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Review

An overview of solar photovoltaic panels' end-of-life material recycling

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ABSTRACT

End-of-life (EOL) solar panels may become a source of hazardous waste although there are enormous benefits globally from the growth in solar power generation. Global installed PV capacity reached around 400 GW at the end of 2017 and is expected to rise further to 4500 GW by 2050. Considering an average panel lifetime of 25 years, the worldwide solar PV waste is anticipated to reach between 4%-14% of total generation capacity by 2030 and rise to over 80% (around 78 million tonnes) by 2050. Therefore, the disposal of PV panels will become a pertinent environmental issue in the next decades. Eventually, there will be great scopes to carefully investigate on the disposal and recycling of PV panels EOL. The EU has pioneered PV electronic waste regulations including PV-specific collection, recovery and recycling targets. The EU Waste of Electrical and Electronic Equipment (WEEE) Directive entails all producers supplying PV panels to the EU market to finance the costs of collecting and recycling EOL PV panels in Europe. Lessons can be learned from the involvement of the EU in forming its regulatory framework to assist other countries develop locally apposite approaches. This review focused on the current status of solar panel waste recycling, recycling technology, environmental protection, waste management, recycling policies and the economic aspects of recycling. It also provided recommendations for future improvements in technology and policy making. At present, PV recycling management in many countries envisages to extend the duties of the manufacturers of PV materials to encompass their eventual disposal or reuse. However, further improvements in the economic viability, practicality, high recovery rate and environmental performance of the PV industry with respect to recycling its products are indispensable.

1. Introduction

Solar photovoltaic (PV) energy technologies, which were first applied in space, can now be used ubiquitously where electricity is required. Photovoltaic (PV) energy production is one of the most promising and mature technologies for renewable energy production. PV technology is environmentally friendly and has become a popular means of generating power. Solar energy technology is currently the third most used renewable energy source in the world after hydro and wind power, which occupy the first and second position, respectively [1]. Moreover, PV energy sources generate power with low levels of carbon emissions that cause global warming [2]. In addition, fossil fuel-generated electricity accounts for CO_2 emissions of between 400 g and 1000 g CO_2 eq/kWh, whereas CO_2 emission from silicon-based solar panels are negligible [3].

Solar power is safe, efficient, non-polluting and reliable. Therefore, PV technology has a very exciting prospect as a way of fulfilling the world's future energy needs. During the past several decades, the

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utilization of solar PV power has increased. There is now a large market for PV panels which have the potential to globally produce clean energy. Moreover, it is expected that within the current century, PV-generated electricity will become the primary global energy source [4]. The year 2017 was especially notable for solar PV sector, with the level of solar PV generation capacity globally installed, rivalling other energy production technologies [5]. In fact, solar power has added more new capacities than both nuclear and fossil fuel energy-generation capacity as shown in Fig. 1. The installed capacity of solar and wind power technology has almost doubled, with an additional of 99.1 GWh of solar PV energy that became grid-connected in 2017 [5].

Large-area solar PV installations help to reduce production costs. Saudi Arabia put out tenders for a 300 MW plant in February 2018, which would produce solar energy at the world's lowest price of 0.0234 USD/kWh [6]. Solar energy prices have rapidly reduced because of developments in solar technologies. China led the world in solar power production in 2017 and installed 50% of the world's new solar power generation capacity [5]. On the other hand, in the same year, Europe had a slower rate of increase in its solar generation capacity, which grew by only 30% as compared to the previous year [5]. Nevertheless, by the end of 2022, global solar energy generation capacity may grow to as much as 1270.5 GW and solar generated power will therefore exceed 1 TW (TWh) [6].

However, with the increase in installations, the number of solar panels reaching their EOL stage will rise steadily [3]. Solar panels will become a form of hazardous waste when the useful life is over and may harm the environment if they are not recovered or disposed of properly. The recycling of waste panels was not a concern during the first 25 years of development [4]. However, a sound management of solar panels EOL is gradually becoming an important environmental issue. Therefore, an appropriate recycling of PV waste will become gradually more significant, considering the growing number of installations and extension of production [8,18]. The utilization of valuable resources and the potential for waste generation at the EOL cycle of PV technologies has imposed a proper planning for a PV recycling infrastructure [4]. To certify the sustainability of PV in large scales of deployment, it is crucial to establish low-cost recycling technologies for the evolving PV industry in parallel with the swift commercialization of these new technologies.

Recently, the European Union (EU) has included PV waste into the new Waste of Electrical and Electronic Equipment (WEEE) directive to limit the negative influence of the persistent growth in PV waste volume and to implement solar module recycling [18]. This directive (2012/19/EU) is now applicable to the management of waste solar panels, both household and industrial in Europe [4,7,8]. The natural resources used in manufacturing solar PV panels qualify as auxiliary raw materials within the applicable regulations [9]. However, PV waste must be properly disposed and treated. In Europe, the export of waste is prohibited. Quite apart from the economic, environmental and social implications of this prohibition, it promotes the recycling of solar PV components [1]. Besides, in line with the EU policy on the treatment of waste, it gives priority to the recovery and recycling of materials.

Therefore, solar PV panel EOL management is an evolving field that requires further research and development. The key aim of this study is to highlight an updated review of the waste generation of solar panels and a sketch of the present status of recovery efforts, policies on solar panel EOL management and recycling. The review also anticipates the base of solar panel recycling recommending future directions for public policymakers.

2. Overview on large-scale PV installations

There are various types of solar PV cells, whereby the c-Si solar cell dominates 80% of the market globally [1,7,8]. Thin film solar cells are second generation, semiconductor-controlled solar cells made from materials such as cadmium telluride (CdTe), and copper indium gallium (di) selenide (CIGS). In 2017, the total newly installed capacity was 99.1 GW globally, which was approximately the same as the total installed capacity up until the end of 2012 (100.9 GW) [5]. By the end of 2017, the total installed capacity exceeded 400 GW, with the capacity in 2015–2016 rising from around 200 GW–300 GW [5]. The cumulative installed solar power capacity increased by 32% between 2016 and 2017 from 206.5 GW to 404.5 GW, as shown in Fig. 2. In 2007, Germany was the first country to sanction the commercial connection of solar power to their national grid commencing a tariff scheme [6]. In 2007, the

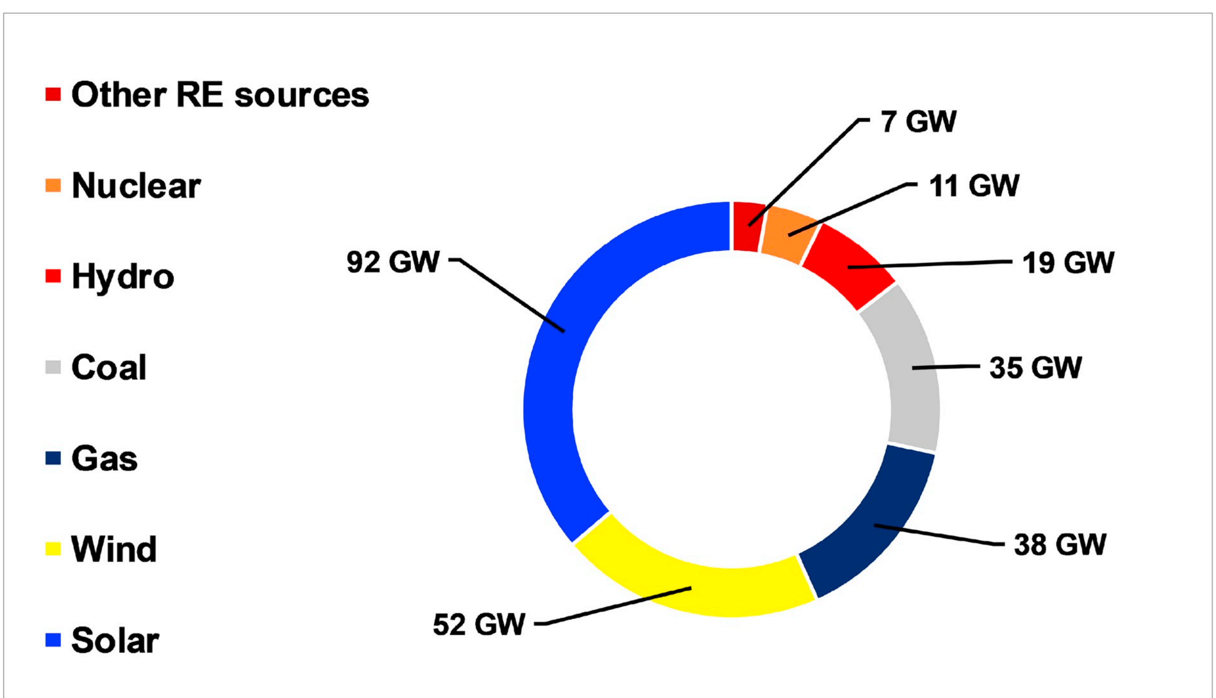

Fig. 1. Power generating capacity installed in 2017 [5,6].

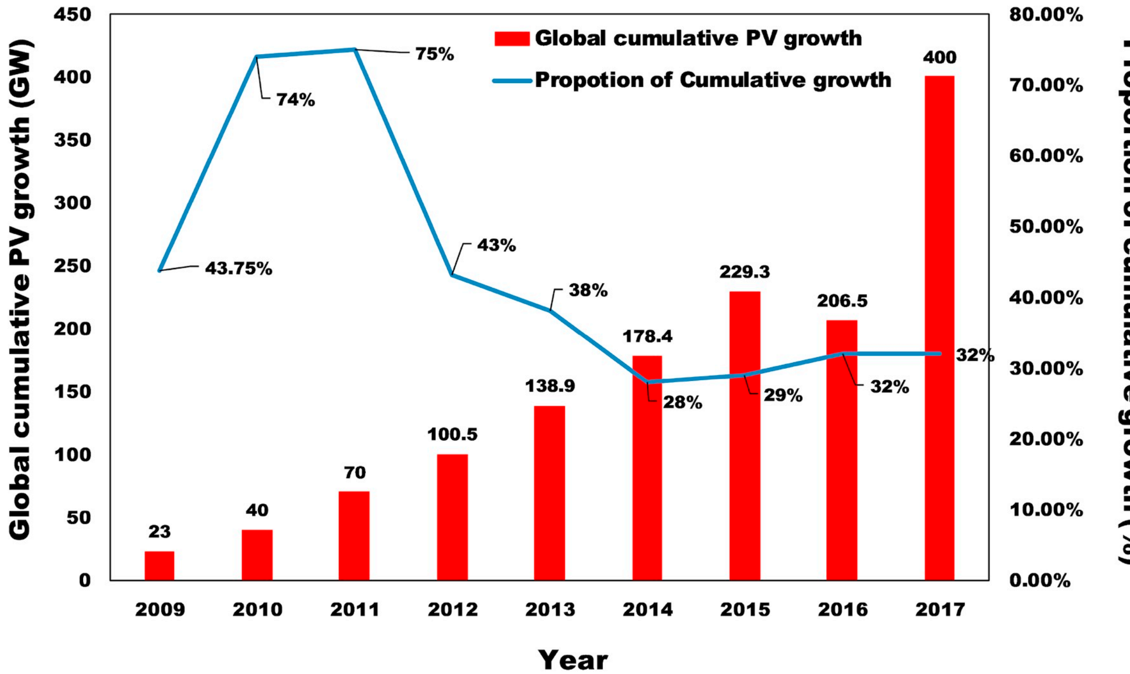

Fig. 2. Global growth of solar PV capacity [5,6,9–11].

installed global capacity was 9.2 GW. At the end of 2017, the cumulative installed capacity increased by around 43% [6].

In 2017, the Asia-Pacific region became the leading area for solar power having increased its capacity by 73.7 GW to reach a total installed capacity of 221.3 GW [5,6]. It represented a 55% share of the global capacity as visible in Fig. 3 [6]. Meanwhile the European nations were the solar power pioneers and still together occupy second position in the world's capacity ranking based on a cumulative PV capacity of 114 GW, while their share has slipped to 28%. The United States of America are in third position with a total installed capacity of 59.2 GW, or around 15% [5]. The share of Africa and the Middle East was reduced in 2017. Even after adding 2.1 GW, the total solar capacity of 6.9 GW represented only 1.7% of the global capacity [5]. Almost one third (32.3%) of the world's solar power generation capacity was operated by China based on a substantial increase from 2016 [11]. China for the first time became the world's largest solar power generating nation in 2017, having increased its share from around 25% in the previous year, followed by Japan and USA. In 2017, USA overtook Japan although the share of the total world capacity of both countries were reduced [7].

Based on their share of worldwide capacity, Japan's 49.3 GW was reduced to 12.2% in 2017, as compared to 13.8% in 2016 [6]. None of the European individual nations was among the top three solar power generating nations. Only Germany had the fourth largest capacity achieving a double-digit global share, due to a low new-installation of 1.8 GW in 2017, which resulted in a drop-in global share to 10.6% from 13.4% in 2016 [6]. Further, for the first time in 2017, India was among the top five countries, having added more than 10 GW of solar generation capacity to increase its share of global installed capacity by 4.7%, and doubling its total PV capacity in 2017 to 19 GW [5]. At the end of 2017, the United Kingdom and Italy were the only other two countries with more than 10 GW of installed solar capacity, with Italy at 19.4 GW and the United Kingdom at 12.7 GW [11]. Based on the current

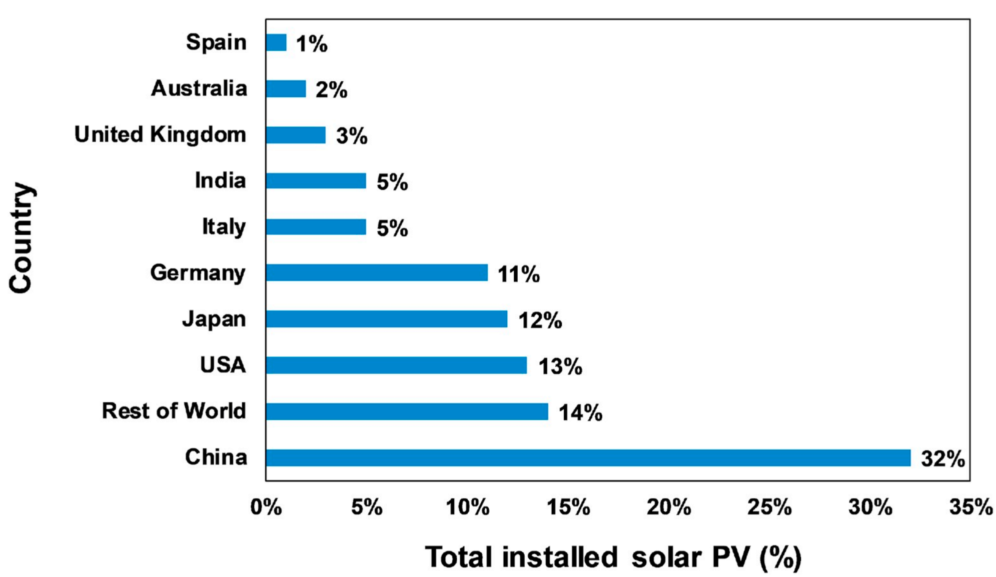

Fig. 3. The top 10 countries worldwide by total installed solar PV capacity at the end of 2017 [6].

estimates, it is unlikely in 2018, that any other countries will increase their installed capacities to 10 GW with Australia (7.3 GW), France (8 GW) and Spain (5.6 GW) some way below that level in 2017 [6].

3. Global photovoltaic market and waste generation

The market share of solar panels by technology group is shown in Fig. 4. Currently, the volume of comprehensive connected PV panels is rising sharply. Rapid growth is anticipated in the coming years with the typical useful life of a solar panel of 25 years [1,12]. However, it is expected that the total quantity of PV panels EOL will reach 9.57 million tonnes by 2050 [4]. In 2014, the market was dominated by silicon-based c-Si panels, which accounted for a 92% share of the market with those based on CdTe technology at 5%, copper indium gallium (di) selenide (CIGS) at 2%, with 1% accounted for by those manufactured from other materials (dye-sensitized, CPV, organic hybrids) [4,14,15]. The market share of c-Si PV panels is projected to decrease from 92% to 44.8% between 2014 and 2030 [13,14]. The third-generation PV panels are predicted to reach 44.1%, from a base of 1% in 2014, over the same period [4,13–15].

Solar PV panels will probably lose efficiency over time, whereby the operational life is 20–30 years at least [7,13,16]. The International Renewable Energy Agency (IRENA) estimated that at the end of 2016, there were around 250,000 metric tonnes of solar panel waste globally [12]. The solar panels contain lead (Pb), cadmium (Cd) and many other harmful chemicals that could not be removed if the entire panel is cracked [17–19]. In November 2016, the Environment Minister of Japan advised that Japan's production of solar panel waste per year is expected to rise from 10,000 to 800,000 tonnes by 2040 and the country has no plans to dispose of them safely and effectively [17,20]. A recent statement found that the Toshiba Environmental Solutions will take approximately 19 years for reprocessing all solar massive waste of Japan produced by 2020 [21]. The yearly waste will be 70–80 times higher by 2034 than the year before 2020 [21]. China with a larger number of solar plants, currently operates around two times as many solar panels as USA and has no proposals for the dumping of the whole old panels. Despite the presence of environmental awareness, California, another world leader in solar panels, also has no waste disposal plan. At the end of their useful lives, only Europe requires the manufactures of solar panels to collect and dump solar waste. Although solar panels were disposed of on regular sites, it is not advisable because the modules can degrade, and harmful chemicals can leach into the ground causing drinking water contamination [22].

The lifetime of PV modules has been estimated for 25 years. Therefore, it can be assumed that the installed PV power (MW) becomes waste after that period. To identify the time shifting, the years of installation and the years of waste generation may be denoted as x and y, respectively where $y = x+25$ [1].

Currently, two types of PV recycling technology are commercially available but other technologies are also under research. Panels manufactured by using c-Si technology occupy the major market share with thin film technology by using either CdTe or CIGS technology as the second largest market sector [13,19,23]. The recycling processes for c-Si PV panels are different from those applied to thin film PV panels because of their different module structures [5]. One important distinction is that the aim of disposing of the encapsulant from the layered structure of compound PV modules is to recover the quilted glass and the substrate glass that contain the semiconductor layer [19,23]. Therefore, the purpose for recycling c-Si modules is to divide the c-Si glass and to recover the Si cells and other metals. The method incorporated in recycling Si-based PV panels is to separate the layers, which necessitates removing the encapsulant from the panel and the Si cells to recover the metals [23]. The removal of the encapsulant from the laminated structure is not straightforward and many possible approaches exist, including thermal, mechanical, and chemical process. Chemical methods recapture metals from Si cells, for instance, by etching and other processes. The substrate

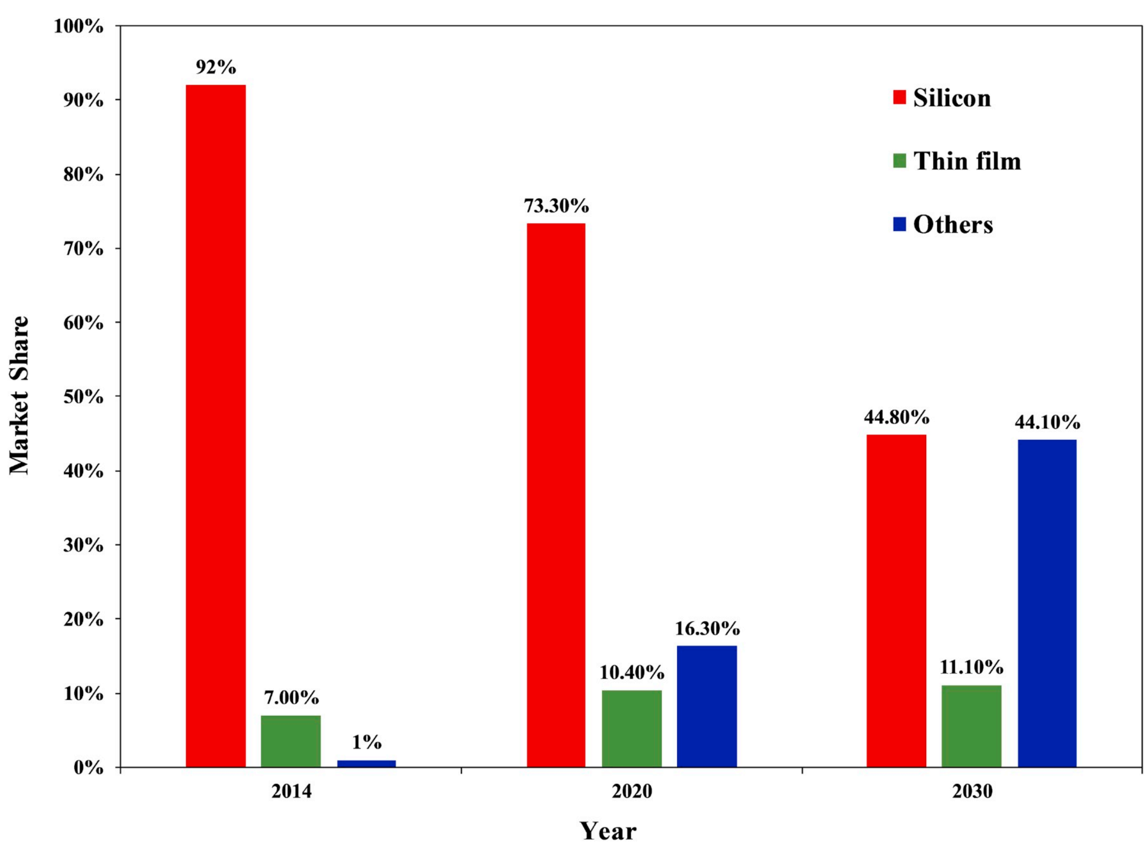

Fig. 4. Market share of PV panels by technology type (2014–2030) [4,13,14].

glass and the metals in the semiconductors are separated, recovered and can be isolated and purified [5,13].

Most of the waste is typically generated during four primary life cycle phases of any given PV panel. These are 1) panel production 2) panel transportation 3) panel installation and use, and 4) EOL disposal of the panel [13]. The following waste forecast model covers all life cycle stages except for production. This is because it is assumed that production waste is easily managed, collected and treated by waste treatment contractors or manufacturers themselves and thus not a societal waste management issue.

3.1. Causes of solar PV panel failure

There are relatively few defects found in new solar panels, with light erosion (0.5%–5%), with poor design and defects arising during manufacture being the main causes [13,19,22]. From Fig. 5, other causes of panel failure have been claimed to be due to electrical equipment, such as junction boxes, fuse boxes, charge controllers and cabling as well as issues with grounding [24,25]. In the early years of production, solar panels suffered from degradation of the anti-reflective coating layer of colourless ethylene vinyl acetate (EVA) applied onto the glass, as well as incoherency due to cracked solar cells [26]. During the first 12 years of use, failures were caused by repeated load cycles due to, for instance to wind or snow, as well as temperature changes which caused degradation, contact defects in junction boxes, glass breakage, burst frames, breakage of cell interconnections and problems with the diodes associated with a higher rate of cell degradations and interconnectors [13,21]. Previous research has shown that 40% of PV panel failures were due to microscopic cracks and failures [21]. This reason has been the most common in newer panels manufactured after 2008 when the production of thin cell panels began [13,21].

4. Existing methods of the recycling process

4.1. Recycling process

Nowadays, Japan, Europe and the US are focused on research and development related to solar module recycling [28–32]. Most efforts related to solar panel recycling concentrate on Si panels and aim to recover and recycle the most important parts. As stated above, there are presently three different types of recycling process applied to solar PV panels which are physical, thermal and chemical as illustrated in Fig. 6 [4].

4.2. Physical separation

In this process, panels are primarily dismantled by removing the surrounded Al frame, as well as the junction-boxes and embedded cables [25,26]. The single part of the PV modules (panel, junction-box and cables) are shredded and crushed to inspect the individual toxicity of each part and total toxicity of the module for disposal [25]. Frame is the last component to be attached to the module. It serves as a bonding component, isolates the module edges from the exterior (to avoid water infiltration, for instance) and provides a mechanical strength while keeping the overall structure light [23,35,36]. After the frame component is separated from the module, it can be recovered through a secondary metallurgy. Other elements present in small quantities (iron, silicon, and nickel) are typical components of aluminium alloys [23,35].

The replacement of elements in solar cells to repair systems is confined to replace electrical components and does not include material separation or cell treatment [37,38]. There are two widely used types of process to check for and repair the junction box faults. By repairing the junction box faults, it can help to increase the output power of the older solar panels. However, this method can only be used for external junction boxes located outside the main body of the solar panel.

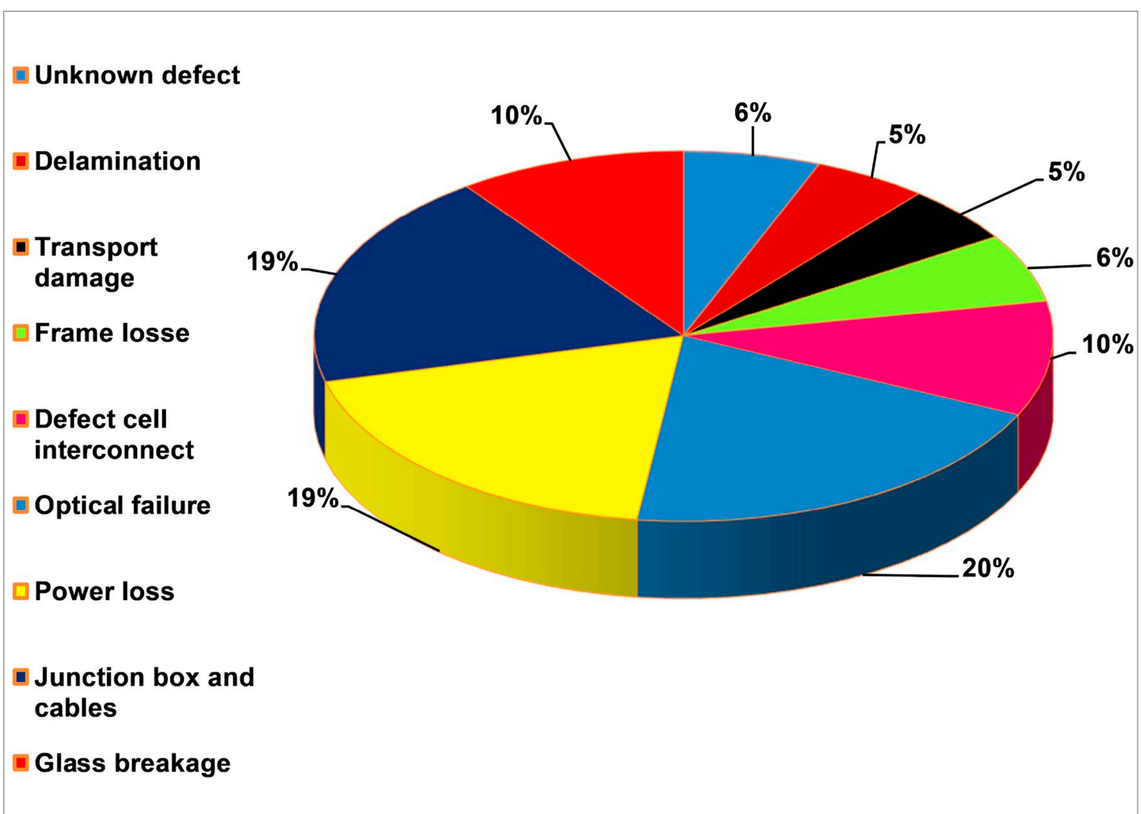

Fig. 5. PV panel failure rates according to customer complaints [21,27].

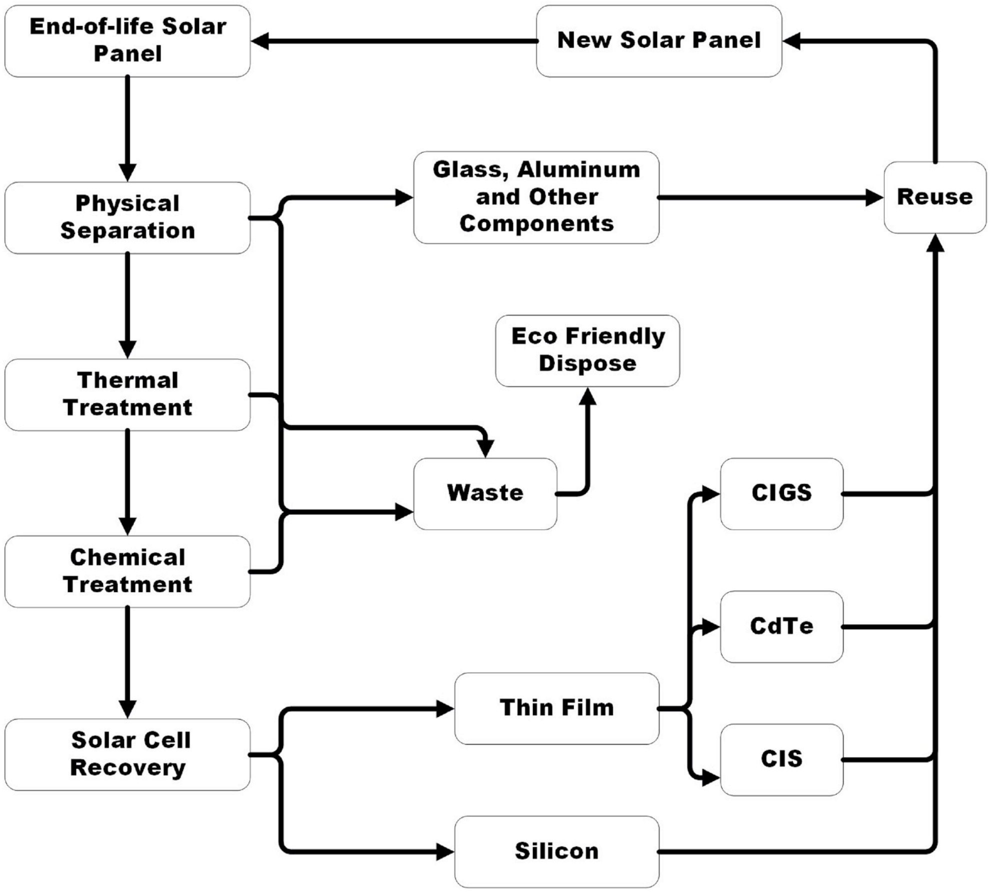

Fig. 6. Different types of solar PV recycling processes [33,34].

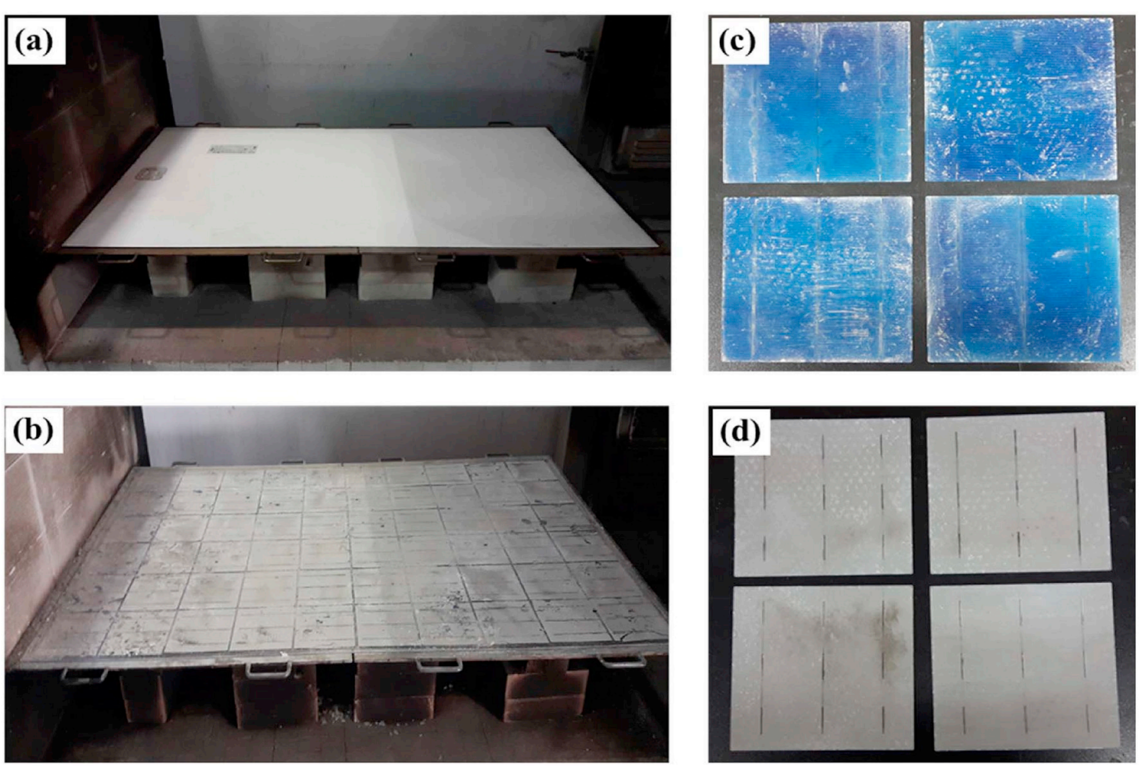

Fig. 7. PV wafers during heating procedure: (a) before heating; (b) after heating; (c) reverse side before heating and (d) reverse side after heating [3].

4.3. Thermal and chemical treatment

Fiandra et al. [8] applied thermal treatment to recover the polycrystalline silicon by using a high temperature Lenton tubular furnace. Samples were taken from the PV module by manual dismasting of the external Al frame. Each sample was obtained by cutting a piece of about 10 × 10 cm by using a diamond blade for glass cutting, followed by panel cutting. The gas supply flow rates for the furnace were managed by two flow meters to get nitrogen/oxygen mixtures at different ratios. The gas was supplied at a flow rate of 24 L/h. Then the reactor was heated up to the process temperature (500 °C) at a heating rate of 450 °C/h and the temperature was finally held for 1 h [18].

Pagnanelli et al. [39] used mechanical crushing to reduce the glass to >1 mm and further crushing was done to recover different grades of the glass fraction, all of which were <1 mm. Thermal treatment, with an air flux of 30 L/h was then applied to recover the glass and metal fractions. The heating rate was gradually increased until it reached 650 °C at a rate of 10 °C/min. The furnace was then maintained at that temperature for 1 h. An overall glass recovery rate of 91% was achieved by this means.

Meanwhile, Orac et al. [38] used thermal pretreatment followed by acid leaching to recover copper and tin from the used circuit boards.

Shin et al. [3] recycled 60 multi-crystalline Si wafers (156 mm × 156 mm) which was manufactured in South Korea by JSPV Co. Ltd. Thermal treatment was first applied to separate the layers of the solar panels [33, 40] as shown in Fig. 7. The thermal treatment was conducted in a K-Tech. Co (South Korea) furnace (1500 mm wide x 1700 mm high x 2000 mm long). The wafers were first coated with a phosphoric acid paste and then heated for 2 min at five temperatures ranging from 320 °C to 400 °C. The resulting recovered wafers were successfully used in manufacturing solar panels and the efficiency of the cells was found to be similar to that of the original product.

Doi et al. [31] applied various organic solvents to crystalline-silicon solar panels to remove the EVA layer, which was found to be melted by diverse types of organic solvents, of which trichloroethylene was found to be the most effective. The solar panels (125 mm × 125 mm) were treated in a process by using mechanical pressure, which was essential to suppress the swelling of EVA during soaking in trichloroethylene for 10 days at 80 °C. The reclaimed Si panels could be used efficiently after the recycling process.

Kim and Lee [41] reported on enhancing the rate of EVA layer dissolution by using different types of organic solvents (trichloroethylene, O-dichlorobenzene, benzene, and toluene) aided by an ultrasonic process. The research tested different solvent combinations, temperatures, ultrasonic power and radiation times. After 1 h, the EVA layer was fully dissolved in 3 mol/L of toluene at a temperature of 70 °C with exposure to ultrasound at a power of 450 W. However, a problem was noted with this process in which lead was resulted as a hazardous by-product.

Marwede et al. [42] reviewed the available means of treating EOL PV materials and noted that the pH value changed during three periods when sodium hydroxide was used for metal recovery [43,44]. In other research works, 5 N Plus recovered metals by evaporation in a thickening tank and the metals were recovered by filtering during dewatering.

First Solar announced 95%–97% recovery rate for both Cd and Te which were capable of being reused in First Solar products [46,47].

Wang and Fthenakis [48] conducted Cd and Te separation by using various ion-exchange resins on the metals in a sulphuric acid solution over different time periods [49–51]. The recovered metals were eluted from their ion-exchange/acid solutions, and a high recovery rate of above 90% was recorded. In another study, the recovery of Te from solution was noted to be accelerated by the use of sodium carbonate and sodium sulphide.

Dattilo [52] reported the wet-chemical extraction of metals from CIGS panels. The method dependent on desalinizing of composites, recovering the Cu and separating other metals such as In and Ga. CIGS materials were directly decomposed by electrolysis with the Cu and Se settling on the cathode plate, which were then removed and separated by oxidization and distillation to produce Cu, Se with ZnO and InO being compounded by exhalation.

Table 1 and Table 2 summarizes the currently available solar panel recycling technologies. While many of these methods have been the subject of laboratory-based research, there are currently only two commercially available treatments. The US-based solar manufacturer First Solar applies both mechanical and chemical treatment methods to thin film solar panels. On the other hand, c-Si solar-panel modules have been recycled by a company in Germany [6,61]. China has limited facilities for recycling involving component repair and panel separation and hires an external technology to conduct the separation and recycling of individual materials. Similarly, other countries have problems in applying recycling technologies. Physical or mechanical processes generate a huge amount of dust which contains glass. Therefore, it is toxic, and the processes are also a source of noise pollution. The separation of the EVA layer by inorganic solvents leads to nitrogen oxide

Table 1
Silicon solar module recycling processes.

Technology	Process	Advantages	Disadvantages	Ref.
Delamination	Physical disintegration	➢ Efficient waste handling	➢ Other materials mix with EVA. ➢ Solar cells damage. ➢ Apparatus decomposition.	[3,53,54]
	Thinner dissolution (Organic Chemistry)	➢ Organic layer removal from glass ➢ Waste chemical reuse ➢ Simple removal of EVA	➢ Time necessary for delamination depends on area. ➢ Expensive equipment. ➢ Hazardous for human health.	[31,55]
	Nitric acid dissolution	➢ Complete removal of EVA and metal layer from the wafer ➢ Possible recovery of the whole cell	➢ Dangerous emissions. ➢ Cell defects due to inorganic acid.	[56]
	Thermal treatment	➢ EVA fully eliminated. ➢ By reusing wafers, possible to regain whole cell	➢ Involves high energy consumption. ➢ Dangerous emissions	[47,57,58]
	Ultrasonic irradiation	➢ Used as a supplementary process to accelerate dissolution process ➢ Simplified removal of EVA.	➢ Very costly process. ➢ Waste solution treatment.	[41]
Material Separation	Dry and wet mechanical process	➢ Non-chemical process. ➢ Simple process. ➢ Requires low energy. ➢ Equipment available.	➢ No removal of dissolved solids	[45]
	Etching	➢ Simple and effective process. ➢ Recovery of high purity materials	➢ High energy demand because of high temperatures. ➢ Use of chemical.	[59]

Table 2
Thin film solar module recycling methods.

Technology	Process	Advantages	Disadvantages	Ref.
Delamination	Physical disintegration	➢ Feasible to obtain various wastes by treatment (Split modules, submodules and laminated modules).	➢ Mixing of the various material fractions. ➢ Loss from each material fraction. ➢ Glass still partly combined with the EVA. ➢ Breakage of solar cells.	[3,53,54]
	Thinner dissolution (Organic Chemistry)	➢ Organic layer removed from glass. ➢ Reprocessing solutions. ➢ Simple removal of EVA.	➢ Time necessary for delamination depends on area. ➢ Cannot be dissolved fully and EVA still adheres to glass surface.	[31,54]
	Thermal treatment	➢ Complete elimination of EVA. ➢ Possible to recover whole cell by reusing wafers.	➢ High energy consumption. ➢ Hazardous emissions.	[32,41,42]
	Radiotherapy	➢ Easy to eliminate EVA	➢ Slow procedure ➢ Very expensive process.	[34,47]
Material Separation	Erosion	➢ No chemicals required ➢ Glass can be recovered	➢ Additional treatment of pre-purification is necessary	[60]
	Vacuum blasting	➢ Removal of semiconductor layer without chemical dissolution. ➢ Glass can be recovered	➢ Emission of metallic fractions ➢ Relatively long processing time.	[42,61]
	Dry and wet mechanical process.	➢ Non-chemical process. ➢ Simple procedure. ➢ Needs low energy. ➢ Apparatus usually available.	➢ No removal of dissolved solids	[45]
	Tenside chemistry	➢ Tensides are reusable. ➢ Metals fully removed from glass.	➢ Emulsions must be adapted to different cell technologies ➢ Delamination time depends on the area.	[49,51]
	Leaching	➢ Complete elimination of metal from glass. ➢ Further extraction of metal solutions possible.	➢ Very high use of chemicals. ➢ Complicated control of the chemical reactions.	[49,62]
	Flotation	➢ Comparatively easy method. ➢ Limited use of chemicals	➢ Material separated at various stages of flotation ➢ Inadequate purity of materials.	[54,60]
	Etching	➢ Recovery of high purity materials. ➢ Low cost and effective process	➢ High energy demand because of high temperatures. ➢ Chemical usage.	[59]
Material purification	Hydrometallurgical	➢ Commercially applicable. ➢ Low and controllable emissions ➢ Easy water management	➢ Many separation and absorption steps. ➢ Chemical process steps must be adapted to respective technology.	[47,49,60]
	Pyrometallurgical	➢ Established industrial process. ➢ Feedstock can contain different materials	➢ High throughput necessary. ➢ Some materials are lost in slag. ➢ Heavy metals or unwanted materials	[47,49,55,60]

emissions and other harmful gases [56], and their inhalation constitutes a health risk. In addition, the process of reusing the silicon wafers involves frame removal and it is difficult to dispose of the remaining liquid. Furthermore, the time required for EVA dissolution by familiar organic solvents is long, but it can be accelerated by using ultrasound. However, the process also produces a very large amount of organic-melted waste, which is difficult to treat. The thermal and chemical methods are therefore a combined and advanced technology but with the disadvantage that they produce toxic gases and consume high amounts of energy.

5. Recycling approaches

Within the European Union, the first country to adopt the EU's WEEE directive that relate to the disposal and recycling of solar PV materials was the UK [63]. Then, the second EU country to ratify the directive was Germany, which now also follows the WEEE regulations [64]. Under the directive, all producers or importers of solar PV materials, including solar panels, have to register under a product consent scheme in which all data about the panels must be provided by the manufacturers [63,65]. In addition, the producers and importers have to accept responsibility for the EOL treatment of their products or they are subjected to large fines. Moreover, the European Union and the Czech Republic have entered into a joint venture for the recycling and recovery of solar PV panels EOL, following the WEEE directive [65]. Worldwide, the recycling of PV products requires producers to employ waste management techniques or employ the service of companies or non-profit organizations and solar PV waste management advisors to help them deal with the problem of EOL panels [63]. Currently, the Czech company, Retina offers both reprocess and advisor service in relation to the reprocessing management. In Europe, the WEEELABEX organization which operates out in Czech Republic is responsible for the preparation of standards and the awarding of certification in respect to collection, storage, processing and reprocessing of WEEE and the monitoring of waste-processing companies [65]. In Italy, a significant drive towards the accountable management of the EOL PV modules were the Legislative Decree No. 49 of 14 March 2014 that implements the Directive on WEEE (Directive 2012/19/EU) [66]. According to this decree, decommissioned PV panels were involved in the types of household and professional WEEE for boosting the exploitation of secondary raw materials to endorse a more efficient use of the natural resources used in their production. The Decree also states the minimum aims assuring that at least 75% (by weight) of the modules be recovered, and that at least 65% (by weight) undergo the recycling process. Subsequently, recovery of 80% and recycling of 70% is projected. The public body member for monitoring the accomplishment of the objectives set is the Italian National Institute for Environmental Protection and Research (ISPRA) [66]. It annually transmits a detailed report to the Ministry of the Environment and Protection of the Territory and the Sea notifying about the quantities and categories of electrical and electronic equipment located on the market, prepared for reuse, recycled, and recovered.

Outside of Europe, a few countries have addressed the issue of solar panel waste regulations. Some developing countries, for instance, India, North Korea, Thailand etc. are yet to consider any waste management regulation for solar PV waste recycling [13]. South Korea has just initiated the discussion about PV waste. PV waste is included as one of industrial wastes in Annex Table 4 of Article 4.2 of South Korea's Enforcement Rule of Wastes Control Act (Act No. 14783). Article 4.2 outlines complete classifications of waste and possible recyclables [67]. In 2017, the Ministry of Trade, Industry, and Energy decided to establish a facility to recycle PV module waste in North Chungcheong Province, South Korea [67]. In Japan, solar panel waste recycling is under the control of the Japanese environment ministry and solar panel manufacturers participate with local companies in research on recycling technology that relates to recycling technology in Europe [13]. Moreover, the European PV organization and Shell Oil Company (Japan) have entered into an association. NPC, a solar-panel and equipment manufacturer, has entered into a joint venture with Hamada (an industrial waste-processing company), to recycle solar panels. In 2016, the two companies jointly established a PV processing improvement project through the New Energy Industrial Technology Development Organization (NEDO) [4,68]. In USA, the state of California Department of Toxic Substances Control (DTSC) offered to take responsibility for solar waste treatment, when European facilities' capacity decreased and the DTSC has now increased its recycling capacity and upgraded their facilities for the disposal of hazardous materials after treatment [69]. USA-based solar panel manufacturing company, First Solar has established factories in the United States, Germany and Malaysia, which also employ recycling methods with recovery rates of 95% for Cd and 90% for glass [13,70]. Even China does not yet have strong policies relating to recycling and even its environmental protection authority has not yet focused on waste recycling [64,71]. However, Both Yingli Solar and Trina Solar are studying solar PV development and recycling. Moreover, the state of Victoria (Australia) government have established the consequence of ensuring that procedures are in place to deal with the issues related to solar PV waste [72]. The decision of Australian ministry would lead pioneering systems reducing the environmental impact caused during the lifecycle of solar PV techniques [24,72]. These attempts are part of an industry-led charitable invention organization composition to focus on the capability developing dangers of solar PV structure and their waste. The solar PV components are listed under the National Product Administration Act as a signal to the objective to believe a programme in contracting solar waste [24,73].

Different types of waste, particularly electronic waste, are being regarded as a liability which should be managed by the manufacturer of the products [13]. Making manufacturers liable for PV panels EOL would encourage a sustainable management of PV materials [74–77]. Moreover, manufacturers should be encouraged to adopt environmentally friendly designs by enforcing appropriate regulations. This would help to reduce the environmental impact of PV products. It can also be aided by conserving resources through the collection and recycling of EOL products as well as promoting the manufacture of new solar panels by using recycled materials [78]. Finally, strict laws should be passed in relation to the collection and recycling process, which will help the creation of a logistical network to support the productive technology and to create links in an environmentally friendly supply chain [79].

6. Social and environmental advantages

At the end of 2016, various estimates of the volume of solar PV waste was ranged between 43,000 and 250,000 tonnes worldwide. Comparatively, the small amount that is currently being produced renders reprocessing not economically viable with the projected growth of waste PV panels up to 2050 with different projections based on regular and early loss scenarios [14]. Based on the increase in the installed PV generation capacity in the current decade, the number of EOL panels will necessitate a strategy for recycling and recovery. The worldwide ratio of solar PV waste to new installations is expected to increase considerably over time as shown in Fig. 8. It will reach between 4% and 14% of total generation capacity by 2030 and approximately rise over 80% by 2050. Based on literature, analysing the expected rates of panel installation and solar panels EOL, most of those will be c-Si over the next several years [43,59,80]. Therefore, the methods of dealing with solar PV waste material, principally by recycling need to be established by 2040. By recycling solar PV panels EOL and reusing them to make new solar panels, the actual number of waste (i.e., not recycled panels) could be considerably reduced. Scenarios that involve recycling were analysed by Cucchiella and Rosa [81] based on net present value and discounted payback period rubrics with the aim of supporting management strategies in respect to recycling plants, with particular reference to the economic viability of plants of various sizes. A 2.6 MW conventional power station causes an annual volume of 1480–2220 tonnes CO_2 eq emissions and this could be saved by recycling 186 tonnes solar PV waste [14]. Such a saving would have a considerable positive impact on the environment and would reduce emissions from power generation by around 49470 tonnes CO_2 eq over the 20-life of a power station [14]. It has been estimated that the output from a 1903 MW conventional generating facility would be equivalent to recycle 1480 tonnes solar PV waste. It would reduce emissions by around 11840–17760 tonnes CO_2 eq over the lifetime of the plant, a saving that equate to 396770 tonnes CO_2 eq [13,14]. Moreover, Te recovery is important from both the environmental and economic perspectives. CdTe modules can be produced from recycled Te, and thus reducing the need to extract more of this limited natural resource.

7. Conclusion

Based on the swift growth in the installed PV generation capacity, we propose that the number of EOL panels will necessitate a strategy for recycling and recovery which need to be established by 2040. CO_2 emissions could also be reduced by recycling solar PV waste which will consequently pose substantial positive impact on the environment.

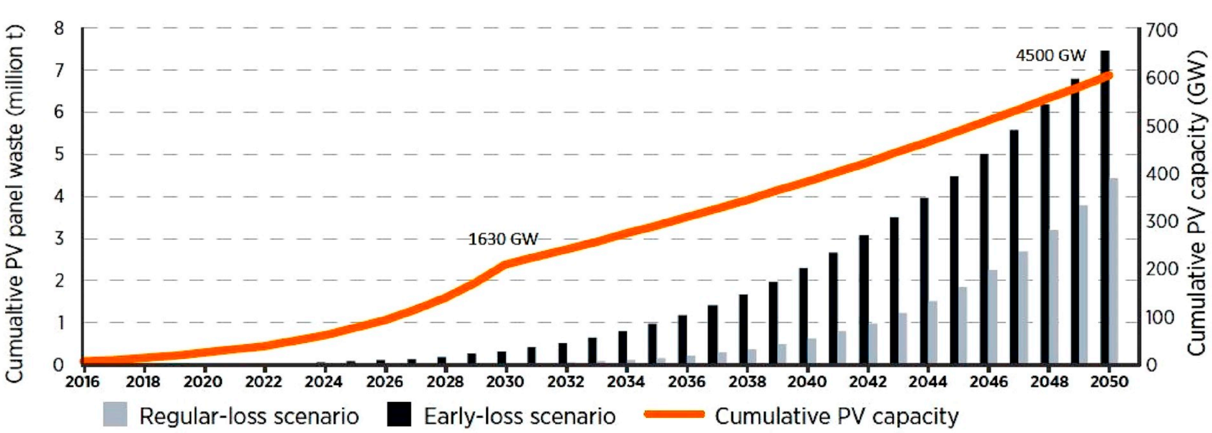

Fig. 8. The estimated cumulative worldwide solar PV module waste (tonnes) 2016–2050 [13,14].

Therefore, this review scrutinized the necessity for solar PV recycling policies by analysing the existing recycling protocols. Recent studies have found it difficult to assess the future consequences of current research, development and testing efforts for PV panel recycling techniques. There are currently not enough indications on policies to handle these problems. Particularly in China, there is a lack of regulations on solar panel recycling. Furthermore, in Asia, countries should help to protect their natural environments by developing an environmentally friendly recycling industry and enforcing regulations to encourage reprocessing and the safe disposal of waste. This study contributes to literature on evaluating the sustainability of EOL management of PV panels, and paves the way for future researchers to comprehend the issues involved in the sustainable development of the PV sector. We recommend that recycling should be made commercially necessary by making manufacturers responsible for recovering materials from solar PV panels EOL. In summary, the management of panels EOL and other hazardous waste is obligatory. Additionally, governments must adopt hard-line policies to enforce the manufacturers of solar PV materials to consider the consequence of their products on the environment. It is also essential to gain the support of the mass-media, social media, public, and non-governmental organizations. It is indispensable to put pressure on manufacturers to act responsibly and to extend the responsibilities of producer not only in the solar PV manufacturing sector, but also throughout the entire energy industry, to be responsible for the eventual disposal or reuse of the products. All in all, it is expected that the pace of R&D will accelerate permitting researchers to resolve issues and contribute to the PV module recycling schemes, as well as for the end-of-life management of PV modules.

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