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling", *Waste Management*, Vol. 91, pp. 156-167.
- Aryan, V., Font-Brucart, M. and Maga, D. (2018), "A comparative life cycle assessment of end-of-life treatment pathways for photovoltaic backsheets, prog. Photovolt", *Research Applications*, Vol. 26, pp. 443-459.
- Askari, M.B., Salarizadeh, P., Seifi, M. and Rozati, S.M. (2019), "Ni/NiO coated on multi-walled carbon nanotubes as a promising electrode for methanol electro-oxidation reaction in direct methanol fuel cell", *Solid State Sciences*, Vol. 97, pp. 106012.
- Askari, M.B., Beheshti-Marnani, A., Banizi, Z.T., Seifi, M. and Ramezan Zadeh, M.H. (2018a), "Synthesis and evaluation of MoWCoS/G and MoWCuS/G as new transition metal dichalcogenide nanocatalysts for electrochemical hydrogen evolution reaction", *Chemical Physics Letters*, Vol. 691, pp. 243-249.
- Askari, M.B., Seifi, M., Rozati, S.M., Beheshti-Marnani, A. and Ramezan Zadeh, M.H. (2018b), "One-step hydrothermal synthesis of MoNiCoS nanocomposite hybridized with graphene oxide as a high-performance nanocatalyst toward methanol oxidation", *Chemical Physics Letters*, Vol. 706, pp. 164-169.
- Bakhiyi, B., Labrèche, F. and Zayed, J. (2014), "The photovoltaic industry on the path to a sustainable future - environmental and occupational health issues", *Environment International*, Vol. 73, pp. 224-234.
- Berger, W., Simon, F.G., Weimann, K. and Alsema, E.A. (2010), "Resources, conservation and recycling a novel approach for the recycling of thin film photovoltaic modules", *Resources, Conservation and Recycling*, Vol. 54 No. 10, pp. 711-718.
- Can, H. and Korkmaz, Ö. (2019), "The relationship between renewable energy consumption and economic growth: the case of Bulgaria", *International Journal of Energy Sector Management*, Vol. 13 No. 3, pp. 573-589.
- Cucchiella, F., D'Adamo, I. and Rosa, P. (2015), "End-of-life of used photovoltaic modules: a financial analysis", *Renewable and Sustainable Energy Reviews*, Vol. 47, pp. 552-561.
- De Oliveira, G.C., Cardoso Correia, A., de, J. and Schroeder, A.M. (2017), "Economic and environmental assessment of recycling and reuse of electronic waste: multiple case studies in Brazil and Switzerland", *Resources, Conservation and Recycling*, Vol. 127, pp. 42-55.
- Doi, T., Tsuda, I., Unagida, H., Murata, A., Sakuta, K. and Kurokawa, K. (2001), "Experimental study on PV module recycling with organic solvent method", *Solar Energy Materials and Solar Cells*, Vol. 67 No. 1-4, pp. 397-403.
- Dong, L. (2014), *Research on Waste Crystalline Silicon Solar Panels Resource Recovery Technology*, Southwest Jiaotong University.
- European Parliament (2008), "Directive 2008/98/EC of the European parliament and of the council of 19 november 2008 on waste and repealing certain directives", *Official Journal of the Europe Union*, pp. 3-30.
- Fernández, L.J., Ferrer, R. and Aponte, D.F. and Fernández, P. (2011), "Recycling silicon solar cell waste in cement-based systems", *Solar Energy Materials and Solar Cells*, Vol. 95 No. 7, pp. 1701-1706.
- Franz, M. and Piringer, G. (2020), "Market development and consequences on end-of-life management of photovoltaic implementation in Europe", *Energy, Sustainability and Society*, Vol. 10 No. 1.
- Fthenakis, V.M. (2000), "End-of-life management and recycling of PV modules", *Energy Policy*, Vol. 28 No. 14, pp. 1051-1058.
- Gautam, A., Shankar, R. and Vrat, P. (2021), "End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy", *Sustainable Production and Consumption*, Vol. 26, pp. 65-77.

-
- Granata, G., Pagnanelli, F., Moscardini, E., Havlik, T. and Toro, L.J.S.E.M. (2016), "Solar energy materials and solar cells recycling of photovoltaic panels by physical operations", *Solar Energy Materials and Solar Cells*, Vol. 123, pp. 239-248.
- Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S. and Komoto, K. (2020), "Research and development priorities for silicon photovoltaic module recycling to support a circular economy", *Nature Energy*, Vol. 5 No. 7, pp. 502-510.
- Huang, B., Zhao, J., Chai, J., Xue, B., Zhao, F. and Wanga, X. (2017), "Environmental influence assessment of china's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process", *Solar Energy*, Vol. 143, pp. 132-141.
- IEA and IRENA (2016), "End-of-life management: solar photovoltaic panels", available at: www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf (accessed 16 June 2020).
- IRENA and IEA-PVPS (2016), "End-of-Life management: solar photovoltaic panels", available at: www.irena.org
- IRENA (2018), "Planning and prospects for renewable power: WEST AFRICA", International Renewable Energy Agency, Abu Dhabi, available at: www.irena.org/publications/2018/Nov/Planning-and-prospects-for-renewable-power
- Kadro, J.M. and Hagfeldt, A. (2017), "The end-of-life of perovskite PV", *Joule*, Vol. 1 No. 1, pp. 29-46.
- Kumar, A., Kumar, N., Baredar, P. and Shukla, A. (2015), "A review on biomass energy resources, potential, conversion and policy in India", *Renewable and Sustainable Energy Reviews*, Vol. 45, pp. 530-539.
- Leal, P.H., Marques, A.C. and Fuinhas, J.A. (2018), "How economic growth in Australia reacts to CO₂ emissions, fossil fuels and renewable energy consumption", *International Journal of Energy Sector Management*, Vol. 12 No. 4, pp. 696-713.
- Ludin, N.A., Mustafa, N.I., Hanafiah, M.M., Ibrahim, M.A., Teridi, M.A.M., Sepeai, S., Zaharim, A. and Sopian, K. (2018), "Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: a review", *Renewable and Sustainable Energy Reviews*, Vol. 96, pp. 11-28.
- Luo, D.W., Zhang, G.L., Zhang, J., Li, J. and Li, T.J. (2008), "Principle and research progress on preparation solar grade (SonG) silicon by metallurgical route", *Foundry Technology*, Vol. 29 No. 12, pp. 1721-1726.
- Mahmoudi, S., Huda, N. and Behnia, M. (2021), "Critical assessment of renewable energy wastes generation in OECD countries: decommissioned PV panels", *Resources, Conservation and Recycling*, Vol. 164, pp. 105145.
- Mahmoudi, S., Huda, N., Alavi, Z., Islam, M.T. and Behnia, M. (2019), "End-of-life photovoltaic modules: a systematic quantitative literature review", *Resource Conservation and Recycling*, Vol. 146, pp. 1-16.
- Malandrino, O., Sica, D., Testa, M. and Supino, S. (2017), "Policies and measures for sustainable management of solar panel end-of-Life in Italy", *Sustainability*, Vol. 9 No. 4, p. 481.
- Nain, P. and Kumar, A. (2020a), "Identifying issues in assessing environmental implications of solar PVs-related waste", *Recent Developments in Waste Management*, pp. 71-90.
- Nain, P. and Kumar, A. (2020b), "Understanding the possibility of material release from end-of-life solar modules: a study based on literature review and survey analysis", *Renewable Energy*, Vol. 160, pp. 903-918.
- Ndzibah, E. (2003), *Product Strategies of Finnish Photovoltaic Technology Manufacturers for Africa*, University of Vaasa.
- Ndzibah, E. (2013), "Marketing mechanisms for photovoltaic technology in developing countries", PhD Dissertation, University of Vaasa. ISBN 978-952-476-469-8 (online).
- Padoan, F.C., Altimari, P. and Pagnanelli, F. (2019), "Recycling of end of life photovoltaic panels: a chemical prospective on process development", *Solar Energy*, Vol. 177, pp. 746-761.
-

-
- Pagnanelli, F., Moscardini, E., Granata, G., Atia, T.A., Altimari, P., Havlik, T. and Toro, L. (2017), "Physical and chemical treatment of end of life panels: an integrated automatic approach viable for different photovoltaic technologies", *Waste Management*, Vol. 59, pp. 422-431.
- Pandey, A.K., Tyagi, V.V., Jeyraj, A., Selvaraj, L., Rahim, N.A. and Tyagi, S.K. (2016), "Recent advances in solar photovoltaic systems for emerging trends and advanced applications", *Renewable and Sustainable Energy Reviews*, Vol. 53, pp. 859-884.
- Peltola, T. and Viana, E. (2016), "Value capture in business ecosystems for municipal solid waste management: comparison between two local environments", *Journal of Cleaner Production*, Vol. 137, pp. 1270-1279.
- Pinilla-De La Cruz, G.A., Rabetino, R. and Kantola, J. (2020a), "Public-private partnerships (PPPs) in energy: co-citation analysis using network and cluster visualization", *Intelligent Human System Integration 2021, IHSI 2021, AISC 1322*.
- Pinilla-De La Cruz, G.A., Rabetino, R. and Kantola, J. (2020b), "Public-Private partnerships (PPPs) in energy: identifying the key dimensions from two different bibliometric analyzes", in Kantola, J., Nazir, S., (Eds), *Advances in Human Factors, Business Management and Leadership. AHFE 2020. Advances in Intelligent Systems and Computing*, Vol. 1209, Springer, Cham, pp. 65-71.
- Poudyal, R., Koskot, P., Nepal, R., Parajuli, R. and Khadka, S.K. (2019), "Mitigating the current energy crisis in Nepal with renewable energy sources", *Renewable and Sustainable Energy Reviews*, Vol. 116, pp. 109388.
- PV CYCLE (2018), available at: www.pvcycle.org/press/breakthrough-in-pv-module-recycling/ (accessed 29 December 2020).
- Rani, P., Mishra, A.R., Mardani, A., Cavallaro, F., Alrasheedi, M. and Alrashidi, A. (2020), "A novel approach to extended fuzzy TOPSIS based on new divergence measures for renewable energy sources selection", *Journal of Cleaner Production*, Vol. 257, pp. 120352.
- Salarizadeh, P., Askari, M.B., Beheshti-Marnani, A., Rozati, S.M., Rohani, T., Askari, N., Salarizadeh, N. and Mohammadi, S.Z. (2019), "Synthesis and characterization of (Co, Fe, Ni)₃S₈ nanocomposite supported on reduced graphene oxide as an efficient and stable electrocatalyst for methanol electrooxidation toward DMFC", *Journal of Materials Science: Materials in Electronics*, Vol. 30, pp. 3521-3529.
- Salarizadeh, P., Askari, M.B., Hooshyari, K. and Saeidfirozeh, H. (2020a), "Synergistic effect of mos₂ and fe₃o₄ decorated reduced graphene oxide as a ternary hybrid for high-performance and stable asymmetric supercapacitors", *Nanotechnology*, Vol. 31 No. 43, pp. 435401.
- Salarizadeh, P., Askari, M.B., Seifi, M., Rozati, S.M. and Eisazadeh, S.S. (2020b), "Pristine NiCo₂O₄ nanorods loaded rGO electrode as a remarkable electrode material for asymmetric supercapacitors", *Materials Science in Semiconductor Processing*, Vol. 114, pp. 105078.
- Salim, H.K., Stewart, R.A., Sahin, O. and Dudley, M. (2018), "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: a systematic literature review", *Journal of Cleaner Production*, Vol. 211, pp. 537-554.
- Salim, H.K., Stewart, R.A., Sahin, O. and Dudley, M. (2019), "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: a systematic literature review", *Journal of Cleaner Production*, Vol. 211, pp. 537-554.
- Sambrani, V.N. (2014), "PPP from asia and african perspective towards infrastructure development: a case study of greenfield bangalore international airport, India", *Procedia – Social and Behavioral Sciences*, Vol. 157, pp. 285-295.
- Sander, K. and Al, E. (2007), *Study on the Development of a Takeback and Recovery System for Photovoltaic Modules*, Berlin.
- Santos, J.D. (2018), "Projection of the photovoltaic waste in Spain until 2050", *Journal of Cleaner Production*, Vol. 196, pp. 1613-1628.
- Sasala, R.A., Bohland, J. and Smigielski, K. (1996), "Physical and chemical pathways for economic recycling of cadmium telluride thin-film photovoltaic modules", *25th IEEE Photovoltaic Specialists Conference, Institute of Electrical and Electronics Engineers, Piscataway, NJ*, pp. 865-868.

-
- Shukla, A.K., Sudhakar, K., Baredar, P. and Mamat, R. (2018), "Solar PV and BIPV system: barrier, challenges and policy recommendation in India", *Renewable and Sustainable Energy Reviews*, Vol. 82, pp. 3314-3322.
- Sica, D., Malandrino, O., Supino, S., Testa, M. and Lucchetti, M.C. (2018), "Management of end-of-life photovoltaic panels as a step towards a circular economy", *Renewable and Sustainable Energy Reviews*, Vol. 82 No. 3, pp. 2934-2945.
- SolarPower Europe (2018), "Global market outlook for solar power/2018-2022", available at: www.solarpowereurope.org/global-market-outlook-2018-2022/
- SunShot initiative (2018), "U.S. Department of energy energyusage", available at: <https://news.energysage.com/best-solar-panel-manufacturers-usa> (accessed 1 January 2019).
- Thapar, S., Sharma, S. and Verma, A. (2018), "Key determinants of wind energy growth in India: analysis of policy and non-policy factors", *Energy Policy*, Vol. 122, pp. 622-638.
- Vargas, C. and Chesney, M. (2021), "End of life decommissioning and recycling of solar panels in the United States: a real options analysis", *Journal of Sustainable Finance and Investment*, Vol. 11 No. 1, pp. 82-102.
- Wambach, K., Schlenker, S., Müller, A., Klenk, M., Wallat, S., Kopecek, R. and Wefringhaus, E. (2006), "The second life of a 300 kW PV generator manufactured with recycled wafers from the oldest german PV power plant", *21st European Photovoltaic Solar Energy Conference and Exhibition 2006, Dresden*, pp. 20-21.
- Weckend, S., Wade, A. and Heath, G.A. (2016), *End of Life Management: Solar Photovoltaic Panels*, National Renewable Energy Lab.
- Winneker, C. (2013), "Global market outlook for photovoltaics", 2013–2017.
- Xu, Y., Li, J., Tan, Q., Peters, A.L. and Yang, C. (2018), "Global status of recycling waste solar panels: a review", *Waste Management*, Vol. 75, pp. 450-458.
- Zacho, K.O., Mosgaard, M. and Riisgaard, H. (2018), "Capturing uncaptured values – a danish case study on municipal preparation for reuse and recycling of waste", *Resources, Conservation and Recycling*, Vol. 136, pp. 297-305.

Further reading

- Energy Commission Ghana (2018), "Energy commission Ghana", available at: www.energycom.gov.gh/ (accessed 10 January 2019).
- Etikan, I., Musa, S.A. and Sunusi, A.R. (2016), "Comparison of convenience sampling and purposive sampling", *American Journal of Theoretical and Applied Statistics*, Vol. 5 No. 1, pp. 1-4.
- Krippendorff, K. (1989), "Content analysis", international encyclopedia of communication", in Barnouw, E., Gerbner, G., Schramm, W., Worth, T. L. (Eds), *Content Analysis*, Oxford University Press, available at: http://repository.upenn.edu/asc_papers/226
- Palinkas, L.A., Horwitz, S.M., Green, C.A., Wisdom, J.P., Duan, N. and Hoagwood, K. (2015), "Purposeful sampling for qualitative data collection and analysis in mixed method implementation research", *Administration and Policy in Mental Health and Mental Health Services Research*, Vol. 42 No. 5, pp. 533-544.

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