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Sustainable Solutions for the Disposal of End-of-Life Solar Panels

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ABSTRACT

Solar PV recycling methods currently in use are elaborated in this paper. This paper explains in detail the recycling methods of crystalline, CdTe, and CIGS solar panels which are being currently used in the industries. As there are a lot of recycling methods this paper finds you the best recycling method with a high recovery rate of recycled products up to 99%. The use of plant-based materials to create solar PV modules is also suggested as one of the main innovations needed to fight used solar PV disposal. Because of this, there is still a great deal of effort to be made to develop the subject of solar PV recycling by material scientists and other related professionals.

Keywords: *Solar, Photovoltaic (PV), Recycle, Panel, Module, Industry*

1. INTRODUCTION

We all commonly know how do solar panels work. It converts light energy into electrical energy. The average break-even point for solar panel energy savings occurs six to 10 years after installation. The industry standard for solar panels' lifespan is 25 to 30 years and now what can we do the solar panels after its life span is over [1]. It causes serious environmental issues if not disposed properly. More than 1.2 terawatts of solar power have already been deployed globally. Solar panels are currently being distributed at a rate of more than 400 gigawatts per year, and the rate is expected to increase to a whopping 3 TW per year by 2030, according to a literature analysis by researchers at the National Renewable Energy Laboratory (NREL). Recycling solar panels is critical for ensuring the sustainability of the solar energy industry. Not only does recycling help reduce the environmental impact of decommissioned panels, but it also allows for the recovery of valuable materials such as silicon, silver [2] cadmium, tellurium. Currently, solar panel recycling involves several processes, including mechanical, thermal, and chemical methods, each with varying degrees of efficiency in material recovery. However, the development of effective and scalable recycling technologies is still in its infancy and faces several technical, economic, and regulatory and purification techniques. Furthermore, this paper will explore the various recycling methods recovery used currently in the industries that has highest recovery rates and less affecting the nature.

2. TYPES OF SOLAR PANELS

This paper talks about the recycling types of solar panels that is being manufactured at the highest rates worldwide, explains the three types of solar panels.

i. Crystalline solar panels
ii. CdTe solar panels
iii. CIGS solar panels

Crystalline silicon (c-Si) solar panels are the most widely used solar technology, accounting for approximately 90% of the global PV market. These panels are made from silicon wafers and are divided into two types: monocrystalline (mono-Si) and polycrystalline (poly-Si). Monocrystalline panels, known for their high efficiency, are produced using a single crystal structure, while polycrystalline panels are composed of multiple silicon crystals. The advantage of c-Si panels lies in their efficiency, reliability, and long lifespan, although they require significant energy input during manufacturing [3].

Cadmium telluride (CdTe) solar panels are another type of thin-film technology. CdTe panels are known for their low-cost manufacturing and relatively low material requirements compared to crystalline silicon. They are less energy-intensive to produce and perform well in high temperatures and low-light conditions [4]. However, concerns about the toxicity of cadmium and the availability of tellurium present challenges for the widespread adoption of this technology.

Copper indium gallium selenide (CIGS) solar panels are part of the thin-film technology family. They consist of a semiconductor layer made of copper, indium, gallium, and selenium. CIGS panels offer flexibility, lightweight design, and better performance in low-light conditions [5]. They are more efficient than other thin-film technologies, such as amorphous silicon (a-Si), and can achieve comparable efficiencies to crystalline silicon, although they are generally more expensive to produce.

3. EXISTING METHODS

Mechanical Recycling: Separates glass, silicon, and metals via shredding, crushing, and sieving Recovers around 95% of glass and 85% of aluminum. Commonly used for crystalline silicon (c-Si) modules. These methods are being performed at the industries of Veolia in France and PV Cycle in Europe. Ineffective for thin-film panels and lower recovery rates for rare metals like silver.

Thermal Processing: High-temperature treatment to remove polymer layers and recover silicon. Up to 95% recovery for silicon, but lower rates for metals. Used for crystalline silicon panels. This recovery process is being done in 9-Tech in Italy for silicon recovery.

Chemical Treatment: Uses solvents or acids to dissolve specific metals. Around 90% for silver and 95% for silicon. Widely used for CdTe and CIGS panels, especially by First Solar. Generates hazardous waste and requires careful handling of chemicals.

4. RESULTS AND DISCUSSION

The recycling process of crystalline silicon (c-Si) solar panels involves a series of systematic steps to recover valuable materials efficiently. Initially, manual separation is carried out to remove components like the aluminum frame, junction box, and tempered glass. Mechanical separation follows, using rollers to recover copper and glass by isolating the copper grids in fig After the manual separation, the remaining layers of silicon and polymers are fed into a combustion furnace, where high temperatures vaporize the polymers, leaving the silicon behind for further processing. The next step involves sieving, in which broken pieces of glass and silicon are sorted based on size and thickness using multiple sieves, allowing for effective separation of the silicon from glass [6]. Once separated, silver is extracted from the silicon using two methods: an organic acid bath (typically nitric and hydrochloric acids) dissolves the silver into a soluble compound, and ultrasound treatment is employed to dislodge silver particles from the silicon surface using cavitation bubbles.

Fig. 1. Copper grids separated by mechanical roller

Following silver separation, the solution undergoes centrifugation to further isolate silver particles by spinning the solution at high speeds, causing the dense silver to settle at the bottom. Filtration is then used with fine-pore filters to physically remove any remaining silver particles from the liquid. This process results in high recovery rates, with 95% of the silicon, 90% of the silver, and 99% of copper, aluminum, glass, and photovoltaic (PV) modules being successfully recovered. This approach maximizes the recycling efficiency of crystalline silicon-based solar panels. The above recycling process of crystalline solar panels are being processed inside a shipping container in an industrial area of Venice, the Italian startup 9-Tech without toxic chemicals.

The below recycling process of CdTe and CIGS completely talks about the process of first solar company [7,8]. The recycling process of cadmium telluride (CdTe) solar panels focuses on efficiently recovering glass and other valuable materials through a multi-stage procedure. It begins with shredding and crushing the collected glass to reduce particle size, with the majority of the material being reduced to sizes below 40mm, and most around 5mm. Following this, the crushed glass undergoes filtration to remove fine particles and minimize contamination of remaining elements. Next, a refining drum reactor is employed, where hydrogen peroxide and sulfuric acid [7] break down oxides and dissolve contaminants such as tin (SnO_2), preparing the glass for further purification. In the leaching stage, chemical solutions are used to remove unwanted elements like lead and zinc, effectively dissolving these non-glass components and leaving behind purified glass.

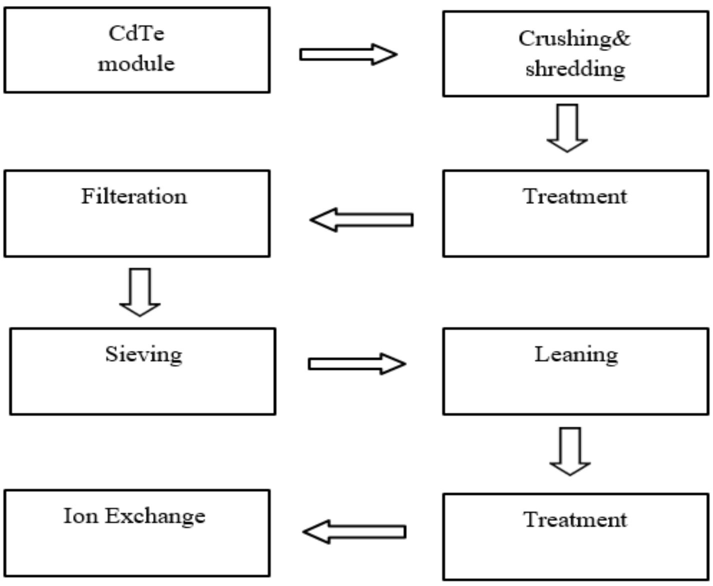

Fig. 2. CdTe recycling

The final stage involves electrode treatment using a solution of sodium hydroxide and sodium carbonate [8]. This process precipitates titanium dioxide, which is resistant to the solution, and an ion exchange procedure removes calcium and other elements. The process achieves a high recovery rate, with 99% of materials effectively separated and recovered. This systematic approach ensures the efficient recycling of CdTe solar panels, contributing to the sustainable recovery of valuable resources.
The recycling process for Copper Indium Gallium Selenide (CIGS) solar panels involves several stages aimed at efficiently recovering both semiconductor and glass materials [9].

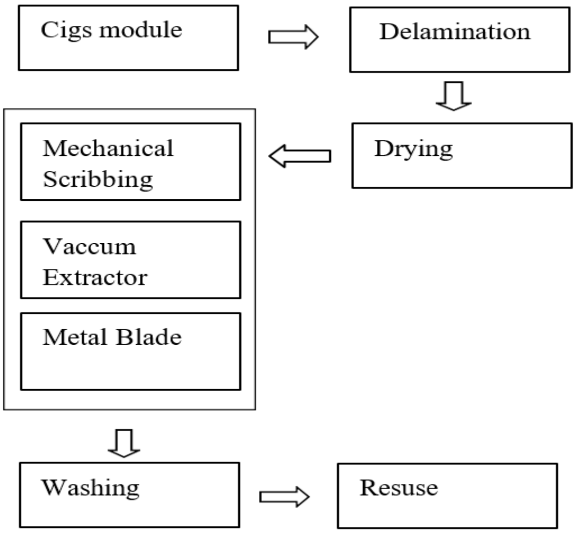

Fig. 3. GIGS recycling

The process begins with shredding and crushing the modules and scrap into small pieces, facilitating the dissolution and separation of glass and semiconductor components. Next, the shredded material is ground further in a hammer mill during the pre-film removal stage, reducing particle size for improved separation. Tumbling in a rotating drum follows, which helps remove the glass layer from the remaining material. The solid-liquid separation stage involves filtering the solid semiconductor components from the liquids. The liquids, now containing dissolved materials, move to the leaching stage, where chemicals are added to dissolve and recover the desired semiconductor materials [10]. In the subsequent glass separation and extraction stage, acids and bases are introduced to separate the glass from the semiconductor components. The decanting stage then removes excess liquid, leaving behind the solid semiconductor material. In the final filtration stage, this material is collected as a cake containing silicon, which is now ready for further processing. The process achieves approximately 98% recovery of semiconductor material and 90% recovery of glass, making the recycled materials suitable for reuse in manufacturing new CIGS solar cells or other electronic devices.

5. RECOMMENDATIONS FOR FUTURE RESEARCH

Extended Producer Responsibility (EPR) programs place the responsibility for waste management on the manufacturers of solar panels. Under EPR schemes, manufacturers are required to take back and properly dispose of or recycle their products once they reach the end of their life cycle. EPR programs create incentives for companies to design panels with recycling in mind, encouraging innovations that make panels easier to dismantle and recycle.

The technologies in solar PV recycling of CdTe and CIGS are still underdeveloped, and the number of recovered materials is still low compared to those left unrecycled or unused. Therefore, there is a need for the development of materials that can be fully recycled. Also, these materials can be environment-friendly to reduce the effects they add regarding pollution. Many solar panels still retain some level of efficiency after their initial life cycle. These panels can be repurposed for second-life applications, such as in lower-demand systems like solar- powered streetlights or backup power supplies. Repurposing extends the functional life of the panels and delays their entry into the waste stream.

6. EMERGING AND DEVELOPING METHODS

These methods are experimental or in early-stage industrial application and show promise for higher efficiency or eco-friendliness.

Laser Ablation: Uses lasers to selectively remove layers without physical contact. Precise separation, potentially up to 95% recovery for high-value metals. Suitable for high- precision separation of metals and glass. Currently expensive and not widely available due to equipment costs.

Electrochemical Recycling: Electrolysis to selectively dissolve and recover metals. High purity, especially for rare metals like indium and gallium. Particularly useful for thin- film panels such as CIGS. High equipment costs and time- intensive processing.

Pyrolysis: Decomposes polymers in an oxygen-free environment to extract silicon and metals. Around 85-90% recovery for silicon and metals. Research-based, currently in limited industrial application. High energy requirement for heating, with limited scalability.

7. CONCLUSION

The suggested recycling process of crystalline silicon solar panels in being practiced inside a shipping container in an industrial area of Venice, the Italian startup 9-Tech is taking a crack at a looming global problem. The startup 9-Tech operates its pilot plant out of a modified shipping container housed at the Green Propulsion Laboratory in the industrial port of Marghera in Venice. The startup's recycling process is more expensive than existing methods that recover only aluminium and glass. But the extraction of high-purity silicon, silver, and copper should offset the extra cost says their reports. Plus, it's more efficient than mining for virgin elements. You can extract about 500 grams of silver from a tonne of solar panels, but only 165 grams of silver from a tonne of ore. "A photovoltaic panel at the end of its life still has a lot to give," says their team. "It can be considered a small mine of precious elements.

The suggested recycling process for CIGS and CDTE is being practiced at First Solar Company. Recycles thin- film modules such as CIGS. Thus far, the majority of material recycled is manufacturing scrap, along with a small quantity of modules from warranty returns. During the process, PV waste is shredded and crushed; afterward, the semiconductor film is removed via acid and hydrogen peroxide and glass materials are separated from the liquid. The company reports that 90% of glass and 95% of semiconductor can be recovered. Based on the high recovery rate of the First Solar recycling process, the First Solar model is an attractive model for this project. For that reason, the remainder of this project will expand on further analysis and application of the First Solar recycling process. This process was originally based on the recycling of Cadmium Telluride (CdTe) modules, but will now be applied to the recycling of CIGS modules.

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