

Chapter 2

LITERATURE REVIEW

2.1. Introduction

The chapter provides an overview of the literature on global solar photovoltaic waste accumulated across different regions of the world. Due emphasis on the Indian solar PV waste scenario, solar panel waste recycling policies, end life management of waste solar panels, material recovery and economic analysis, life cycle impact analysis, and environmental impact analysis of waste solar panels. Further, the chapter summarizes the literature review and provides the research gaps.

2.2 Review of Literature

Attainment of sustainability has become an important agenda for humans today. To full fill it there has been a shift from conventional sources of energy to renewable sources of energy. Solar photovoltaic technology produces electricity at much lower prices than conventional energy sources in an environmentally friendly manner. A particular solar Photovoltaic plant can produce electricity for up to 25-30 years. After its life cycle is over effective waste management is required for this PV waste disposal. Scanty manufacturers have initiated the recycling of Solar PV waste management. Globally only a few countries have taken the initiative for PV waste recycling. To eradicate the issues of rising solar panel, waste the researcher has put forward an in-depth review of the literature.

(Keoleian & Lewis, 1997) analyzed that manual disassembly of components and materials is usually not economically viable. Retired modules may be disposed of in landfills; large quantities of modules may be shredded in hammer mills, just as automobiles and white goods are currently processed at the end of their useful lives.

(Markvart & Castañer, 2003) have analyzed that hazardous materials like HF, SiH₄, Cd, H₂Se, and AsH₃ are used in the manufacturing of solar panels and these are responsible for causing cancer, explosions, etc. further critical effects can be seen on the liver, CNS, sense organs, kidney, etc. by chemicals like diborane, carbon tetra

chloride, H₂Se, H₂S, etc. These effects are occupational hazards and also human health risks for all three generations of solar PV technology.

(Mcdonald & Pearce, 2010) have suggested recycling policy favoring economic benefits with due emphasis on Extended Producer Responsibility to tackle environmental impacts of hazardous materials.

(Gottesfeld & Cherry, 2011) have suggested investments in environmental controls in lead smelting, battery manufacturing, and recycling industries along with improvements in battery take-back policies should complement the deployment of solar PV systems to mitigate the negative impacts of lead pollution.

(Canada, 2012) have analyzed that small amounts of heavy metals and other chemicals such as cadmium and lead are used in the production of PV cells and can arise from waste created by decommissioning. But PV modules can be an environmentally friendly means to sequester elemental cadmium, and it can be reclaimed and used again when PV modules are recycled.

(Raugei et al., 2012) have found out that the actual levels of Cd emissions to air and water from the end-of-life of CdTe PV are relatively low and considerably lower, for instance than those from the end-of-life of common NiCd batteries.

(Al-Thyabat, 2013) have shown that recycling process complexity includes uncertain quality of EoL products, products dispersed in various geographical locations, various technologies required since there are various types of PV panels.

(Dubey et al., 2013) have analyzed that health hazards and risks during the manufacturing phase affect human health due to the toxic properties of materials in use along with their concentration and the frequency of exposure to humans and the ability of absorption by the receptor cells. Arsine, phosphine accidental gaseous release, inhalation of acidic fumes of HF, HNO₃, and the chemicals which are disposed of in landfill pose the greatest threat to the lungs and the gastrointestinal tract by entering into the food chain through leaching from the ground. CdS layer used in the thin films is also carcinogenic if leaked.

(Giacchetta et al., 2013) has presented that enabling responsible EoL management of PV panels with circular economy concepts will prevent a shortage of rare materials and ensures that resources are used to their fullest potential.

(Peng et al., 2013) have analyzed that factors like lifecycle energy requirement, EPBT, and GHG emission rate of PV systems affect the estimation results.

(Baharwani et al., 2014) proposed the environment load of photovoltaic power generation system during its life cycle by energy payback time and Greenhouse Gas emissions through LCA study and also found out that there were no emissions during the operational phase but the manufacturing of solar panels involves emissions.

(Cyrs et al., 2014) found that for CdTe panels specifically, the income made from selling recovered materials was currently less than the cost of recycling. The scarcity of tellurium could render recycling more economically favorable in the future. The health risks of improper handling of end-of-life CdTe PV panels and poor exposure controls during recycling could easily outweigh any cost savings achieved by the process.

(Park & Park, 2014) have presented that the etching of broken panels was carried out firstly by nitric acid , hydrofluoric acid mixture, and potassium hydroxide , second time etching was carried out using phosphoric acid , HNO₃ and HF mixture.

(Aman et al., 2015) analyzed Arsenic -heartbeat problems, throat infection, lung cancer, nausea, vomiting, reduced blood cells, skin darkening, red spot-on skin, liver problem, etching in hands and feet. Strict guidelines should be followed during the disposal of hazardous wastes, generated in solar panel manufacturing.

(Ardente et al., 2015) concluded that end of life of solar technologies is still not sufficiently investigated due to the limited amount of solar plant waste (negligible compared to municipal and electronic waste flows) and their long lifetime. A sustainable approach for the design of solar technologies should focus on the whole lifecycle to avoid the potential shifting of burdens from one phase to the other.

(Kang et al., 2015) observed that there were no policy currently exists in Australia for end-of-life management, collection, or recycling. The current technology requires a substantial amount of acid and alkaline liquid to recover silicon and extract silver. Thus, appropriate management of waste chemicals needs to be considered.

(Palitzsch & Loser, 2015) concluded that Methane sulfuric acid and hydrogen peroxide resolve semiconductor and silver. Polyaluminium chlorides react with water to form insoluble aluminum hydroxides which precipitate in big volumetric flakes solution of silver mesylate. By the use of alkyl sulfonic acids extract all used metals in a very short reaction time.

(Prakash & Rayabagi, 2015) assessed that technologies have to evolve for efficient recycling and disposal of these panels, along with leading research in the manufacturing processes, to enable the world to be prepared for it, when the time for massive disposals arrives.

(Rocchetti & Beolchini, 2015) established the need of innovative recycling policies for recovery of Ga, In, Te approved by society, no risk towards the environment and without legislative, economical, technical constraints will be very successful.

(Tao & Yu, 2015) assessed that the economic viability of recycling end-of-life modules is still unfavorable, and policies are required to encourage producer responsibility not only in the PV manufacturing industry but also in the entire energy industry. Additionally, an effective collection network should be crucial to the economic viability of the PV module recycling business. End-of-life module recycling has a significant positive impact on reducing environmental loads.

(Yu & Halog, 2015) concluded that Trina Solar encourages Extended Producer Responsibility, and it collects end-of-life PV modules sold in Europe through the PV Cycle initiative. In Europe, the end-of-life or defective PV modules are recycled at facilities with certified environmental management systems.

(Zapf-Gottwick et al., 2015) found that photovoltaic modules have a high-risk potential by releasing hazardous substances to the environment if they are not properly

disposed of in domestic waste landfills, in building rubble dumps, or in wild waste dumps as might be the case in developing countries. Toxic materials, such as Cd and Pb will be leached out completely. 30 % of the cadmium is leached out from milled cadmium telluride module pieces, increasing to 50 % after 56 days. At the same time, more than 15 % of lead is leached out from c-Si module pieces. Tellurium elutes in the range of 30 to 40 % with a weak dependence on the pH value of the solution indicating instability of the compound cadmium telluride out of the cadmium telluride modules.

(Besiou & Van Wassenhove, 2016) established that countries with less developed PV and BESS markets will see only a small quantity of EoL PV panels and thus making the recycling process unprofitable.

(Chatzisideris et al., 2016) concluded that stakeholders should have better information from a holistic perspective based on LCA findings and should carefully consider toxicity-related and resource depletion impacts.

(Goe & Gaustad, 2016) have found that lack of adequate material supply is opening the way for the recycling of PV module material. Recycling solar cells can aid in reducing resource waste. Human health impact can be studied from the recovery of photovoltaic materials.

(Jia & Fang, 2016) assessed that no specific regulations for EoL PV modules, Policy suggestion includes special regulations or laws need to be established for EoL PV modules recycling in China. The responsibility and financing of recycling should be ensured. The recent mid-long-term target of the mass recycling rate should be pointed out. The standards and guide rules for EoL PV modules recycling need to be drafted to guide the recycling and disposal more cost-effective and environmentally friendly.

(Latunussa et al., 2016) studied the disposal of PV panels as a major environmental issue. Incineration of the encapsulation layer on the solar panel is carried out and after it, the recovery of metals is done. Both these processes have their environmental effects.

(Nassar et al., 2016) studied that increasing primary production via enhanced recovery rates of the byproduct metals during the beneficiation and enrichment operations is

improving end-of-life recycling rates.

(P. R. Dias et al., 2016) assessed that mechanical milling followed by sieving was able to separate silver from the copper while chemical separation using sulphuric acid was able to detach the semiconductor material. A thermal gravimetric analysis was performed to evaluate the use of a pyrolysis step before the component's removal. The analysis showed all polymeric fractions present degrade at 500 °C.

(Ravikumar et al., 2016) by hotspot analysis shows that reducing the energy required to recover unrefined semiconductor material from the module and ensuring high recovery of steel and glass from the end-of-life CdTe PV system will have the greatest impact on the energy benefit of recycling.

(V. Fthenakis et al., 2016) in end-of-life allocation, the benefit of recycling is realized from recycled material displacing primary production in the future, with the environmental burdens and benefits of recycling allocated to the product producing the waste at its end of life. In recycled content allocation, the recycling benefit is realized by the product using the recycled content in its production. In the manufacture of wafer-based crystalline silicon solar cells, occupational health issues are related to potential chemical burns and the inhalation of fumes from hydrofluoric acid, nitric acid and alkalis, used for wafer cleaning, removing dopant oxides, and reactor cleaning.

(Weckend et al., 2016) studied that since early 2000 the deployment of the PV sector has increased. With the increasing installations, the volume of the decommissioned panels has also increased. End-life management can foster employment boon for society and high economic value. Sustainable end-life management policies are to be established. Research and development programs are to be established the support additional value-creating from solar panels at their end life.

(W. Chen et al., 2016) found the key substances that contribute to the overall environmental impact are lead, arsenic, mercury, copper, and nickel to air generated from Ag paste, electricity, and glass production, as well as Ag used for Ag paste production.

(**W.-H. Huang et al., 2016**) analyzed valuable and toxic metals including Ag, Pb, Sn, and Cu can be recovered from end-of-life Si solar modules. The metals are first dissolved in an aqueous solution of HNO₃. Sn precipitates in the solution as SnO₂, which can be separated by filtration or sedimentation. Ag and Cu had recovery rates of 74% and 83%, respectively.

(**Ashfaq et al., 2017**) concluded that recycling is attempted to develop a safe and cost-effective process for the disposal of PV solar panels. Reclaiming such materials keep precious natural resources from being depleted, as well as keeping these wastes out of our landfills.

(**Brenner & Adamovic, 2017**) studied that cooperation among stakeholders is required to enable constructive and collaborative discussions on policy or recycling solutions.

(**B. Huang et al., 2017**) focused that a network for collecting end-of-life solar modules is to be proposed, based on the current distribution network for solar modules including the collection cost.

(**D'Adamo et al., 2017**) concluded that large capacity of recycling plants will reduce the cost. Transportation of waste to treatment facilities accounts for pollution too. Innovative recycling policies for recovery of Ga, In, Te approved by society, no risk to the environment, and without legislative, economical, and technical constraints will be very successful. Environmentally friendly recovery of Ag from end-of-life c-Si solar cell using organic acid and its electrochemical purification.

(**Dassisti et al., 2017**) analyzed the effects of a thermal cycle at cryogenic temperatures as a preliminary industrialization analysis of a new and sustainable de-manufacturing process in which delamination, i.e., the separation of the layers in laminated material, can be obtained by inducing sufficiently large stress and, thus a material failure in the layers.

(**Domínguez & Geyer, 2017**) found out the recovery includes precious metals including 139 mt of cadmium, 100 mt of tellurium, 10 mt of indium, 17 mt of gallium, 271 mt of silver, and 10 mt of gold. Metal recycling faces challenges in recycling

technologies, product design, and social behavior.

(Kadro & Hagfeldt, 2017) studied that recycling is also to be performed on a using various solar panels' components and materials once more. By shredding, detaching, solubilizing, chemical bathing, and material sorting, solar panel components are separated; further recycling is possible by processing panels in the designated glass. To avoid garbage piling up, it is necessary to recover both hazardous as well as non-hazardous items that may be either reused or disposed of in the land. Burying or disposing of trash in land is the least preferred option for waste treatment.

(Kusch, 2017) analysed that the optimal strategy for the number and type of (e.g., centralized or decentralized) collection centers and recycling plants ensures an optimal balance between the collection rate as well as economic and environmental feasibilities.

(Malandrino et al., 2017) focused on the exploration of the end-life management of solar photovoltaic panels, particularly in Italy and Europe. Effective end-life management of the solar panels is also necessary for the safe disposal of the PV waste as the CdTe and c-Si panels contain hazardous Cd and Pb respectively. Cd causes plant chlorosis, and toxicity to animals, and in humans, it can result in kidney dysfunction, pulmonary emphysema, etc. Pb affects the CNS, endocrine system, cardiovascular system, etc. The decommissioned solar panels were included in the WEEE directives of household waste. The responsibility of the producers is extended to take back their product from the market. By developing skills and knowledge in the solar photovoltaic industry effective end-life management is to be curtailed in the process to establish a green PV industry. The circular economy is to be established.

(Glatthaar et al., 2017) studied that broken front glass parts can be removed only partially by chemical treatment. After warm-up to temperatures between 80°C to 140°C, the back sheet is easily removed from the laminate. Chemo-mechanical removal of the aluminum frame. Chemo-thermal removal of the glass and back sheet. Dissolution of the encapsulant, mainly ethylene vinyl acetate.

(Peeters et al., 2017) concluded that an adequate recycling strategy with framed legislation can only reduce the environmental burden of hazardous waste due to their

dumping.

(Sampaio & González, 2017) have assessed that for energy market the competitive position of each solar technology is determined by the efficiency factors, lifetime, cost, and environmental factors.

(Savvilotidou et al., 2017) have found that the 2012/19/EU recast's recent inclusion of end-of-life PV modules necessitates sound and sustainable handling. The critical risk of metals like indium and gallium is also to be considered. Acids utilized for the chemical treatment during recycling also pose detrimental effects on the respiratory system and CNS. Sulfuric acid is considered for proper panel delamination in the case of amorphous and CIS panels, respectively. Inhalation and oral exposure lead to storage and disease in the kidney. Huge potential for new companies which collaborate with manufacturers and academic researchers to recycle PV modules or properly dispose-off if recycling is not possible to make this world more sustainable and a better place to live.

(Shin et al., 2017) found that Ag and Al metal electrodes were dissolved sequentially in solutions of HNO_3 and KOH to recover the Si wafers. Impurities on the wafer surface were removed by using an etching paste containing H_3PO_4 . This method is environmentally friendly because it can reduce the amount of water used for cleaning and also do away with the necessity for toxic surfactants.

(Strachala & Hylský, 2017) concluded that recycling PV modules by the thermal method are more advantageous than using a chemical method. The length of the process is significantly shorter and there are lower financial costs. The disadvantage of thermal treatment is the formation of emission gases during decomposition of the EVA copolymer and also the risk of wafer damage. In the mechanical recycling process, it is very important to know which technologies and devices are suitable for the creation of crushed material. Silver-containing crushed material up to 0.07 % is not economically advantageous to process chemically.

(Vellini et al., 2017) have presented that although CdTe modules require less material input than c-Si technology, their catastrophic consequences are significantly worse than

those caused by c-Si. The manufacturing process, utility phase, and end-of-life phase all result in the discharge of hazardous gaseous pollutants into the environment. Additionally, not only the production process but also the resource usage is taken into account when assessing the influence on the environment. The disposal and end-life plot of the c-Si and CdTe panel is given a comprehensive analysis. 25.68% Human Toxicity Potential is also estimated from Si panels and 91.09 % for CdTe panels. CdTe modules are more economical and beneficial for recycling but the toxic effects of the cadmium need a solution. For the manufacture of CdTe panels, the environmental effects related to human, marine, and terrestrial toxicity are extremely severe without recycling at the panel end-life because Cadmium is an extremely toxic substance.

(V. Fthenakis & Raugei, 2017) studied the environmental impacts of the life cycle of PVs as assessed by the common metrics of GHG emissions, toxic emissions, and heavy metal emissions are very small in comparison to those of the power generation technologies they replace.

(Varade et al., 2017) have found that while implementing the improvement techniques capital cost increases but the return period significantly decreases which is indirectly beneficial. Comparison of the current electricity bill with the bill before installation of the solar panel system and conducting detailed analysis to understand Energy consumption.

(Wade et al., 2017) assessed that with no appropriate regulatory framework and infrastructure for the management of end-of-life photovoltaic panels could lead to environmental and health risks.

(Abdalla & Agarwal, 2018) have studied that greater responsibility will be pointing to the customers and recyclers by bringing out the e-waste guidelines of the government. The setting combined formal and informal recycling centers with the facility to collect, segregate and dismantle. Environment protection management training with incentive provision for all the transportation routes.

(Amarakoon et al., 2018) found that dust of the metals used in CIGS cells, copper exhibits the highest toxicity impacts, including aquatic toxicity. Substitute recycled

metals for virgin materials, and substitute the cadmium sulfide with the zinc oxysulfide alternative.

(Arora et al., 2018) have assessed that solar photovoltaic technology use has increased in India since 2010. Life cycle assessment of the different stages of the solar photovoltaic technology is dully noted from the initial stage of designing the solar panels to its product stage which involves restricting the use of harmful material in manufacturing and also finding the alternative material. Solar photovoltaic waste at the end of life can also be handled by the reuse, recycle and recover methods.

(Bosio et al., 2018) concluded that recycling is essentially a profit-making procedure by reducing the harmful impacts of redundant solar panels. The methods of recycling are governed by the components present in the solar panels.

(Celik et al., 2018) have studied that cadmium sulfide (compared to zinc oxide and tin oxide) and lead (II) sulfide (compared to lead (II) iodide) were fewer toxic alternatives for electron selective layer and light absorber, respectively.

(Dadhich & Pahwa, 2018) attempts to understand its financial feasibility using an approach of investment analysis. The paper is an effort to the development of an approach for estimating the financial impact of huge investments to be done in SPVs in non-commercial undertakings like Universities which may help contribute to energy consumption but also provide technical education to the students. Energy generation per year multiplied by the cost of a unit lead to years of payback period which is very low in term of recovering the entire cost of the whole PV installation.

(Gu et al., 2018) have proposed a recycling methodology for obtaining high-purity products from CIGS waste. Using this process, Cu and Se, as well as Gallium and Indium trichloride, were collected at high recovery and purity rates.

(Ibanescu et al., 2018) concluded that developed economies invest in complete and coherent measures that assure the proper treatment of key waste streams, such as WEEE. Fragile economies have still issues related to the implementation of EU legislation.

(Ilias et al., 2018) have shown that recent advances in PV modules recycling include a combination of physical and chemical technologies to follow the zero waste concepts and to enter PV recycling into the circular economy.

(J.-K. Lee et al., 2018) have discussed that unbroken solar cell recovered from the module using the combustion process were immersed into a mixed acid solution to reclaim the c-Si wafer. Solar cell was then remanufactured using the conventional solar cell manufacturing process. Pyrolysis not only has the benefit of no chemical oxidation of the constituents but also a relatively clean separation of the subsequent layers without the need for hazardous chemicals.

(Komoto et al., 2018) have analysed that technical innovations are to be established to gain valuable materials at a low cost. Policies responsible for the effective management of PV waste at its end of life should be entertained. Specific regulations based on WEEE household waste are established by the European Union for PV waste regulations at the end of life. In USA general waste regulations are applied for the PV end life. In California, the hazardous toxic PV waste is to be treated under the Toxic substance control bill within its borders. First Solar Company has established a recycling program for thin film solar panels. Solar Energy Industries Association of the U.S has established a committee to incorporate social responsibility for the recycling of PV panels. Under this at the end life stage dismantling of waste PV panels, collection and transportation, and further their reuse, recycling and disposal are covered. China is lacking in regulations for end-life management. However, under the twelfth five-year plan research technology for the PV recycling and their safe disposal is proposed to be initiated. Thin film technology will be the focus of recycling as it contains materials of economic importance and also toxic metals. In Korea, the Ministry of Trade, Industry, and Energy (MOTIE) has initiated recycling centers to be built for thin film and c-Si modules and also to establish a system for the collection and transportation of waste PV panels.

(Luo et al., 2018) have focused that frameless double-glass module technology can significantly enhance the environmental performance of silicon PV technologies.

(Ludin et al., 2018) concluded the highest cumulative energy demand, longest energy

payback time, and highest emission rates were assessed in mono-crystalline silicon panels through Life Cycle Assessment among others.

(Matsubara et al., 2018) have studied Copper and aluminum particles derived from waste crystalline silicon solar cell modules were etched using mixed acid of HNO₃ and HCl. The rate-determining steps of Cu and Al etchings were represented by a volume reaction model instead of a surface reaction model.

(Mughal & Sharma, 2019) have concluded that International Agency for Research on Cancer classified Cd as Category 1 human carcinogen. Human exposure to these hazardous chemicals by inhalation, ingestion, or skin contact poses a great risk to human health and social conditions. The toxicity of Cd first came to light with the outbreak of the “Itai-Itai” disease in Japan in the 1950s.

(Padoan et al., 2019) have considered even taking into account the drawbacks of solar panel recycling, such as the cost of chemicals and gas emissions, these procedures are still practical and may be improved with wastewater treatment, gas emission filters, and the reuse of chemicals. Europe is now the only region with a robust and well-defined legal framework to enable the PV recycling process. The recycling of PV modules should not stop just because the present approaches are not profitable. End-of-life PV panel recycling is legally required in several European countries, which has sped up the development of reclaiming techniques. There are several patented recycling techniques in the commercial sector, with the hydro-metallurgical treatment of CIGS panels accounting for 43% of all of them.

(Santos & Alonso-García, 2018) have emphasized on the gravity of reprocessing solar waste due to the high economic value of the metals like Si, Cu, In, Ag, Ga, and Te which reduce the architectural cost of the new solar PV materials. Reclaiming methods of waste PV materials play an important role in economic sustainability.

(Senthil Kumar & Gunasundari, 2018) analysed that the heavy metals reach the human body, they can cause vomiting, nausea, anorexia, dermatitis, and gastrointestinal abnormalities. The toxic nature of heavy metals also can alter blood composition and disrupt or damage the metal and central nervous systems, livers, lungs, and kidneys. In

the bioremediation process, microorganisms or plants are involved in different enzymatic actions, which may decompose the contaminants that result in producing the harmless product.

(Smith & Bogust, 2018) have shown that recycling practiced at panel's end life is significant to lessen environmental hazards. Challenges pertain in terms of efficiency, complexity, chemicals, and energy utilized to recover materials.

(Sica et al., 2018) analyzed that regulations can force consumers, producers, and recyclers to return/collect the products at the end of their life cycle as well as urge producers or recyclers to meet a certain standard of recovery rate.

(Tasnia et al., 2018) assessed that proper management and recycling can at a time protect our environment from being polluted by PV- waste, also it will support considerable economic value creation by adding financial support to our economy.

(Tiew et al., 2019) concluded that policymakers involved in planning, organizing, and implementing community recycling programs have to emphasize strategies how to engage community residents by changing their attitudes, addressing environmental impact issues, and adopting recycling practices.

(W.-H. Huang, 2018) have shown that the recycling process generates a revenue stream of over dollar (\$) 12/module from the recovered solar-grade Si and Ag, which is more than enough to cover the cost of recycling. The potential need for solar PV recycling policies by analyzing existing recycling protocols for the various solar panels. One way to make recycling economically feasible is by implementing stricter laws and increasing the fines related to the proper disposal of these hazardous wastes.

(Yousef et al., 2019) have found out that Al layer disintegration process using Dimethyl Sulfoxide (as an eco-friendly and sustainable solvent) supported by ultrasonic treatment to break van der Waals' bonding between spherical Al microparticles that compose the Al paste layer, thus liberating Al in microparticle suspension form with particle size approximately 3 mm, recovery rate >98%. After that, leaching by nitric acid and other eco-friendly reagents (Sodium Chloride, Ammonia solution, and glucose syrup)

assisted by ultrasonic treatment was used to dissolve Ag and later precipitate it in form of nanoparticles with avg. size 30 nm, yield >92%. Finally, etching using a paste containing phosphoric acid was done to remove the anti-reflection coating and purify the Si substrate with a final recovery rate >99%.

(Camp, 2019) concluded that recycling utility-scale solar sites can greatly reduce the environmental impacts and energy payback time of solar. There is an opportunity to reuse many of the materials, as well as the site location for future solar energy installations. All electrical equipment will require replacement, while mounting structures may last longer.

(Del Pero et al., 2019) studied that mechanical treatment is operated by disassembly, crushing, sieving, sorting, and other processes, which are now limited to pretreatment as complete separation of each material is hard to be satisfied.

(Deng et al., 2019) have found that solar panels, if not handled at their end of life, pose a negative impact on the environment. It's essential to make recycling technologies at their end of life economically feasible and sustainable. Silicon technology is less economically feasible for recyclers due to the difficult separation of the components. End-life responsibilities should be taken care of by the manufacturers to facilitate the steps for easy and economic recycling and also to eradicate toxic components. The landfill disposal cost of the occupied land area is also to be added to the recycling cost. Recycling technologies employed at the end of life are analyzed based on techno-economic methods. Technological improvements are to be imparted at the environmental and economic stages. The landfill process appears to be the cheapest method where land costs are low. Recycling glass is feasible economically even in places of high land cost. For recycling at a commercial scale collaboration of the various stakeholders requires to discourage the landfill process and also to lessen the transportation cost. The foremost aim of the recyclers should be to recover economically important materials like Ag and silicon.

(Faircloth, 2019) have analysed that recycling methods affect the environment, though they are better than landfilling but need added monetary cost. Cadmium is a highly toxic element and potential exposure to Cd dust and vapors can be carcinogenic.

(Fiandra et al., 2019) stated that mechanical treatment at preliminary allows the removal of fluorinated polymers to exclude dangerous emissions of hydrofluoric acid and fluorinated compounds from conventional heat treatments. Thermal treatment allows the complete removal of the residual polymers and the separation of valuable materials.

(Gangwar et al., 2019) concluded that the handling of solar waste is currently not transparent in India. To separate the PV scarp from the general waste systemization, the sustainable energy pillar act must be endowed. Recycling of solar PV material is currently not governed by any rules. The Ministry of Environment, Forestry and Climate Change is in charge of managing other waste and hazardous waste in accordance with 2016 solid waste management regulations as well as transboundary movement regulations. Hazardous chemicals are used in the production of solar PV materials; if they are not treated or recycled, the environment will suffer.

(Lahtela et al., 2019) have shown that with mechanical abrasion pre-treatment, 96.2% of indium was recovered and a black mass with an indium content of 15.6 wt percent was obtained. Following the mechanical recovery, sulfuric acid leaching was used to produce leachates with an indium purity ranging from 86.3 to 98.0% with an 88.7% to 98% yield for indium. Indium was recovered from the leachate by cementation with zinc powder, but also the impurity metals were cemented.

(Mahmoudi, Huda, Alavi, et al., 2019) have focused that a holistic strategy for end-life treatment should be established. Even if the PV installations are increasing very less has been done for end-life management only focusing on recycling to gain valuable materials. Further policies are to be built upon for the end life management and also a PV waste management commercial process establishment. The universal monitoring system is to be developed for the end-life management of solar PV waste including decision makers, companies to invest in the end-life treatment methods, and also the active participation of recycling firms on a commercial scale to build environmentally friendly end-life management.

(Mahmoudi, Huda, & Behnia, 2019) assessed that an appropriate policy is needed to

manage the emerging PV waste stream in Australia better to ensure a reliable and sustainable recycling procedure maximizing resource efficiency.

(Maani et al., 2020) found that chemical-based processes such as nitric acid dissolution, solvent, ultrasonic irradiation, and chemical etching produce higher impacts compared to the thermal methods. The thermal-based recycling techniques had less of an impact on the environment while recycling c-Si and CdTe PVs.

(Miliute-Plepiene & Youhanan, 2019) concluded that zero waste economy can help in achieving the concept of the circular economy. Business models to enhance this should be adopted by initiating a hierarchy to manage the generated waste by re-use, recovery, and minimization to prevent waste generation.

(Michas et al., 2019) assessed that policymakers examining the market designs which will enable the adoption of novel energy services, in a manner acceptable for consumers, need to investigate the national requirements to replicate successfully implemented financing initiatives and business models in other countries. The policy design process should also focus on promoting self-consumption, with the development of business models fit for both final consumers and energy service providers. Standardization of the recycling procedures should be accelerated to ensure the safe disposal of PV system components. Furthermore, frameworks and directives like the WEEE (2012/19/EU) holding specific market entities responsible for the recycling of PV systems should be further standardized.

(Raina & Sinha, 2019) concluded that the recycling of e-waste remains a big challenge in combating the impact of PV technology on the environment.

(Salim et al., 2019) depicted that end of life e-waste strategy is highly dependent on effective voluntary or mandatory approaches, incentives as well as consumers' willingness to pay for collection and recycling either upfront or at the end of the life cycle.

(Sharma et al., 2019) found that the development of regulatory framework & guidelines and innovative business models, and building up the capacity of local

institutions and the PV recycling industry are very important for the PV end-of-life management system.

(Suresh et al., 2019) mentioned that with the support of government policies solar PV industry has grown drastically to a level that its end-life management is posing a great challenge ahead. By 2030 the PV waste will reach 200,000 tons and 1.8 million by 2050. Cumulatively it can reach 18 million tons. The Indian government needs to take hasty actions for increasing solar waste. Establishment of the regulatory framework for handling end-life waste along with the focused liability of producers and stakeholders towards end-life management. Financial aid along with an operational infrastructure for recycling is to be provided.

(Turaga et al., 2019) focused that extended producer responsibility is utilized across the globe to regulate e-waste and also it internationalizes the disposal cost at the end life of the product.

(Vargas & Chesney, 2019) stressed upon regulation needs to be developed and implemented to establish guidelines for proper management of PV panels after deployment in the United States, and subsidies could be an important part of it.

(Quek et al., 2019) found out that kerf, from waste silicon dust, can cause breathing difficulties to workers handling this stage of the production. Other harmful chemicals include sulfur hexafluoride, for cleaning reactors in silicon production, hydrochloric acid, sulphuric acid, nitric acid, 1,1,1-trichloroethane, and acetone, for cleaning and purifying the silicon substrate.

(A. Kumar & Turner, 2020) concluded that regulation and reinforcement of producer responsibility in EoL are still weak. The solar waste that does arrive at the WEEE Centre is sent there for disposal rather than refurbishment and is handled much in the same way as old computers, mobile phones, and other types of e-waste.

(A. Lucier & J. Gareau, 2020) shown that disposal and recycling of the electronics are mandatory to be paid to the manufacturer through an extended producer responsibility initiative.

Table 2.1 Comparison of Photovoltaic Materials (S. H. Lee & Kang, 2014) (Masoumian & Kopacek, 2015) (Duflou et al., 2018) (Shellenberger, 2018) (Bogust & Smith, 2020) (Dobra et al., 2020) (Muteri et al., 2020)

Photovoltaic Material	Advantages	Disadvantages
1st Generation PV Cells: Silicon Based Solar Cells:		
sc-Si	This type of solar panel is the purest one and has a high efficiency	Manufacturing process is both material and energy intensive
mc-Si	A suitable alternative to reduce PV module cost	Less efficient than sc-Si cells
Second Generation PV Cells: Thin Film Solar Cells		
a-Si	a-Si solar cells are the cheapest on the market	The layers are much thinner and there is less material to absorb solar radiation compared to sc-Si and mc-Si hence, the efficiencies of thin-film solar modules are lower than crystalline ones' Degradation in their power output (in the range 15–35%) when exposed to the sun
GaAs	High efficiency and less thickness than silicon ones	High cost
CdTe	CdTe cells can exploit a broader wavelength spectrum than Si cells, close to the natural one. Low costs, as cadmium is abundant and generated as a by-product of important industrial materials like zinc.	Cadmium by itself is one of the most toxic materials known, and cadmium telluride has some toxic properties
CIGS	Process is less energy intensive than manufacturing of the crystalline silicon solar cell Good resistance to heat	Less efficient than Si solar cells CIGS cells use toxic chemicals Currently very expensive to produce.

CIS	Processes are less energy intensive than manufacturing of crystalline technology Good resistance to heat compared to silicon based modules	Relatively expensive due to the materials used
Third Generation Solar Cells PSC	Good efficiency and possibilities for improvement Perovskite is cheaper to produce than silicon	Perovskite breaks down quick when exposed to heat, snow, moisture, etc. The presence of lead in perovskite is largely debated for toxicity concerns
Polymer solar cells	Lightweight, mechanical flexibility, disposability and large-scale roll-to-roll production capability	Low efficiency, low durability and low stability.

(Chowdhury et al., 2020) have analyzed that solar panels at their end life are a source of hazardous waste and their disposal will become a pertinent issue for the environment. WEEE directives of the EU regulate the producers to finance the collection and recycling of PV waste. Further, the improvements in the recovery rate of recycled materials, economic viability, and environmental impacts are important. No specific policy framework to handle PV waste. In China and Asia no specific regulations for the recycling of solar panel waste. Environmentally friendly recycling industries to be developed along with safe disposal of PV waste. Recycling has to be made mandatory for the manufacturers on commercial grounds for obligatory management of hazardous waste. Hard-line policies are to be imposed on the manufacturing firms to tackle the impact of their products at the end of life. Various schemes are also to be put into effect for the PV panels end life management.

(Delcea et al., 2020) shown that attitude and awareness towards e-waste recycling were the primary influencing factors for the intention to recycle, which underlines the need for campaigns that contribute to increasing people’s understanding of the harmful influence on environmental and human health.

(Grant, 2020) have concluded that acute Pb poisoning impairment of red blood cell formation, severe central nervous system or peripheral nervous system damage, functional impairment, notable kidney damage, or renal dysfunction. In Adults hypertension, coronary heart disease decreased red blood cells survival and function, and altered heme synthesis and developmental male reproductive function effects are reported.

(Hansen et al., 2020) have taken consideration of the economic and ecological aspects of worn-out parts during collection, transportation, and storage is important in process of recycling.

(Jaunich et al., 2020) focused that extended producer responsibility is put forth to increase the e-waste recycling rate however monetary investments for material recovery like transportation, collection, reprocessing of material, and disposal to cover environmental impacts would outweigh recycling benefits due to its ineffective implementation.

(Joël Tchognia Nkuissi et al., 2020) assessed that Cadmium-containing vapors or dust can result in harmful effects on bone and kidney, lung cancer, metal vapor fever, pneumonitis, pulmonary edema, and finally death. Although the toxicity of elemental selenium is fairly modest, the hydrogen selenide utilized in the production of CIGS is very poisonous and hazardous to human life and health. Recycling is expected to be the preferred disposal option for spent PV modules in the future, to minimize the potential environmental impacts and recover the source of metals.

(Kwak et al., 2020) studied from an environmental point of view, insufficient toxicity and risk information exist for solar cells Major components of solar cells include lead, tin, cadmium, silicon, and copper, which are damaging to ecosystems and human health when released through broken-down garbage items or in the wake of environmental catastrophes. Government policies and solar cell manufacturers should consider the worst-case scenarios for leachable compounds that could adversely impact human and environmental health to prepare for emergencies or consumer demands.

(Markert et al., 2020) calculated the private and externality cost of PV recycling in

their EoL. FRELP method is used in recovering materials from c-Si PV waste. results indicate that the cost of EoL management of c-Si PV module is USD 6.72 / m² and of the cost components of PV EoL management, the transportation associated cost was found to be the highest (USD 3.36/m²) while the cost of the recycling process (the cost of consumed materials, electricity or the investment for the recycling facilities) was found to be the most insignificant (USD 0.25/m²). The net benefit is so small, that appropriate policies may need to be enacted to further motivate PV manufacturers to recycle their EoL panels.

(Mathur et al., 2020) found that effective EoL management methods need to be aggressively developed and implemented to prevent large volumes of hazardous wastes from being disposed of in landfills.

(Ranasinghe & Athapattu, 2020) concluded that insufficient legislation, awareness among folks, and lacking extended producer responsibility program practice to manage the proliferating waste are the major challenges in the way to making a dedicated policy. The policy will deal with the entire process of collection, dismantling, material recovery, transportation, preprocessing, storage, and recovery of metal by end-life processing.

(Ratner et al., 2020) have analyzed to concentrate further attention on financial factors, especially in ensuring the economic viability of recycling tiny volumes of PV waste and improving the eco-design of the entire life cycle. The paper concludes by arguing that further advancements in PV recycling technology will have little influence on the environment throughout the course of their complete life cycle. To achieve the economic viability of recycling modest quantities of PV waste, in particular, it is more advantageous to concentrate future efforts on economic criteria. Develop accurate data centres for the forecasting of waste flow. It will help to elaborate a reasonable proactive strategy and optimize the number and locations of recycling plants.

(Thotakura et al., 2020) shown that the energy generation from the installed solar PV plant is monitored for 12 months. In addition to real-time monitoring, the energy analysis of the plant is simulated using three different tools and then a comparison is made. These simulation tools will assist in the analysis of solar PV projects, feasibility

of the solar plant estimation before installation, long-term performance predictions, and energy estimations.

(Vargas & Chesney, 2020) directed that waste management and recycling infrastructure will need to be developed accordingly. Early action results in less expensive implementation. Since the cost structure of recycling silicon panels seems to be too expensive, subsidies are required to trigger seed investments, and the amounts required under different scenarios seem to be reasonable, as described by this work. This could allow for private investments to be started.

(W.-S. Chen et al., 2020) found out that Silicon cells contain 90% of Si, 0.7% of Ag, and 9.3% of Al. Silicon cells were leached by 4M nitric acid at 80°C for 4 hours then 3M sodium hydroxide at 70°C for 3 hours and the leaching efficiency was 99.7% of Ag, and 99.9% of Al, respectively. The leaching process separated Silicon from other metals. Na-Cyanex 272 in kerosene was employed to separate Al from Ag. The efficiency of extraction is 96%. After the process of extraction, 1M hydrochloride acid was employed to strip Al from the organic solvent. The efficiency of stripping is 99.9%. The recovery of Si and Ag was 99.5% and 98% respectively.

(Curtis et al., 2021) concluded that policy measures and industry standards can enable actors along the PV value chain to take proactive and collaborative action to implement environmentally sustainable EoL PV management decisions. federal and state regulation can mandate and /or incentivize PV recycling and resource recovery, while changes to the current regulatory scheme for the management of solid waste could also reduce the barriers associated with the handling, transport, accumulation, storage, and treatment of PV modules destined for recycling and resource recovery.

(Jariwala & Soni, 2021) assessed that the economic feasibility of photovoltaic module recycling remains unfavorable. Regulations and policies are needed to increase producers' responsibility in both the energy sector and the solar industry.

(Gautam et al., 2021) have shown that lack of recycling guidelines and infrastructure puts India in a poor position to handle solar PV waste. The results of our study estimate that solar PV and its BOS will produce around 2.95 billion tons of waste by 2047; this

waste will consist of 51% glass for covering purposes, 31% aluminum for module frames, 5% EVA for panel lamination, 6% copper for cabling and 1% silicon for PV module cells. The waste components are made up of 21 metals with a total commodity price of USD 645 trillion, the main contributors of which are gold (44%), aluminum (26%), copper (16%), and silver (10%). The results show that resources worth USD 452 trillion can be recovered from EoL waste using state-of-the-art recycling techniques.

(Majewski et al., 2021) showed that the development of regulatory directives and the modeling of their economic and environmental impact on the recycling of solar PV panels also appears essential, to identifying clear responsibilities of manufacturers, users, and governments. As for other significant consumer goods, such as electronics, car tires, and batteries, the implementation of efficient policy frameworks to regulate the end-of-life management of solar PV panels is essential for the further success of this industry.

(Pankadan et al., 2021) have concluded that recycling PV also can potentially retain harmful substances and recover rare earth materials that can be used again. But there is a level of unprofitability attached, which does not mean we need to discard the recycling processes. But there is a level of unprofitability attached, which does not mean we need to discard the recycling processes. The European legislation pushes to mitigate this issue through the directive of Waste Electrical and Electronic Equipment (WEEE) which includes E-o-L photovoltaic panels as e-waste the complete recovery of materials using the proposed method is unlikely to be profitable and this may only be achievable where labour is not expensive. The proposed recycling route is capable of completely recovering the main materials in waste PV (aluminum frames, junction box, silver, copper tabbing, silicon, back sheet, and unbroken glass) and can have a positive environmental impact, but it is not economically profitable.

2.3. Summary of Literature

A growing number of pieces of literature have been carried out for the analysis of solar PV recycling policies across the globe while the Indian scenario still lacks the policy framework and incentives to be provided for reclaiming process. Due to the increased

efficiencies of the solar PV materials, the amount of waste to be accumulated in near future is increasing, and material recovery is insisted to avoid the detriment of valuable materials at the end of the wheel of life. It is concluded that CIGS panels are economically feasible for recycling however disposal costs for the CdTe panels are the highest and they also possess environmental hazards due to the presence of Cd. Recycling of a-Si panels isn't practiced on a commercial level due to less recyclable semiconductor material. Environmentally friendly recycling needs to be practiced along with aiming for economic value. With the growing planetary demands for clean energy, solar photovoltaic system electricity generation has become mandatory in today's world. At the same time, when we look at photovoltaic waste volume in India, it is estimated to burst forth to 200,000 by 2030 and around 1.8 million tons by 2050.

Both bulk and thin-film solar photovoltaic panels are environmentally friendly when in use. Nephrotoxicity can result from exposure to arsine, cadmium, germane, lead, and phosphorous oxychloride, which also affect the kidney. Carbon tetrachloride and aristolochic acid both have harmful effects on the lungs. Indium compounds and hydrogen fluoride, which are employed in the production of thin film photovoltaic materials, are bad for bones and teeth. Skeletal and dental fluorosis is caused by the buildup of fluoride and indium compounds on bones and teeth. Phosphine exposure can induce gastrointestinal problems, cardiovascular malfunction, and pulmonary irritation. A fast increase in the surrounding temperature can also cause phosphorus to catch fire, which can result in bleeding, neuropsychiatric problems, and respiratory and renal failure within a few hours of exposure. When producing thin layer photovoltaic materials, germane inhalation can cause headaches, nausea, and dizziness.

Germane ignites easily when exposed to air; it can also explode when exposed to high temperatures and pose a risk. Long-term exposure to germane and arsine damages blood cells, reducing their ability to transport blood. Additionally irritating to the eyes, skin, and oesophagus are indium compounds. On inhalation, silane, selenium oxides, and selenium hydroxides can irritate mucous membranes, the skin, and the eyes. The environmental aftereffects on humans included the carcinogenic effects of Cd, Te, Se, arsine, carbon tetrachloride, etc., and other health issues as discussed above on various body organs. Currently, the degenerated solar panels are handled by the manufacturer only by considering them into the e-waste category. India lacks any regulative guidelines or any infrastructure setup on the treatment of waste solar panels in the e-

waste rules. With the onset of the end of life of the first lot of installed solar panels, the dire need to manage that waste is approaching through a specific recycling protocol with effective legislation. This particular rising in solar panel waste is to be treated before it becomes worse.

Several kinds of literature have been done regarding recycling policies of the solar PV system but still, there is some lack. Regarding prior studies, the preceding life span reassessment of solar PV materials revealed that India still lacks a recycling strategy for PV materials. Till the present hour, the largest fraction of the PV materials is dumped in landfills recycling processes are yet not monetary. The amount of PV material scrap reaching the recyclers is still negligible due to the fair life span of 25–30 years of the solar PV system because of this, the recycling of PV scrap lacks in bringing forth a lucrative turnout.

The study could help decision-makers and researchers to explore the field and will also act as a database for future development of a closed-loop supply chain, economic feasibility studies, and life-cycle analysis. This study could be further extended to perform classifications of metals, material flow analysis, and a cost-benefit analysis for the smooth collection, disassembly, and recycling of e-waste.

From the literature following research gaps were identified:

- 1) The PV panels contain various hazardous materials so proper treatment of these materials is essential.
- 2) Due to the use of various metals in the manufacturing of solar panels and further their inefficient recovery will ultimately lead to the depletion of valuable resources.
- 3) In the case of certain thin film and amorphous silicon solar cell modules comprising PV array, additional disposal problems are likely to be caused due to the presence of cadmium and arsenic.
- 4) No Indian policy has been adopted yet to tackle solar panel waste.