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Methodological approaches for resource recovery from end-of-life panels of different generations of photovoltaic technologies – A review

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ABSTRACT

The rise in prominence of solar energy as a green technology demanded economical and sustainable waste management due to the anticipated surge of end-of-life panel waste streams. While there are many advantages to the increase in solar power output, end-of-life solar panels could become a source of hazardous waste. Therefore, the disposal of photovoltaic panels will become a major environmental concern in the next decades. Generations of photovoltaic technologies, namely crystalline silicon, thin-film, and third-generation solar panels, share the goal of achieving waste reduction through useful strategies for recovery of secondary raw materials from obsolete panels. This research reviews the current status and future prospects for valuable constituents, waste projections, and trends in technological advances for recycling and recovery of resource materials from different generations of photovoltaic solar systems. Projections of global photovoltaic waste driven by the expansion of solar system installations illuminate the influx of waste streams that burden the environment if there are no measures in place for sustainable waste management. The crystalline silicon and thin-film PV technologies have demonstrated sufficient advancements in resource recovery technologies for industrial use in circular economy and closed-loop recycling to minimize environmental impacts and prevent leaching of toxic elements. Industrial application of pyrolysis and chemical etching has emerged as a promising approach to recovery of high-purity secondary valuable materials from obsolete c-Si panels. Substantial recoveries of critical from obsolete thin-film panels are notable with the application of mechanical and hydrometallurgical waste treatment techniques. Third-generation waste treatment methods are largely based on laboratory experiments because these solar systems are on the verge of commercialization.

1. Introduction

Conventional burning of fossil fuels to generate electricity in order to meet energy demand is associated with the release of greenhouse gases that contribute to climate change and negative impacts on human health. In the midst of ongoing worldwide environmental concerns about reducing the amount of energy produced by burning fossil fuels, renewable energy technologies have created new avenues for the utilization of renewable energy resources to promote a sustainable and healthy environment [1]. The basis for addressing the global energy crisis, resource depletion, and gradual environmental degradation brought on by climate change is the establishment of clean and green energy technologies to replace the production of fossil fuels [2]. Reducing reliance on coal-based grid electricity supply by using solar photovoltaic (PV) systems has become a viable global solution for energy issues. Furthermore, erratic electricity supply and the growing expense of producing electricity using fossil fuels can both be realistically addressed by PV technology [3]. The PV sector has been greatly prompted to improve the supply of clean and renewable energy because of the considerable environmental benefits and cost-effectiveness of PV technology. The tremendous potential of solar cells as a green energy technology to surpass traditional fossil fuel technologies is driving the global expansion of the PV sector in large geographic regions [4].

The cornerstone of ongoing developments in the PV industry is the capacity to build and install well-constructed solar plants from off-grid small-scale manufacturing with low maintenance costs. Moreover, solar plants have demonstrated the potential to combine electricity production to shield crops from high temperatures and enhance crop water availability during periods of intense rainfall [4,5]. According to

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Abbreviations

a-Si	Amorphous silicon
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
c-Si	Crystalline silicon
DSSC	Dye-sensitized solar cells
EVA	Ethylene-vinyl acetate
FRELP	Full recovery end-of-life PV project
FTO	Fluorine-doped tin oxide
GaAs	Gallium arsenide
IRENA	International Renewable Energy Agency
ITO	Indium-tin oxide
NREL	National Renewable Energy Laboratory
OPV	Organic photovoltaic
PCE	Power conversion efficiency
PSC	Perovskite solar cells
PV	Photovoltaic
QDSC	Quantum dot solar cells
WEEE	Waste from Electrical and Electronic Equipment

Farrell et al. [6], the modular nature of solar PV is intended to allow for the addition of more modules to enable large-scale panel expansion for varied applications with no global impact. PV technology uses solar cells which include an active layer with semiconducting materials acting as light absorbers to generate both photovoltage and current. These solar cells are often wired in parallel or series circuits to expand the panels and provide higher voltages, currents, and megawatts of power. Solar energy excites electrons on a light-trapping material embedded within these cells and raises the energy level to produce a voltage that drives a current through a circuit to generate system-level outputs [4]. The two main parts of the PV energy producing system is the panel and the balance of system. PV systems are intricate and need numerous components to function in tandem in order to collect, transform, and store solar energy as electricity. All PV systems, whether off-grid or grid-connected, require solar panels, which are essentially useless without a balancing component. The balance of system consists of additional components of PV panels such as inverter, tracking system, transformer, wiring, mounting, charge regulators and batteries. Inverters can change direct current electricity into alternative current electricity, while transformers and mounting structures are necessary for rooftop systems or utility-scale power plants. Cabling and tracking systems can enhance solar light output and batteries in the event that an off-grid PV system needs energy storage [7]. Although balance of system manufacturers and suppliers represent an important part of the PV value chain, the scope of this study provides limited information on waste assessment and management generated by balance of system.

It is evident that PV technology is rising to prominence as a renewable energy source. Over the course of its ideal operating life, it will gain significant advantages in the global energy market due to an increase in the use of off-grid solar power, which has been influenced by cost savings and potential integration with energy storage systems [8]. Three generations of PV technology have been identified: first-generation solar cells, which includes crystalline silicon (c-Si), wafer-based (monocrystalline or polycrystalline); second-generation solar cells, also known as thin-film, which comprises amorphous silicon (a-Si), cadmium telluride (CdTe), gallium arsenide (GaAs) and copper indium gallium selenide (CIGS); and third-generation solar cells, which comprises dye-sensitized solar cells (DSSC), organic photovoltaic (OPV) solar cells, quantum dot solar cells (QDSC), and perovskite solar cells (PSC). The most widely used types of panels are thin-film and wafer-based (monocrystalline and polycrystalline), with c-Si offering a higher power conversion efficiency (PCE) than other PV technologies [8]. The manufacture of a-Si thin-film is being phased out due to insufficient efficiency and instability of the solar cells, while development of third-generation solar panels is still in its early stages with continuous efforts to increase PCE and stability [9]. The demand for generating new modules drives the increasing amount of end-of-life module waste which contains a combination of valuable, critical and hazardous materials. Understanding waste streams is becoming an important aspect to predict the availability of recycled valuable materials and their potential contribution to manufacturing of required cumulative demand [10].

To guarantee efficient PV waste management, it is important to estimate and characterize upcoming waste output from PV panels through waste projections in assessment of material usage amounts, recovery rates, actual and projected installation capacities (ideally location-based), practical module lifetimes, and past, present, and future market shares of different module technology types [11]. The projected exponential rise in the quantity of obsolete PV panels could result in appalling waste streams that burden the environment through landfills should a thorough waste management plan not be adequately implemented [12]. Conventional c-Si panels are regarded as rich waste because the end-of-life solar panels contain minerals such as Pb, Sn, Ag, Cu, Al, and Si. Currently, CIGS and CdTe are the competing thin-film technologies that are produced at a lower cost and with a much lower amount of raw materials like Ga, Se, Cd and In. Recycling of both the PV module and balance of system components is significant from an economic and environmental perspective since it can reduce resource depletion, the environmental effects of extracting and processing rare and valuable virgin minerals, and energy costs. Estimates show that between 2010 and 2030 efficient end-of-life balance of system recycling of steel, Fe, Al, and Cu will have the biggest influence on mitigating valuable mineral depletion [13]. Ongoing research, development and implementation in the PV sector has concentrated on optimization of resource recovery for environmental protection and resource preservation in order to overcome challenges related to PV waste management.

To prevent improper disposal mechanisms from compromising the environmental benefits of solar panels, recycling must be done correctly. Approaches to recovering resource materials from several generations of PV have a fundamental impact on the value, scalability, and economy of recovery, among other issues encountered in the recycling process. This study was conducted to evaluate a broad range of laboratory-based and industrial-scale PV waste treatment techniques in order to identify sustainable and scalable methods that could be used to promote the circular economy. Numerous studies have reported, with limitations, laboratory-based methods for dissolution and recovery of secondary resources after thermal, mechanical and chemical delamination processes. Different recovery rates of resource materials have been reported with methods such as solvent extraction, ultra-sonication irradiation, acid leaching, electro-winning, electroplating, precipitation and ion-exchange [14]. However, the International Renewable Energy Agency (IRENA) has reported that low quantities, limited recycling techniques, logistical challenges, and undeveloped material recovery markets have led to a high-cost, low-revenue scenario for global PV module recycling due to lack of efficient waste treatment methodologies and technologies [15].

This study examines components of three generations of PV technologies, market share and waste estimation, as well as technologies for recovery of secondary materials. Establishing large-scale, sustainable waste treatment technology is crucial for waste reduction and recovery of valuable materials that can be used to in support of a circular economy approach. The study reviews technological advances and methodological approaches for PV waste treatments to determine economical and environmentally sustainable laboratory and industrial techniques that are efficient for the recovery of critical materials from obsolete PV panels. Furthermore, it evaluates a prospective all-encompassing method for treating panel wastes and provides an outline of future possibilities for large-scale, sustainable treatment technologies. In addition, this research examines recycling and treatment methods for different PV generation wastes over the last decade, while underlining the recovered valuable resources from each generation. It also examines the economic feasibility of PV recycling procedures and the sustainability of each technique. This study reviewed records from various databases such as Scopus, PubMed, ACS Publications, Google Scholar and Web of Science. The records were screened for removal of duplicates, eligibility assessment and selection of studies relevant to the topic. The overall process for the methodological approach of the study is presented in Fig. 1.

1.1. Classification of generations of PV solar technologies

Three generations of technological advancement in solar energy have evolved, as Fig. 2 illustrates. The first generation of solar PV technology is well-matured and fabricated by c-Si as active material. Because of its superior PCE and dependability, it has been profitable worldwide, capturing the highest output share in the PV market, accounting for over 95 % of all solar energy [10]. However, the first-generation PV system's widespread use has gradually been impeded by the need for expensive quality Si single crystals as a core material to support its global commercialization [16]. Thin-film devices are the second-generation of solar cells, which uses less materials and is more efficient, lightweight, flexible, and economical. In comparison to c-Si panels, they are often 20 times smaller and require less effort to install, thus enabling rapid commercialization rate [17]. In spite of their superior efficacy, CIGS and CdTe solar cells continue to lag behind c-Si solar cells in terms of dependability and PCE, even though they hold a larger market share of thin-film solar technology [17]. Moreover, rarity of hazardous elements like Cd, As, and Ga impede the development of large-scale, sustainable thin-film solar panels. For instance, GaAs solar cells are developed using costly materials, and their large-scale, sustainable production is difficult due to very toxic metalloids such as As and the rare Ga, found in the earth's crust.

Third-generation PV technologies refer to a rapidly growing sector of the renewable energy industry that encompasses a wide range of state-of-the-art PV technologies designed to overcome some of the limitations of conventional solar cells. DSSC, OPV, QDSC, and PSC have demonstrated high intensity of light absorption and a broader spectrum of solar radiation absorption, which enhances their PCE [18]. Some third-generation solar cells technologies are either at or approaching commercial viability. For instance, PSC has broken efficiency records in the lab, and several companies are supporting the establishment of commercial production lines for the product [19]. In addition, extensive research is being conducted to determine whether PSC will be commercially feasible [20].

1.1.1. The c-Si panels

A c-Si panel or module is made by stacking PV cells between semiconducting materials to convert solar energy into electricity. The other components of the solar panel which allow efficient flow of current to the Si cells include about 10 % encapsulant ethylene-vinyl acetate (EVA), a junction box, Tedlar protective backsheets, 8 % Al frame, 5 % Si solar cells, 75 % glass substrate, 1 % Cu, and 0.1 % Ag and other metals [21]. Tedlar backsheets increase output and efficiency, and EVA polymer acts as an electrical pottant and protects the module from foreign impurities. Si is the most widely used semiconductor in c-Si based PV technology, accounting for approximately 95 % of the modules that are currently on the market [22]. In comparison to other PV technologies, various semiconductor and conductive materials can be used to achieve efficient photon absorption depending on their relative band gaps. These materials include B, P, SnO_2, Ni, Ag, Se, In, Ga, As, Cu, Sn and Pb.

The component materials of a c-Si module are in a firmly bound laminate. Fig. 3 shows the general layout of the module. In an effort to prevent appalling waste streams of the end-of-life PV panels, effective recycling and recovery procedures are necessary for major components such as substrate glass, polymer, Si, and other important minerals, to establish models for PV in the circular economy. In this regard, the PV research sector seeks to create innovative technologies that maximize recovery of secondary resource and recycling procedures for obsolete panels. The feasibility of thermal, mechanical and chemical processes is scrutinized in relation to potential methods for disassembling and recovering EVA polymer. Moreover, sustainable chemical processes for recovering valuable minerals from obsolete PV solar panels is the subject

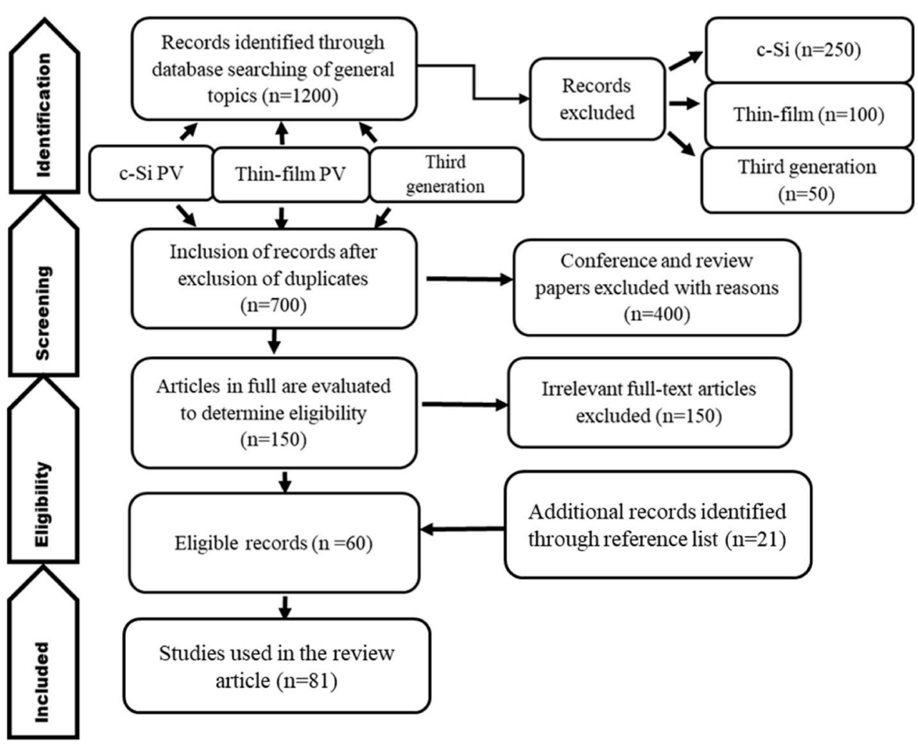

Fig. 1. Methodological approach of the study.

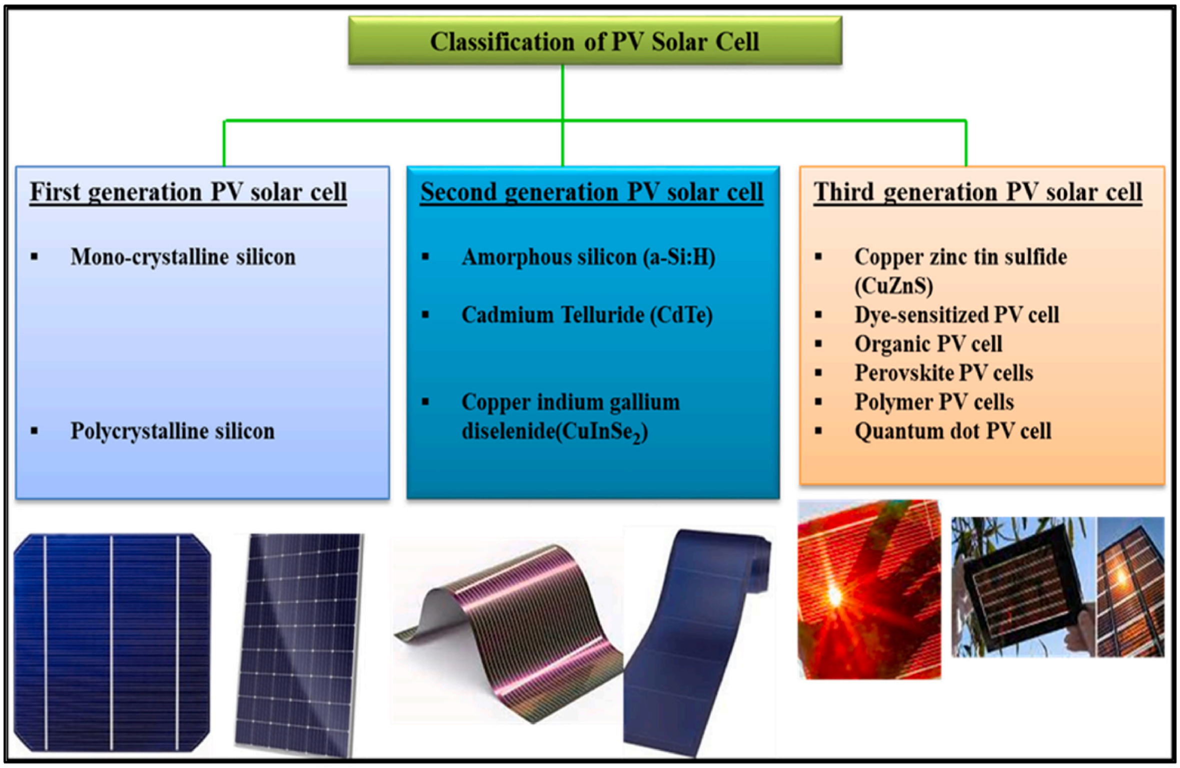

Fig. 2. Classification of the three generations of solar PV cells [21].

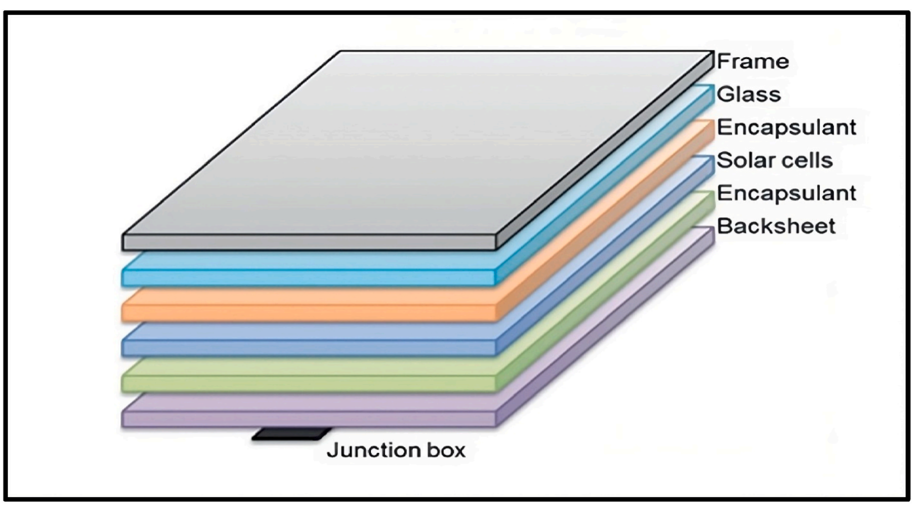

Fig. 3. c-Si layout of the module [24].

of continuing research efforts.

1.1.2. *Thin-film PV solar panels*

Thin-film solar technology obtained a 5 % production share in the PV industry in 2021 [23]. Currently, the most commonly used thin-film solar technology is CdTe, which has tripled in size in its application as rooftop PV systems, parking space applications, and building-integrated PV. Thin-film solar cells' band gap permits for high deposition rates, resulting in efficient utilization and long-term performance [24]. Most thin-film PV panels are extremely adaptable to architectural integration, and their performance is not limited by the amount of light absorbed [25]. The Cu, Si, In, and Ga semiconductor components included in the CIGS solar cell provide a lightweight, flexible cell with a high PCE.

The CdTe solar cell has emerged as the pinnacle of all second-generation solar cells, however due to high levels of hazardous Cd, its large-scale practical application is limited. Cd also poses an environmental risk and necessitates thorough recovery from obsolete PV panels [25]. Fig. 4 depicts a second-generation PV module made up of semiconductor materials (Cd, Pb, Sn, Cu, Mo, Cr, Ni, In and Al, Cd and Te) cast on a glass substrate, a transparent conducting oxide (TCO), polymer, encapsulant, and backsheet. The components of thin-film solar cells generate power with great efficiency and effective light absorption [26]. Because of the potential toxicity of Cd and the rarity of In and Te, extensive effort has been made to develop alternative materials with high absorption coefficients comprising of non-toxic and abundant Cu, Zn, Sn, and Se [20]. Where there are no preventive measures for waste management, end-of-life PV systems potentially produce waste streams that contain materials from damaged thin-film panels. In contrast,

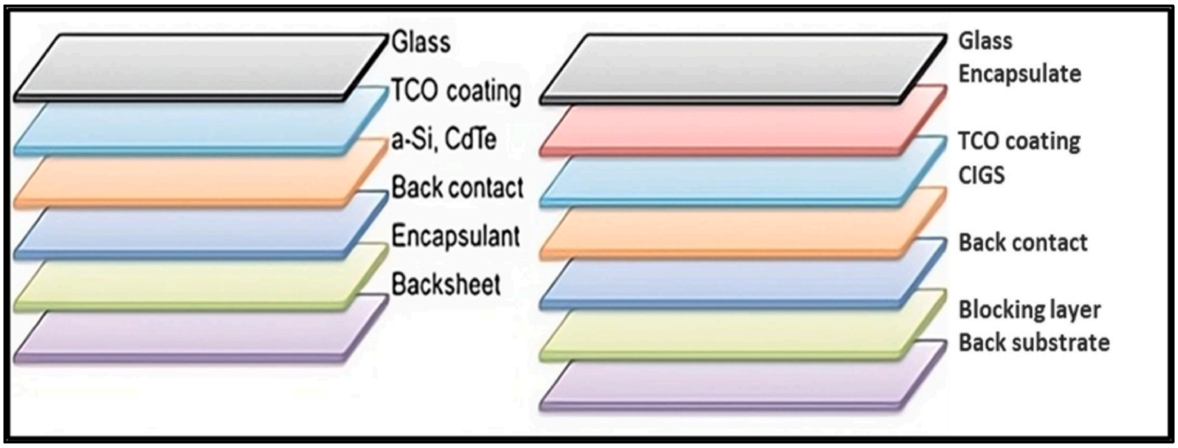

Fig. 4. A second-generation module structure [24].

implementation of appropriate recycling procedures not only enhances security of raw materials but also benefits the economy and environment by creating a potential secondary stream of valuable resources that support the long-term expansion of PV systems.

1.1.3. Third-generation solar technologies

Third-generation solar cells explore a variety of alternative materials, including organic polymers, perovskites, quantum dots, and state-of-the-art thin-film technologies, in contrast to first- and second-generation solar cells that rely on Si-based technologies. Through the use of these materials, solar cells with higher absorption capacities and a broader spectrum of solar radiation may be produced, leading to an increase in PCE [27]. The latest PV research recommends that a systematic waste treatment technology be implemented concurrently with new technology commercialization to hinder a sudden increase in untreated obsolete PV panels. The evolution of some of the most commonly explored third-generation thin-film solar cells, such as OPV, DSSC, QDSC, and PSC, is reviewed in this study.

Organic semiconductors embedded in the OPV as a photoactive layer has drawn substantial interest due to their semi-transparent nature, light weight, cost-effectiveness, and large-area flexibility in fabrication [28]. Extensive research on interfacial engineering and device processing approaches has led to significant advances in PCE, with improvements exceeding 18 % [29]. The eminent PCE is attributed to organic semiconductors fabricated on single-junction OPV cells using active layer made of PBQx-TF polymer donor and non-fullerene acceptor [28]. The single-junction solar cell utilizes wide band-gap polymer donors and narrow band-gap small molecule acceptors as its bulk heterojunction photoactive layers. Although OPV technology has advanced tremendously in its competitive commercial viability, it is still constrained by durability and instability. However, ongoing research endeavours to incorporate the tertiary structure into the active layer of OPV for enhanced stability have exhibited significant capabilities for large-scale manufacturing and commercialization of OPV in the future.

The DSSC is one of the emerging third-generation PV devices made up of dyes based on Ru or Pt that are coated over electrodes made of TiO_2 nanocrystals. The ease of installation of DSSC modules allows for maximum efficiency, which is aided by liquid electrodes that transport ions over the electrode [23]. However, liquid redox electrolyte-based DSSCs have difficulties in terms of durability and conductivity [30]. Continuous research on DSSCs has been conducted in order to increase efficiency and stability, as well as to accelerate their commercialization. The research efforts seek to replace liquid redox electrolytes with high-conductivity solid-state electrolytes to allow materials to facilitate the transportation of materials for efficient light absorption [30]. Moreover, metal-free dyes based on organic or porphyrin hybrids were discovered as alternatives to Ru dyes for development of DSSC with much higher efficiency and long-term stability [20].

A developing PV technology that is being manufactured at a low cost and with significant efficiency is the QDSC, which aims to outperform c-Si, CIGS or CdTe PV technologies. CdS, CdTe, CdSe, PbS, PbSe, SnS, or SnSe chalcogenide nanocrystals are solution-processed semiconductor compounds that have surface chemistry-tunable optical properties that are supplied by the QDSC [31]. QDSC panels are highly considered as an emerging commercial candidate due to their size-tunable band gaps and multiple exciton generation; however, low open-circuit voltages may impede mid-gap states and the inherent disorder in QD films [32]. Moreover, sustainability and upscaling of QDSC solar panels may be limited by the possible leach of hazardous elements such as Sn, Se, As, Cd, and Pb [33]. In contrast, semiconductor $AgBiS_2$ and $CuInS_2/ZnS$ nanocrystals have demonstrated potential competitiveness in the development of high-performing QDSC thin-film technology as non-toxic, earth-abundant materials [31,34].

The most common and widely used third-generation technology is perovskite, which has been commercialized due to its exceptional efficiency, extended carrier lifetime, and resistance to defects [35]. This technology been developed using a solid-state dye-sensitized approach and absorber layers of the hybrid organic-inorganic Pb/Sn-halide as $CH_3NH_3PbX_3$, (where X = I, Br, or Cl), $HC(NH_2)_2Pb(I_{1-x}Br_x)_3$, $CH_3NH_3Pb(I_{1-x}Br_x)_3$ and $CH_3NH_3SnI_3$), which provide high band gap tunability and strong diffusion lengths [23]. PSCs' remarkably stable performance can be attributed to their components, which include a glass substrate coated with either fluorine-doped tin oxide (FTO), indium-tin oxide (ITO), metal oxides (TiO_2, ZnO, SnO_2), polyoxometalates, perovskite absorber layer ($CH_3NH_3PbX_3$) or 2,2′,7,7′-tetrakis-(N,N-di-4-methoxyphenylamino)-9,9′-spirobifluorene (spiro-MeOTAD), which serves as a hole transport material, and a back contact electrode composed of C, Au, Ag, or Au [33]. Pb and Sn limit the wide application of PSC due to their toxicity whereas Bi and Ge-based PSC are considered viable substitutes for hazardous elements due to their comparable electro-optical characteristics [20]. In addition, studies on the application of multilayer electrodes and carbon-based metal grids show a strong potential to enhance the stability, effectiveness, and long-term commercialization of PV technologies based on PSC [30].

1.2. Market share predictions and relative conversion efficiencies

The rise in market share of groups of PV technology is proportional to the increasing number of interconnected PV panels. Fig. 5 shows market shares predictions for several PV generational technologies from 2014 to 2030. The c-Si PV, CIGS, and CdTe technologies held corresponding 92 %, 2 %, and 5 % of the market share in 2014. According to statistics on market share; 1 % of the market share accounted for companies based on new PV technologies (QDSC, DSSC, OPV, and PSC). It is interesting to

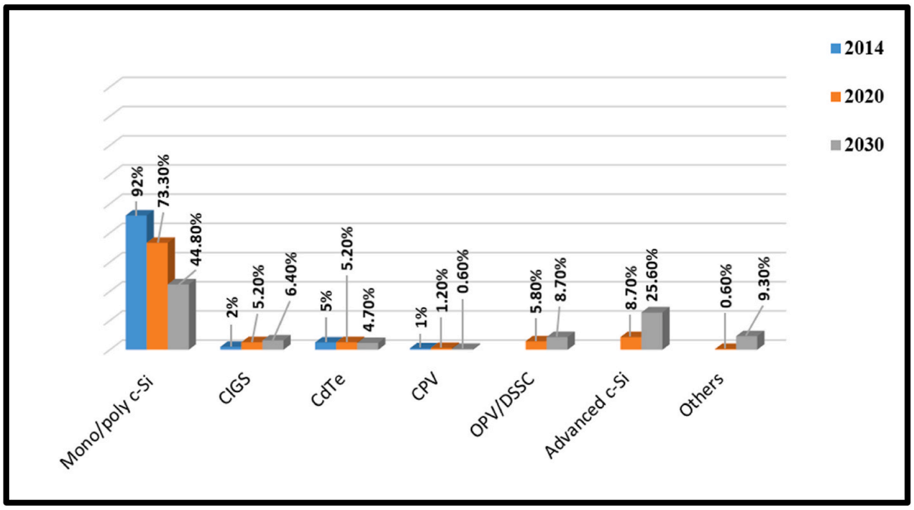

Fig. 5. Market share estimates for PV Technology categories from 2014 to 2030 [20].

note that a PV report (2022) [29], discovered that in 2020, c-Si PV panels accounted for approximately 95 % of global output, despite the fact that the technology was predicted to decrease to 44.8 % by 2030. Buitrago et al. [20] have indicated that the market share of third-generation solar cells is anticipated to increase significantly from 1 % to 44.2 % by 2030.

The recent exponential surge in PV expansion suggests a great increase in the quantity of panels reaching their end-of-life stage. As PV panels eventually lose their warranty, so does their PCE decrease, depending on the lifespan of each type of technology used. As predicted by a global probability-based forecasting model, the capacity of solar energy is expected to reach approximately 4500 GW, resulting in the production of 60–78 million tonnes of waste from PV panels [36]. In order to offset the waste streams, one area of research in the solar industry is devoted to the continuous improvement of resource recovery, as well as the development of recycling infrastructure to reduce the energy required to transport the obsolete panels. When solar panels operate within the warranty period, stability and optimal performance are determined by PCE, which is referred to as the quantity of solar radiation that reaches a PV device to be transformed into useable electricity. Fig. 6 presents an overview of recent PCE of various solar technologies based on reports from the National Renewable Energy Laboratory (NREL) and other pertinent studies. The majority of solar cells have efficiencies ranging from 18 % to 47 % and significant

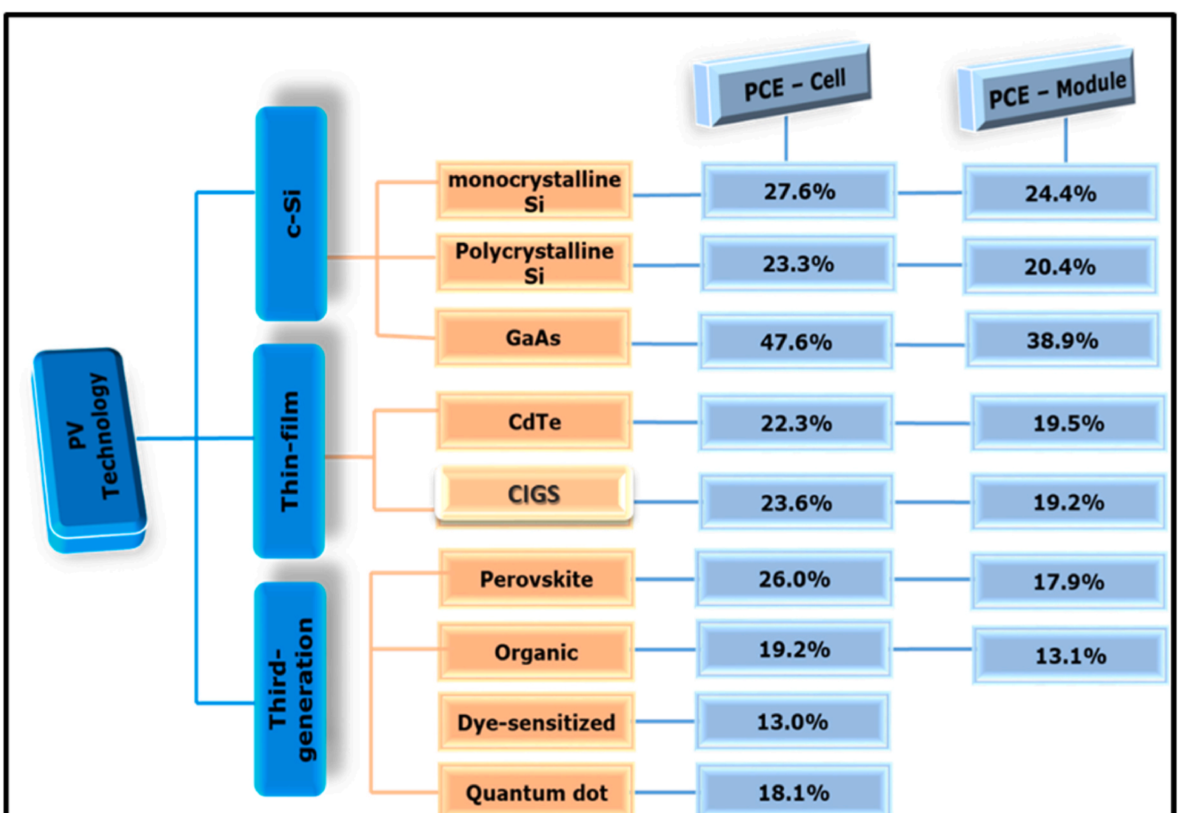

Fig. 6. PCEs of solar cells and modules of various PV technologies [40].

research and development has improved the efficiency of commercial modules to about 40 % [37].

The progressive advancement of CdTe and c-Si technologies, which attained higher efficiencies and enhanced yearly energy yield, could reduce system cost to meet the 2030 levelized cost of energy target [38]. This is notable because in recent years, for instance, CdTe efficiency has increased drastically, reaching 22.1 % for PV cells and 18.6 % for modules. In contrast, the limitations on annual energy yield, imposed by the difficulties in achieving higher CIGS efficiencies, necessitated greater cost reductions for CIGS systems despite the champion module efficiencies remaining higher than 19 %, even though aperture-area record efficiencies for small CIGS devices in the lab are currently beyond 23 % [39]. PSC technology has seen impressive advancements in efficiency, with cell efficiencies rising from 14 % when they first appeared on the NREL efficiency chart in 2013 to a record-breaking 26 % in 2020 [40]. Considering the improvement in cell efficiency of 18.2 %, a predicted performance lifespan of over 10 years without encapsulation, and a proven ability for roll-to-roll manufacturing through solution processing, OPV is a sophisticated and rapidly evolving PV technology. Advancement in waste management research has improved the 10 % recycling rate of currently in-use PV modules and reduced the effects of metal depletion associated with PV by designing sustainable end-of-life treatment technologies.

2. Global challenges related to the growth of PV technologies

Solar panel waste streams may lead to pressing environmental issues if there are no strategic implementation plans for sustainable recycling processes. Depending on the components of each type of solar panel, there is substantial evidence of different waste treatment technologies to handle obsolete panels of various PV technologies. Landfill waste management is not a reliable, viable solution as it drives environmental and groundwater pollution. Based on the assumption that the module's mass during the observed period averaged 60 kg/kW, a waste quantity of 60 tonnes would be generated for every megawatt of the installed capacity. Fig. 7 shows the projection of 96 thousand tonnes of waste from PV modules that will be produced globally by 2030, and approximately 86 million tonnes by 2050 [43]. Europe is expected to produce approximately 35.5 thousand tonnes of waste from c-Si modules and 1.9 thousand tonnes of waste from thin-film modules by 2030 based on IRENA projections [43]. The estimated amount of waste from c-Si and thin-film modules by 2050 is 15.3 and 0.6 million tonnes, respectively. In addition, Buitrago et al. [20] established an annual production target of 2000 tonnes of thin-film modules made with 0.1 % semiconductor material in order to decommission an equivalent quantity of outdated PV modules. It has been anticipated that approximately 95 % of the obsolete modules are expected to be recovered; these may have resulted from initial and continual defects over the year of steady-state production. This notable exponential rise in panel waste of PV technologies is a result of yearly PV installations for wide range of uses. There is currently no global monitoring or reporting system in place so it is impossible to precisely determine the recycling rate of PV modules [43]. Moreover, one of the most important issues facing PV researchers is the lack of a global standard for recycling of PV modules, which has led to disparate regulations from various governments and areas. PV modules have an 85 % collection rate requirement, of which 80 % must be returned to the materials cycle [43].

Improper waste management strategies of end-of-life PV panels have a significant effect on the environment. Some of the valuable raw minerals used as the semiconductor in the solar cells are rare and require extraction from the crust of the earth. Lack of appropriate recovery technologies may lead to a depletion of raw materials, and, as reported by Hunt et al. [41], the depletion period of Ag, Sn, Cu, Pb, were estimated. Waste streams of obsolete PV panels may leach some of the semiconductor materials of solar cells into the environment, and accumulation of Cd and Pb have long-term detrimental effects, despite the fact that they make up less than 1 % of PV panel composition [42]. The European Union (EU) recognizes the WEEE Directives as a legislative measure to address the growing problem of waste from electrical and electronic equipment. A review on solar panels' inclusion under the WEEE Directives suggests that because solar systems differ from other electrical and electronic equipment, they should be exempted from the EU Directives [33]. In accordance with the most recently updated EU waste legislation, PV panel producers are required to take responsibility for the recycling and disposal of obsolete modules [33]. The exemption of PV waste management from WEEE Directives has provoked an emergence of sustainable waste management strategies. The relevant steps for waste assembly, decommissioning, initial processing, and recovering important raw materials with lower greenhouse gas emissions are examined in this study.

3. Causes of the end of life of PV systems

PV modules are considered to have reached the end of their useful

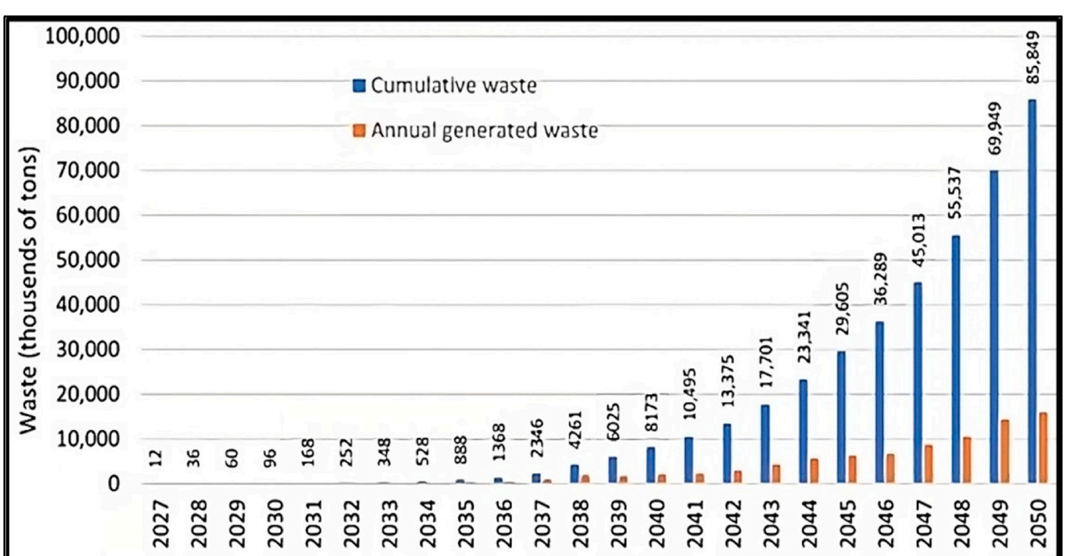

Fig. 7. Estimated amount of global PV waste [43].

life when their total power output is less than 80 % of initial capacity [10]. The module is the most important component of the system and the basis of a dependable and extended lifespan of PV technology. As most PV module manufacturers offer their clients a less than 20 % power drop and a 25-to-30-year guarantee term, PV module dependability is becoming a significant concern. However, deterioration rate is still considerable in light of the possibility that it could intensify over time and cause losses for the manufacturers, who might need to supply a new module in order to meet the warranty. Given the extended warranty time period, the degradation rates should be clearly established and limited to a maximum of 0.8 % annually.

The amount of light that a PV system absorbs and the rate at which solar panels deteriorate are both significantly influenced by normal wear, light-induced degradation, and adverse weather conditions [44]. Three types of forecast scenarios were identified with inefficient PV performance; early failures occurring up to 4 years after installation, continuous accidental failures occurring after 5–11 years after installation, and wear-out failures occurring until the PV becomes obsolete [44]. Over the course of the product's lifespan, early failure projections resulting from manufacturing, shipping, and installation, accidents or errors are more significant than the other forecast scenarios [12]. Other factors such as quality, maintenance and weather also affect degradation rate of solar panels. The degradation rate could be accelerated if low-quality materials and components, such as solar glass, an Al frame, and solar cells, were utilized in a panel to save costs. Although solar panels require minimal maintenance, it is critical to perform routine inspection on connections, cabling and inverters to ensure that there are no defects. Furthermore, inadequate handling of panel assembly and installation might accelerate the rate of degradation. Even with high-quality components, panel longevity can be affected by its construction, because not all materials function well together. Incompatible materials and components could increase light-induced and potential-induced degradation, while microcracks, scratches, and improper electrical connections during installation affect the panel's performance. Fig. 8 shows degrading panels that are influenced by various factors, including extreme weather events (heatwaves, hurricanes, snowstorms, temperature).

Numerous studies report that the life expectancy of PV panels is about 25–30 years, with manufacturers guaranteeing their performance during that time. This warranty does not imply that PV cells will last beyond their shelf life. The guarantee states that energy production will not decrease by approximately 20 % of total electricity production during the panel's lifetime. The majority of PV panels installed in the early 21st century by manufacturers who based their predictions on average lifespan of 30 years have essentially reached their end of life. This is because weather-related factors cause the electrical units to corrode and the colour of the manufactured metal changes, thus lowering efficiency and causing irreversible failures that diminish the warranty [39]. In large cities, for example, the efficiency of PV systems may be affected by the deposition of liquids, solids and gases that include organic compounds and potentially harmful metals that are emitted primarily from vehicle travel and industry [44]. The optimal performance of PV systems in desert or semi-desert areas can be affected by compositions of dust particles deposited on the panels [45]. The majority of defects that have been reported and are likely to occur at different stages are presented in Fig. 9.

4. Complexity and cost of recycling end-of-life solar panels

The detrimental impact on complexity, pollution and cost of the recycling process arises during the opening of the laminated structure (delamination) of the solar module, which is the most challenging part [46]. In spite of extensive research on new and efficient methodologies for cost-effective solar panel recycling, there are significant technological barriers which hinders its widespread adoption. In most studies of first- and second-generation solar cells, each panel type i.e. c-Si, CIGS and CdTe, require a unique process for the recovery of resource materials, which impedes standardization efforts, delays implementation and increases the costs [47]. Additionally, maintaining the purity and high quality of a material during the recovery process is a technical challenge.

In c-Si solar module recycling, the encapsulate polymer EVA, which is used to protect the PV cells, complicates the separation of backsheet, glass cover and the recovery process of the solar panel [48]. Additionally, c-Si PVs need a labour-intensive, energy-intensive chemical process as well as an expensive disassembly procedure [49]. The c-Si recycling process begins with disassembly of the glass from encapsulate, EVA, using the chemical, mechanical and thermal methods. Each disassembly method will result in different challenges in the purification process. Among the disassembly methods, the mechanical method is most commonly used due to its simplicity and cost-effectiveness. However, low Si and Ag of about 50 % makes it an unreasonable and unprofitable method to use in the recycling process. In relation to third-generation PV, PSC, with an efficiency higher than that of c-Si based solar cells, have attracted considerable interest in solar cell development. However, the toxicity of Pb-based PSC has led to an urgent call to improve management for end-of-life PSC panel recycling to ensure the sustainable

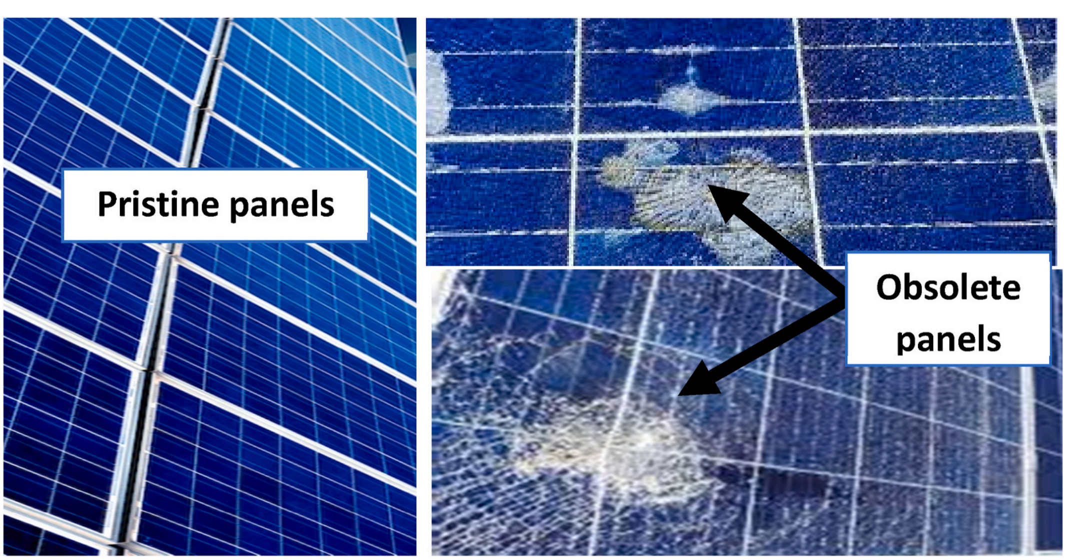

Fig. 8. Pristine and obsolete solar panels [48].

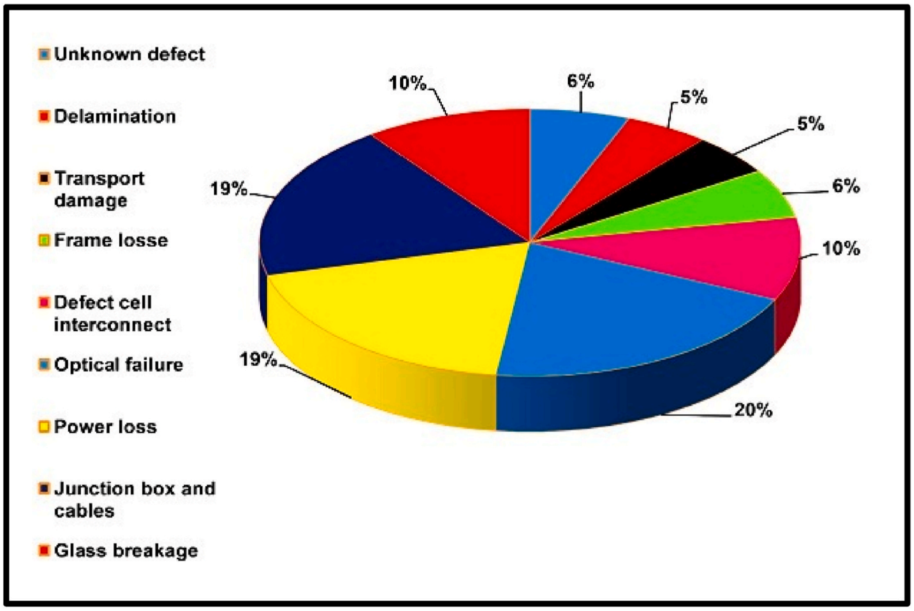

Fig. 9. Percentage rate of defects [49].

future of the technology. Currently, research and development in PSC recycling technologies which could yield lower costs for recovery of valuable material is largely in the laboratory stage. Improving the performance of recycling technology and module durability would lower the amount of end-of-life PV materials generated [48].

The growing demand for PV technology as a dependable source of green energy in the global energy market has expanded waste beneficiation research. PV recycling revenue is based on market demand relative to the context and the quality of recovered materials. The expense of recovering and separating materials must be weighed against this revenue. Valuable materials recovery when recycling solar panels can provide not only environmental benefits but also economic value. Recycling of Al frames, with an approximate value of USD 2.7/m^2 module, yields the most economic advantage. Furthermore, recycling Al frames can lower the global warming potential (kg CO_2-eq) of solar panels across their life cycle by 12 % [46].

Thermal delamination by means of pyrolysis operating at 150 °C and 500 °C to remove backsheet foil and EVA binder respectively, assists with decreasing the production of toxic fluorinated gases. If an efficient method is used and PV panels are recycled efficiently, they can be used on the market once more without having to pay for their entire initial manufacturing cost. Previous studies have reported that it is predicted that by 2030 the total value of recycled solar panels materials will reach up to USD 450 million [50]. This amount can be used to generate up to 60 million PV modules, or 18 GW of total capacity, which is almost 33 % of the output in 2015. Studies on the remanufacturing and reuse of panels have indicated the significance of creating specialized, economical, and efficient resource recovery infrastructures for panel recycling [51]. For instance, there is a sizeable, well-established market for recycled Al frames, Cu and Ag. However, the disadvantage of extracting these valuable materials from obsolete solar panels is that it exposes other toxic materials that are of environmental concern [52].

5. Recycling end-of-life panels from different generations of photovoltaic systems

Studies have reported that most valuable metals found in different generations of PV panels are Cu, Ag, Si, Te, Cd, Cu, In, Ga, Se and transparent conductive oxide (TCO). These resource materials are recovered using different approaches with different techniques, as presented in Table 1. These valuable materials from PV panels must be maximized in accordance with their market value in order to maximize their benefits. Based on the life cycle assessment, solar waste recycling technology ought to be sustainable for the environment and prevent the discharge of any toxic substances into the surrounding area [42]. Recycling methods should retain valuable metals and encourage new business ventures that boost competitiveness in market share for waste beneficiation. However, the primary impediments to PV recycling are infrastructure, storage, collection, energy considerations, and a lack of regulations, which completes the recycling value chain [53]. The recycling process presents opportunities for improvement when facing challenges with collection and transportation, design for recycling, hazardous materials, scalability and economics, and value recovery. By building effective infrastructure for collecting and recycling facilities, notable transportation and collection issues can be eliminated and the appropriate disposal of obsolete solar panels can be facilitated. Furthermore, promoting eco-friendly treatment technologies improves recycling and neutralizes hazardous compounds. In addition, the mitigation of environmental and health concerns can be accomplished through effective collaboration with manufacturers, recyclers, and policymakers. Increasing recycling capacity and streamlining procedures may result in more affordable and scalable solutions, and investigating cutting-edge technology and market strategies may boost the feasibility of the recovered value from recycled materials [16].

6. Resource recovery from c-Si-based solar panels

PV studies are interested in closed-loop systems, which encompasses the concept of sustainable management of end-of-life PV panels as a means of recovering valuable resource materials from outdated c-Si panels. Examples of high-value recycling systems that have been assessed for their economic feasibility, practicality, recovery rate, and environmental sustainability are the industrial-scale recycling facilities of the European projects such as Recovery of Silicon and other materials from End-of-Life Photovoltaic Panels (ReSiELP), Full Recovery End-of-Life PV (FRELP) Project, and baseline procedures The ReSiELP has employed a thermomechanical-hydrometallurgical technique to recover high-quality Si and Ag. Although the research has shown promise for recovery on an industrial scale, further work is required before it can be considered as a high-value closed-loop PV recycling system [59].

The FRELP is an industrial-scale recycling process that is energy-intensive, economical, and effective. The FRELP process lacks the

Table 1
Different recycling techniques for different generations of PV.

Recycling process	Materials recovered	Generation	Advantages	Disadvantages	Reference
Thermal (pyrolysis)	Al, Si wafer and Ag	c-Si	- Decrease of toxic fluorinated gases, achieves high silicon recovery. - Separate approximate 80 % Si wafer, and 100 % glass -Cost effective	- Slight damage of cells	[46,54]
Combination of mechanical and thermal processing	Te, In, Cu	CdTe and CIS	- High-purity glass (ITO), 90 % recovery efficiency	- Slow recycling process	[55]
Chemical etching	Al, Ag, Si, Te, high-purity glass	c-Si and CdTe	- Makes it easy to access EVA, recovery of glass −80 % recovery of Si and glass	- Expensive process due to multiple components - Uses chemicals	[56]
Chemical method, through acid leaching and precipitation	Ag, In, Se, Cu	CIS	- Capable of treating waste, EVA removed completely	- Slight cell defects due to inorganic acid	[57]
Chemical method (Dissolution, DMF)	TCO/Glass, HTL	PSCs	- Simplifies access to polymer (EVA)	- Toxic waste and emission	[33]
Chemical (solvent free) and thermal delamination	HTL Pb, Au	PSCs	- More effective as compared to solvent dissolution - EVA is easily accessed	- High-cost equipment	[58]

requirements for collection of valuable material scraps and the transportation of separated materials to recovery facilities, which brings into question the economic viability and practicality of the process [60]. Nonetheless, it is strongly advised that the FRELP process's recovery and recycling is supported, which is primarily for treatment of obsolete c-Si panels. The stages of waste unloading, glass disassembly, and thermal separation account for approximately 10 % of the whole recycling process. Following the panel disassembly and thermal separation, acid leaching and electrolysis treatments are introduced to recover Al, Si, Ag, Cu, and glass scraps. Landfills acquire the waste materials created throughout the entire process [60]. In consideration of the potential environmental impact of landfills, the FRELP recycling process has been optimized for further recovery of valuable materials using acid leaching and sequential electro-winning processes. Moreover, the combination of hot-knife glass separation, advanced mechanical separation of Al frame, and high-voltage pulsed discharge for metal recovery, demonstrates improved recovery of resources and reduced landfill waste, which is in line with the expanding demand for efficient end-of-life PV panel recycling [61].

Despite the environmental advantages of FRELP, lack of data on the environmental impact of recycling plant construction could potentially offset the benefits of recycling [10]. In contrast, Ardente et al. [62] observed a notable recovery of secondary materials generated by the FRELP process in relation to a baseline procedure. Representatives of typical practices in the WEEE Directives have criticized the baseline procedure, as it is deemed ineffective for recycling PV since it lacks specialized recycling capabilities [62]. Research on PV recycling has been a focal point due to the increasing use of PV and the need to manage end-of-life panels sustainably. Upscaling research-based methods for economic and sustainable industrial applications highlight the significance of on-site recycling potential for economic and environmental benefits. Systematic approaches for recovery of valuable resource materials from PV modules in a closed-loop recycling system pose a major challenge for the PV industry. This study investigates research on various methods employed for treatment of end-of-life PV panels, and mostly those methods that involve less waste-related emissions and show potential for feasible upscaling for industrial application in a closed-loop system were examined.

Innovative approaches to comprehensive recycling of outdated PV cells have been presented as a result of continuous research on PV recycling. These technologies emphasise mechanical separation, module delamination techniques, and resource recovery via acid leaching or electrochemical processes to minimize material consumption and environmental impact. Solar panel recycling technologies are primarily designed to recover valuable resource and toxic materials (glass, Al, Ag, Si, Pb, Sn) from end-of-life PV panels. The process flow is presented in Fig. 10. During the c-Si recycling process, glass and cells are treated through mechanical processes and encapsulant polymer (EVA) is extracted or removed, alternatively using pyrolysis and chemical treatments to recycle critical components such as Si, Al, and Ag in solar cells.

6.1. Mechanical recycling

In general, mechanical techniques of recycling obsolete PV panels are inexpensive and more sustainable than chemical techniques, heat treatment, automatic separation, and manual separation. Obsolete panels are collected and disassembled to separate Al frames, junction boxes, wiring and laminated glass, EVA polymer and metals through sorting, cutting, crushing, and shredding [16]. Although mechanical recycling yields exceptional material recovery rates, it is most effective for panels that have not been severely damaged. The high-voltage fragmentation, shredding or sieving in mechanical recycling is capable of concentrating metals to different particle sizes after crushing. The dismantled Al frames and Cu wires can be reused or sent to raw material producing facilities, depending on their condition. Mechanical recycling yields major components such as Cu, Al and glass cullet amounting to approximately 41, 74 and 92 % by mass of these available materials, respectively [63]. The ease-of-disassembly design determines the efficiency of resource recovery and improves their recovery rate [2].

Before introducing the collection and transportation of waste to the plant and treatment processes, Mahmoudi et al. [12] used a mechanical arm procedure in conjunction with an automated Cartesian robot to disassemble and isolate the Al frame, cables/junction box, glass, and EVA polymer. Glass cullet is usually contaminated with valuable and toxic materials such as Ag, Si, Pb and Sn that are difficult to extract with mechanical separation as further processes are required to recover these secondary materials. Recovered glass cullet is of low-grade and can be subjected to thermal and chemical treatments to separate EVA polymer, solar cells and plastic backsheet layers from each other [62]. Mechanical separation, described as a high-value recycling technique by Deng et al. [46], exhibits higher recovery of glass cullet and a mixture of Si and metal powder. The authors argue that mechanical separation can be adopted as universal mechanical recycling technology, as compared to chemical and thermal delamination [46]. Moreover, Sah et al. [14] report mechanical treatments as an effective approach to recovering valuable and toxic metals.

6.2. Module delamination

As waste becomes a significant issue, a feasible delamination process ought to be considered such that the evolution of recycling processes from mass recovery to value recovery should emphasise the importance of selective delamination and material sorting for achieving high recycling yields with minimal waste production [60]. The most important

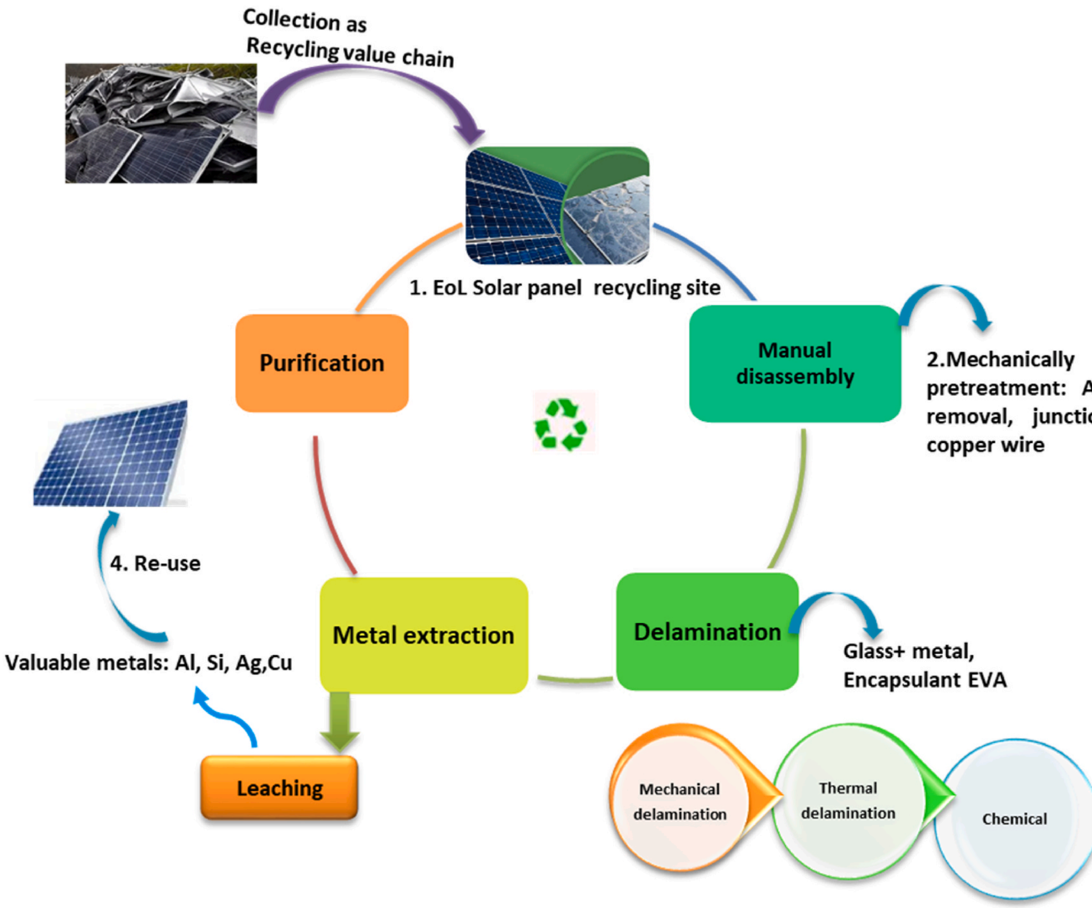

Fig. 10. Recycling approach for obsolete c-Si solar panel.

process in removing the EVA encapsulant layer and separating the glass from the solar cells in order to recover secondary resource materials is module delamination. Several methods have been reported for module delamination, such as incineration, solvent extraction, ultrasonic irradiation, acid leaching, electro-thermal, heat knife, laser, and pyrolysis in a fluidized bed. These techniques have attracted interest due to their relatively lower impacts as compared to incineration and chemical treatment methods [26,62]. Sah et al. [14] report the solvent extraction method for recovery of EVA polymer.

Chemical and solvent treatment requires usage of expensive and toxic reagents, which requires longer time to delaminate the glass resulting in a low EVA layer. Because of high cost and low efficiency as compared to chemical etching, laser treatment appears to be an incompatible method for module delamination [64]. The use of infrared radiation for the mechanical separation of glass from PV cell and EVA layers following the incineration process is documented by Mahmoudi et al. [12]. Incineration has the potential to generate energy and reduce waste volume, but it also generates toxic pollutants like HF and poisonous gas into the atmosphere. Pyrolysis processing in mechanical recycling of PV waste has emerged as the most preferable approach for EVA delamination. This discovery has prompted more research into leaching techniques to separate Si, Ag, Pb and Sn from solar cell powders and ashes after the removal of metal electrodes, anti-reflective coating and n-p junction on the surface of the Si cells. This has prompted a further investigation to determine a sustainable treatment method for recovery of high-value resource materials that can be compatible with mechanical separation and the pyrolysis delamination process.

6.3. *Valuable material separation and recovery*

The c-Si PV module is composed of bulk components such as Al frames, glass and Cu, as well as valuable and toxic elements, including Ag, Si, Pb and Sn, that requires a combination of bulk and high-value recycling to minimize depletion of resources and environmental pollution. Treatment techniques including thermal, chemical, electrochemical, and metallurgical approaches were reviewed for recovery of Ag, Si, Pb, and Sn. The assessment of these methods has prompted apprehension with regard to the scalability of high-value recycling techniques that can be associated with mechanical separation and pyrolysis module delamination in order to develop a circular economy within the PV industry.

Klugmann-Radziemska and Ostrowski [64] discuss the significance of refining the chemical processing method to recover high-quality Si. Chemical etching processes using variable concentrations of HF, H_2SiF_6, HNO_3, CH_3COOH, NaOH, KOH, H_2O_2 and Br with optimal temperature and time were explored to recover large quantities of Si in an effort to create a universal acid or alkaline leaching processes. Some of these leaching processes produce low Si yield and increase costs due to autocatalysis reactivity effects, which could influence the controllability of the proposed procedures. The authors also state that leaching methods require further optimization for treatment of obsolete panels. Conversely, these proposed leaching methods produce significant levels of poisonous gases and different Si derivatives, which could be detrimental to the environment, thus requiring expensive disposal measures. The Si recovered mostly by the acid leaching methods was of low quality. Klugmann-Radziemska and Ostrowski [64] highlight that methods for treatment of obsolete PV should be environmentally friendly. The forecast of large quantities of HNO_3, H_2O_2, HF, etc. that are indispensable for industrial scale use, hinders the suitability of chemical treatment methods as a sustainable technology. Numerous studies offset chemical etching methods for recovery of resource and toxic materials treatment, considering the large quantities of hazardous chemicals that could be required [11,26].

The prospect of combining electrochemical procedures like electrowinning, electrocoagulation, and electroanalytical electrodeposition with diluted acid leaching has emerged as a practical, sustainable method for resource material recovery. For instance, acid leaching facilitated by sequential electro-winning or electrocoagulation, filtration phase, and the ultimate use of neutralisation processes, minimize the environmental impacts since no residues were produced for landfills [65]. Sah et al. [14] have explored the electroanalytical approach as an effective approach to recovering glass, Cu, Al, Ag, Si, Pb and Sn. The Cu strips from connecting wires were stripped using diluted HCl to recover Pb and Sn by precipitation and electrolysis, respectively, which were collected as $PbCl_2$, SnO_2, and $SnCl_2$. Optimized conditions for KOH and H_2SO_4 were used in a sequential treatment process to recover Al as $Al(OH)_3$ whereby HNO_3 was used in a further treatment to reduce $AgNO_3$ using Cu strips.

The reuse of recovered Cu strips for Ag recovery can be viewed as a cost-cutting measure for the stated recycling procedure [14]. Lim et al. [21] have demonstrated the effective recovery of resource materials from obsolete PV panels through the use of chemical acid etching and electrodeposition methodologies. Through the use of an innovative and effortless technique, 86 %, 95 % and 97 % of Ag, Pb, and Al were successfully recovered, accounting for an overall recovery of 86 %. The laboratory results were expanded for life cycle evaluation, and the recycling procedure was contrasted with a standard landfilling technique for the disposal of used solar panels by precipitation process. From an economic, technological, scalability, and environmental perspective, the recycling method has proven to be feasible.

Recovery of high-value secondary raw resources is vital for PV waste management. This research finds merit in the mechanical separation recycling technique for recovery of glass, Al and Cu followed by pyrolysis of EVA for extraction of secondary raw materials and electrochemical methods for recovery of pristine Ag, Si, Pb and Sn. Recovery of resource materials in closed-loop processes could unlock the long-term economic viability and environmental sustainability of the c-Si based PV technology. A recycled EVA can be used as a potential fuel source for on-site applications, thus promoting the circular economy. Recycled broken cells are eligible secondary material to build ingots for different technologies, while recovered Si, Al, Ag, Cu, and Pb can be integrated back into the solar cell to produce new PV modules.

7. Resource recovery from second-generation thin-film PV panels

Thin-film PV panels consist of critical minerals such as In, Ga, Se, Te and toxic Cd materials, among other components of the solar cells. It is of utmost importance to recycle these minerals from obsolete modules in order to maintain the availability of secondary raw materials to sustain second-generation PV technologies. To identify sustainable treatment methods that could support resource management within the framework of the circular economy, an analysis was conducted of the recycling procedures used in laboratories and on an industrial scale [66]. Similar to c-Si module recycling techniques, second-generation PV technologies involve interconnected processes such as delamination, material separation, resource material dissolution, and recovery of valuable resource materials, as presented in Fig. 11.

7.1. Module delamination and material separation

Numerous research has commented on the technical feasibility of achieving the delamination process by mechanical and thermal methods. Marwede et al. [24] investigated the physical disintegration of obsolete thin-film modules using shredding and milling, techniques that are also used in First Solar's industrial recycling line. This procedure involves crushing, milling, and micro-emulsion of the modules, which results in the lamination foil and semiconductor coatings on the glass being partially removed. Using thermal treatment, the EVA polymer was completely separated from the glass. Pyrolysis was then used to break down the polymer, which allowed the thin-film materials to be removed from the substrate. Pyrolysis has been shown to be an economically viable process for module delamination when compared to solvent extraction, chemical etching, and microwave delamination, similar to

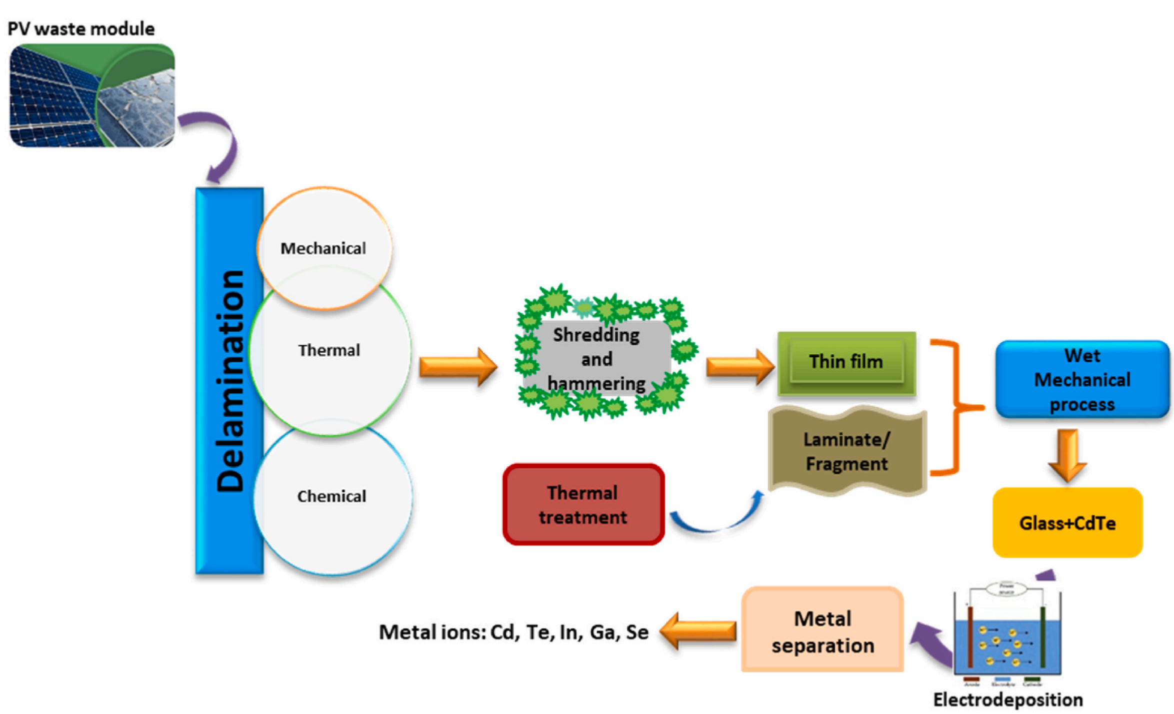

Fig. 11. Schematic representation of resource recovery from thin-film PV waste.

c-Si recycling techniques [24]. The gradual heating mechanism of pyrolysis is capable of facilitating complete removal of EVA without needing further chemical treatments. Consequently, there could be no requirement for chemical treatment of the bulk of the materials, therefore reducing the demand for leaching agents.

Decoating is an essential step in many industrial processes that involve separating metal compounds from non-metallic fractions. To effectively accomplish this, various coating techniques have been developed. Camargo et al. [66] have reported on a wet mechanical decoating method that, among other module delamination techniques, allows total attrition of the semiconductor materials from the carrier glass and subsequent separation into different fractions by sieving. Using acid leaching with H_2SO_4 or HCl and H_2O_2, the Cd and Te can be recovered in an inert materials following the flotation process. Flotation is an effortless technique that requires limited chemicals, but during the sieving and rinsing stages it loses a high volume of valuable material. Mechanical or gravitational solid-liquid separation techniques like screening, skimming, decantation, sedimentation, sieving, and fluidization can remove glass and lamination foil after leaching and attrition processes [66].

High-value recycling of decontaminated glass using a dry-mechanical approach was achieved by means of a vacuum blasting pilot line that removed the semiconductor layer from the substrate with minimal glass abrasion. Although vacuum blasting is relatively slow and requires subsequent mechanical or chemical treatment, it is an effective method of removing semiconductor materials without the need for chemicals [67]. The capacity to separate abrasives from metals using a multi-step mechanical-pneumatic separation technique which employs fluidization has been demonstrated. This technique concentrates the valuables and separates them from abrasives and glass, resulting in a high recovery rate of Te and In Ref. [24]. Module fragments generated by the dry-mechanical method's mechanical disintegration and pyrolysis procedures can be subjected to a gas containing chlorine at a temperature higher than 400 °C to begin the etching process that causes gaseous $CdCl_2$ and $TeCl_4$ to condense [55].

7.2. Valuable resource recovery

Within the framework of a chemical beneficiation process, high-grade Cd, Te, Se, and In can be recovered from glass module scrap and production waste scrap by employing ion-exchange, acid leaching, precipitation, liquid-liquid extraction, electro-winning, and oxidation-reduction. The use of H_2SO_4, HNO_3, Na_2O_2 $FeCl_3$, or HCl for acid leaching procedures has been reported to improperly separate Cd from Fe and Te [24]. Furthermore, the processes generate secondary wastes that require disposal measures that are capital intensive. For the recovery of valuable resource materials, the use of diluted acid leaching in combination with other chemical techniques was studied. Industrial precipitation and refinery method investigations achieved 95 % Cd and Te from recycling residues and production scrap, which were purified for reuse in CdTe synthesis. Furthermore, Marwede et al. [24] discussed the significance of using electro-winning techniques in an industrial setting to recover Te. A slurry containing Cd and additional contaminants was subsequently transported to a recycler of Cd. The ion-exchange method has effectively separated Cd from Te in H_2SO_4 solution in the cation exchange resin. The Cd eluted was recovered by electro-winning while Te in the diluted acid solution was precipitated using Na_2CO_3.These processes are economically impractical because of the high costs related to transporting and storing module scrap and production waste scrap to the metal refinery for recovery of valuable resource materials [24,68].

Gustafson et al. [69] employed hydrometallurgical techniques with oxidizing-reducing acids to extract semiconductor materials from CIGS by using Di-(2-ethylhexyl)H_3PO_4. The stripping of the organic layer allowed feasible recovery of In, while the use of a reducing agent for SO_2 led to the recovery of Se, and through precipitation, Ga was recovered as $Ga(OH)_3$. Inadequate recovery of In, Se and Cd prompted further investigation of high-value recycling using high-temperature chlorination, which achieved 97 % Ga and 93 % In recovery rates from obsolete CIGS [69]. However, the high-temperature chlorination approach employed in the laboratory to recover Ga had a negative impact on the separation process, and the inability to achieve a high recovery rate impeded the method's upscaling for industrial usage.

Gu et al. [70] has described a novel laboratory-based methodology that combines electrochemical techniques with dehydration and distillation to recover high-rates of Cu, Se, Ga, and In. In addition to providing a viable method for the sustainable and environmentally benign recycling of CdTe and CIGS materials, the dissolution-electro-deposition-dehydration-distillation process allows for the separation and recovery of high-purity Cu, Se, Ga and In from obsolete panels. Kavousi and Alamdari [68] present an alternative approach to recovery of valuable resource and toxic materials from the obsolete solar panels of different generations of PV. The process begins with the recovery of Ag using diluted HNO_3, the subsequent dissolution of base metals using glycine, and the leaching of valuable materials using HCl. The recovery of valuable resource materials was achieved by optimizing parameters like the initial pH, acid concentration, solid-liquid ratio, and hydrogen peroxide concentration.

The diluted HCl process allowed for 100 % recovery of In, Ga, Se, and Te through electrochemical separation and recrystallization [68]. The method has not yet been established for industrial application, and the authors suggest that method parameters developed in their study have the potential to reduce environmental impact. Marchetti et al. [71] highlight the importance of a high-value recycling technique known as double green panel, which could be incorporated into mechanical delamination treatments to manage panel waste streams of CdTe, or CIGS and c-Si PV. The double green panel process has minimal environmental effects and it is economically viable. Moreover, it competes with thermal treatments in comparison to other existing methods to reduce the amount of chemicals needed for the recovery of resource materials in favour of mechanical processes [71].

This study conducted an extensive review and found that an additional area of research that has to be addressed is the use of mechanical delamination techniques other than grinding. By incorporating mechanical delamination techniques into the principles of double green panel proposed by Marchetti et al. [71] consumption of leaching agents, thus improving economic cost and environmental impacts, could be significantly reduced. The need to separate the back glass layer from EVA without removing semiconductors could emerge as a feasible approach for reduction of mass material that requires further chemical treatments. Based on the studies reviewed, the most preferable methods for recovery of high-value materials from thin-film panels are those that involve mechanical delamination for removal of EVA, pyrolysis for production of module waste scrap, and electrochemical or hydrometallurgy recovery of Cd, Te, Se, In and Ga resource materials.

8. Resource recovery from third-generation PV panels

A large number of newly developed third-generation PV technologies have garnered interest because of their distinctive adjustable optical, electrical, and nanostructured features [72]. The primary focus of recent intensive research conducted on these new PV technologies has been on enhancing the PCE and long-term stability during the prototype stage prior to upscaling for commercial use. Even though PSC and DSSC are gradually invading the marketplace, PSC in particular continue to have issues with stability, lifespan, and adverse environmental impact. Nonetheless, as commercialized PSC approach end-of-life, valuable and toxic materials (Ag, In, Sn, Ti, Pb) that form the basis of the solar cells drive the imperative for and proactive research in development of recycling and material recovery technologies [33]. PSC contain toxic and water-soluble Pb, which, if it cannot be recovered, can disperse the ecosystem and pose risk to human health and environment.

To maintain resource usage of PSC valuable materials and preserve environmental sustainability, systematic treatment technologies are necessary due to the high potential for producing a rapid surge of waste products containing harmful compounds [33]. There have been extensive studies on methods to recover Pb in various environmental compartments, including surface water. The methods such as electrodeposition, ion-exchange, adsorption, and chemical precipitation are suitable for Pb recovery from aqueous media [73]. The Pb in PSC requires an organic solvent for recycling and high-Pb solubility. Chen et al. [74] reported the recovery of Pb from PSC modules and transparent glass by using weakly acidic resins to liberate ($Pb(NO_3)_2$) and subsequently precipitated into PbI_2 for reuse purposes. Schmidt et al. [58] extracted high purity Pb from PSC, demonstrating a 100 % recycling efficiency of PbI_2 utilizing a solvent-free technique requiring hot water.

Apart from extracting Pb, recovery of other valuable PSC components such TCO is crucial and has drawn considerable interest. Liu et al. [33] conducted a comprehensive review on the effective recycling process of FTO/TiO_2 which maintained its original optical and electric properties from the original $CsPbBr_2$-based architecture devices. Recently, the In from TCO has been recognized as valuable materials from various perovskite architectures. Another valuable TCO is FTO, which has attracted a significant interest due to its high cost. Chowdhury et al. [75] report the sequential (layer-by-layer) extraction procedure for recovery of FTO by applying one solvent at a time. The C_6H_5Cl was used to separate Au electrode and spiro-OMeTAD-based hole transporting layer, followed by DMF dissolution to separate the PbI_2 and the pure FTO was recovered [75]. The process flow for recycling of PSC panels is presented in Fig. 12.

Several studies have outlined that the main recyclable components of PSCs, including TCO (FTO or ITO), electron transfer layer, perovskite layer, hole transfer material, Pb and Sn, and recovery of glass, FTO, TiO_2 in DMF dissolution [9,76]. One intriguing method for recycling FTO and glass substrate is the effective removal of the electron transport layer from deteriorated PSC using low-energy techniques at room temperature. Huang et al. [74] have effectively executed a chemical treatment method that is environmentally friendly, sustainable, and scalable. This method involves DMF dissolution, ultrasonic cleaning, and ultraviolet ozone treatment to enable possible reuse of electron transfer layer and FTO in the fabrication of PSC.

The environmental impact and economic reasons for recycling PbI_2 and FTO/glass from degraded PSC by DMF extraction are addressed by Gustafson et al. [69]. To support the quantitative recovery, the extracted PbI_2 was examined using inductively coupled plasma and ultraviolet visible spectrophotometry. Additionally, utilizing an electron-selective TiO_2 layer and a conventional deposition process, the FTO/glass substrate was recovered. Thin-film ITO, a costly and rare material derived from limited quantities of In, is the component that affords PSC their exceptional optical transparency and low resistance [35]. The cost of producing PSC could be considerably decreased by implementing a successful recovery and effective reuse of ITO.

The novel aspect of using KOH solvent for efficient recovery of ITO has been demonstrated, and the non-volatile alkaline solvent technology was endorsed for the recovery of resources for different types of third-generation solar cells. By using sonication in neutral water to separate intact ITO electrodes from extraneous components, Gu et al. [70] further illustrate the potential recovery of In. The conductive polymer PEDOT: PSS was precisely invaded and dissolved in this method by subsequent treatment with an ionic buffer layer, which detached the underlying ITO electrode. In a study by Feng et al. [77], In was successfully recovered from ITO through the use of a very dependable two-step dialkylamine method. The authors also reported a closed-loop recycling procedure that recovered 98.9 % of Pb by removing high-quality $MAPbI_3$ crystals from PSC using N-butylamine. The PCE of recycled PSCs was higher than that of devices fabricated with pristine materials in both In and Pb recovery and remanufacturing trials [77]. More recently, Bogachuk et al. [78] successfully investigated the application of a thermally assisted mechanochemical method for PSC constituent recycling, achieving 90 % of initial performance, utilizing remanufactured components. The studies that have been reported on the recycling and recovery of valuable materials from PSC were based on laboratory demonstrations using solvent dissolution. This is an indication that extensive research is needed to determine whether these methods could be up-scalable and practicable for industrial for use in industrial settings.

9. Conclusion and future prospects

Ongoing research efforts in PV treatment technology aims to invest

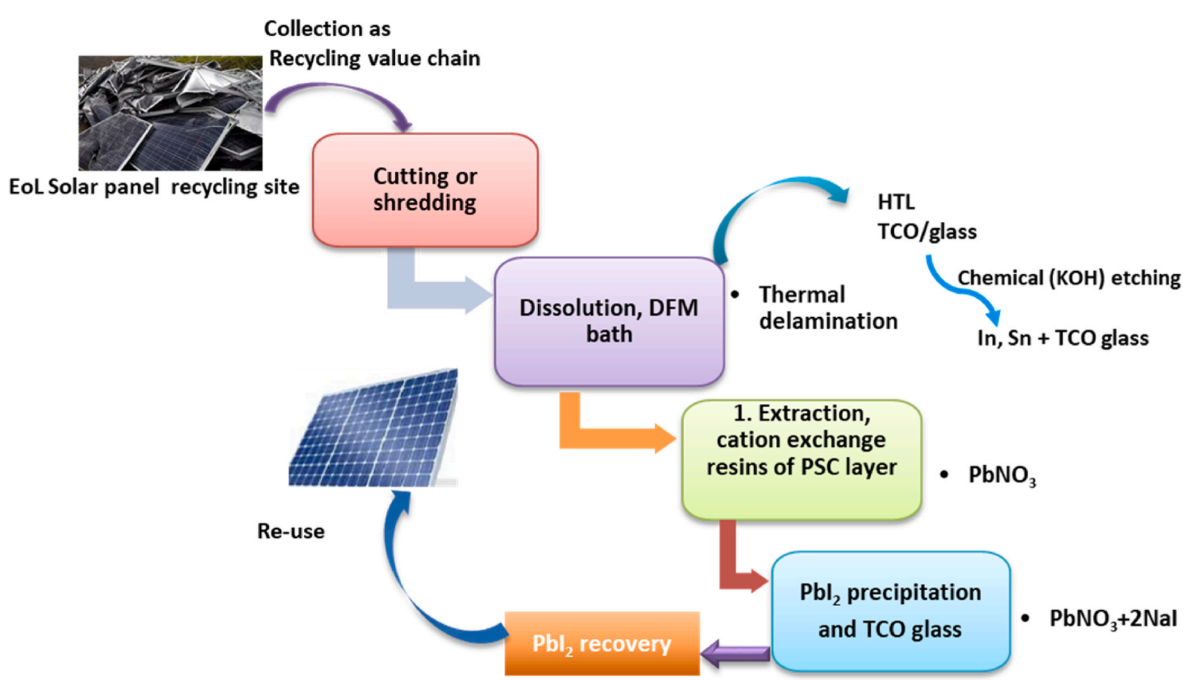

Fig. 12. Schematic representation of perovskite solar cell recycling process.

in technological developments to minimize the production cost of PV systems by converting waste into secondary raw materials. Despite PV technology being considered a clean and green technology, economically feasible and non-toxic technology for large-scale waste treatment has not been developed as yet. Despite PV technology being regarded as clean and environmentally friendly, there has not been a non-toxic, commercially viable technique for treating waste on a large-scale. Bošnjaković et al. [43] have projected tonnes of PV module waste that could be produced from c-Si modules and thin-film modules with the global exponential growth of PV installations and commercialization. In this research, large-volume studies were reviewed to identify sustainable options for waste treatment of c-Si, thin-film and third-generation PV technologies. The majority of studies on the treatment of c-Si waste panels at the laboratory scale have produced some intriguing results. However, when these studies were scaled up for industrial use, they encountered problems such as the release of toxic gases and a significant amount of acid waste, which could have an adverse effect on the environment. Module delamination has been posing a risk of loss of valuable materials from recycling of both c-Si and thin-film PV. The use of pyrolysis with gradual temperature increase could be adopted by the majority of recycling facilities because of its capability to achieve practical removal of glass with ease. Moreover, electrodeposition with the use of dilute acid is becoming a favourable approach for resource recovery in both c-Si and thin-film PV. Prospects for upscaling waste treatment in industrial applications may be hindered by a noticeable shortage of active research and development targeted at enhancing economic feasibility, practicality, and high recovery rate.

This study suggests sound, proper planning for infrastructure as a key requirement for recycling and waste management to validate solar energy's feasibility as a clean energy source. Moreover, a novel technique that can be used in PV waste management is artificial intelligence (AI). It can offer an opportunity to improve PV waste sorting with high accuracy, which may significantly decrease the amount of waste generated for landfills and increase the number of materials that can be recovered during recycling process. The combination of modern methodologies and AI-driven processes improves the overall recycling efficiency through real-time waste classification of recyclable materials. The practicality of convolutional neural networks and robotic systems provide improved accurate sorting and environmental contamination reduction thereby enhancing recycling rates and promoting sustainability in waste management [79]. Machine learning algorithms have exhibited capabilities of optimizing the recovery Si and polymers and predict waste quantities [80]. AI tools are promising PV waste management that could assure sustainable recycling operations because of significant reduction of landfill use by up to 40 % and transportation expenses by 15 % [81].

It is imperative that studies in the PV sector develop large-scale, commercially feasible and efficient treatment technology. To ensure that the treatment technology is applied and implemented in a way that is both feasible and low risk, with adequate financial resources available, this research recommends the use of a centralized system and standard policies for handling obsolete panels. Recent studies have shown that variations in the economic crisis have no effect on the feasibility of PV waste treatment technology. The adoption of comprehensive treatment technology can prevent damage and loss that may arise from improper management strategies and enable the recovery of high-quality secondary materials from end-of-life panels.

With sufficient progress made in upscaling c-Si-based and thin-film treatment technologies for industrial application, this research recommends optimization and implementation of the pyrolysis method for thermal decomposition of c-Si obsolete panels as a sustainable and eco-friendly resource recovery technique. This is because pyrolysis has shown the ability to promote a circular economy and closed-loop recycling while inhibiting the emission of toxic waste. This research further recommends a large-scale mechanical and hydrometallurgical approach for recycling of thin-film obsolete panels because of the use of non-hazardous chemicals which have no harmful effects on the environment. Regarding recycling processes of PSC, solvent dissolution of active materials demonstrated at laboratory experiments appear to be a viable strategy for waste management of end-of-life third-generation PV technology, provided these methods are feasible for upscaling to industrial use.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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