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Sustainable Solar: Recycling Photovoltaic Panels for a Greener Tomorrow

*[1]H.M.D.M. Herath, [2]Vikum Premalal, [3]K.L.D.P. Perera.

[1,2]Department of Civil and Environmental Technology, Faculty of Technology, University of Sri Jayewardenepura, Sri Lanka,
[3]Department of Electrical and Electronic Engineering, Faculty of Engineering, University of Peradeniya, Sri Lanka.
*[1]deshanh56@gmail.com

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Abstract—The fast expansion of solar photovoltaic (PV) technology has placed it as a prominent participant in the worldwide transition towards renewable energy but the rising quantity of end-of-life (EOL) solar panels creates substantial environmental and economic issues. This review paper addresses the composition and construction of solar panels, present recycling procedures, and the accompanying social, environmental, and economic effects. This review is undertaken on the efficiency and capacity for expansion of current recycling technologies, such as mechanical, thermal, and chemical processes and Challenges such as excessive cost, environmental impacts, and logistical challenges have been noted, coupled with non-technical hurdles including gaps in rules and insufficient infrastructure for obtaining data. Potential advancements like advanced silicon recovery, supercritical water technology, and simulation modeling are considered as means to enhance material recovery and process sustainability in the future. The study underscores the significance of a circular economy, pointing out the necessity of strong global policies, extended producer responsibility (EPR) programs, and collaboration among stakeholders. This thorough assessment highlights the importance of sustainable recycling in tackling the end-of-life challenges of PV panels, which helps in creating a more environmentally friendly future.

Index Terms—Circular economy, end-of-life PV panels, extended producer responsibility (EPR), photovoltaic recycling, renewable energy waste management, silicon recovery, sustainable solar energy.

1. Introduction

Solar PV technology has made significant progress from being used in space to being a key component of renewable energy worldwide. Currently, PV systems show great potential as one of the most promising technologies for generating sustainable energy. Solar power is the third most popular renewable energy source after hydropower and wind power, known for its safety, dependability, and ability to produce electricity without harming the environment [1]. Solar PV systems produce minimal greenhouse gas emissions during operation, unlike fossil fuels which emit 400 to 1000 grams of CO2 per kilowatt-hour of electricity generated [2,3,4]. The quick increase in the use of solar PV in recent decades highlights its ability to address the increasing global energy needs. In 2017, there was a significant increase in global PV energy production capacity, with China leading by installing half of the world's new solar capacity [5]. Progress in technology and increased economies of scale have also reduced expenses, making solar energy more attainable. In 2018, Saudi Arabia set a record with a bid of $0.0234 per kilowatt-hour for a 300 MW solar plant [6].

Nevertheless, the increasing dependence on solar power also presents fresh obstacles. PV panels, specifically c-Si modules, typically last around 25-30 years before needing either to be replaced or recycled. If not managed correctly, these end-of-life (EOL) panels may lead to dangerous waste and harm the environment. As the number of installations and the scale of production continue to grow, the effective recycling of PV waste will become increasingly important [7,8]. Acknowledging this, the European Union implemented regulations like the WEEE Directive, which establishes aggressive recycling and recovery goals to guarantee sustainable disposal methods [9,10]. Attempts to recycle PV panels have resulted in unique technologies, including applying chemical ways to extract silicon and using mechanical procedures for thin-film modules like CdTe and CIGS. These approaches have tremendous potential but also underscore the requirement for more economically feasible and scalable solutions [11,12]. Furthermore, the notion of "cradle-to-cradle" recycling, which focusses on creating materials for endless reuse, has been acknowledged for its potential to minimize waste and optimize resource efficiency [13]. With the rising need for PV technology and the related development in waste output, there is a vital necessity to supply recycling solutions that are efficient, low-cost, and ecologically benign. Research shows the relevance of adopting advanced recycling technology and circular economic strategies to successfully handle this dilemma [13]. This review evaluates the current advancements, obstacles, and projected prospects in the recycling of PV panels, highlighting its vital role in assisting the solar industry's transition towards a circular economy [9].

2. Composition and Design of PV Modules

Photovoltaic (PV) panels convert light energy into electricity by integrating organic and inorganic materials. As illustrated in Fig. 1, panels are typically made up of multiple layers, starting with a backing of Tedlar and polyethylene terephthalate for support and protection. Encasing layers of ethylene vinyl acetate (EVA) protect the semiconductor from environmental degradation, with a sturdy glass layer providing the top protective surface. An aluminum frame including a junction box for electrical connections holds these parts together [14]. Although the overall construction of PV panels stays the same throughout several generations, the three main generations of PV panels are distinguished by the photosensitive material and semiconductor technology [15]. Dominant on the market, first-generation panels comprise monocrystalline and polycrystalline silicon modules, representing 41% and 51% of worldwide installations correspondingly [15]. Produced using the Czochralski technique, monocrystalline silicon panels have consistent atomic structure and thus high efficiency of up to 21% [16]. Polycrystalline panels, characterized by a less uniform crystalline structure, are somewhat less efficient at 19%, however they are more cost-effective. A useful material targeted for recycling is silver, utilized as electrodes on both sides of crystalline silicon panels [17,18,19].

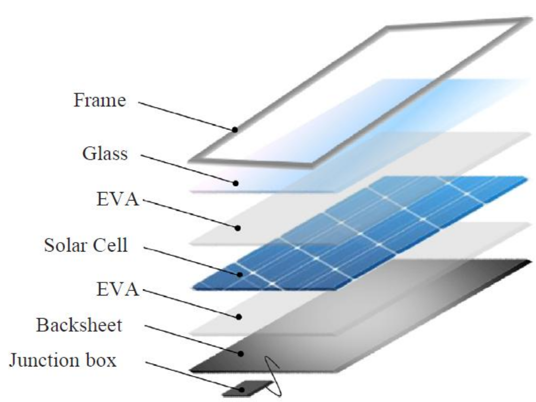

Fig. 01. The typical design of a photovoltaic panel [1].

Thin-film modules, often known as second-generation panels, are built via semiconductor deposition onto glass or stainless-steel substrates. This category comprises amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) panels. With their low performance and sporadic manufacturing, amorphous silicon panels with an efficiency of 10% have a tiny market share [15]. In contrast, CdTe panels have attained efficiency equivalent to polycrystalline silicon at 17%, but their use is hindered by the toxicity of cadmium and the rarity of tellurium [20]. Similarly, CIGS panels, which yield efficiencies of roughly 15%, show potential but face obstacles due to high manufacturing costs and complicated production procedures [15,20].

Third-generation PV panels include developing technologies such as concentrator photovoltaics (CPV), dye-sensitized cells, organic cells, and hybrid cells. CPV systems employ lenses or mirrors to focus sunlight on high-efficiency cells and require accurate tracking systems to improve sunlight collection [21,22]. Dye-sensitized solar cells consist of a semiconductor material, such as TiO_2, covered with dye molecules that collect light energy, an electrolyte, and a cathode [23,24]. Hybrid cells, which blend organic and inorganic technologies or merge crystalline and amorphous silicon layers, provide unique techniques to boost efficiency [25]. Across all generations, the photosensitive material accounts for around 3.5% of the panel's total weight, whereas the rest components, such as glass and aluminum, are frequently readily recyclable [26,27]. The operating lifespan of most PV panels is roughly 20–30 years, after which they lose efficiency and must be retired. By 2016, an estimated 250,000 metric tons of solar panel trash had accumulated globally, with this amount anticipated to climb considerably in the future decades. For example, Japan's yearly solar panel waste is predicted to rise from 10,000 tons in 2016 to 800,000 tons by 2040, with recycling facilities falling significantly behind these demands [28,29,30,31]. Solar panels include toxic compounds like lead and cadmium, which may leak into the environment if not disposed of appropriately, causing dangers to soil and water systems [32,33,34]. While nations like Europe have established legislation mandating manufacturers to collect and recycle PV waste, other major producers, like as the United States and China, still lack comprehensive waste management strategies [35,36,37]. As a result, enormous volumes of solar waste may wind up in landfills, compounding environmental problems. The longevity of PV panels has been associated with their year of installation, with waste production generally occurring 25 years following deployment [38].

3. Current recycling methods

Currently, Japan, Europe, and the United States are focusing their research and development efforts on solar module recycling [39,40,41,42,43]. The majority of initiatives in this area target silicon-based (Si) panels, aiming to recover and reuse the most valuable components. As mentioned earlier, three primary recycling methods are currently employed for solar PV panels: physical, thermal, and chemical, as depicted in Fig. 2 [4].

3.1 The method of physical separation.

In this operation, solar panels are initially taken apart by removing the aluminum frame, junction boxes, and embedded wires [44,45]. Each component, including the panel, wires, and junction box, is then shredded and crushed to evaluate both individual and overall module toxicity for safe disposal [44]. The aluminum frame, the final portion to be joined during assembly, serves a critical function by holding the components together, shielding the module edges from external causes such water penetration, and providing structural strength while keeping the design lightweight [46,47,48]. After removal, the aluminum frame can be recovered using secondary metallurgy. Small quantities of elements including iron, silicon, and nickel, which are abundant in aluminum alloys, may also be removed during this procedure [46,47]. Repairs on solar cells often entail replacing damaged electrical components rather than separating materials or treating the cells themselves [49,50]. Junction box issues are handled using two conventional repair procedures, which assist in restoring the output power of older solar panels. However, these solutions are confined to junction boxes situated outside on the panel, outside its core structure.

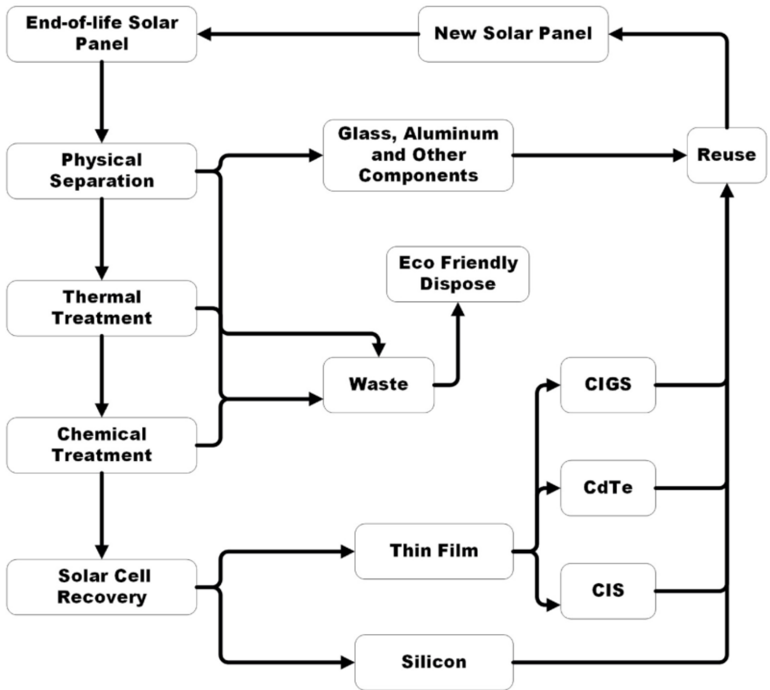

Fig. 02. Various methods for recycling solar PV panels [51,52].

3.2 Heat-based and chemical processing

Recovered polycrystalline silicon using thermal treatment in a high-temperature Lenton tubular furnace [7]. The exterior aluminum frame of the PV module was physically dismantled first. Samples of approximately 10 x 10 cm were created by first cutting the glass with a diamond blade and then sectioning the panel. Two flow meters were used to adjust gas flow rates in the boiler, resulting in nitrogen-oxygen mixes of various ratios. Then Gas was supplied at a rate of 24 L/h, and the reactor was heated to 500°C at 450°C per hour, with the temperature held for one hour [33].

Employed mechanical crushing to reduce the glass to shards bigger than 1 mm, which were then crushed again to generate smaller fractions, all less than 1 mm [53]. A heat treatment was then used to recover the glass and metal fractions, with air flowing at a rate of 30 L/h. The furnace temperature steadily increased at a rate of 10°C per minute until it reached 650°C, at which point it remained stable for one hour. This approach has an overall glass recovery rate of 91%. Orac et al. [50] utilized a combination of heat pretreatment and acid leaching to remove copper and tin from old circuit boards. Shin et al. [3] recycled 60 multi-crystalline silicon (Si) wafers (156 mm x 156 mm) produced by JSPV Co. Ltd., South Korea. The method began with heat treatment to separate the layers of the solar panels as shown in Fig. 03. This treatment was performed in a furnace from K-Tech Co. in South Korea with dimensions of 1500 mm width, 1700 mm height, and 2000 mm length. The wafers were covered with phosphoric acid paste and heated for two minutes each at five different temperatures ranging from 320°C to 400°C. The recovered wafers were successfully reused in solar panel manufacture, attaining efficiency levels comparable to the original cells [51,54]. Doi et al. [100] dissolved the EVA coating on crystalline silicon solar panels using a variety of chemical solvents. Among the solvents studied, trichloroethylene was the most effective. To avoid EVA swelling, the solar panels (125 mm × 125 mm) were subjected to mechanical pressure and soaked in trichloroethylene at 80°C for 10 days. Following recycling, the recycled silicon panels performed well. Kim and Lee [55] investigated how to speed the breakdown of the EVA layer by combining several organic solvents, such as trichloroethylene, O-dichlorobenzene, and toluene, with an ultrasonic procedure. Their investigation looked at varied solvent combinations, temperatures, ultrasonic power levels, and exposure periods. They discovered that the EVA layer dissolved entirely in 1 hour at 70°C in 3 mol/L of toluene using ultrasound at 450 W. However, this approach generated toxic lead-containing byproducts.

Marwede et al. [56] investigated methods for managing end-of-life (EOL) PV materials and discovered pH changes during metal recovery when sodium hydroxide was utilized [57,58]. In previous research, 5N Plus used a thickening tank to recover metals by evaporation, followed by filtering during the dewatering step. First Solar claimed 95-97% recovery efficiency for both cadmium (Cd) and tellurium (Te), which were utilized in their products [59,60]. Wang and Fthenakis [61] removed Cd and Te from a sulphuric acid solution using several ion-exchange resins over varying time durations [62,63,64]. The metals were recovered from their respective ion-exchange or acid solutions with a recovery rate of above 90%. Another investigation found that adding sodium carbonate and sodium sulphide improved the recovery of Te from solution.

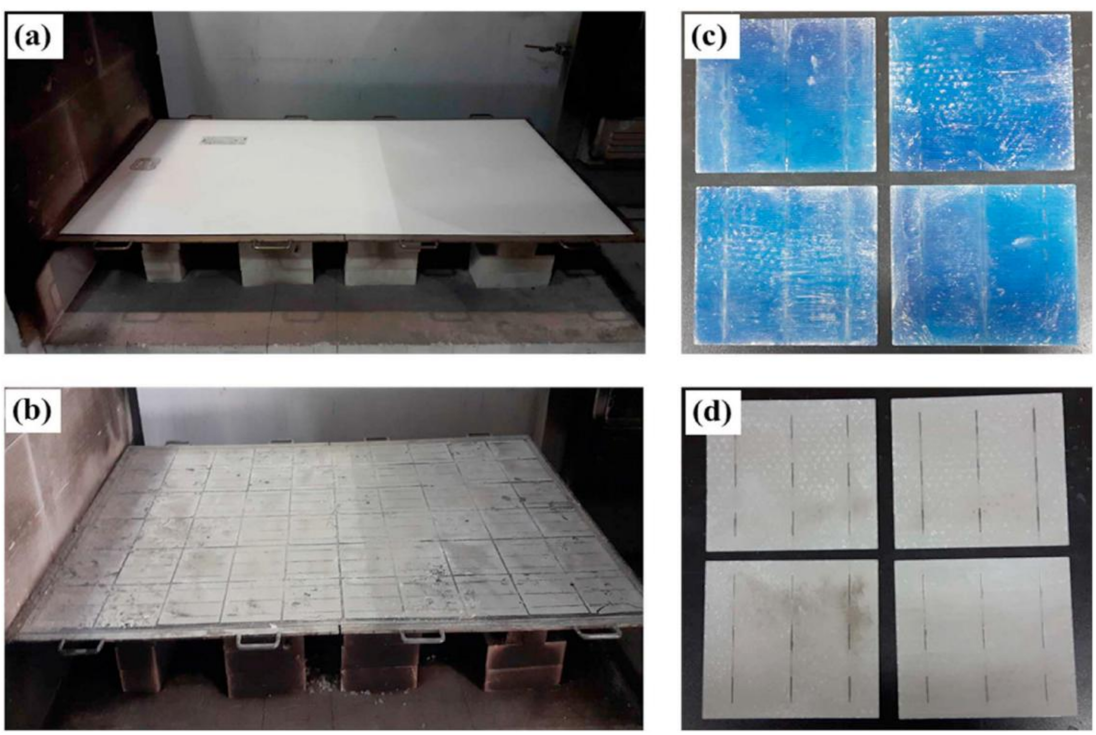

Fig. 03. Photovoltaic wafers during the heating process: (a) prior to heating, (b) following the heating process, (c) the reverse side before heating, and (d) the reverse side after heating [3].

Dattilo [65] investigated the wet-chemical extraction of metals from CIGS panels, focusing on desalination, copper (Cu) recovery, and the separation of other metals such as indium (In) and gallium. Electrolysis was utilized to degrade CIGS materials, with Cu and selenium (Se) accumulating on the cathode plate. These were then removed and refined using oxidation and distillation to get Cu and Se, while zinc oxide (ZnO) and indium oxide (InO) were produced using vaporization. Many of these approaches are still in the research stage, but just two have been commercialized. In the United States, First Solar recycles thin-film solar panels using both mechanical and chemical techniques. Meanwhile, a German business recycles c-Si solar panels [6,13]. Recycling facilities in China are mostly confined to component repair and panel separation, with material separation and recovery largely reliant on external technology. Similarly, other countries experience difficulty in implementing recycling technology owing to a variety of factors.

Mechanical and physical recycling operations generate enormous volumes of dust including glass particles, which are hazardous and cause noise pollution. Separating the EVA layer with inorganic solvents produces nitrogen oxide and other toxic gases, which pose health risks [66]. Furthermore, reusing silicon wafers requires frame removal, which results in liquid waste that is difficult to dispose of. While ultrasonic techniques can shorten the time it takes to dissolve the EVA layer compared to standard organic solvents, they generate large amounts of organic waste that are difficult to handle. Thermal and chemical processes combine modern recycling technology, but they have significant downsides, including harmful gas emissions and excessive energy usage [66].

4. Social, Environmental, and Economic Impact of Recycling PV Panels

Recycling photovoltaic (PV) panels offers critical social, environmental, and economic benefits, particularly in the context of the projected increase in solar PV waste. As of 2016, the global volume of solar PV waste was estimated to range from 43,000 to 250,000 tons. This relatively small volume currently poses challenges for economic viability in large-scale reprocessing. However, projections indicate a sharp rise in PV panel waste by 2050 under both regular and early-loss scenarios, necessitating the development of robust recycling and recovery strategies [67].

The global ratio of solar PV waste to new installations is expected to grow significantly over time, reaching 4%–14% of total generation capacity by 2030 and surpassing 80% by 2050. Given the expected dominance of crystalline silicon (c-Si) panels among end-of-life (EOL) panels over the coming years, recycling methods must be established by 2040 to manage this growing challenge effectively [57,68,69]. Recycling EOL panels and reusing recovered materials for manufacturing new PV systems could drastically reduce actual waste. For example, recycling 186 tons of solar PV waste could offset 1480–2220 tons of CO2 equivalent emissions annually. Over a 20-year power station lifespan, this could result in a total reduction of 49,470 tons of CO2 equivalent emissions [67]. Recycling waste from a 1903 MW conventional power plant could further save 11,840–17,760 tons of CO2 equivalent emissions, totaling 396,770 tons over the facility's lifetime [29,67].

From an economic perspective, PV recycling provides secondary raw materials, reducing reliance on primary resources. Materials such as tellurium (Te) recovered from recycled panels are essential for producing cadmium telluride (CdTe) modules, which helps conserve limited natural resources. However, the market value of recovered materials like Te, indium (In), and gallium (Ga) is subject to significant price fluctuations. For instance, Te prices have varied widely since 2010, while in prices dropped notably in 2015. These fluctuations, combined with the purity levels of recovered materials, influence the profitability of recycling processes. As noted by Cucchiella et al. (2015), the economic feasibility of recycling processes often requires adjustments to account for material purity and market volatility [70].

Economic potential (EP) assessments suggest that recycling processes for CIGS (copper indium gallium selenide) and CdTe panels have similar feasibility. This similarity persists despite the higher prices of In and Ga in CIGS panels compared to Cd and Te in CdTe panels, primarily due to the low concentrations of In and Ga in CIGS panels. High recovery rates, often exceeding 97%, are critical for ensuring the economic viability of these processes. These findings align with analyses presented by Cucchiella et al. (2015) and Paiano (2015) [20,70]. The data presented in Table 1 offers valuable insights into the potential for achieving economic feasibility with the proposed processes [71].

Table 1: Recovery rates of materials and overall revenue generated by patented processes. [71].

Reference	Treated panel	Recovery products and rates	Total revenues (€/ton of treated panel)
US5997718 A	CdTe	Glass (100%) Cd (99% as CdO) Te (100% as TeO)	76
US 6391165 B1	CdTe	Glass (100%) Cd (not reported) Te (67% as Te elemental)	66
US2012325676 A1	CdTe	Glass (100%) Te (37.8% as Te metallic)	58
US5779877 A	CIGS	Glass (100%) Cd (not reported) Cu (not reported) Se (59.4% as SeO) Zn and In (not reported)	47
US0329970 A1	CIGS	Se (97.6% as Se elemental) Cu (97.7% as Cu metallic) and In (97.7% as In metallic)	62
WO2013089630A1	CIGS	Se (88.4%)	8
CA 2721518C	CIGS	Ga (68.8%) In (99.4%)	48
CN103184338A	CIGS	In (97.46%) Se (97.94%) Cu (98.79%)	63

5. Challenges in PV Panel Recycling

The recycling of crystalline silicon (c-Si) photovoltaic (PV) panels has various technical and non-technical problems, impeding the creation of high-quality recycled materials required for the manufacture of new solar panels. These restrictions promote less sustainable behaviors such as hoarding, landfilling, and downcycling [18].

5.1. Technological Challenges

Recycling c-Si PV panels is a pricey task, ranging from $600-1000 per ton (minus material revenue), making it a considerable concern. Below economically feasible, this cost must be cut below $300-400 per ton [72,73]. To enhance recycling efficiency, innovative and energy-saving techniques are necessary. Some of the proposed techniques include delamination [74], automatic material selection [75], increased silver retrieval [76], improved thermal and chemical processes [77], and methods for reducing waste [78]. many existing thermal and chemical treatment techniques either result in a substantial increase in recycling expenses or are ineffective for PV panels that have been damaged [79].

Recycling processes release harmful substances into the environment, such as poisonous fumes in pyrolysis, particles in mechanical shredding, and chemical waste during leaching and extracting metals [80,81]. Materials that are not able to be recycled, like fluorinated back sheets, create further challenges when it comes to disposal [82]. Catalytic converters and waste treatment facilities can help tackle these difficulties. Lack of proper recycling infrastructure for solar PV panels causes inefficiencies. Current facilities designed for recycling nonferrous metals, WEEE, and glass need to be improved to effectively recycle PV panels [83].

Few recycling plants worldwide can achieve high recovery rates for PV panels. For example, Italy's "Sasil S. r.l." recovers over 100% of materials, including silver and copper, with a capacity of over 8,000 tons per year [84]. In France, "Veolia" has excellent recovery rates, whereas First Solar in the United States recycles CdTe-based panels at a 95% rate [85,83]. Achieving sustainable recycling requires resolving technological feasibility, economic limits, and socio-desirability considerations.

5.2. Nontechnical Challenges

Recycling economies of scale are limited due to low trash quantities and poor garbage collection networks. Collection rates below 10,000 tones frequently limit market feasibility [86,87]. The significant collection of end-of-life panels presents logistical issues for recyclers, constraining efficiency and market sustainability [88,89]. Legislation requiring panel collection and recycling is needed to address this issue.

In certain nations, a lack of recycling rules and high pricing led to buyers discarding defective panels owing to cheap entrance fees. Although recycling rules have been introduced in regions such as the EU and the UK via the WEEE directive, adherence to these laws remains low. Only two of the 26 solar PV recycling plants completed in the EU exceed CENELEC criteria, according to Genovese et al., 2023 and Joshi et al., 2023 [90,91]. Similarly, both Victoria State in Australia and California in the United States have adopted legislation against the dumping of PV panels [92,93].

6. Future Prospects and Innovations

Current recycling systems for photovoltaic (PV) panels confront considerable challenges, such as low efficiency, high operating costs, and the discharge of harmful chemicals and pollutants. Overcoming these obstacles necessitates the development of novel, energy-efficient, and cost-effective methods capable of recovering valuable materials at high rates. Interdisciplinary efforts in pyrometallurgy and hydrometallurgy are required to accomplish this aim. For example, electrostatic separation technology, which has been emphasized for its environmental friendliness and economic feasibility, is particularly successful in separating conductive and non-conductive materials [94,95]. Plus, current methods such the hot knife, high-voltage pulses, and microwave field give fascinating potential for separating ethylene-vinyl acetate (EVA) layers from PV panels while reducing environmental damage.

Thermal treatments also might completely transform silicon recycling. Vacuum and gas refining techniques can help to allow non-polluting recovery of electronic-grade silicon. Using a Bridgeman furnace, this recovered silicon might then be utilized in the production of silicon carbide, therefore reducing energy use, material costs, and greenhouse gas emissions. Innovations in chemical treatments can also help to minimize acidification and eutrophication by substituting iodine and iodide (I2-K2) for standard nitric acid (HNO3), as has been shown to maximize material recovery with minimum human health hazards [96].

Emerging technologies, such as supercritical water processing, provide another viable answer. This strategy reduces environmental effect while increasing material recovery by employing wastewater rather than fresh water and combining efficient gas treatment systems. Beyond technological advancements, tackling logistical and regulatory issues is as important. Effective solar panel collecting, transportation, and recycling need coordinated efforts from consumers, industry partners, and governments. Large-scale recycling facilities, together with the smart allocation of economic resources to recyclers, manufacturers, and policymakers, can help to speed development [97].

Globally, more collaboration among governments, international organizations, academic institutions, and PV stakeholders is critical for developing strong legislation for PV panel recycling. Countries with significant PV installations, including as the United States, China, India, and South Korea, should create laws that are consistent with the European Union's Waste Electrical and Electronic Equipment (WEEE) directive to enforce appropriate recycling procedures. Together with gradual decline policies, carefully specified criteria for subsidies can boost investment returns and raise high-value material recovery rates [98].

Extended producer responsibility (EPR) projects are another crucial tool that guarantees manufacturers take accountability for their products over their lifetime. This strategy promotes the development of environmentally friendly and energy-efficient recycling methods. Simulation modeling will also play an important part in future breakthroughs, allowing for virtual testing of essential parameters to refine processes and optimize designs. Industries may use computer-aided modeling to develop cost-effective and sustainable recycling systems that optimize material recovery while reducing environmental impact [99].

7. Conclusion

The worldwide quest for renewable energy has elevated solar photovoltaic (PV) technology to the forefront of sustainable alternatives. However, the increasing number of end-of-life PV panels poses a serious environmental and economic concern. This article investigated the composition of PV modules, existing recycling techniques, and their socioeconomic implications, with a focus on technological and non-technical hurdles to recycling. Efficient recycling is crucial not just to avoid environmental hazards but also to establish a circular economy that optimizes resource consumption and lowers dependency on raw resources. Advancements in mechanical, thermal, and chemical recycling are vital for generating energy-efficient and inexpensive solutions. The combination of regulations like the WEEE Directive and extended producer responsibility (EPR) programs highlights the significance of worldwide collaboration among governments, industry, and research organizations.Moving forward, improvements in supercritical water technologies, increased silicon recovery techniques, and computer-aided simulation modeling promise to further optimize recycling operations. Addressing increasing garbage needs will require the establishment of financially viable recycling companies on a large scale, along with efficient collection systems. In conclusion, effectively managing the disposal of PV panel waste is crucial for reducing the environmental impact of solar technology and ensuring its importance in the worldwide shift to renewable energy.

8. References

[1] A. Paiano, Photovoltaic waste assessment in Italy, Renew. Sustain. Energy Rev. 41 (2015) 99–112.

[2] International Energy Agency, Energy Technology Perspectives: Mobilising Innovation to Accelerate

Climate Action 2015, 2015, https://doi.org/10.1787/energy_tech-2014-en.

[3] J. Shin, J. Park, N. Park, A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers, Sol. Energy Mater. Sol. Cells 162 (2017) 1–6.

[4] Y. Xu, J. Li, Q. Tan, A.L. Peters, C. Yang, Global Status of Recycling Waste Solar Panels: A Review, Waste Management, 2018.

[5] S. Of, G. Photovoltaic, The International Energy Agency (IEA) - Photovoltaic Power Systems Programme - 2018 Snapshot of Global Photovoltaic Markets 1–16, 2018.

[6] Michael Schmela, SolarPower Europe, Global Market Outlook for Solar Power: 2018 - 2022, 2018.

[7] V. Fiandra, L. Sannino, C. Andreozzi, F. Corcelli, G. Graditi, Silicon photovoltaic modules at end-of-life: removal of polymeric layers and separation of materials, Waste Manag. 87 (2019) 97–107.

[8] I. D'Adamo, M. Miliacca, P. Rosa, Economic feasibility for recycling of waste crystalline silicon photovoltaic modules, Int. J. Photoenergy (2017), 2017.

[9] Official Journal of the European Guideline (24/07/2012).

[10] L.J. Fernàndez, R. Ferrer, D.F. Aponte, P. Fernàndez, Recycling silicon solar cell waste in cement-based systems, Sol. Energy Mater. Sol. Cells 95 (2011) 1701-1706.

[11] R.A. Sasala, J. Bohland, K. Smigielskic, Physical and Chemical Pathways for Economic Recycling of Cadmium Telluride Thin-Film Photovoltaic Modules, Solar Cells Inc., Toledo, OH, 43607, 1996.

[12] Sica, D.; Malandrino, O.; Supino, S.; Testa, M.; Lucchetti, M.C. Management of end-of-life photovoltaic panels as a step towards a circular economy. Renew. Sustain. Energy Rev. 2018, 82, 2934–2945.

[13] McDonough, W.; Braungart, M. Cradle to Cradle: Remaking the Way We Make Things; Vintage: London, UK, 2008; ISBN 9781784873653.

[14] F.C.S.M. Padoan et al. Solar Energy 177 (2019) 746–761 https://doi.org/10.1016/j.solener.2018.12.003

[15] International Renewable Energy Agency (IRENA) and International Energy Agency (IEA), 2016. End-of-life management: solar photovoltaic panels.

[16] Bagnall, D.M., Boreland, M., 2008. Photovoltaic technologies. Energ. Pol. 36, 4390–4396.

[17] Nieland, S., Neuhaus, U., Pfaff, T., 2012. New approaches for component recycling of crystalline solar modules. In: Electronics Goes Green, Berlin, Germany.

[18] Tao, J., Yu, S., 2015. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Sol. Energ. Mat. Sol. C. 141, 108–124.

[19] Dias, P., Javimczik, S., Benevit, M., Veit, H., Bernardes, A.M., 2016. Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules. Waste Manage. 57, 220–225.

[20] Paiano, A., 2015. Photovoltaic waste assessment in Italy. Renew. Sust. Energ. Rev. 41, 99–112.

[21] Bagher, A.M., Vahid, M.M.A., Mohsen, M., 2015. Types of solar cells and application. Am. J. Opt. Phot. 3 (5), 94–113.

[22] International Energy Agency (IEA), 2014. Technology Roadmap: Solar Photovoltaic Energy.

[23] Grätzel, M., 2000. Perspectives for dye-sensitized nanocrystalline solar cells. Prog. Photovolt.: Res. Appl. 8, 171–185.

[24] Wan, H., 2004. Dye-Sensitized Solar Cells. University of Alabama, Department of Chemistry.

[25] Wu, L., Tian, W., Jiang, Z., 2005. Silicon-based solar cells system with a hybrid PV module. Sol. Energ. Mat. Sol. C. 87, 637–645.

[26] Bio Intelligence Service (BioIS), 2011. Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE directive.

[27] Dubey, S., Jadhav, N.Y., Zakirova, B., 2013. Socioeconomic and environmental impacts of silicon-based photovoltaic (PV) technologies. Energy Proced. 33, 322–334.

[28] S. Mahmoudi, N. Huda, Z. Alavi, M.T. Islam, M. Behnia, End-of-life photovoltaic modules: a systematic quantitative literature review, Resour. Conserv. Recycl. 146 (2019) 1–16.

[29] I. IRENA, End-Of-Life Management: Solar Photovoltaic Panels, International Renewable Energy Agency and the International Energy, 2016.

[30] E. Briese, K. Piezer, I. Celik, D. Apul, Ecological network analysis of solar photovoltaic power generation systems, J. Clean. Prod. 223 (2019 Jun 20) 368–378.

[31] W.H. Huang, W.J. Shin, L. Wang, W.C. Sun, M. Tao, Strategy and technology to recycle wafer-silicon solar modules, Sol. Energy 144 (2017) 22–31.

[32] V. Fiandra, L. Sannino, C. Andreozzi, G. Graditi, End-of-life of silicon PV panels: a sustainable materials recovery process, Waste Manag. 84 (2019) 91–101.

[33] I. D'Adamo, M. Miliacca, P. Rosa, Economic feasibility for recycling of waste crystalline silicon photovoltaic modules, Int. J. Photoenergy (2017), 2017.

[34] Y. Smith, P. Bogust, Review of solar silicon recycling, Energy Technol. (2018), 2018, 463–470.

[35] Y.K. Yi, H.S. Kim, T. Tran, S.K. Hong, M.J. Kim, Recovering valuable metals from recycled photovoltaic modules, J. Air Waste Manag. Assoc. 64 (7) (2014) 797–807.

[36] K. Komoto, J.S. Lee, J. Zhang, D. Ravikumar, P. Sinha, A. Wade, G. Heath, End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies. IEA PVPS Task 12, International Energy Agency Power Systems Programme, Report IEA-PVPS T12, 2018, p. 10.

[37] R. Frischknecht, G. Heath, M. de Wild Scholten, Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, third ed., International Energy Agency Photovoltaic Power Systems Programme Task 12, 2016. IEA-PVPS-TASK 12.

[38] A. Paiano, Photovoltaic waste assessment in Italy, Renew. Sustain. Energy Rev. 41 (2015) 99–112.

[39] Conference record of the, IEEE Electron Devices Society., & Institute of Electrical and Electronics Engineers, IEEE Photovoltaic Specialists Conference, New York,1970. Institute of Electrical and Electronics Engineers).

[40] E.P.S.E. Conference, 20th European Photovoltaic Solar Energy Conference:Proceedings of the International Conference Held in Barcelona, WIP-Renewable Energies, Spain, 2005, 6-10 June 2005.

[41] O H A, A. J€ager-Waldau, P. Helm (Eds.), E.C. Photovoltaic Solar Energy Conference, 21st European Photovoltaic Solar Energy Conference Proceedings of the International Conference Held in Hamburg, 2006. Germany, 4-6 September 2006.

[42] T. Doi, I. Tsuda, H. Unagida, A. Murata, K. Sakuta, K. Kurokawa, Experimental study on PV module recycling with organic solvent method, Sol. Energy Mater. Sol. Cells 67 (1–4) (2001) 397–403.

[43] W. Palitzsch, U. Loser, Economic PV waste recycling solutions -Results from R&D and practice, in: Conference Record of the IEEE Photovoltaic Specialists Conference, 2012, pp. 628–631.

[44] V. Savvilotidou, A. Antoniou, E. Gidarakos, Toxicity assessment and feasible recycling process for amorphous silicon and CIS waste photovoltaic panels, Waste Manag. 59 (2017) 394–402.

[45] P. Dias, S. Javimczik, M. Benevit, H. Veit, A.M. Bernardes, Recycling WEEE: extraction and concentration of silver from waste crystalline silicon photovoltaic modules, Waste Manag. 57 (2016) 220–225.

[46] P. Dias, H. Veit, Recycling crystalline silicon photovoltaic modules, in: Emerging Photovoltaic Materials: Silicon & beyond, John Wiley & Sons, 2018, pp. 61–102.

[47]P. Dias, L. Schmidt, L.B. Gomes, A. Bettanin, H. Veit, A.M. Bernardes, Recycling waste crystalline

silicon photovoltaic modules by electrostatic separation,J. Sustain. Metall. 4 (2) (2018) 176–186.

[48] J. Pern, Module Encapsulation Materials, Processing and Testing (Presentation) (No. NREL/PR-520-44666), National Renewable Energy Lab.(NREL), Golden, CO (United States), 2008.

[49] Lin, W., Chen, E., Sun, Y.L., n.d. Analysis of old photovoltaic component junction box disassembling mode. Sol. Energy Volume 7, Pages 26-29.

[50] D. Orac, T. Havlik, A. Maul, M. Berwanger, Acidic leaching of copper and tin from used consumer equipment, J. Min. Metall. B: Metallurgy 51 (2) (2015) 153–161.

[51] E. Klugmann-Radziemska, P. Ostrowski, Chemical treatment of crystalline silicon solar cells as a method of recovering pure silicon from photovoltaic modules, Renew. Energy 35 (8) (2010) 1751–1759.

[52] S. Kang, S. Yoo, J. Lee, B. Boo, H. Ryu, Experimental investigations for recycling silicon and glass from waste photovoltaic modules, Renew. Energy 47 (2012) 152–159.

[53] F. Pagnanelli, E. Moscardini, G. Granata, T.A. Atia, P. Altimari, T. Havlik, L. Toro, Physical and chemical treatment of end-of-life panels: an integrated automatic approach viable for different photovoltaic technologies, Waste Manag. 59 (2017) 422–431.

[54] B. Jung, J. Park, D. Seo, N. Park, Sustainable system for raw-metal recovery from crystalline silicon solar panels: from noble-metal extraction to lead removal, ACS Sustain. Chem. Eng. 4 (8) (2016) 4079–4083.

[55] Y. Kim, J. Lee, Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent, Sol. Energy Mater. Sol.Cells 98 (2012) 317–322.

[56] M. Marwede, W. Berger, M. Schlummer, A. M€aurer, A. Reller, Recycling paths for thin-film chalcogenide photovoltaic waste–Current feasible processes, Renew. Energy 55 (2013) 220–229.

[57] K. Sander, Study on the Development of a Take Back and Recovery System for Photovoltaic Products, Brussels: Belgium: PV Cycles, 2007, https://doi.org/10.2314/GBV:59163323X.

[58] A. Mezei, M. Ashbury, M. Canizares, R. Molnar, H. Given, A. Meader, K. Squires, F. Ojebuoboh, T. Jones, W. Wang, Hydrometallurgical Recycling of the Semiconductor Material from Photovoltaic Materials-Part One: Leaching, Hydrometallurgy, 2008, p. 209.

[59] K. Weimann, F.-G. Simon, Resolved - recovery of solar valuable materials, Enrich. Decontamination (2007) 1–4.

[60] M. Suys, January. Recycling valuable metals from thin film modules, in: 1st International Conference on

PV Module Recycling, vol. 26, 2010.

[61] W. Wang, V. Fthenakis, Kinetics study on separation of cadmium from tellurium in acidic solution media using ion-exchange resins, J. Hazard Mater. 125 (1–3) (2005) 80–88.

[62] V.M. Fthenakis, W. Wang, Extraction and separation of Cd and Te from cadmium telluride photovoltaic manufacturing scrap, Prog. Photovolt. Res. Appl. 14 (4) (2006) 363–371.

[63] R. Deng, N.L. Chang, Z. Ouyang, C.M. Chong, A techno-economic review of silicon photovoltaic module recycling, Renew. Sustain. Energy Rev. 109 (2019) 532–550.

[64] V. Fthenakis, W. Wang, System and method for separating tellurium from cadmium waste, U.S. Patent Appl. 12/756 (2010) 507.

[65] M. Dattilo, February. CI (G) S PV modules: recycling technology status, in: 2nd International Conference on PV Module Recycling, vol. 25, 2011.

[66] T.M. Bruton, Re-cycling of high value, high energy content components of silicon PV modules, in: In Proc. of 12th EC-PVSEC, 1994, pp. 303–304.

[67] D. Sica, O. Malandrino, Lucchetti, M C, Management of end-of-life photovoltaic panels as a step towards a circular economy, Renew. Sustain. Energy Rev. (2018).

[68] C.E. Latunussa, F. Ardente, G.A. Blengini, L. Mancini, Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels, Sol. Energy Mater. Sol. Cells 156 (2016) 101–111.

[69] T.A.N.G. Shao-jun, Discussion on confusion and correction for the concept of extended producer responsibility regime, J. Chongqing Univ. (Soc. Sci. Ed.) (2009), 4, p.018.

[70] Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sust. Energ. Rev.51, 263–272.

[71] Recycling of end of life photovoltaic panels: A chemical prospective on process development Flavia C.S.M. Padoan∗, Pietro Altimari, Francesca Pagnanelli*Solar Energy 177 (2019) 746–761*

[72] Deng, R., Chang, N.L., Ouyang, Z., Chong, C.M., 2019. A techno-economic review of silicon photovoltaic module recycling. Renew. Sustain. Energy Rev. 109, 532–550.

[73] Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., Wade, A., 2020. Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy 5, 502–510.

[74] Li, J., Lin, Y., Wang, F., Shi, J., Sun, J., Ban, B., Liu, G., Chen, J., 2021. Progress in recovery and

recycling of kerf loss silicon waste in photovoltaic industry. Sep. Purif. Technol. 254, 117581.

[75] Dias, P.R., Schmidt, L., Chang, N.L., Lunardi, M.M., Deng, R., Trigger, B., Gomes, L.B., Egan, R., Veit, H., 2022. High yield, low cost, environmentally friendly process to recycle silicon solar panels: technical, economic and environmental feasibility assessment. Renew. Sustain. Energy Rev. 169, 112900.

[76] De Souza, R.A., Veit, H.M., 2023. Study of electrostatic separation to concentrate silver, aluminum, and silicon from solar panel scraps. Circular Econ. 2 (1), 100027.

[77] Prasad, D.S., Sanjana, B., Kiran, S., Srinivasa, P.P., Ratheesh, P., 2022. Process optimization studies of essential parameters in the organic solvent method for the recycling of waste crystalline silicon photovoltaic modules. Sol. Energy Mater. Sol. Cell. 245, 111850.

[78] Wang, X., Tian, X., Chen, X., Ren, L., Geng, C., 2022. A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology. Sol. Energy Mater. Sol. Cell. 248, 111976.

[79] Zhang, L., Chang, S., Wang, Q., Zhou, D., 2022. Is subsidy needed for waste PV modules recycling in China? A system dynamics simulation. Sustain. Prod. Consum. 31, 152–164.

[80] Artas, S.B., Kocaman, E., Bilgic, H.H., Tutumlu, H., 2023. Why PV panels must be recycled at the end of their economic life span? A case study on recycling together with the global situation. Process Saf. Environ. Protect. 174, 63–78.

[81] Ramos-Ruiz, A., Wilkening, J.V., Field, J.A., Sierra-Alvarez, R., 2017. Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions. J. Hazard Mater. 336, 57–64.

[82] Chowdhury, M.S., Rahman, K.S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S.K., Sopian, K., Amin, N., 2020. An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Rev. 27, 100431.

[83] Neubauer, C., Tesar, M., Karigl, B., Oliva, J., Lampert, C., Wolf, J., 2021. Study on Quality Standards for the Treatment of Waste Electrical and Electronic Equipment (WEEE). European Commission 390.

[84] Latunussa, C.E., Ardente, F., Blengini, G.A., Mancini, L., 2016. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol. Energy Mater. Sol. Cell. 156, 101–111.

[85] Wade, A., 2014. Evolution of First Solar's Module Recycling Technology. PV Life Cycle Management & Recycling, Amsterdam.

[86] Faircloth, C.C., Wagner, K.H., Woodward, K.E., Rakkwamsuk, P., Gheewala, S.H., 2019. The environmental and economic impacts of photovoltaic waste management in Thailand. Resour. Conserv. Recycl. 143, 260–272.

[87] Mahmoudi, S., Huda, N., Behnia, M., 2020. Environmental impacts and economic feasibility of end of life photovoltaic panels in Australia: a comprehensive assessment. J. Clean. Prod. 260, 120996.

[88] Peplow, M., 2022. Solar panels face recycling challenge. ACS Cent. Sci. 8, 299–302.

[89] Mathur, D., Gregory, R., Simmons, T., 2020. End-of-life Management of Solar PV Panels.

[90] Genovese, M., Cigolotti, V., Jannelli, E., Fragiacomo, P., 2023. Current standards and configurations for the permitting and operation of hydrogen refueling stations. Int. J. Hydrogen Energy 48, 19357–19371

[91] Joshi, S., Sharma, M., Barve, A., 2023. Implementation challenges of blockchain technology in closed-loop supply chain: a Waste Electrical and Electronic Equipment (WEEE) management perspective in developing countries. Supply Chain Forum Int. J. 24, 59–80.

[92] Fiandra, V., Sannino, L., Andreozzi, C., 2023. Photovoltaic waste as source of valuable materials: a new recovery mechanical approach. J. Clean. Prod. 385, 135702.

[93] Mahmoudi, S., Huda, N., Behnia, M., 2021. Critical assessment of renewable energy waste generation in OECD countries: decommissioned PV panels. Resour. Conserv. Recycl. 164, 105145.

[94] Li, J., Yan, S., Li, Y., Wang, Z., Tan, Y., Li, J., Xia, M., Li, P., 2023. Recycling Si in waste crystalline silicon photovoltaic panels after mechanical crushing by electrostatic separation. J. Clean. Prod., 137908

[95] Cenci, M.P., Dal Berto, F.C., Camargo, P.S.S., Veit, H.M., 2021. Separation and concentration of valuable and critical materials from wasted LEDs by physical processes. Waste Manag. 120, 136–145.

[96] Vallejos-Michea, C., Barrueto, Y., Jimenez, Y.P., 2022. Life cycle analysis of the ionic liquid leaching process of valuable metals from electronic wastes. J. Clean. Prod. 348, 131357.

[97] Pereira, M.B., de Souza, G.B.M., Espinosa, D.C.R., Pav˜ao, L.V., Alonso, C.G., Cabral, V.F., Cardozo-Filho, L., 2023. Simultaneous recycling of waste solar panels and treatment of persistent organic compounds via supercritical water technology. Environ. Pollut. 335, 122331.

[98] Qu, Y., 2015. Study on Legal Issue of Electronic Waste in EU. North China Power University.

[99] Miao, X., 2015. Research on the Extended Producer Responsibility of Electronic Waste Recycling. Huazhong University of Science & Technology.

[100] T. Doi, I. Tsuda, H. Unagida, A. Murata, K. Sakuta, K. Kurokawa, Experimental study on PV module recycling with organic solvent method, Sol. Energy Mater. Sol. Cells 67 (2001) 397-403.