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Photovoltaic (PV) Modules Waste Management: A Holistic Framework For Sustainable Growth

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Abstract:

India largely depend on coals based thermal power, but now world is moving toward renewable energy as coal extinction and over exploitation. Solar energy has the maximum potential to be exploited to the maximum level to full fill the energy demands of the world. The Sun has been worshiped as a life-giver to our planet. About 5,000 trillion kWh energy/year is over India's land area with most parts receiving 4-7 kWh per sq. m/day. Solar energy has become a leading solution to meet the increasing energy demand of growing populations. Solar photovoltaic (PV) technology is an efficient option to generate electricity from solar energy and mitigate climate change. The development and growth of solar photovoltaics has had a positive impact on energy system decarbonization, but end-of-life solar panels might become toxic waste, if not properly disposed. Presently in India, approx. 200,000 tons of solar photovoltaic (PV) waste are expected to be produced by 2030 and 1.8 million tons by 2050 by which time solar waste could grow to 60 million tons globally (Rathore et al, 2022). Solar waste recently included in the category of electrical and electronic equipment waste to restrict the negative impact of continual development. The present focus is only on increasing the efficiency of solar PV panels without considering the impact of waste on the environment. The solar waste management and recovery of components from waste, would prevent the leaching of various toxic elements into the environment. PV module recycling is a multistep process involving dismantling, delamination, and metal recovery. Several techniques are available to recover the intrinsic components in the PV modules, like chemical delamination, yield undamaged solar cells, which could be reused directly or with refurbishing. Mechanical and combustion delamination, on the contrary, yields damaged solar cells that are treated electrochemically or metallurgically to recover the metals.
There is a need to critically investigate & manage the disposal and recycling of solar panels waste in a scientific manner to minimize the negative environmental impacts. This paper addresses handling and recycling of solar waste, which will be present in large quantities after 25 years and explain multiple adopted technologies to recycle solar waste and technological advancement achieved while recycling photovoltaic waste.

Index Terms: *PV (photovoltaic), kWh (kilo watt hour), EPR (Extended Producer Responsibility), IRENA (International Renewal Energy Agency), GW (Gigawatt), ISA (International solar alliance), WEEE (Waste Electrical and Electronic Equipment), EU (European Union), EPR (Extended Producer Responsibility).*

1. INTRODUCTION

Energy demand is rising day by day. The total installed capacity for electricity generation of India has increased to 399.47 GW as of 31.03. 2022. Thermal power plants contributed ~63.40% and renewable energy (small hydro projects, biomass gasifiers, biomass power, solar energy and wind energy) contribute ~ 21.9%. The country's solar installed capacity reached 52 GW as of 31 March 2022 (ET dt 25.05.22). Solar PV modules are mainly of two types, one is crystalline Silica C-Si) PV module and other is Thin-film Solar Modules. India has tremendous solar energy potential. Every year, India receives ~ 5,000 trillion kWh of solar energy with most parts' radiation of 4–7 kWh/m2/day. Utilizing this freely solar energy offers a solution to global climate change and fossil fuel emissions (Sica et al. 2018). Solar power using solar photovoltaic (PV) technology which is a promising option for mitigating climate change. The PV market is developing quickly and further market production of electricity with the usage of solar photovoltaic technology is the most promising after wind and hydro technology. The increased installations of solar panels, the energy production has risen to drastic level in India &

other countries. Various policy initiatives have been initiated by Govt of India for quick development of solar power with rising installations of solar panels, will lead to rise to huge extent on their life cycle completion. Rising installations hold the due diligent crisis of waste management in terms of primary and secondary waste generated. Globally, only a few regulations cover PV modules in waste category. The European Union (EU) is first to revise its Waste Electrical and Electronic Equipment (WEEE) legislation & bring PV modules under its ambit. PV module recycling initiatives, promising more than 90% of the recycling yield. Approximately 2.95 billion tons of solar panel waste consisting the solar panels and the balance of system will be accumulated from 2020 to 2047 (Rathore & Panwar et, al, 2021) in India. To handle this imminent amount of waste, an effective strategic planning is the utmost need of the approaching times. Currently in market, various types of solar panels are available which have different semiconductor material (silicon, cadmium, etc). The range of current technologies in manufacturing photovoltaic modules (or PV modules) is divided mainly into two generations, according to the operation and materials of the photovoltaic cell. Most of the solar panels are crystalline silicon (c-Si) solar cell as they have comparatively cheaper than others.

1.1 Photovoltaic technologies

1. **First generation**: Crystalline silicon (c-Si)

2. **Second generation:** Thin film solar panels

Crystalline Si (c-Si) technologies dominate the current market share ~90% of PV modules. A (c-Si) PV module contains ~75% of total weight is from the module surface (glass), 10% polymer (encapsulant & back sheet foil), 8% aluminum (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin & lead). The rest of the components have a small percentage of the module weight.

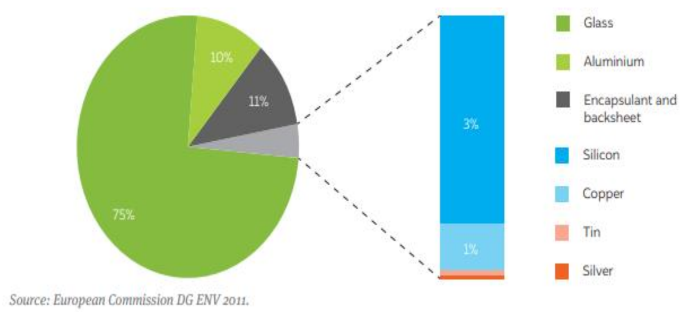
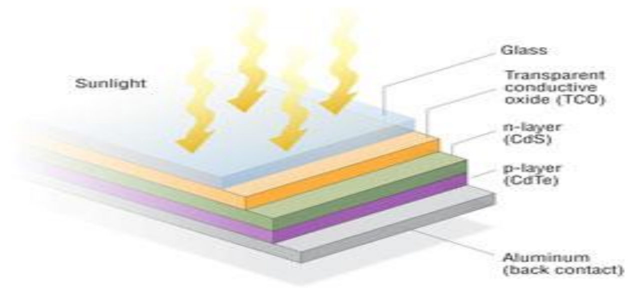


Figure-1: Composition of the crystalline silicon module.

Thin films represent 10% of the PV industry. The currently dominant technologies are cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) with, approximately, 65%, 25% and 10% of total thin-film market share., respectively. Thin-film solar cells were developed with the aim of low cost and flexible geometries, using relatively small material quantities. CdTe, CIGS and a-Si are the main technologies for thin-film PV modules. CdTe is the most widely used thin-film technology. It contains significant amounts of cadmium (Cd), an element with relative toxicity, which presents an environmental problem. A-Si has low toxicity and cost but also low durability and it is less efficient compared with the other thin-film technologies. The low energy and materials demands during production. The energy pay-back time for such module is as low around 1 year for CdTe- (Fthenakis et al., 2008). However, based on the average prices for the rare materials indium and tellurium may continue to increase. The estimated lifetime of a thin film module is about 25–35 years of power generation. These panels are destined to make a big impact in the future, but when they reach their end-of-life, hazardous sub-stances used in the panels may harm the environment if they are not recycled or disposed of properly. For example, heavy metals present in them can be toxic as well as carcinogenic or teratogenic.



Source: U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO)

STRUCTURE OF SOLAR PV MODULES:

C-Si (crystalline silicon) solar modules main components as shows in Table-1.

- Tempered Glass
- Aluminum frame
- Anti-reflective layer
- Silicon cell wafer
- Aluminum and Copper or silver wires (wire electrodes)
- EVA (ethylene vinyl acetate)
- Electrical Junction box

Material	% w/w in a module	Relative economic
Silicon	2-3	Yes
Glass	69-75	Yes
Polymers (EVA, Tedlar/back sheet/ polyvinyl fluoride-PVF)	7	No
Copper	0.6-1.0	Yes
Silver	0.006-.06	Yes
Aluminum	10-20	Yes
Source: Abhishke, Nikita et,al., 2022		(Table-1)

2.0 THE NEED FOR PV WASTE MANAGEMENT

Solar PV waste management & recycling becomes quite important from environmental & resource management aspects. The constituent elements could negatively impact the local surroundings upon exposure, if not disposed properly. Hence, PV modules need to be safely disposed of to have a minimum environmental impact. Many of the elements present in the modules are valuable from an economic viewpoint. They are extensively used in alternate industries and have a significant demand outside the clean energy sector. So, it is essential to recover them from the waste modules. India's existing informal scrap collectors can benefit from the formalization of recycling processes. The PV waste management policy could have a multifaceted impact on the Indian economy. The management of PV module waste & recovery components prevents the leaching of toxic elements into the environment. PV module recycling is a multistep process involving dismantling, delamination & metal recovery. Techniques are available to recover the intrinsic components of PV modules, like chemical delamination, yield undamaged solar cells, could be reused directly or with little refurbishing. Mechanical & combustion delamination and recover the metals. Literatures suggested to analyze to insight of the governing policies, inculcated key objectives, targets, obligations, The evaluations to establish a management strategy of regulations for solar PV waste pertaining in India is essential. The framed strategies also take the involvement of each stakeholder in the supply chain to manage the solar PV waste. Solar panels on reaching their end life are usually thrown away or casual recycling to obtain glass & aluminum. Resource recovery is an important prospective which is to be fulfilled to establish circular system. This achieved by establishing the concept of **4R** which are reduce, reuse, recycle and recover. The range of recycling material output in solar photovoltaic sector is 60 % to 90%. The prominent recyclable output from the solar panel waste has put forward a huge capacity of commercial recycling in the solar panel at their end life. These confrontations to be taken care at the end life management of panels. Synchronized and well-ordered approach needs to be applied for the reduction of resource availability at the end life management. Circular economy needs to be developed for obtaining the utilized resources at end life management. 60% to 90% recoverability has been projected from the end life of panels by end life management by literatures & expertise and it is opinioned that there is a lack of commercial facility of recycling aluminum and glass utilized in solar panels.

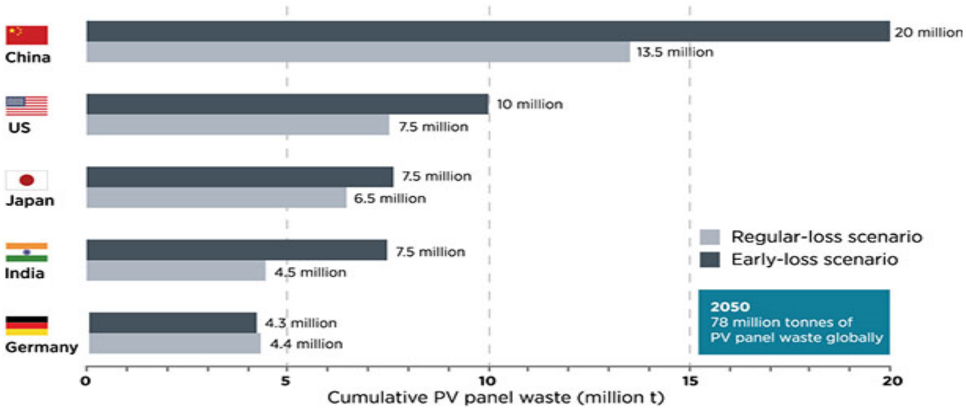


Fig-1: Cumulative waste volumes of PV panels by 2050, by country

3.0 Solar PV waste Management:

The "PV Waste Management in India", is recommendations based on the extended producer responsibility (EPR) policy for PV modules in European countries. Chowdhury et al., 2020, reported that Europe, Japan and the USA are currently carrying out research on recycling of solar panels. One major purpose of recycling technologies is to recover important and valuable components of used solar panels. The differences in composition and module structure, different types of PV modules require different recycling technologies. Like physical separation, chemical and thermal treatment and recycling, optical approach for recycling. The International Renewable Energy Agency (IRENA) and International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), is the first-ever projection of PV panel waste volumes to 2050. It highlights that recycling solar PV panels at the end of their roughly 30-year lifetime can unlock an estimated ~ 78 million tons of raw materials and other valuable components globally by 2050. If fully injected back into the economy, the value of the recovered material could exceed USD 15 billion by 2050. Sectors like PV recycling will be essential in the world's transition to a sustainable, economically viable and increasingly renewables-based energy future. To unlock the benefits of PV end-of-life industries, Policy action is needed to address the challenges ahead, with enabling frameworks being adapted to the needs and circumstances of each region or country. In the manufacturing process of solar modules, various hazardous materials, such as lead and cadmium compounds, and polymers are used. In a study (Suresh et, al. 2019) reported that 90% of Indian PV system installations were dominated by crystalline silicon (c-Si) modules and remaining 9–10% consisted of thin film solar modules. It is assumed that a panel have 30 years of life, and an early loss scenario takes into consideration 'infant', 'mid-life' and 'wear-out' failures before 30 years of panel life. it is estimated that dramatic increase of 60 million tons by the end of 2050 is expected, while in an early loss scenario, the waste is expected to rise to 80 million tons by 2050.

3. PHOTOVOLTAIC RECYCLING TECHNOLOGIES

PV modules are largely recyclable. Materials such as glass, aluminum and semiconductors can, theoretically, be recovered and reused. Hence it is vital that consumers, industry, and PV producers take responsibility for the EoL of these modules. So far, the most common methods for recycling c-Si PV modules are based on mechanical, thermal and chemical processes. Although thin-film solar cells use far less material than c-Si cells, there are concerns about the availability and toxicity of materials such as tellurium (Te), indium (In), and cadmium (Cd), for example. Furthermore, the production processes also generate greenhouse gases emissions during some reactor-cleaning operations. Because of these issues, it is very important to focus on the recycling of PV modules for all the technologies. The separation of the materials allows them to be sent to specific recycling processes associated with each material. For silicon modules, two recycling methods based on pyrolysis in a conveyer belt furnace and in a fluidised bed reactor were demonstrated (Frisson et al., 2000), The recycling process starts with the shredding of the modules into large pieces and subsequently into small fragments (5 mm or less) by a hammer mill. During the next 4–6 h the semiconductor films are removed in a slow leaching drum. The remaining glass is exposed to a mixture of sulfuric acid and hydrogen peroxide aiming, to reach an optimal solid–liquid ratio. After that process, the glass is separated again. The next step is to separate the glass from the larger ethylene vinyl acetate (EVA) pieces, via a vibrating screen. The glass is cleaned and sent to recycling. Sodium hydroxide is used to precipitate the metal compounds, after which they are sent to another company where they can be processed to semiconductor grade raw materials for use in new solar modules. This process recovers 90% of the glass for use in new products and 95% of the semiconductor materials for use in new solar modules.

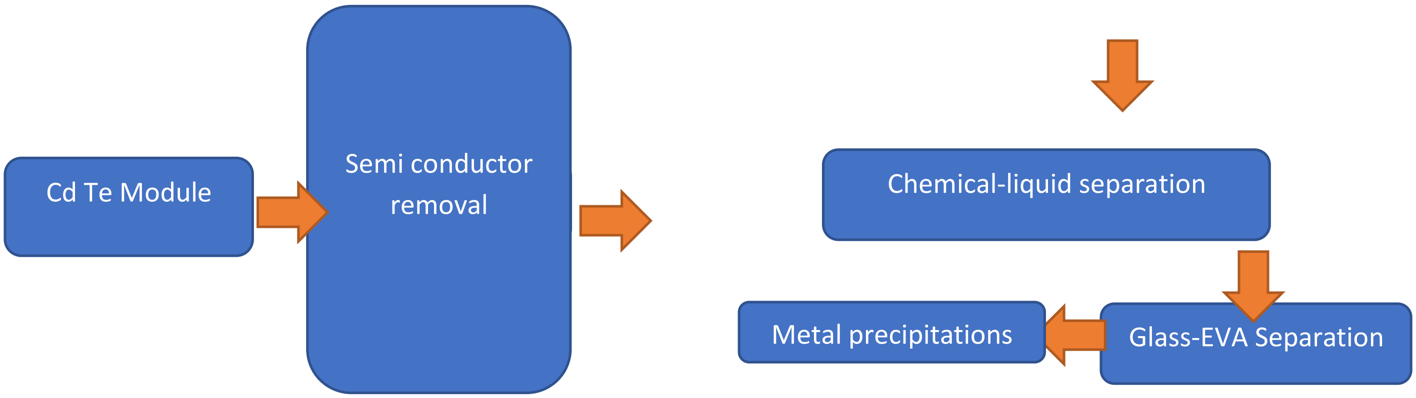


Fig: -2: Solar PV recycling process for CdTe modules.

An advanced example for recycling of CdTe thin film modules is the method from First Solar which has been scaled to full production. The recycling includes the following process steps.

- Particle size reduction using a shredder to break the glass into large pieces and a hammer mill to crush the broken glass into 4–5mm pieces.
- Semiconductor film removal in a slowly rotating leach drum using sulphuric acid and hydrogen peroxide. • Solid–liquid separation by emptying the content of the leach drum into a classifier where glass is separated from the liquids.
- Glass-laminate material separation by means of a vibrating screen where the glass is separated from the larger pieces of Ethylene Vinyl Acetate (EVA).
- Glass rinsing to remove any residual semiconductor material that physically remains on the glass.
- Precipitation of the separated metal components using sodium hydroxide and concentration in a thickening tank; the resulting filter cake is packaged for metals recovery by a third party.

4.0 ENVIRONMENTAL IMPACT

Solar PV industry waste is harmful & toxic chemical materials. The manufacturing is responsible for byproducts as sulfuric acid, hydrogen fluoride, hydrochloride acid & nitric acid. Traditionally silicon PV technology consists of fewer toxic materials than thin film PV technology. The film PV cells are made of gallium, selenium, telluride and indium. These materials need to be disposed of carefully, to prevent dangerous environmental problems.

Thin film technology includes compounds like cadmium sulfide (CdS), copper gallium diselenide (CuSe. GaSe), cadmium telluride (CdTe) & gallium arsenide (GaAs) & copper indium diselenide (CuSe. InSe) & solvents like HCl, nitric acid, hydrogen fluoride, acetone, ethanol are used for cleaning wafers & removing impurities during the fabrication process. Nkuissi et al., 2020 has mentioned that 37% of this waste is discharged to offsite treatment facilities & 35% of waste is expelled as diluted acid solutions to treatment plants and 0.8% of wastes are reported to be dumped. Materials like cd, Pb and polymer are disposed in an uncontrolled manner. As a result, these chemicals cause environmental impact. Cd, Te cause severe pulmonary inflammation and fibrosis (Ramos-Ruiz et al., 2017). Leaching of Pb cause reduced growth & reproductive rate in plants, animals, biodiversity loss and various other health issues like effects on kidney function, immune &nervous systems (Leccisi et al., 2016). Back sheet and encapsulants of PV panels are manufactured from polymer fractions consisting of fluorinated & cross-linked plastics which cannot be recycled. The burning of this polymer causes significant health issues and release of corrosive gases due to uncontrolled burning. These are the cause damage to ecosystem if this polymer is disposed of improperly. Crystalline silicon (C-Si) & thin-film (mainly cadmium telluride, Cd,Te) are the two most prominent module technologies. The major components of a c-si module are glass, silicon (Si), aluminium (Al), copper (Cu), silver (Ag) and lead (Pb). The compounds of tin (Sn) & cadmium (Cd) (compounded semiconductor) are the main components of thin-film modules besides glass and polymer sheets. Other bulk components of the modules also contain metals. The Hazardous materials used in PV manufacturing as mentioned in table 2.

Table-2

Type of cell	Material used	Critical issues if disposed of improperly
GaAs	Arsenic (As)	Poisonous, cancer promoting, lung affecting
	Arsine (As H3)	Toxic gas, blood, kidney damaging

	Trimethyl gallium	Pyrophoric liquid
	Hydrochloric acid	Corrosive material
	Methane Flammable gas	Methane Flammable gas
a-Si	Diborane (as dopant)	Flammable gas
	Silane (in deposition)	Pyrophoric gas, irritant, fire hazard
	Silicon tetrafluoride (in deposition)	Toxic and corrosive gas
CuSe. InSe	Selenium	Poisonous and irritant
CdTe	Tellurium	Adverse effect on liver
	Cadmium	Cause lung cancer.

Source: Nkuissi et al., 2020.

Various researches experiments studied, to remove silicon & other valuable metals from solar panel. In this process, they have carried out primarily two methods, thermal process (to remove EVA layer and glass) and chemical method (to remove Si and other valuable metals from solar panel).

5. TECHNOLOGIES FOR SOLAR MODULES RECYCLING.

A. **Separation of Glass and EVA layer:** Glass on solar panels are used to provide structural support to solar panel wafers and protect them from any external. EVA layer, a material that has good radiation transmission and low degradability to sunlight. It is an important component of solar modules used as an encapsulating agent since, by applying heat to the assembly, it forms a sealing and insulating film around the solar cells. It can also be reused if recycled properly. Various different methods for removing the EVA layer from solar panel available but most common methods are heating of solar panel so that EVA layer will eventually burn and main silicon wafers with electrodes can be received, while other method uses the organic solvents so that EVA layer will be dissolved in organic solvents.

B. **Applying organic chemical**: Organic chemicals like Odichlorobenzene (O-DCB), trichloroethylene (TCE), benzene, and toluene are used to separate EVA from solar cells in more of less percentage but they require much process capabilities to maintain in certified range like different solvent concentrations, temperatures, ultrasonic powers, and irradiation times. Toluene to recover EVA but it damages the solar panel cells due to swelling at 70o C and 450 W ultrasonic radiation. TCE and benzene organic chemical reduces the dissolution of EVA as temperature from 55 to 70o C because of pyrolysis and pyrolytic reactions. After cross linking treatment at 155o C, sample of solar module placed in TCE for several days. This causes the swelling of EVA which may damage the solar cell that can be overcome by applying mechanical pressure. O-DCB is also used for separation of EVA from solar cell. Solar module is placed in O-DCB for 120o C for one week and without applying mechanical pressure, solar cell was recovered. But this also requires much parameters to maintain at a time to get optimum result in separation of EVA, making overall method difficult to sustain. Y Kim and J Lee uses ultrasonic waves to reduce the time required for dissolution of EVA in c-Si PV modules from 7-8 days to less than 1 hour. Temperature of organic solvents is controlled by water jacket and thermocouple provide in container. This study shows that of EVA layer dissolution rate can be reduced conveniently. Similar process was adopted by Sukmin Kang, S Yoo, J Lee, et al for separation of tempered glass and EVA layer, process is continued by chemical etching of silicon cells.

C. Module and physical separation.

This involves physical separating of modules, like Junction boxes, embedded cables and Al frames are removed by dismantling the panels. The individual various parts (junction boxes, panels and cables) by crushing and shredding (Savvilotidou et al., 2017). EVA (ethylene vinyl acetate) is an encapsulant and sealant for solar modules. After they are separated, frames recycled using secondary metallurgy (Dias et al., 2018). Silicon cells also be recovered using an organic solvent method utilizing trichloroethylene solutions. Savvilotidou et al.,2017 assessed toxicity & recycling for thin films (amorphous silicon (a-Si) and copper–indium-selenide) by determining the optimal recycling condition using different acid mixtures under different concentration ranges and varying agitation rates. They concluded that a mixture of sulfuric & lactic acids performs the most efficiently and has low energy requirements. Zhang and Xu (2016) also used nitrogen pyrolysis and vacuum decomposition methods for separating and recycling plastic, glass and gallium under different conditions.

D. Chemical and thermal treatment for recycling.

Thermal treatment involves combustion. The PV modules are heated in between 500- 600°C. Components containing polymers are burned in a furnace but other materials like glass, Si cells & metals are separated manually. Leftover glass and metals removed can be sent to recycling units. Chemical treatment involves immersing PV modules in solvents where components are separated after chemical reactions. This approach is more time consuming than the thermal treatment. The recovery of Si cells is higher in chemical treatment compared with thermal processes. The recycling process was found to have 99% efficiency for recovering glass of dimension less than 1 mm along with separation of EVA and was tested using thermal treatment at a temperature of 650°C and a heating rate of 10°C/min with an air flux of 30 L/h. Fiandra et al., 2019 removed & separated polymeric layers from PV module structure using Lenton tubular furnace and thermal treatment by applying different ratios of nitrogen/oxygen mixture using two flow meters. Optimum flow rate of gas was analyzed to be 24 L/h with a process temperature of 500°C and heating rate of 450°C/h maintained for one hour was sufficient to separate polymers. Moreover, recycling of silicon wafers of greater than 180 μm investigated using acids like nitric acid (HNO3) or alkalis like potassium hydroxide (KOH) followed by etching paste for dissolving silver and aluminum electrodes and separating different layers of solar PV by thermal treatment at 480°C at 15°C/min (Shin et al., 2017). Organic solvents & thermal decomposition used by heating a PV cell at 600°C for 1 hour under argon gas with a flow rate of 200 mL/min for removal of EVA. HCL, HNO3, acetic acid & sulfuric acid were major constituents of the solution used along with stirring at room temperature for a duration of 60 min (Kang et al., 2012). Pyrolysis is also used as a new & effective process for recovery compared with combustion & solvent leaching. It has a relatively low environmental impact, as it avoids pollution from combustion gases and waste organic solvents (Wang and Xu, 2016). Pyrolysis technology, Wang and Xu (2016) removed 99.77% of organic matter & obtained 98.33% yield of acetic acid during recycling of the polarizing film of waste liquid crystal display panels. They recycled plastic, glass and gallium (Ga) from solar PV waste using nitrogen pyrolysis and achieved an organic conversion rate of 100% and also studied the optimum pyrolysis temperature, which should not exceed 500°C otherwise it will form more harmful products like benzene and its derivatives. A study of separating silicon & recovery of Tedlar Polyester Tedlar (TPT) backing material was conducted using a two-stage heat treatment based on pyrolysis. The pyrolysis processes that operates at a temperature of 500°C removes the EVA binder with the main products being acetic acid and hydrocarbon. At a low temperature, silicon solar panels were heated by electric heating at 150°C for 5 minutes which integrally peeled off EVA and TPT backing material. Recycling of PV modules is started by polymer removal which helps in recovering silicon, copper and silver. Hence, Dias et al. (2017) recycled polymer present in PV modules by determining optimum temperature and pyrolysis duration using thermogravimetric analysis (TGA) and statistical analysis; results revealed that removal of more than 99% of polymers is possible if a pyrolysis temperature of 500°C is maintained for a duration of 30 minutes. Furthermore, they concluded that temperatures over 500°C will surely degrade solar PV material but will also reduce mass loss rate as well.

E. Optical approach for recycling.

This involves separation of glass structure. The used PV module is loaded into optical treatment after removal of the frame & terminal box. Optical treatment. The treatment time is only 1 minute/module. The cover glass & substrate glass are separated after treatment is complete. CdTe and CIGS are treated using an acid like methane sulfonic acid (CH4SO3H). Metals in modules can be recovered, recycled, and purified by further processing. Each of these metals has distinct environmental impact, entailing specific handling & disposal procedures. While Al and Si are relatively less toxic, the heavy ones such as cd, tin& Pb are an environmental hazard. The analysis identifies silicon, germanium, lithium & cobalt as critical minerals based on their economic value. Further the metals such as Co, Ni & Fe have relatively low supply risk. The competitive consumption of these metals in other industries, coupled with limited availability and geopolitical uncertainty in the supply chain, which can increase the cost of end products. The supply of these critical minerals threatens the future of these clean energy So, the end-of-life(EOL) management & recycling of these products are crucial & adhering to concept of circular economy.

6. RECYCLING PROCEDURES & END OF LIFE TREATMENT OF PV MODULES

The PV modules recycling include dismantling, combustion, and etching. Dismantling involves removal of frames & boxes of modules. Combustion involves burning of modules to remove the organic encapsulant. This process ensures recovery of glass and solar cells (silicon or thin film) with minimal breakage. After recovering glass, the composition of acid or alkali solution is changed to recover the different metals.

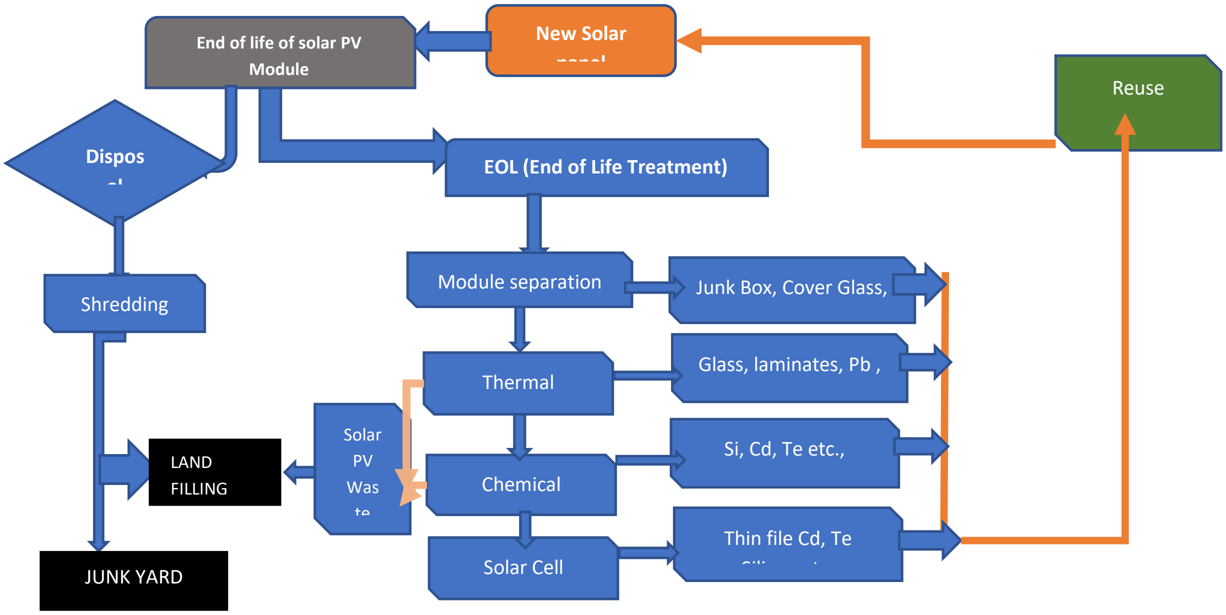


Fig:3- Recycling Process of solar modules & End of life treatment LCA)

6.1 Life cycle assessment of recycling processes.

It is necessary to assess impacts caused during the whole life cycle from extraction, production and manufacturing of material, recycling and disposal. Life cycle assessment (LCA) are carried out to support environmental product improvements, strategic planning, benchmarking with competing technologies. Stolz & Frischknecht et al, 2016., described the environmental life cycle assessment of crystalline silicon (c-Si) and cadmium telluride (CdTe) PV modules for various environmental indicators identified as most relevant for PV electricity. Two types of modelling approaches were used, that is, the 'cut off approach' and 'end of life approach'. The cut off approach used economic allocation to divide the total efforts of recycling process between treatment of recovered products and the used PV module. While the other process separately considers the recycling process from the potentially avoided burdens due to recovered materials.

The environmental impact generated by production of a 3 kWp (kilowatt peak) residential PV system mounted on a slant roof came out to be large as compared to recycling of c-Si PV modules (maximum 1.1%). In the case of CdTe PV module recycling, the treatment of the PV panels has the highest but still rather minor contribution in the indicator for climate change (4.8%). The highest contribution of environmental impacts in the life cycle is due to the use of fossil energy resources and respiratory effects caused by air emissions of particulate matter (PM) and nitrogen oxides. Among all other types, for copper-indium-selenide (CIS) thin film the lowest environmental impact was found as it uses more copper for coating and contact purpose in manufacturing. The highest impacts are for CdTe panels due to the large amount of cadmium used in coatings. Thin film systems tend to have lower impacts per kWp of cells, but due to lower efficiencies, they have a larger surface area and thus need more materials for the mounting systems. Latunussa et al. (2016) carried out mass and energy flows at various recycling stages for 1000 kg solar PV waste. About 73 m2 (with mass of 22 kg and surface area of 1.6 m2) of panels creates 1000 kg of waste. Life cycle impact assessment for 1000 kg silicon waste, assuming a distance of 400 km between collections and recycling plant (Latunussa et al., 2016). Credits achieved from energy recovery are separated from that impact which occurs due to the recycling process. The credits for the energy recovery are observed as negative values. These credits can be particularly relevant for impact categories such as: ozone depletion, ionizing radiation in ecosystems and ionizing radiation on human health (around 30%); climate change, particulate matter (PM) and freshwater eutrophication (around 30%). Major impact categories are due to transportation, incineration and metal recovery processes like sieving, electrolysis, neutralization and acid leaching. % age contribution of transportation ranges from 10% (for freshwater ecotoxicity) to 80% (abiotic depletion potential). Cancer effects caused by fresh water ecotoxicity are mainly a result of incineration of plastics, cables, PV sandwich and uncontrolled disposal of ash to dumping sites. Although incineration has a large negative effect on the environment, on the other side, it is expected to recover about 250 MJ of electricity and 500 MJ of thermal energy from combustion of polymers. Stages like disassembly, waste unloading, and thermal separation have the least impact (below 10%). A novel approach to recycling of PV panels, that is, Full Recovery End of Life Photovoltaic (FRELP) investigated by Latunussa et al. (2016), who report a recycling rate of 83%. The baseline process which is the base case used in European WEEE recycling plants is not efficient to separate more than 10% of glass, PV cells & plastics. Ardente et al. (2019) compared the FRELP process and baseline process for climate-change scenario and savings for the recycling process.

6.2 Recycling costs

The large-scale adoption of PV waste management and recycling is closely linked to the overall economics. The main costs in this process are waste collection, transportation to recycling facility, treatment, and residual waste disposal fee. A direct benefit is from the sale of the recycled materials. Other benefit could come from monetizing the reduction in greenhouse gas emissions resulting from amount of virgin minerals replaced by recovered minerals. A study for PV waste recycling in China estimates the recovery cost of PV modules as 25.11 USD/kW against a benefit of 25.68 USD/kW (Liu, Zhang and Wang et, al., 2020). The total benefits/cost ratio for recycling was 1.023. It underlines the importance of the sale of recycled materials to improve the overall economics.

6.3 Regulatory framework of various countries.

The EU WEEE directive on the processing of PV components was first approved by the UK, came into effect on 01.01.2014. It includes requirements to register the number of panels produced or imported from distribution channels. Germany has also revised WEEE regulations to make them more register products related to PV and assume accountability for EOL treatment. The European organization WEELABEX offers collection, storage, processing, and recycling of electrical and PV waste, and also directs waste processing companies. In the Czech Republic, a joint venture of PV waste processors was started to recover and recycle waste solar panels, to provide a service for complies with legal requirements for the processing of solar waste. Outside the European market, very few countries have made to regulate and recycle PV waste. Therefore, there is an urgent need among manufacturers who take a keen interest in the recycling of waste.

The US state has a project to administer & regulate the wastes related to solar equipment. The California Department of Toxic Substances Control (DTSC) promotes recycling to reduce the dumping of harmful substances into landfills. The utility scale project developer 'First Solar' has authorized various industries in the US and Germany to treat available solar PV waste. Almost 95% of Cd & ~ 90% of glass components reused. China is also leading country in the installation of PV panels, even in the absence of any policies for recycling and waste treatment. China has very few recycling ventures to deal with the problem of solar PV wastes (Ding et al., 2016). Opinion is divided over the urgency of addressing this issue and feel the 25-year lifetime of modules offers plenty of time to prepare an action plan.

As far as India concern, India will have 2 lakh tons of solar waste by 2030. According to the International Renewable Energy Agency (IRENA) by 2050 India will be number four ranking, behind China, the U.S. and Japan. India still has no solar waste plan in place. Not surprisingly, solar waste recycling was a hot topic at this year's Renewable Energy India summit in New Delhi, with attendees split between concern at the lack of action and a blasé belief the 25-year lifetime of PV panels offers India plenty of time to get its house in order. However, 25 years may be optimistic as IRENA has pointed to the rising volume of panels discarded long before that point thanks to improper installation, manufacturing defects, poor maintenance and soiling, and unforgiving climatic conditions. Laws to manage electrical waste have been in place in India since 2011, and mandate only authorized dismantlers and recyclers collect such 'e-waste'. The EU defines solar panels as e-waste under its Waste Electrical and Electronic Equipment (WEEE) directive but when India implemented its E-waste (Management) Rules 2016 legislation, in October 2017, PV products were again absent. The Ministry of New and Renewable Energy at least recognizes the problem and concept on management of antimony-containing glass from end-of-life solar PV panels document it issued stated: "Management of PV module need to follow the cradle-to-grave lifecycle assessment in four stages: (1) component production (2) module manufacturing (3) module use (4) end of-life-use stage." In India under the Extended Producer Responsibility (EPR) guidelines the 2016 E -waste management rules were put forward for handling the solar PV waste. The absence of managerial regulatory framework in the collection, regulation, recycling & recovery from solar waste is putting a next level burden on the Indian solar waste management. The major portion of the waste is dumped into the barren lands without treating it and thrown away of the garbage in such a disorganized manner is an indication of lack of cooperation and responsibility among the personals involved in solar panel manufacturing industry & installation. Extended Producer Responsibility (EPR), collaboration of solar panel manufacturers with the recyclers and collectors from the recycling centers at the end life are various governance approaches to be implemented as effective strategies. Establishment of effective supply chain among the managerial sectors of solar industry, solar panel installing authorities, which surpass the tenders of solar installations, manufacturing units of solar panels are utmost necessary for practicality and effective implementation of solar panel end life waste management policies in India.

7.0 EVOLUTION OF E-WASTE RULES IN INDIA.

The county needs to prepare itself for the rapidly rising volume of PV waste. Urgent action is required by policy makers to manage the PV waste. The provisional initial phase emphasizing the introduction of regulations for PV waste treatment is important. Private stakeholders and policy makers are required to act sincerely for the outgrowth of this sector. The following suggestions can be undertaken to handle this emerging problem (Suresh et al., 2019).

- All manufacturers should keep in mind the EOL stage for panels while designing various components for PV plants.
- Liabilities and responsibilities should be defined for each stakeholder involved in treating these wastes.
- Norms for PV waste collection, treatment and disposal are required.
- Agreements like mutual recycling between developers, modules manufacturers and purchasers should be encouraged.
- Awareness could be created by conducting surveys related to recycling treatment.
- PV recycling infrastructures that focus on high value recovery of waste should be promoted.

India has no separate specific rules for solar modules waste. The Ministry of New and Renewable Energy (MNRE) has issued a message for developers in its guidelines to ensure disposal or recycling of all solar PV modules. Developers are required to follow WEEE waste (management and handling) rules but no specific mechanism is active regarding waste disposal. In 2011, rules were notified regarding waste recycling. New rules were framed in 2022 by the MOEF&CC. These rules focus on distributing responsibilities to various manufacturers, distributers, and dealers. It should be made mandatory for all consumers to return the product for recycling, only then consumers will return. Each producer must set a certain collection centers target based on sales, volumes & lifespan. According to a report, only 4% of wastes were recycled out of available total electronic wastes between 2015- 2017; The target by 2023 is fixed for 70% (Suresh et al., 2019). India has to develop recycling infrastructure to deal with available e-waste volumes. Certified e-waste recyclers in India have the capacity to handle only 0.4 million tons/annum as per CPCB. India is under-prepared to manage the increasing e-wastes volumes due to low targets and poor implementation.

8.0 WAY FORWARD FOR INDIA

Presently, solar waste is treated under the E-Waste rules of MOEF&CC. However, given the distinct nature of this waste and the economic value of components, it is necessary to have a separate regulation in place. At present, India's PV module manufacturing industry is underdeveloped, and majority of the modules are imported from countries like China. The recycling policy can make India self-reliant by ensuring a sustainable supply of raw materials & creating employment opportunities.

First, working in lines of EU's WEEE Directive, India has revised its existing electronic waste management framework to include PV modules. The revised regulation, an expansion of the extended producer responsibility (EPR), should set the targets for collection and recovery efficiency of waste and lay out financing schemes for the same. Under the EPR, developers should report the sale of their products, collect the damaged or discarded products from consumers free of cost & update the status with targets. They should also maintain transparency & inform consumers of the procedures of module with battery waste management. This information should be mentioned on products to be easily accessible to consumers.

Second, as the current recycling processes are capital intensive, access to finance is crucial. Depending on the market share, Indian developers can choose any of the globally available financing models, such as pay-as-you-go, pay-as-you-put, and joint and several liability scheme. In the pay-as-you-go model, the developer pays for the process at the time of waste creation. This model is often implemented with a last-man-standing insurance. The insurance covers for an unforeseen event of a developer going out of business. In such scenario, the insurance company finances the waste collection and recovery. On the contrary, the pay-as-you-put model requires pre-allocating a fixed amount for the waste management process.

First Solar, a leading solar PV manufacturer in the US, uses this approach for recycling the waste from its modules. With the sale of each module, it sets aside a lump sum to meet the estimated future collection and recycling cost of its modules. In addition to these two models, developers can also opt for a collective producer responsibility scheme. Here, they jointly set a financing guarantee with last-man-standing insurance to pay for the collection and recycling costs corresponding to the market share of their products. Then, they use the pay-as-you-go model to cover the cost of managing the waste from their products. This model is successfully implemented in Germany.

Third, a market-driven initiative is important for a thriving waste collection and recycling industry. The various stakeholders of the Indian solar industry should take responsibility to invest in recycling technologies, finance routes, and feasibility examination by pilot projects. They can learn from the Solar Energy Industries Association (SEIA) in the USA and Japan. New Energy and Industrial Technology Development Organization (NEDO), which have taken a lead on clean energy waste collection and management. Japan, NEDO has been undertaking extensive research activities for PV recycling. In 2014, it developed an automated PV recycling technology that separates different types of panels (crystalline Si, thin film) to recover valuable materials such as aluminum, Si, glass, and metal semiconductor. This technology is currently in the experimental phase. In India, the Ministry of MNRE has endorsed several solar associations, such as the National Solar Energy Federation of India (NSEFI), the Indian Solar Manufacturers Association (ISMA), and FICC-Renewable Energy.

These associations have to collaborate & develop guidelines for reporting the sale and damage of modules, invest in new recycling technologies and examine the feasibility of existing services, and create a financing scheme for the same. As distributed renewable energy sources such as solar PV and energy storage penetrate deep into the Indian electricity sector. it is necessary to prepare for managing the waste generated from these technologies. The local manufacturing industry will benefit from decreased dependence on the import of raw materials. It is imperative for the government to introduce a holistic policy framework for handling the waste from clean energy technologies, highlighting the responsibility of different stakeholders, and creating an enabling environment to implement the same.

9.0 RESULTS & DISCUSSION:

As per literature, it is estimated that by 2022, 100 GW solar power plant installation target is setup by the MNRE. Among this target 60 GW grid connected solar power plants and 40 GW rooftops are to be targeted for installations. Solar Power parks are also to be installed for up to 40 GW capacity till 2022. The increasing installations are only giving a message that the focus of the Indian government is on the installations and not much in the waste management approach at the onset of end life of particular solar PV plant. Core realities of solar waste management in India. Approx. 2.95 from 2020-2047 an effective strategic planning is the utmost need of the approaching times. Rapid industrialization, increased standard of living, urbanization, raised energy demands of people and the availability of indispensable amount of solar energy in India are the promoting features or enablers for increased installations of solar power plants in India. These driving forces are promoting the way of Indian government to move towards the achievement of 100GW installation capacity by 2022. Besides the skyrocketing solar photovoltaic installations there is a prominent and dire need of identification of enablers related to resource recovery and management of solar photovoltaic waste. Solar PV installations in India are dependent on import from other countries due to zero commercialization of solar manufacturing. Due to this the cost of the product on its end life treatment is increased as their lies uncertainty in the product import. Utilization of semiconductor materials like Silicon, Germanium and alkali metals like lithium are cost consuming. Further the utilization of Silver in the manufacturing of solar panels is a major confrontation prevailing in the solar PV sector. These confrontations are also to be taken care at the end life management of solar panels. Synchronized and well-ordered approach needs to be applied for the reduction of resource availability at the end life management. Circular economy needs to be developed for the obtaining the utilized resources at end life management. 60% to 90% recoverability has been projected from the end life of solar panels.

Under EPR, E-waste management rules -2022 put forward for handling the solar PV waste. Vagueness and absence of managerial regulatory framework in the collection, regulation, recycling, and recovery from solar panel waste is putting a next level burden on the Indian solar waste management. Major portion of the waste is dumped without treating it. Throwing away of the garbage in such a disorganized manner is an indication of lack of cooperation and responsibility among the personals involved in solar panel manufacturing industry and installation. Such negligence by the higher authorities has made it difficult to establish rightful control and order following the footsteps of EPR commercialized among European nation. The present solar industry of India with the rising installations, accumulated waste will be hiked drastically, so a systematic regulatory approach in term of commercial policy making must be practiced. EPR collaboration of solar panel manufacturers with the recyclers and collectors from the recycling centers at the end life are various governance approaches to be implemented as effective strategies.

Establishment of effective supply chain among solar industry, solar panel installing authorities, authorities which surpass the tenders of solar installations, manufacturing units of solar panels are utmost necessary for practicality and effective implementation of solar panel end life waste management policies in India.

10.0 RECOMMENDATIONS & CONCLUSIONS.

The rapid evolution of the solar PV sector & production of waste generated of PV modules contains certain hazardous & toxic substances like Cd and Pb are used in small quantities. Hence, it is essential to monitor & manage these substances of waste, which will be present at end of life (after 25 years). To avoid their detrimental effects on humans and the environment due to these pollution issues, two solutions concern the use of less hazardous materials and performing more thorough research and development. In addition, it is pertinent to develop production processes that pose less impact on the environment. Such processes are expected to reduce the risks related to EOL PV systems in line with the improving conversion efficiency and material usage of both CdTe and Si PVs. As the solar sector gains popularity and makes further progress, advancement in technological methods for managing wastes should consider appropriate recycling techniques. Adoption of a closed-loop management system is necessary to directly reduce the harmful environmental impact of manufacturing and recycling of solar panels. Although elements like gallium, indium and germanium are used in constructing PV panels, only silicon, which is employed in the panel terminals, can be recycled. Another problem facing recycling processes is the subsequent release of solvent emissions, which can be reduced by using an activated carbon fiber adsorption recycling condensation device. Various actions are needed to encourage economic growth in the chain involving both production and consumption stakeholders.

The feasibility of waste management of PV panels, presents various ways for R&D in this sector to overcome complex issues. A combined approach is required among policy makers, institutions and business community to grasp models that may support systematic change for economic goals. A regulatory framework is suggested involving several methods for stakeholders to work appropriately on recycling agreements. Sustainable materials should be used for developing PV modules during production. Module manufacturers should emphasize qualitative models to use sustainable materials during the production stage. The LCA also plays an important role in the design of future panels in a way that reduces the impact of recycling, hence maximizing recovery. Besides the rapid development in the solar PV sector, it is proposed to have an appropriate approach for recovery and recycling of the EOL wastes. It is recommended that recycling is made necessary for all manufacturing companies after their EOL. In summary, policies must be adopted by government to ensures that all manufacturers consider the impact of their waste on the environment. It is vital to require whole solar manufacturing sectors to act responsibly and recycle, reuse & recover their products.

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