

Progress in Recycling and Processing of End-of-Life Crystalline Silicon Photovoltaic Modules

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Abstract:

The global photovoltaic sector has rapidly developed and enhanced the application of solar energy to its fullest potential. The sector has matured from large scale industrial applications to residential self-generation and self-consumption. Photovoltaic modules are plagued by significant problems associated with their recycling and disposal when they reach the end of their useful lives. This paper identifies the major components of photovoltaic modules and explains the pros and cons of current recycling methods based on their recycling potential and technological challenges. This concern includes the conventional physical delamination, thermal and chemical delamination methods, and other recently proposed separation and recycling methods such as bioleaching, high-voltage pulse and supercritical carbon dioxide foaming methods. Ultimately, the recycling technologies of the future should enable the recovery of the maximum percentage of components and materials to decrease waste and pollution, and at the same time, minimize the energy consumption of the system. Delamination methods should also be environmentally sound, and this should all be systemically integrated to provide a standard for a low carbon for photovoltaic modules in support of the sustainable development of the photovoltaic industry as a whole.

Keywords: Photovoltaic modules; Crystalline silicon; Recycling.

1. Introduction

The development of photovoltaic technology has been very fast since the turn of the 21st century, with a major contribution towards the global energy tran-

sition. The world photovoltaic (PV) sector has had massive potential and an increasing number of solar technology firms have sprung up across the globe. Photovoltaic power generation has been used in more and more applications and factories, shopping malls,

schools, hospitals and even households are now using this technology. Saudi Arabia, despite being a leading oil producing country, is also promoting the use of solar power technology in its North to solve any possible air pollution and greenhouse gas emission in the environment [1].

The crystalline silicon PV modules, with the most mature technology, have continued to take over the market in the current photovoltaic industry, owing to their simple installation and a relatively low cost. Crystalline silicon PV modules have a potential service life of 25-30 years under favorable conditions. Nevertheless, older generation modules had a high concentration of technical immaturity and use of old materials and manufacturing processes, which led to high level of end-of-life crystalline silicon PV modules that are in dire need of recycling and disposal. According to the trends, the amount of waste solar modules is expected to reach more than 80 million metric tons in 2050 [2]. The current recycling and treatment methods have a number of challenges, including low recovery rates, high impact on the environment, relatively expensive, and complicated processes.

This paper provides a detailed description of the composition of crystalline silicon photovoltaic modules, analyzes existing recycling methods, and summarizes emerging recycling approaches proposed in recent years—such as bioleaching, high-voltage pulse technology, and supercritical carbon dioxide foaming technology. To provide guidance for the sustainable development of the photovoltaic industry in the future.

2. Composition of Crystalline Silicon Photovoltaic Modules

As shown in Fig. 1, current crystalline silicon photovoltaic modules are primarily composed of crystalline silicon solar cells, front glass, encapsulant, backsheet, aluminum frame, junction box, interconnector and busbar [3].

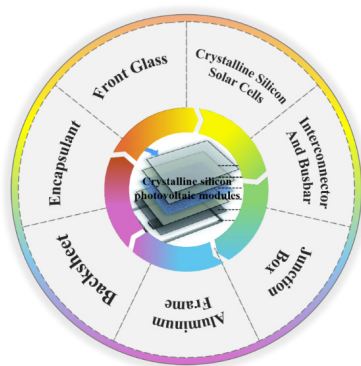


Fig. 1 Composition of Crystalline Silicon Photovoltaic Modules

2.1 Front Glass and Encapsulant

The outermost layer of the module is front glass which is commonly made of tempered or semi-tempered glass. Below front glass is the encapsulant film that encloses the solar cells. EVA and EPE are the most widely used encapsulant types. The solar cells remain safe from external disruptions thanks to this film. Moreover, the module's ability to transmit light improves, further enhancing the solar cells' efficiency in generating power.

2.2 Crystalline Silicon Solar Cells

Crystalline silicon solar cells are the most critical component of the entire module; the technology is based on silicon wafers and generates electricity through the separation of photo-generated charge carriers at the PN junction. When sunlight strikes the solar cell, photons with sufficient energy excite electrons within the semiconductor, creating electron-hole pairs. Under the influence of an electric field, the electrons are driven toward the N-region, while the holes are driven toward the P-region. Currently, aluminum back surface field (Al-BSF) solar cells and passivated emitter and rear cells (PERC) represent the most widely adopted p-type cells in the photovoltaic industry [4]. In the future, there will be a gradual transition to high-efficiency N-type cells, such as those based on TOPCon technology, which offers low degradation, a low temperature coefficient, and a high bifaciality ratio.

2.3 Interconnector and Busbar

The interconnectors and busbars used to connect solar cells in series or in parallel are made of tin-based solder applied to the surface of copper strips. Interconnectors are used to connect individual solar cells within a module, conducting and collecting the generated current. Busbars connect strings of cells and direct the collected current to the junction box. Controlling the temperature during welding is particularly important; insufficient temperature can result in cold joints, while excessive temperature can cause overheating. Both of these issues can affect the component's operating power and may even damage the electrodes.

2.4 Backsheet, Aluminum Frame and Junction Box

Backsheet is an encapsulation material used in crystalline silicon solar modules and is a critical component of photovoltaic power generation systems. Located on the back of the module, it provides insulation and protection, weather resistance and moisture barrier properties, and structural support. Additionally, it blocks moisture vapor and resists chemical corrosion. The outermost layer con-

sists of an aluminum alloy frame, which provides sealing protection, secure mounting, and mechanical support. It has high recycling value and can be directly remelted and recycled. Another essential component is the junction box, which connects the electricity generated by the modules to the external circuit, ensuring the circuit operates normally. In the event of a short circuit, it automatically disconnects the circuit to prevent serious damage to the module.

3. Delamination Methods

The layered composite structure described previously focuses the majority of the current delamination methods to reduce the binding ability of the EVA encapsulant layer leading to the separation of the glass, solar cells, and back sheet. Among the conventional delamination methods, there are as follows: Physical delamination, Thermal delamination, and Chemical delamination. Their recovery rate, cost, and eco-friendliness are compared in Table 1.

	Recovery Rate	Cost	Environmental Impact
Physical Delamination	Moderate recovery rate, Contains many impurities	Low equipment costs, low barrier to entry, and easy to scale	Minimal environmental impact, but produces noise and dust
Thermal Delamination	Relatively high recovery rate and good material integrity	Moderate cost, high energy consumption, temperature control equipment is required	Moderate environmental impact; produces toxic exhaust gases
Chemical Delamination	High recovery rate and precise delamination	High costs, requires corrosion-resistant equipment, and reagents are difficult to recycle	Significant environmental impact; generates organic waste liquid

Table 1. Analytical Comparison of Different Delamination Methods

3.1 Physical Delamination

Physical delamination refers to the direct mechanical processing of waste photovoltaic modules, including methods such as shearing, hammer milling, and crushing [5]. Equipment like hammer mills and shear presses can be used to directly separate and extract aluminum and silicon components.

First, the pretreatment begins with the removal of the wiring components and aluminum frames, and the solar panel is cut into uniform pieces using shearing equipment. A crushing machine performs the stepwise grinding of the parts. Gradation is performed using multiple specifications of vibrating screens: large glass pieces are separated and purified with a fine screen, while the remaining mixed material is subjected to secondary grinding. To separate the different materials along with the collected dust and impurities, multiple methods such as mechanical screening are performed to separate the plastics and various kinds of metals along with silicon and copper. With the combination of multiple stage crushing and secondary screening, the process of the physical separation of different materials is completed.

This method is simple and fast. It operates at a dismantling rate of 60 modules per hour, achieving aluminum and glass purity levels of 99% [6].

3.2 Thermal Delamination

The thermal delamination method exploits the heat-sensitive properties of the EVA encapsulant in photovoltaic

modules. By heating the module under oxygen-free, temperature-controlled conditions, the EVA softens, melts, or undergoes thermal degradation, causing it to fail. This breaks the bond between the glass, solar cells, and back sheet, thereby separating the various structural layers. First, the aluminum frames and junction boxes are removed from the modules, and surface contaminants are cleaned off to complete the pretreatment. The modules are then subjected to temperature-controlled treatment using heating equipment. This can be done either by heating the modules at medium to low temperatures to soften the EVA film, or by subjecting them to high-temperature pyrolysis in an oxygen-free environment to decompose the EVA and disrupt the adhesive bonds. Following this, the modules undergo a cooling process, after which the individual components are separated and disassembled. At temperatures above 300°C, EVA's side chains break down, producing acetic acid and a series of hydrocarbon compounds, with complete degradation occurring above 500°C [7]. After mechanical removal of the backsheet, processing time is reduced by approximately 45% under different temperature conditions [8].

Park et al. suggested in 2016 to add a small load in thermal delamination so breakage is less likely due to the release of gases between the load and the wafer [9]. In the case of nitride protection, oxidation caused by pyrolysis does not occur and the activity of the electrodes is maintained. Box-type pyrolysis furnaces and rotary kilns are the common equipment for pyrolysis. So far, the technology of thermal delamination has gained acceptance all

around the world. However, the environmental damage caused by it is still considerable. The photovoltaic industry has the imperative of seeking recycling technologies that contribute to the development of the whole industry in an eco-friendly way.

3.3 Chemical Delamination

Chemical delamination employs particular organic, or green, solvents to dissolve and swell the cross-linked EVA encapsulation film in the solar module when applying heat. This weakens the adhesion of the encapsulation film to the cell and even to the glass. This makes the layers able to be separated more easily. To begin, a low-melting-point toluene-like solvent is prepared. The solvent is set and maintained at a temperature in the range of closed to room temperature, and stirring is performed. Circuit-waste photovoltaic modules are added in the desired ratio. The solvent is used to destroy the inter-layer bond structure for the purpose of delamination. Then, the back sheet is manually peeled off and air-dried at room temperature. Afterwards, the solid is divided and the separated materials are subjected to high-temperature oxidation to complete the separation and recovery.

In 2001, Doi et al. discovered that soaking in trichloroethylene at 80°C for 10 days enabled effective delamination [10]. Prasad et al. experimentally determined that a 1:7.44 ratio of photovoltaic modules to trichloroethylene solvent—where the module weight constitutes 13.44% of the solvent—serves as the benchmark for achieving large-scale recycling via organic solvent methods [11]. In 2024, Yang, Bo-Tai et al. demonstrated that HDES ([methyl] diethyl ester) induces EVA swelling and accelerates its dissolution through hydroxyl-mediated side-chain acetate group substitution reactions. Complete separation of glass and backsheet is achievable after two hours of treatment at 80°C [12]. The primary challenges with chemical delamination methods include the difficulty in controlling reagent toxicity and cost, as well as significant variations in effectiveness across different environmental conditions. At present, chemical stratification still requires further development before it can be widely implemented.

4. Emerging Recycling Technologies

In recent years, research into emerging recycling methods has been advancing worldwide, primarily because existing methods have failed to meet industry expectations. Below are three recycling methods that have contributed to the advancement of the industry.

4.1 Bioleaching

Difficult to obtain precious metal recovery. Pang et al. 2025 Bioleaching methods of recovery value metals such as silver and aluminum from end of life crystalline silicon photovoltaic cells [13]. *Pseudomonas fluorescens* along with other types of microorganisms, accomplish recovery as a result of metabolic activities. This bacterial strain excretes an enzyme named cyanide as a product of the metabolism of glycine. The harmful effect of cyanide on an ecosystem is compensated by the fact that the cyanide molecules attach to the metal surface by more than one adsorption site and form a soluble complex with the silver and aluminum, releasing them to be leached. They are also capable of self-purification. The result is a process that is safe and friendly to the environment and causes little to no pollution. During the experiments, the bacterial strains are cultured in a sterile LB medium and two types of extraction were performed, a one-step extraction and a two-step extraction. The procedure was performed along with constant temperature and agitation. The above techniques were performed to isolate cultures for 7-days. The two-step method for extraction provides a more effective extraction result as it allows for the accumulation of cyanide at a higher concentration due to the lack of metal ion inhibition on bacterial growth. This is due to the fact that metal ions are inhibitory to the growth of the respective bacterial colonies.

4.2 High-Voltage Pulse Technology

Akimoto et al. used high-voltage pulse technology to extract various materials, such as glass, silver, and copper, in 2018 [14]. This is a cheap recovery technique that has a commercial potential. The technology of high-voltage pulse uses two processes to obtain selective material separation: electro-fragmentation and electro-hydrodynamic fragmentation. It uses a high-voltage current to cause electrical breakdown in solid materials, resulting in directional damage at the interfaces of different materials. At the same time, it employs the shock waves, micro-explosions and localized thermal stresses produced by electrical discharges in an aqueous solution to specifically attack the interlayer structures of the materials. The process separates the electrical properties, density, and strength of the different components in order to have interlayer separation and selective fragmentation, thus, minimizing the unnecessary loss of materials and secondary pollution.

In the real-life processing process, waste PV panels are pretreated. This is then succeeded by high-voltage pulse fragmentation that divides the panels into glass and backsheet layers and in the best voltage and pulse conditions. Both layers are then crushed again and the encapsulant,

electrode metals and substrate are well separated. The dried products are screened through various steps to classify the particle size. Lastly, with the heavy-medium separation technology, the glass is further purified and the metals including silicon powder, silver, and copper are separated according to the difference in densities, thus, effectively accomplishing the selective separation and extraction of the various components of the photovoltaic panels.

4.3 Supercritical Carbon Dioxide Foaming Technology

In 2022, Briand et al. explored the supercritical carbon dioxide foaming technology [15]. This is done by the use of supercritical carbon dioxide as a physical foaming agent. The supercritical carbon dioxide is fully penetrated and adsorbed in the photovoltaic modules under particular conditions of high pressure and temperature, which changes the structure of the polymer matrix made of EVA encapsulation resin, under conditions of high pressure and temperature. The CO₂ dissolved in the EVA is then precipitated out in a fast rate due to low pressure and thus foaming is driven off and this causes a volumetric expansion, longitudinal deformation and bending deformation of the EVA. Based on the mechanical shear stress and tensile forces produced by the foaming process, the interfacial adhesive strengths linking the glass, solar cells, back sheet and EVA are broken, thus resulting in non-destructive delamination and separation of the functional layers.

The detailed process of implementing this technology is as follows: First, the photovoltaic modules are put into a high-pressure closed system, and a high amount of carbon dioxide is injected to form a stable supercritical environment, and the temperature and the pressure are fixed. The system is subsequently held at this temperature and pressure over an extended time to aid complete penetration and adsorption of the carbon dioxide. The pressure is then quickly decreased by fine-tuning the valves to foam the EVA and allow the interlayer bonds to be compromised; and lastly, the system is allowed to stabilize at atmospheric pressure, and the photovoltaic modules are peeled off in successive layers. The entire process generates no liquid or gaseous by-products that are harmful and leaves no damage to the high-value recyclable materials including glass, silicon and silver. The initial pressure, pressure-reduction rate and temperature can be manipulated as well enabling optimization of the foaming effect and interfacial delamination efficiency. It is an appropriate method to recover the resources of waste photovoltaic panels and multi-layer polymer composite components.

5. Conclusion

Given the current overall trends in the photovoltaic industry, the market is still some way from reaching full saturation. In other words, the volume of photovoltaic modules in use has not yet peaked. This means that significant recycling pressures will arise in the future. At present, traditional recycling methods are no longer fully suited to the current situation, whether in terms of recycling efficiency or cost control, and emerging technologies are still in their early stages of development.

Today, environmental issues are receiving increasing attention, and the demands on recycling technology are also growing. Not only must recycling be effective, but it must also minimize environmental pollution, with particular attention paid to the treatment of exhaust gases and the discharge of wastewater. Over time, the volume of waste components is set to surge, making the development of recycling technology a matter of urgency.

Future efforts should focus on developing new recycling technologies while improving existing ones. There is room for improvement in both the selection of reagents and the optimization of equipment. Advances in recycling technology will drive the healthy and sustainable development of the entire photovoltaic industry and effectively promote ecological balance.

Finally, there are still some deficiencies. For instance, practical research on certain traditional methods is insufficient, and there is no solid guarantee for the prospects of emerging technologies. In addition, some promising technologies may not have been mentioned. Therefore, further long-term investigation and discussion are still required.

References

- [1] Ghathani, Ahmed, Laith Hadidi, and Awsan Mohammed. "Techno-economic assessment of concentrated solar power generation in Saudi Arabia." *Renewable Energy* 220 (2024): 119623.
- [2] Li, Caixia, Feng Dong, and Victor Nian. "Global photovoltaic waste under ratcheting climate ambition: Spatio-temporal distribution and future pathways." *Resources, Conservation and Recycling* 221 (2025): 108388.
- [3] Sanathi, Radhesh, Sourish Banerjee, and Shantanu Bhowmik. "A technical review of crystalline silicon photovoltaic module recycling." *Solar Energy* 281 (2024): 112869.
- [4] Sun, Zhaoqing, et al. "Toward efficiency limits of crystalline silicon solar cells: recent progress in high-efficiency silicon heterojunction solar cells." *Advanced Energy Materials* 12.23 (2022): 2200015.
- [5] Del Pero, Francesco, et al. "Innovative device for mechanical treatment of End-of-Life photovoltaic panels: Technical and

- environmental analysis." *Waste Management* 95 (2019): 535-548.
- [6] Xie, Wenhao, et al. "Recycling of crystalline silicon photovoltaic modules in China: Policies, technologies and prospects." *Sustainable Production and Consumption* (2026).
- [7] Xu, Wenjun, et al. "Progress and environmental impact assessment of recycling end-of-life crystalline silicon photovoltaic modules: A Comprehensive Review." *Journal of Environmental Chemical Engineering* (2026): 121870.
- [8] Dobra, Tudor, Daniel Vollprecht, and Roland Pomberger. "Thermal delamination of end-of-life crystalline silicon photovoltaic modules." *Waste management & research* 40.1 (2022): 96-103.
- [9] Park, Jongsung, et al. "An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: from separation to cell fabrication." *green chemistry* 18.6 (2016): 1706-1714.
- [10] Doi, Takuya, et al. "Experimental study on PV module recycling with organic solvent method." *Solar energy materials and solar cells* 67.1-4 (2001): 397-403.
- [11] Prasad, D. S., et al. "Process optimization studies of essential parameters in the organic solvent method for the recycling of waste crystalline silicon photovoltaic modules." *Solar Energy Materials and Solar Cells* 245 (2022): 111850.
- [12] Yang, Bo-Tai, Yen-Hui Huang, and Chun-Chi Chen. "Hydrophobic deep eutectic solvents as novel media for the recycling of waste photovoltaic modules." *Chemical Engineering Journal* 498 (2024): 155011.
- [13] Pang, Chenxi, et al. "The study of adsorption mechanisms and kinetics of recovering Ag and Al on the bioleaching of end-of-life crystalline silicon photovoltaic cells." *Separation and Purification Technology* 354 (2025): 128999.
- [14] Akimoto, Yuta, Atsushi Iizuka, and Etsuro Shibata. "High-voltage pulse crushing and physical separation of polycrystalline silicon photovoltaic panels." *Minerals Engineering* 125 (2018): 1-9.
- [15] Briand, Axel, et al. "Deformation-induced delamination of photovoltaic modules by foaming ethylene-vinyl acetate with supercritical CO₂." *Journal of CO₂ Utilization* 59 (2022): 101933.