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Recycling and Reuse Strategies for End-of-Life Solar Panels

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***Abstract-** This paper reviews about investigating sustainable recycling and reuse strategies for End-of-Life solar panels in the Indian context. The rapid growth in solar photovoltaic (PV) capacity is expected to generate substantial end-of-life panel waste in the coming years. Combining literature review, material flow analysis and lifecycle assessment we can evaluate the effectiveness of global and Indian recycling practices. Here, we have conducted case studies and comparison between technical and economical methods of mechanical, thermal and chemical recovery process. Policy gap between India's e-waste and renewable energy regulation are analyzed which directs us to focus on extended producer responsibility, public private partnership and circular economic models. This paper aims to provide actionable insight for policymakers, manufacturers, and recyclers to ensure that India's solar energy transition is both green and sustainable.*

***Keywords-**Literature review, material flow analysis, lifecycle assessment, extended producer responsibility, public private partnership and circular economic models.*

I. INTRODUCTION

Solar energy is the renewable source of energy meeting the increasing energy demand worldwide. It is abundant, clean and environmental friendly source of electricity generation. It requires low maintenance and is useful in remote areas without grid access. Solar energy is the radiant light and heat from the sun that is captured and converted using various technologies such as:

- Photovoltaic (PV) cells –Use solar panels to convert sunlight directly into electricity
- Solar thermal systems – Use sunlight to heat water or air.
- Concentrated solar power – Use mirrors/ lenses to focus sunlight to produce high temperature heat to generate steam, which is then used to generate electricity with the help of turbines.

With increased research it is becoming cheaper and more efficient thus leading to increase in solar panel installation worldwide. Considering an average lifetime of solar panels of about 25 years, and increasing installation capacity will lead to considerable percentage of waste generation if we are not ready with appropriate waste management solutions. To anticipate the PV waste generated in upcoming years, some researchers and companies related to solar energy are focusing on developing efficient PV recycling and management strategies.

To recover high purity PV elements from end-of-life solar panels, especially silicon based solar cells, a combination of mechanical, thermal and chemical processes is used. The goal is to extract and purify valuable materials like:

- Silicon wafers (the core photovoltaic element)
- Silver, aluminium, glass and sometimes indium or tellurium (depending on panel type)

This paper is divided into four sections. The first section focuses on different policies surrounding PV recycling in different countries of the world. The second section reviews existing recycling strategies of different solar panels. The third section describes the different steps performed in recycling chain. Lastly, the fourth section discusses the economic and environmental analysis of the recycled elements and recommends policies for effective PV panel recycling. This PV panel recycling can reduce waste and carbon dioxide emissions. This review will help companies and researchers who are active in solar PV recycling.

'Recycling and Reuse Strategies for End-of-Life Solar Panels' means to use solar panels after they are no longer efficient or useful. This includes finding methods to either reuse the panels or their components in new applications or breaking them down to smaller sub parts to recover valuable materials for use in new products, rather than discarding them completely.

II. SOLAR PV INSTALLATION

It is considered as an important source of power generation to meet the increasing electricity demand across the world. It is estimated that solar energy will become one of the most utilized renewable energy resources and will make up a greater percentage in the world's energy mix in the future. As a result there is an increase in solar PV installation. The global PV installed capacity forecast for the year 2025 is 655 GW and is expected to attain about 4500 GW by 2050. For the year 2024 the PV installed capacity was approximately 597 GW. It is assumed that a 10% year-over-year increase in solar PV installation occurs every year. Amongst the various countries which contribute to this increase, China continues to dominate the market with current status as 1.3 TW installed by mid-2025 (more than half of global capacity). At second position European Union stands with a current capacity of 260-300 GW. At third position it is India with current capacity of 175-200 GW. At fourth position it is Japan with current capacity of 85 GW. And then some other countries like Southeast Asia, Latin America, Middle East and Africa all together has current capacity of about 60-80 GW.

PV installation capacity is estimated to increase continuously in the next few years. However, this rise will lead to socio-environmental challenge as these panels will be a source of hazardous waste due to some heavy metals such as lead, cadmium, arsenic used in the production of these panels. Solar PV panels are estimated to last on an average for 25 years, after which they could be considered degraded and may need to be discarded. Considering the notable increase in solar PV installations and their lifetime, solar PV waste is forecasted to be between 4 % to 14 % of its entire installation by 2030, and about 80 % by 2050 (evaluated as about 78 million tons of waste).

According to IRENA i.e., International Renewable Energy Agency, the PV installation capacities by 2050 for countries like China, India, United States, Japan, and Germany are forecasted to be about 1,731GW, 600GW, 600GW, 350 GW, and 110 GW respectively. These countries will become the largest producers of PV waste by 2050.

With respect to the quantity of PV waste generated by 2050, IRENA has defined two different scenarios.

- The early lost scenario in which solar panels which are damaged before reaching their end-of-life are included in the waste capacity
- The regular loss scenario in which only panels which have attended their end of life are considered.

According to IRENA, the PV waste volume (in million tons) obtained from these countries for the regular loss scenario are estimated as 13.5 million (China), 7.5 million (USA), 6.5 million (Japan), 4.5 million (India) and 4.4 million (Germany).
The waste generated for the early loss scenario will be greater than that of the regular scenarios, and are estimated to be (in million tons) 20 (China), 10 (USA), 7.5 (Japan), 7.5 (India), and 4.3 million (Germany). These will require appropriate PV waste management strategies.

For the past few years, land filling was a method of disposing of solar PV waste. However, due to its drawback like land destruction, pollution, hazards from PV metals and the increased scarcity of semiconductor materials for manufacturing, an environmentally friendly option such as PV recycling is being researched and tested. Therefore, appropriate solar PV recycling technologies and waste management are essential.

This paper summarizes the various solar PV recycling strategies for different types of solar PV panels technologies, and further presents the economic, social, and financial analysis, with recommended policies of solar panel recycling. This review will be useful to inform the decisions of solar manufacturers, recyclers and researchers interested in solar PV recycling.

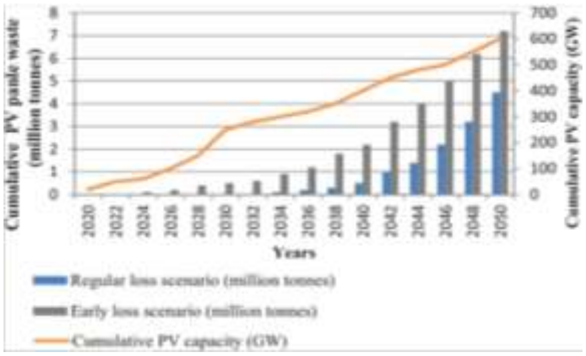

Fig.1 The approximate collective waste from solar PV module worldwide (Tonnes) 2016–2050

III. RECYCLING

Recycling is the process in which we dismantle solar panels and separate its various components like glass, silicon cells, aluminum frame, wiring etc. to recover valuable materials.

Methods used are:

- Thermal Recycling: In this method panels are heated to separate materials. But there is a drawback to this method i.e., it can produce emission.
- Mechanical Recycling: In this method panels are shredded and then components are separated using physical process.
- Chemical Recycling: In this method chemicals are used to dissolve and separate materials.

Benefits:

- It reduces the need for mining new material.
- It prevents hazardous material from interacting with landfills.
- It reduces energy consumption required for manufacturing new products.
- It creates circular economy for valuable resources.

Recycling process:

The solar panels known as silicon-based solar are the most common and dominant type of solar panels in power generation. Out of the top-ten PV manufacturers in 2015, only 1 of them manufactured thin film solar panels. In solar panel market, 73.3% of solar panels are silicon based solar panels. As a result, most PV recycling companies or strategies have been focusing on Silicon-based (Si-based) solar panels. Solar panel waste can be generated during any of its production phases, including panel manufacturing, transportation, installation and during its service life. The different manufacturing processes of different solar PV panels technologies results in different strategies of recycling. In the raw material stage of a Si-based photovoltaic module, a possible waste is the ingot powder generated during the slicing process of ingots. The basic raw material used in the manufacturing of Si-based modules is Solar grade Silicon (SoG-Si). During the PV manufacturing process, SoG-Si is melted and solidified to produce ingots, which are then sliced using different technologies such as a diamond wire sawing or a slurry wire sawing, in which a mixture of silicon carbide and glycol is used as an abrasive that erodes rather than cuts the ingots. In the ingot slicing process, over 32 % of the ingot becomes powder or sludge called silicon kerf. This kerf, considered as waste contains ultra-pure Si which can be recovered to produce SoG-Si ingots. For the second generation of solar panels, Copper Indium Gallium selenide (CIGS) is one of the semiconductor materials used to produce the absorber layers. During the production of the absorber layers, over 60 % of the semiconductor metal is not deposited on the substrate and is considered waste. Given the economic benefits and scarce nature of Selenide, Indium and Gallium, (CIGS) material recycling can be beneficial. The next stage of waste generation in a PV module life cycle is PV module manufacturing. In this stage, the wafers are used to manufacture Si-based solar cells. The waste generated through this process includes glass, plastic waste from back sheets, other wastes frames, junction boxes, copper wires, and cells with manufacturing defects such as micro cracks. Micro cracks defects are also common in thin film solar modules during manufacturing process. The waste generated during the usage phase of the PV could be the module itself as waste, or some components of the module such as junction boxes. As mentioned earlier, modules can also be damaged during transportation/shipping. Some of the module failures that can occur during transportation or usage include electrical failures such as junction boxes, grounding, fuses, diode failures, and cablings; environmental

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related failures caused by snow, wind, degradation due to temperature variations, corrosions. Other failures include cracking of modules, cell interconnection breakages, loose frames, degradation of the anti-reflection coating, the discoloration of the encapsulant (Ethyl Vinyl Acetate (EVA)), Light Induced Degradation (LID), and Potential Induced Degradations (PID).

Based on the structure of PV modules, there are three existing recycling strategies to complete recycling. These are delamination, separation, and purification of the different elements. They can be done either physically, thermally, or chemically as explained below.

- Physically: The panels are dismantled to remove the Aluminum frames, cables, and junction boxes. The junction boxes and cables are inspected for disposal, while the panels are crushed for the next process.
- Thermally: The crushed panels are heated in furnaces. In one of such methods, the crushed panels are put in a high temperature furnace and heated to a temperature of about 500 °C , for one hour, and at 450 °C/h heating rate. In another method, the heat of the furnace is gradually increased at a rate of 10 °C/min to 650 °C, and it's then held at the indicated temperature for about an hour. 91 % of glass is recovered by this method.
- Chemically: Different solvents and solutions are used to recover different elements of solar panels. The desired element determines the solvents. Examples of solution/solvent and recovered elements groups are shown below:
  1. Phosphoric acid paste - used to recover solar wafers.
  2. Crystalline silicon solar panels - soaked for 10 days in trichloroethylene at 80 °C to completely remove Ethylene Vinyl Acetate (EVA) and recover Si cells.
  3. Cadmium (Cd) and Tellurium (Te) - recovered using chemicals such as Sulfuric acid, sodium carbonate and sodium sulphide.

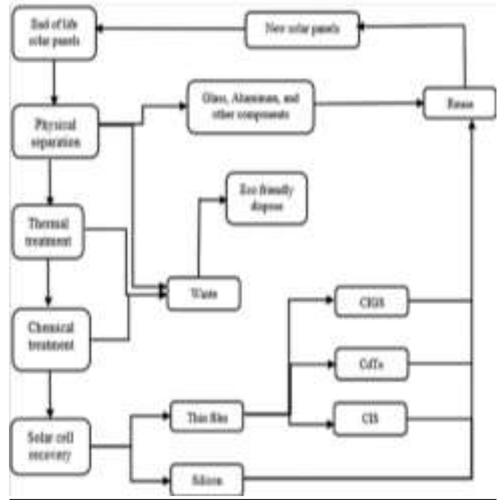

Fig. 2 Various processes of solar PV recycling

Here, Where CIGS, CdTe and CIS signify Copper Indium Gallium Arsenide, Cadmium Tellurium and Copper Indium Selenium respectively and are types of thin film panels (second generation solar panels)

IV. REUSE

Reusing is the process in which used solar panels or their components are used in new applications where they are not as efficient as new panels but are still functional.

Like using old panels for lower power applications or using them for off grid educational purpose projects.
Benefits:

- It increases the life of the materials and avoids disposal.
- Reduces the use of resources to manufacture new product.

V. END OF LIFE MANAGEMENT

It includes all the actions performed when a solar panel reaches to the end of its useful life, including recycling, reuse and responsible disposal.
Importance:

Since solar energy is used widely thus managing its end-of-life is important for its optimal use.

Challenges:

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- The increasing volume of end-of-life panels.
- The cost and efficiency of recycling technologies.

Both recycling and reuse strategies for end-of-life solar panels are important for minimizing the environmental impact of solar energy and maximizing the value of materials and components.

VI. DIFFERENT COUNTRY DEVELOPMENT/ STATUS REGARDING PV RECYCLING

Different recycling methods introduces implementation of various policies and regulations which can govern PV recycling at either the national or international level. These policies are important for handling solar PV panels at the end of their lifetime. Without which, PV recycling may not be efficient.

Some countries have started research on solar PV recycling. Most countries in Europe have started the EU Waste from Electrical and Electronic Equipment (WEEE)'s directives, which is an essential first step towards their involvement in PV recycling. This targets for the collection, restoration, and recycling of panels at the end of their lifecycle. The number of PV recycling companies and research institutions in the United States have notably increased in the past five years. In addition, many other solar manufacturing companies support PV recycling through their sustainability projects. While these developed countries continuously experience the buzz caused by PV recycling, developing countries are still lagging and are yet to initiate discussions regarding solar PV recycling. Table 1 summarizes the developments/engagement of some countries in Solar PV recycling, including the commitments and policies of countries with major PV installation capacities such as China, Germany, USA, Japan, and India.

Table 1. The engagements of different countries in Solar PV recycling.

Country	Status on PV recycling
UK	First European country to adopt EU Waste regulations from Waste from Electrical and Electronic Equipment (WEEE) directives for the handling of solar PV waste.
	The PV manufacturers are expected to provide every necessary information of the panels they manufacture, both for residential and commercial purposes. They are responsible for the cost of collecting residential end of life PV and the cost of collecting and recycling commercial purpose PV panels. The PV installers are to play a role in the collection process.
USA	The state of California Department of Toxic Substances Control (DTSC) proposed to handle the treatment of solar waste. First Solar, a solar panel manufacturing company originally from the USA, also has factories in Malaysia and Germany, and recycles panels with recovery rates of 95 % and 90 % for Cd and glass respectively. Solar PV manufacturing system where the materials recovered from the PV recycling processes and further reused for manufacturing.
Germany	Is the second country to adopt the EU WEEE's directives, and have instituted two financial mechanisms in waste from PV panels: the business to consumer (B2C) transactions in which case the manufactures sell the products and ensures the end-of-life management obligations both in the present and the future, and the business-to-business (B2B) transactions which depends on many factors such as the capacity and quantities and its success depends on if the final installer or user delivers the panels for recycling.
China	In 2023, the National Development and Reform Commission (NDRC) of China made known its aim of setting up recycling systems and facilities for both aging solar panels and wind turbines. Companies in China are now researching and developing strategies to regain valuable material from their PV wastes.
India	No regulations or guidelines currently exist for PV waste management in India, as they are neither considered as e-waste or hazardous waste. However, according to the Ministry of New and Renewable Energy (MNRE) in India, a requirement to setting up a grid-connected solar power plant is that the developers will need ensure the collection and the proper disposal of the solar panels at the end of their life cycle. And it should be done according to the e-waste management and handling rules.
Italy	A Legislative Decree was passed in 2014 to

	apply the Directive on WEEE. And the PV manufacturers are responsible for treating the panel waste
Japan	➢ Guidelines for PV recycling are still in the development stage. The environment ministry, solar panel manufacturers and other Japanese companies are collaborating to research on PV recycling technology. ➢ Solar panel manufacturers, are collaborating with a waste treatment company called Hamada to handle waste from PV panels

VII. PV RECYCLING STRATEGIES

1. Crystalline solar cells

Crystalline solar cells, the first generation of solar cells which are manufactured using silicon. They are one of the oldest solar cell technologies and have a greater share of the solar PV market. Different methods exist to recycle crystalline solar cells. While some of these methods are commercial, others are research-based.

In 2018, the electrical power research institute in collaboration with the National Renewable Energy Laboratory (NREL) published a report on the insight of photovoltaic recycling process in Europe. Using a survey-based approach, they obtained and analyzed Life Cycle Inventory (LCI) data from 5 different commercially active crystalline silicon (c-Si- based) PV recyclers in Europe. Though the data provided by these companies was done on an anonymous basis and didn't contain detailed explanation of the various chemical solutions or methods used, vital information can be learned from the steps used in their processes. Out of the 5 recycling companies, 4 of them used mechanical processes to separate the various components of the PV modules, while one used a combination of mechanical, thermal, and chemical methods. The recycling processes of the first four recyclers are similar. Company #1 follows the process in a laminated-glass recycling company. The process starts with removing the cables, junction boxes and aluminum frames using either a manual or automatic method. The aluminum frames are removed automatically using eddy current devices (non-ferrous metal separators) after the panels are shredded. The cables and junction boxes can sometimes be removed after the first shredding/crushing of the panels. The crushed substance (mixed metals) which generally includes glass, copper, polymers, aluminum, and sometimes junction boxes parts (if automatically separated) are sold to metal recyclers after the removal of polymer substances. Glass and foil are further separated from the polymer residue which includes the encapsulants and back sheet in an aeraulic process in which the energy from compressed air is used. In this process, the solar cells, and interconnectors removed by optical sorting, including the polymers are incinerated or sent to waste-energy plants. Aluminum, copper, and glass, which are the main outputs of the recycling process, are recovered at more than 85 % of weight (cumulative yields). This recycling process can be useful to other laminated glass recycling companies. Note that no chemical or solvent was used in the process. The advantages of mechanical recycling processes are that the health and environmental dangers associated with the use of chemicals are eliminated. The downside of this process is that both the qualitative (level of purity) and quantitative (%value of input material) yields are lower compared to processes which used chemicals to further recover useful materials.

For company #5 known as the Italian company Sasil S.r.l, due to the complexity of their recycling process including chemical and thermal separation method, their process is known to recover high yield and high-quality materials. In their process, after the removal of the junction box and aluminum frames, the module is heated to soften the polymer and separate it from the glass using a vibrating knife. The polymer fraction is incinerated and separated from the metals and solar cells, while the glass is sold to be used in other manufacturing industries such as container manufacturing. The metals and solar cells are then ground, sieved, and nitrous acid is added as a leaching agent. This completely dissolves the metals. Silicon is then separated from the solution through filtration. Silver and copper are recovered from the remaining solution through electrolysis, and the residual sludge is then sent to landfills. About 95 % of the glass is recovered and a total of 85 % of the input module is recovered. This method is advantageous over the mechanical process in that the yields are high, though there can be potential dangers to health or the environment due to the chemicals used.

The recycling process by company #5 involves chemical and thermal methods compared to company #1, hence involving the three recycling processes mentioned in section II above. Other suggested recycling processes involved all three processes (mechanical, thermal, and chemical processes).

Other c-Si recycling strategies which do not necessarily follow the three basic processes of recycling but can be used to recover valuable materials such glass, metals and either Si or cells have also been researched. Solar World, a solar PV manufacturing company in Germany suggested the following recycling method: The modules are heated at 600 °C to obtain solar cells, metals and glass. These three components are further separated manually. The solar cells are re-etched in a chemical process to wafers, while the metals and glass are recycled. Though the various etching agents used by solar world couldn't be found in literature, some of the etching agents used today include HNO3/HF/CH3COOH/Br2, HCL/HNO3/HF, HNO3 /HF/NaOH. This recycling method is known to be efficient, given that about 90 %, 95 % and 97 % of glass, semiconductor materials (Si) and wafers are respectively recovered. This method is advantageous in that the materials recovered are of a high purity, at an excellent recovery rate, and there is a possibility to directly reuse the wafers. The disadvantages of this method are: the manual separation can be inefficient; there is a potential of harmful emissions; the high temperatures can cause a possible defect or degradation to the wafers. Though solar world stopped its recycling activities in 2012 due to economic reasons, other recycling companies can be inspired by its recycling method and process to achieve higher percentages of efficiencies.

The various Si-based recycling methods above demonstrate that depending on the aim and end-product or metals of interest, the recycling methods used are different. About 90 % of the methods use thermal treatments, which are not only energy intensive, but can further make the separation of individual elements complex. The efficiencies and rate of recovery of the methods vary. In conclusion, despite the complexity and requirements of the different methods, they are feasible. The choice of method will depend on the recycler's needs.

2. Thin film solar cells

These solar panels are known as the second generation of solar panels and are made by depositing thin films of semiconductor material on glass. Depending on the semiconductor used, there are different types of thin films solar panels such as amorphous, Cadmium Tellurium and Copper Gallium Indium Diselenide. Materials for thin film production with Cadmium Tellurium and Copper Indium Disulphide/ Diselenide are on increasing demand. In addition, Indium and Tellurium are scarce materials and their prices further increase. As a result, recycling end of life thin film solar panels helps to recover these elements, which can be used to produce new panels.

Just like the Si-based PV technology, different companies and researchers have proposed ways through which valuable materials from thin film solar PV could be recovered. Existing methods are explained below.

First solar, a U.S based company specialized in thin film solar panels, developed, and presented a method to recycling thin film panels. According to the first solar recycling brochure, the first step is a physical disintegration or shredding and hammer milling. In this process, the cells are broken into smaller fractions by destroying the lamination bonds. The second step involves leaching using sulphuric acid as lixiviate and hydrogen peroxide as the oxidant to remove semiconductor films. Glass and other materials used for lamination including solid materials are regained from the remaining mixture (metal rich liquid) by a classifier. The glass and laminate materials are separated using a technology called vibration screening. The metal rich liquid is precipitated at an increasing pH in three steps. Cadmium (Cd) and Tellurium (Te) are then separated from the compound produced by a third party. At the end of this method, 90 %, 95 % and more than 80 % of glass, semiconductor materials (Cd, Te) and 99.7 % of pure Te can be recovered respectively. The advantages of this method are: the process is automated; the recovery rate of glass and semiconductor materials is high and there is a possibility of treating mixed waste. The disadvantages are: possibility of cell breakage, the energy requirements are high, and the process is complex. In addition, the chemicals used are expensive and can later be toxic to the environment.

The EU-LIFE project known as RESOLVED (Recovery of Solar Valuable materials, Enrichment and Decontamination), directed by the Federal Institute for Materials, Research and Testing suggested two different methods of recovering valuable materials from first is broken modules and second is end-of-life modules. For broken modules, after crushing and milling, a wet mechanical attrition and floatation mechanism was used to recover semiconductor layers and CdTe and CIGS respectively. An acidic oxidizing solution with sulphuric acid and hydrogen peroxide was then used in the chemical treatment phase to separate Cd and Te. For the end-of-life modules, crushed modules were heated in a furnace at a temperature of about 500 °C to destroy the EVA. A technology known as vacuum blasting was then used to recover the semiconductor materials. These suggested methods by the EU-LIFE project require less amount of chemicals and have high efficiencies of about 99.99 %. ANTEC Solar GmbH patented by Campo presented a recycling method for thin film solar panels as a pilot facility scaled project. The different technologies used were physical disintegration, pyrolysis treatment, dry etching, and precipitation. The initial step is to mechanically/physically breakdown the modules into smaller fragments. These fragments are heated in the presence of oxygen at a temperature of about 300 °C, a process called pyrolysis. The fragments obtained are subjected at 400 °C in an atmosphere containing chlorine gas, a process called etching. The $CdCl_2$ and $TeCl_4$ obtained are precipitated and condensed by cooling. This process is advantageous because the glass and semiconductors are regained at an excellent rate, smaller amount chemicals are used, the process is less complicated, the waste products can possibly be treated, it is economical and an environmentally friendly method. The disadvantages are that the energy requirements are high, the solar cells cannot be reused, and the purification process of the materials is complex. Held, 2009 described another thin film recycling method which uses physical disintegration, extraction, solid liquid separation and precipitation. This recycling method starts with shredding and milling of the modules to reduce the components of the solar modules and crushing in a hammer mill the pieces. This separates glass, after which the film removal or extraction process is performed which removes the semiconductor film via a rotating leach drum. Hydrogen peroxide is used in this leach cycle to create tellurous acid. Then the solids and liquids are separated using an Archimedean screw. TA vibrating screen separates the foil parts of the laminate from the glass which is recovered. The remaining liquid is precipitated using sodium hydroxide and filtered to recover the metals.

The above thin film recycling methods presents similarities in that the cells are shredded. This represents a drawback to the purity level of the recycled elements because shredding makes it challenging to recover individual elements from the mixture.

3. Organic solar cells

Organic solar cells are known as the third generation of solar cells technology. In organic solar cells, organic semiconductors act as the absorbing layers. In this technology, organic electronics and carbon-based materials are used rather than silicon as used in crystalline solar PV. They are occasionally known as "plastic" or "polymer" solar cells. Organic solar cells are more flexible and cheaper than the conventional crystalline solar PV, though their efficiency is still low. Due to their flexibility, they are an appropriate option for integrated building PV. Organic solar cells are a new technology and research is still ongoing to improve its efficiency and lifetime. As a result, very little has been done regarding their recycling. This review presents two recycling strategies whose desired recycled materials are different.

Sir Y. Zhou, reported a study in which they recycled organic solar cells manufactured on Cellulose Nanocrystal substrate (CNC). They separated the solar cell materials at room temperature using low energy processes. The CNC substrate was observed to disintegrate completely within 30 min after they were immersed in distilled water, leaving solid residues which were recovered by a filter paper. The photoactive layers were separated from the electrodes (made with Ag and Molybdenum oxide (MoO_3))

using chlorobenzene on filter paper to rinse the solid residues. In another study, silver (Ag) was recovered from roll-to-roll processed organic solar cells. In their research, the organic solar cells were incinerated (combusted in heat) at 800 to 1000 °C and later treated with diluted nitric acid. They realized a complete and high silver (Ag) recovery from the ashes of about 101.3 ± 3.8 %. From the recycling methods above, it can be deduced that the final material of interest determines the recycling process used.

4. Gallium Arsenide (GaAs)

GaAs solar cells are a type of direct band gap crystalline PV material based solar cells with a band gap of 1.42 eV at room temperature. With studies indicating efficiencies up to 28.8 % on single junction cells and efficiencies reaching up to 42.3 % on triple junction cells, GaAs based PV technology is one of the most efficient in the current market. GaAs solar cells are mostly used in outer space power generation and concentrated PV power generation due to its high resistance to radiation damage and insensitiveness to overheating . As a result of this, the necessity for recycling strategies of these modules is less thus rendering the development of new strategies in a slower path. The global availability of gallium is moderate, being not naturally existing in its purest state, gallium is often found in combined form with Aluminum and Zinc. Almost 85 % of GaAs is wasted as scrap during production. With the increase in demand for gallium due to its applications in semiconductor industry, the need for recycling strategies has increased in the past years. Materials like glass, gallium and other useful organic components can be successfully recycled from a GaAs solar cell by using methods like nitrogen pyrolysis and vacuum decomposition. Nitrogen pyrolysis is also a very effective method for the removal of EVA (Ethylene vinyl acetate) and PET (Polyethylene terephthalate resin), two of the major plastic materials in the solar module. Using the method, material reduction rates up to 98.2 % and 98.69 % can be attained for the EVA and PET respectively. Manual separation of cathode, anode and the anti-reflective layer is also being widely practiced now.

An experiment conducted by Shanghai Key Lab assessing the feasibility of recycling e-waste (primarily light emitting diodes or LED's) to recover Arsenic and gallium using pyrolysis and vacuum metallurgy shows a stable gallium and arsenic recovery rate at 1273 K. Other processes of recycling such as physical degradation, leaching-selective precipitation and vacuum thermal reduction are also being researched. Vacuum metallurgy separation of solid gallium under optimized experimental conditions provides a recovery efficiency of 93.48 %. A credibility study on III-V GaAs solar cells developed on a recycled substrate made of GaAs shows degradation in performance due to uneven surface morphology affecting the cell's Open Circuit Voltage (Voc) and fill factor (FF). Even though considerably old methods like pyrolysis and vacuum decomposition are still used the most for GaAs solar cell recycling, the developments in new methods appear promising.

5. Perovskite

Perovskites are crystal materials that generally have a chemical formula of XYZ3 where the first two (X and Y) are cations and Z being a bonding anion. Halide perovskites are showing great progress in research making it potentially the face of third generation solar cells of the future. In the last two years, the progress made in perovskite solar technology is significant, with efficiencies reaching up to 25 % in experimental conditions. Being cost efficient, perovskites have the potential to compete with Si based technologies to become the most used PV technology in the future. Commercialization of perovskites is however going to inevitably increase the presence of toxic wastes such as lead. Thus, development in waste management and recycling technologies is crucial for perovskites to develop a commercial market. Closed loop recycling and recrystallization using butylamine of perovskite solar cells is an efficient recycling method with 98.9 % recovery efficiency. A solar cell produced by recrystallization shows a similar performance to that of a fresh solar cell. Common methods like stripping down layers of perovskite cells are also feasible as the collected materials can be reused with little or almost no reduction in performance. The Pbl2 which is recycled using this method can be recrystallized, and reused and has a power conversion efficiency of

13.5 %. Toxic Pb leakage is considered as being one of the biggest environmental concerns associated with PV recycling, but the environmental pollution from Pb leakages from Perovskite recycling is estimated to be modest when compared with other energy conversion methods like coal power conversion.

A rapid dismantling process of perovskite solar cells developed by researchers at Ecole Polytechnique Fédédale, Switzerland shows a cost and time efficient recovery of all major components of the cells which are further used to fabricate recycled cells for performance comparison with new cell. The result of this study shows completely intact recovery of the photoanode without any delamination or scratching along with complete recovery of gold without any residue of lead in the recovered materials confirmed with X-ray fluorescence. The lead content concentration in the solvents after multiple stages of sequestration was found to be as low as 44 PPM per mL showing a substance isolation of 99 %. The comparison of device performance of the cell made from the recycled components shows no significant performance drop. Although, a small drop in short-circuit current density is observed due to residual solvents affecting perovskite recrystallization. On a different comparative feasibility study of recycling different deteriorated perovskite solar cells deposited by three various manufacturing methods or routes, it was found that perovskite cells fabricated by single step acetate method is the most efficient for recycling when compared with other methods like chloride and sequential deposition (single step). With perovskite PV technology making fast progress, future developments in perovskite recycling are crucial to make the technology commercially viable.

6. Dye-sensitized solar cells (DSSC)

DSSC (dye-sensitized solar cell) is a type of thin-film solar cell. DSSC is typically used for architectural and building integrated applications. Efficiencies for DSSC are usually about 11 %. The typical components of a DSSC solar cell include these materials: two layers of glass, two layers of TCO (transparent conducting oxide), Titanium Dioide (TiO2 anode), platinum (cathode) and an electrolyte (liquid conductor). Since DSSC is a growing market and is expected to at least double in revenues by 2030, the amount of DSSC solar that will need to be recycled in the future decades will increase substantially in 10–20 years from now (2023). Recycling DSSC solar cells is a complicated task due to the thin film and compact nature of the cells.

The first step in lowering the amounts of raw materials required in the DSSC lifecycle is on reducing the raw materials used through building DSSC with recycled materials. Extending the lifetime of a solar cell is also being researched. Methods of reducing the environmental impact of DSSC's include lowering the amount of rate and toxic materials in the solar cells (i.e., ruthenium, cobalt, silver, and platinum). However, the negatives of using other options are lower power conversion efficiencies and/or lower cell lifetime. Recovering TiO2 glass from old decommissioned DSSC solar cells is an available option to recycle a valuable and rare component which can be used for creating new cells. The recycled TiO2 can be gathered from Perovskite cells and reapplied with CsPbIBr2 and carbon layers. All these methods to recycle DSSC solar cells require more research and development, as alternative materials to be used which can be more easily recycled than conventional DSSC materials are not yet commercially available or efficient enough .Mechanical processing and separation of the components is expensive, especially if there is a module frame involved. Crushing DSSC's can be done which is a mechanical process involved in making it easier to separate the components. Pyrometallurgical processes could be an alternative approach to the shredding and crushing method, however it is difficult to extract more than one type of metal easily through this process.

VIII. ECONOMIC, SOCIAL AND ENVIRONMENTAL ANALYSIS OF SOLAR PV RECYCLING

Solar PV system decommissioning poses an environmental problem, depending on the method used for the panels' disposal after decommissioning. Compared to land filling, solar PV recycling has been established as an environmentally advantageous process with a potential to be cost efficient in the future. The cost of recycling is expected to decrease with time, and with the maturity of the various recycling technologies. Furthermore, the materials recovered through recycling can be sold, reused, and recycling equally has the potential to reduce CO_2 emissions. On the other hand, though the cost of land filling is currently low, this might increase with time. In addition, the disposal of PV panels by land filling is environmentally unfriendly, given that the panels contain toxic elements which are dangerous. A sustainable analysis of PV recycling helps to evaluate the benefits of solar PV recycling.

The cost of disposing thin film panels in the US was found to be from \$0.09–0.10, which covers the cost of collection and recycling, confirming how advantageous recycling is over land filling. Also, Fthenakis performed an analysis of PV recycling and disposal cost and concluded that the cost of solar panel recycling can be low and within the \$0.08–0.11 range, which can be affordable, hence not act as a barrier to PV recycling, though it may later be a challenge if the PV plant is large and the current cost of installation of PV panels falls below \$2–3/W. Held, 2009 used an already applied recycling method for CdTe thin film solar panels and performed a life-cycle analysis (LCA) of the recycling process to analyze its environmental benefits. The results of the LCA show that the energy initially required by end-of-life modules reduces from 81 MJ/M2 to 12 MJ/M2, and the CO_2 emissions potential will decrease from 6 kg CO_2 equi./m2 to −2.5 kg CO_2 equi./m2. This improvement ascertains the benefits of PV recycling. Daniela-Abigail et al., (2022) performed a sustainable analysis of recycling PV panels in an economically vulnerable regions in Brazil. Their analysis included all three aspects of sustainability which are social, environmental, and economic. The environmental life cycle analysis showed that PV recycling can reduce the level of human and freshwater toxicity by about 78 %. The economic life cycle analysis showed that the LCOE of electricity could drop by 2 % from the current value if PV panels are recycled. Socially, their analysis showed that a successful and profitable recycling process will necessitate an introduction of regulation and policies, and a community awareness and training program to educate the public about the importance of PV recycling as well as facilitate the successful implementation of the various recycling policies.

In terms of technology specific economic analysis, a cost analysis study on the feasibility of recycling toxic lead and other valuable conductor materials showed impressive results. Out of the total material cost of perovskite module which was \$24.8/m2, the value of recycled materials was \$12/m2 making the results considerably promising. Lead was separated from the test module using weakly acidic cation exchange resin at a recycling efficiency of 99.2 %. Another life cycle assessment study of perovskite recycling strategies showed results of up to 72.6 % and 71.2 % of energy payback time reduction and greenhouse gas emission factor reduction respectively. Under a best-case recycling scenario, the energy payback time for a recycled perovskite module is 0.09 years with a 13.4 g CO_2/ kWh of greenhouse gas emission factor, which is lower than the respective values of silicon solar modules.

Another potential way to evaluate the environmental impact, social and economic benefits of PV recycling is to perform a detailed Life Cycle Inventory (LCI) of various PV recycling companies. An LCI can provide information such as the number of tons of PV panel waste material to be recycled by companies within a given period, the amount of water and energy used, the output components of the recycling process, the percentages composition of the various recycled materials, including the emissions to water and air and the waste disposed in landfills or incinerated. As an example, the survey-based approach research performed on 5 PV recyclers in Europe by the electrical power research institute published in 2018 showed that the electricity consumption for recycling using mechanical processes was in the range of 50 to 100 KWh per ton of the PV panels waste inputs to be recycled, including a natural gas per ton equivalent of about 76 KWh of input modules for the thermal and incineration processes. An additional small amount of fuel was reported to be used for front-end loaders. Information on the economic and environmental benefits of the recycling processes can be obtained from a further detailed analysis of these data including the economic worth of the output (recycled materials), and the possible amount of CO_2 emissions generated per a given amount (tons) of waste recycled.

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From the above analysis, PV recycling is undoubtedly a profitable and promising way of disposing of PV waste. It can potentially decrease CO2 emissions and reduce the level of human and environmental toxicity and be economically viable. Different methods to improve the profitability of PV recycling can be considered by governments.

IX. SUGGESTED POLICIES & RECOMMENDATIONS TO PV RECYCLING

Though beneficial, PV panel recycling also faces challenges. According to NREL, some of the challenges or barriers faced by PV recycling can be summarized in the following points: lack of research, development, and analysis support; the lack of exchange of information amongst manufacturers, distributors and recyclers, and the lack of publicly available information by these entities; lack of economic incentives and finally, the challenge due to complex, varied laws, and regulations. Though these barriers are predominantly for the USA, they could equally be potential barriers to PV recycling in many other countries in the world. Addressing these challenges will promote the entry of PV recyclers in the recycling industries.

Different methods to improve the profitability of PV recycling can be considered by governments. This includes providing subsidies for low-cost PV recycling investments, instead of penalties. And for high-cost PV recycling investments, the government should consider the application of penalties to further encourage PV recycling. For the proper management of end-of-life PV wastes, countries with anticipated higher percentages of PV waste by 2050 such as China, USA, Japan, India, and Germany, need to develop a framework and adopt policies which are essential for the management of their PV wastes. The Extended Producer Responsibility policy and the WEEE initiative by the EU can act as a foundation for country respective policies and end-of-life PV waste management engagement for not only countries with anticipated higher percentages of PV waste, but by every country with PV installation capacity worldwide. Implementing the extended producer responsibility system, effective for various waste types, particularly electronic waste, can ensure sustainable PV panel material management. Measures include reinforcing eco-design, encouraging recycled material use with quality guarantees, legislating incentives for producer involvement in recycling, and enabling public monitoring through information disclosure.

The establishment and effective fulfilment of the policies will require substantial data about the quantity and location of PV waste. For every country, it is important to keep track of the location of solar PV installations in different regions and the quantities. This data will be helpful to advise the start and development of PV recycling or waste management industries and the implementation of efficient PV waste collection mechanisms which is an essential aspect of making the PV waste collection financially beneficial. A potential collection network includes using an online platform that will allow the integration and communication of consumers and recyclers of a given region. Consumers will indicate to the recyclers whenever their modules are ready for recycling (have lasted for the module's lifetime or is damaged), and the recyclers will pick up the modules from the consumers when appropriate. The consumers are paid by the recyclers when collecting the modules, while the recyclers benefit by selling the recycled materials to solar manufacturers or manufacturing industries. According to PV recycling can generate \$16–17/Si-based module. Another potential collection network mechanism by proposes that the collection of PV modules for recycling can be done by reversing the current distribution network: Installers pick up the modules from different consumers and ship them to retailers, who later ship the modules to distributors, and finally to the recycling companies. This network of PV module collection is maintained by monetary compensation from one party to another in the value chain. For example, the installers are compensated by the retailers, while they in turn compensate the consumers.

In addition, a public awareness creation and training campaign is vital. Through this, consumer attitudes towards the reuse of recycled PV panels can be changed, as these panels can sometimes be considered to have poor efficiency.

X. CONCLUSION

Solar PV recycling is a progressing field that demands additional research. PV recycling will reduce waste, and CO2 emissions, while contributing to a sustainable environment. This paper reviewed the PV recycling engagements by some countries, the different recycling strategies for different end of life solar cells and the analyses of PV recycling. While a few countries have initiated the discussions and are working towards PV recycling, most developing countries are yet to engage in such discussions. The following disadvantages of the current PV recycling strategies were noted. Given the continuous variation in PV panel composition introduced in the different manufacturing technologies, the existing Solar PV recycling strategies are complex. In addition, while some proposed recycling methods are not economically viable, some use chemicals which might be dangerous. Energy is required for recycling, and the collection networks of the end-of-life PV panels are not efficient.

The sustainable analysis of PV recycling including the economic, environmental, and social aspects shows that PV recycling is a viable option to managing PV waste. This can further be encouraged by the development of regulations and policies, and the provision of recycling subsidies. While recycling strategies for recent solar technologies like organic solar and perovskites are still under research, Crystalline PV recycling methods are the most advanced, followed by thin film technology. It is expected that the research for efficient PV recycling strategies will accelerate as the PV industry grows and as many more organizations and government work towards a sustainable future. The successful management and handling of PV panels at their end of life therefore requires a proactive approach and plan and the introduction of low-cost PV recycling technologies, the introduction of policies and regulations and the provision of subsidies to low-cost PV recycling investors.

Solar PV recycling is a progressing field that demands more research to make the processes efficient, less complex, economically feasible, energy saving and improved logistically. There is also a need for public policy to help encourage solar PV system manufacturer responsibilities in reducing waste at the end of the life of these systems.

REFERENCES

[1] M.S. Chowdhury, et al.An overview of solar photovoltaic panels' end-of-life material recycling
[2] W. Berger, F.G. Simon, K. Weimann, E.A. Alsema A novel approach for the recycling of thin film photovoltaic modules
[3] A. Sharma, S. Pandey, M. Kolhe Global review of policies & guidelines for recycling of solar pv modules
[4] N. Rathore, N.L. Panwar Strategic overview of management of future solar photovoltaic panel waste generation in the Indian context
[5] P. Brailovsky, et al. Insights into circular material and waste flows from c-Si PV industry
[6] I. D'Adamo, M. Miliacca, P. Rosa Economic Feasibility for Recycling of Waste Crystalline Silicon Photovoltaic Modules
[7] J. Ko, et al. Review on Separation Processes of End-of-Life Silicon Photovoltaic Modules
[8] F. Pagnanelli, et al. Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies
[9] T. Doi, I. Tsuda, H. Unagida, A. Murata, K. Sakuta, K. Kurokawa Experimental study on PV module recycling with organic solvent method
[10] 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
[11] W. Wang, V. Fthenakis Kinetics study on separation of cadmium from tellurium in acidic solution media using ion-exchange resins
[12] Y. Kim, J. Lee Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent
[13] C. G. Assembly, "Final Report on the Activities Conducted to Establish a Regulatory Program for the Management and Decommissioning of Renewable Energy Equipment"

[14] "Report of Investigation of Recycling and other Management Methods for Solar Panels , and Recommendations by the New Jersey Solar Panel Commission
[15] M. Ding, Z. Xu, W. Wang, X. Wang, Y. Song, D. Chen A review on China's large-scale PV integration: Progress, challenges and recommendations
[16] P. S. MOLINA, "China plans recycling system for wind turbines , solar panels S. Approach, "Program on Technology Innovation: Insights on Photovoltaic Recycling Processes in Europe."
[17] W.H. Huang, W.J. Shin, L. Wang, W.C. Sun, M. Tao Strategy and technology to recycle wafer-silicon solar modules
[18] X. Wang, X. Tian, X. Chen, L. Ren, C. Geng A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology
[19] 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
[20] G.A. Heath, et al. Research and development priorities for silicon photovoltaic module recycling to support a circular economy
[21] C. Latunussa, L. Mancini, G. Blengini, F. Ardente, and D. Pennington, Analysis of Material Recovery from Silicon Photovoltaic Panels
[22] M. Held Life cycle assessment of CdTe module recycling
[23] Y. Zhou et al., "Recyclable organic solar cells on cellulose nanocrystal substrates,"
[24] R.R. Søndergaard, Y.S. Zimmermann, N. Espinosa, M. Lenz, F. Krebs Incineration of organic solar cells: Efficient end of life management by quantitative silver recovery
[25] R.A. Deshpande Advances in solar cell technology: an overview
[26] T. Takamoto, H. Washio, H. Juso "Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic", 2014 IEEE 40th Photovolt
[27] P. Y. Dehnavi, "Global Cycle of Gallium Production, Use and Potential Recycling,"
[28] L. Zhan, F. Xia, Y. Xia, B. Xie Recycle Gallium and Arsenic from GaAs-Based E-Wastes via Pyrolysis-Vacuum Metallurgy Separation: Theory and Feasibility
[29] W. Ji, K. Xie, S. Yan, H. Huang, H. Chen A new method of recycling gallium from yellow phosphorus flue dust by vacuum thermal reduction process
[30] S.H. Hu, M.Y. Xie, Y.M. Hsieh, Y.S. Liou, W.S. Chen Resource recycling of gallium arsenide scrap using leaching-selective precipitation
[31] R.H. Horng, M.C. Tseng, S.Y. Lien Reliability analysis of III-V solar cells grown on recycled GaAs substrates and an electroplated nickel substrate
[32] F.W. Liu, et al. Recycling and recovery of perovskite solar cells
[33] Z. Zhang, L. Qiao, K. Meng, R. Long, G. Chen, P. Gao Rationalization of passivation strategies toward high-performance perovskite solar cells
[34] A. Binek, et al. Recycling perovskite solar cells to avoid lead waste
[35] J.M. Kadro, et al. Proof-of-concept for facile perovskite solar cell recycling
[36] P. Chhillar, B.P. Dhamaniya, V. Dutta, S.K. Pathak Recycling of Perovskite Films: Route toward Cost-Efficient and Environment-Friendly Perovskite Technology
[37] K. Miettunen, A. Santasalo-Aarnio Eco-design for dye solar cells: From hazardous waste to profitable recovery
[38] V.M. Fthenakis End-of-life management and recycling of PV modules
[39] B. Chen, C. Fei, S. Chen, H. Gu, X. Xiao, J. Huang Recycling lead and transparent conductors from perovskite solar modules
[40] X. Tian, S.D. Stranks, F. You Life cycle assessment of recycling strategies for perovskite photovoltaic modules
[41] V.M. Fthenakis, H.C. Kim, E.A. Alsema Emissions from photovoltaic life cycles: Supporting information