Chapter 4

SOLAR PV MODULES RECYCLING METHOD & THEIR ENVIRONMENTAL IMPACT

The chapter outlines the recycling methods of different solar panels across the globe. Detailed analysis of the various steps of recycling methods along with comparative analysis is put forward. Analysis of the current solar recycling firms also the economic aspect of the reclaimed material is put forward here. Hazardous materials used in the manufacturing of the solar modules with detrimental effects are detailed Environmental impacts related to human health and ecosystem are laid out.

4.1 Introduction

PV recycling can help to save resources by preserving useful raw materials (glass, copper, aluminum, semiconductor materials, etc.) for prospective use in PV modules or other new things, as well as assisting in the management of considerable future waste volumes. PV modules are recycled by several stages that include size reduction (shredding and milling), removal of the semiconductor film, solid-liquid separation, separation and rinsing of laminate foil/glass, and semiconductor precipitation. To progress toward a sustainable closed-loop product trajectory, it is critical to understand the function that materials play throughout the product's existence. Solar panels come in a variety of materials, but the most common are aluminum, glass, silver, and an elastic substance known as ethylene vinyl acetate.

Climate change, including rising global temperatures, pollution, population growth, and economic sluggishness, is one of our society's biggest issues in the twenty-first century. The population growth has led to the maximum use of the natural resources. The conventional energy sources, with mother Earth in her natural state, have further run out due to emerging businesses and the improvement of peoples' lifestyles worldwide. The environment and the energy industry are suffering greatly as a result of the increasing urbanization and modernization in emerging nations. Energy needs and the facilities they support allow people to enjoy a wide range of social, economic, and health advantages. The importance of using renewable energy sources was underlined in order to achieve these objectives. Because of the Sun's constant presence, solar energy has proven to be a reliable and affordable source of power. The development of solar photovoltaic electricity was aided by further government incentives.

4.2 Recycling Methods of Solar PV Modules

By the end of the 1990s a significant aggregate of the PV system was deployed from the tenure of 2005 to 2011, overall installations too got increased and by these years several manufacturing firms have started taking initiatives for the end life management of their product. With the increasing manufacturing of solar photovoltaic technologies and the growing concern towards their disposal, recycling procedure is being the new attraction as the installations have increased drastically and the amount of accumulated waste is also in a significant concentration to make the recycling process economical (Vadoudi et al., 2015).

The world's energy needs are always rising due to the expanding population. This need was further increased by urbanization. Solar energy may be transformed using a variety of devices and methods into a form that can be consumed. To complete the conversion of solar energy, primarily three strategies can be used:

1) Photovoltaic technology enables the conversion of solar energy into electrical energy.
2) Solar thermal technology enables the conversion of solar energy into heat energy.
3) Non-mechanical techniques can be used to convey solar energy directly to structures.

The two categories of the photovoltaic panels' environmental impact are as follows:

1) Positive effect
2) Negative effects

The use of photovoltaic technology to battle the detrimental consequences of conventional resources on the environment, such as pollution and rising global temperature, is used to evaluate the positive impact. The manufacture and decommissioning of solar panels are to blame for the negative effect. As a result of the unchecked use of traditional energy sources, rising energy needs throughout the globe have sparked the development of new energy sources. The most promising technology to provide energy security and lessen climate impact is solar photovoltaic technology. The right end-of-life treatment for PV technology, which has evolved as a sustainable energy source, is a worrying problem. The primary stage in putting an end to greenhouse gas emissions is the transition from conventional resources to environmentally friendly resources.

A typical crystalline silicon solar panel is composed of 65-75 percent glass, 10-15 percent aluminum frame, 10% plastic, and just 3-5 percent silicon. They can include a variety of hazardous and even carcinogenic compounds, including arsenic, chromium, and cadmium. The working panels are sealed off with glass and are quite safe; but, if the glass breaks or the panels are damaged, certain substances may leak. This study gives a complete overview of the recycling options and the destiny of photovoltaic materials. The ultimate goal is to construct a structured PV recycling model that encourages various recycling technologies for different modules and controls for future PV recycling infrastructure design. The intrinsic composition of solar photovoltaic materials is depicted in Fig. 4.1 and Table 4.1.

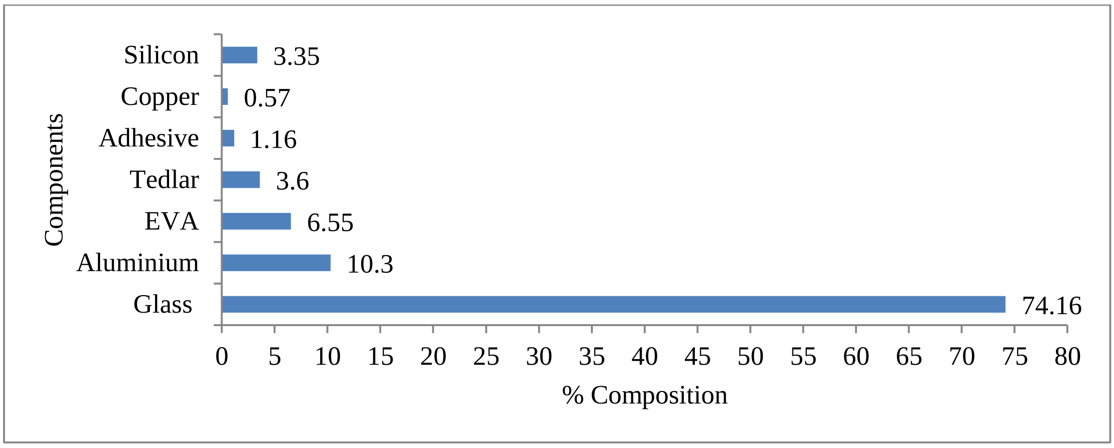
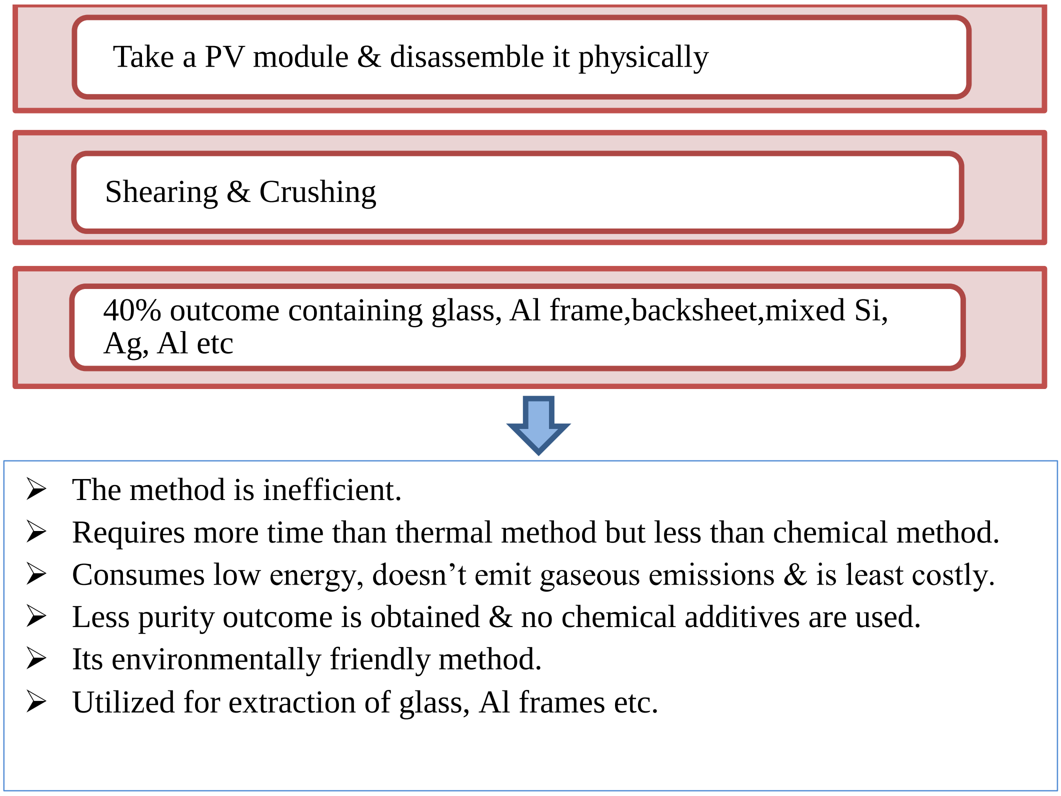


Fig.4.1 Intrinsic % c-Si component proportion

Table 4.1 Intrinsic CIGS & CdTe Component Proportion

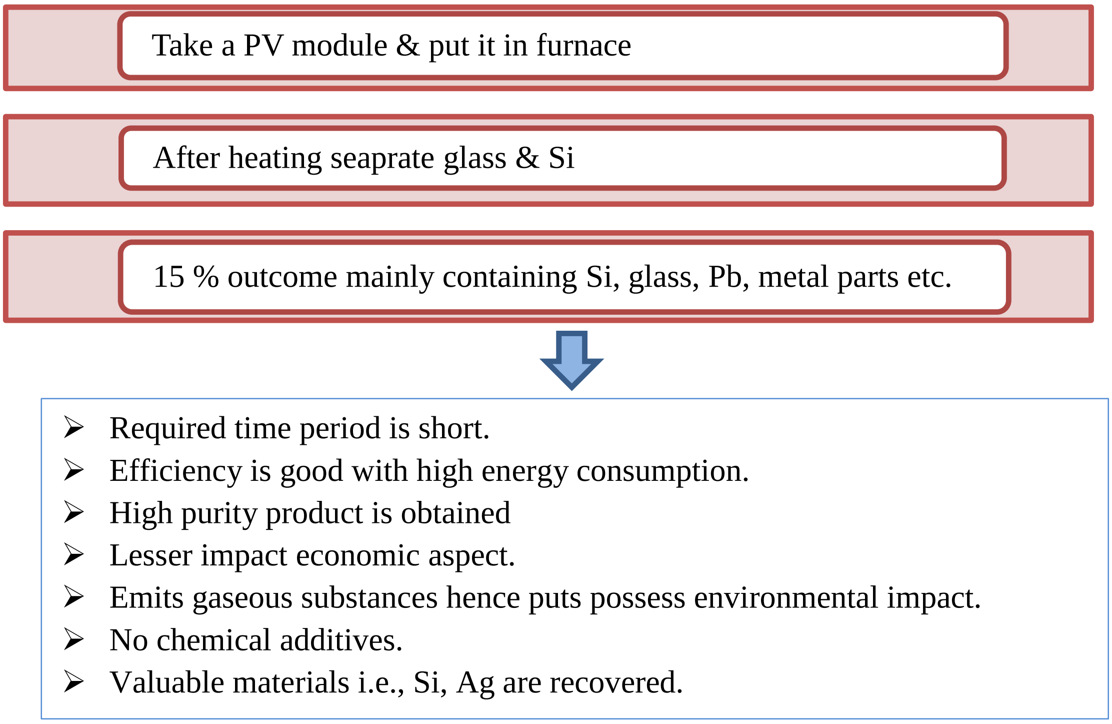
CIGS components	%	CdTe Components	%
Glass	84	Glass	95
Aluminum	12	Aluminum	0.35
EVA	3	EVA	3.5
Copper	0.8	Copper	1
Zinc	0.12	Zinc	0.01
Lead	0.0005	Cadmium	0.07
Indium	0.02	Tellurium	0.07

To the present time, thermal, chemical & mechanical methods of recycling were used (Klugmann-Radziemska, 2012). Mechanical, thermal, and chemical methods are laid out below in Fig. 4.2, 4.3, and 4.4.



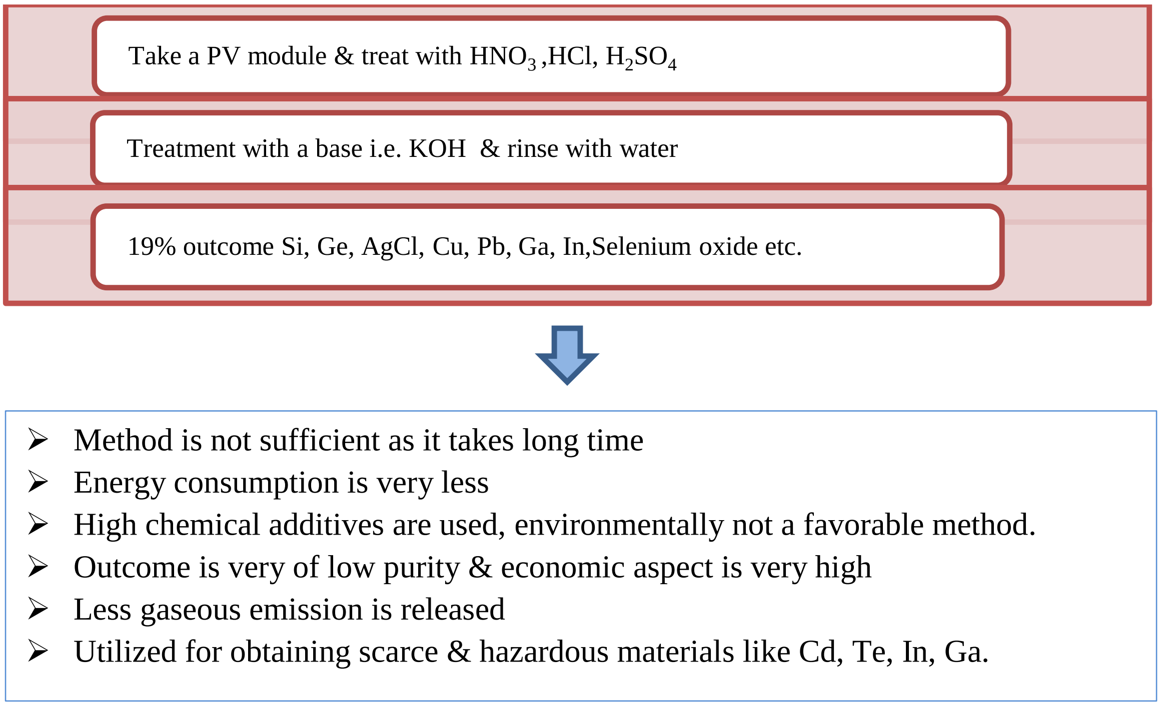
- The method is inefficient.
- Requires more time than thermal method but less than chemical method.
- Consumes low energy, doesn’t emit gaseous emissions & is least costly.
- Less purity outcome is obtained & no chemical additives are used.
- Its environmentally friendly method.
- Utilized for extraction of glass, Al frames etc.

Fig. 4.2 Mechanical Method



- Required time period is short.
- Efficiency is good with high energy consumption.
- High purity product is obtained
- Lesser impact economic aspect.
- Emits gaseous substances hence puts possess environmental impact.
- No chemical additives.
- Valuable materials i.e., Si, Ag are recovered.

Fig. 4.3 Thermal Method



Take a PV module & treat with HNO_3 ,HCl, H_2SO_4

Treatment with a base i.e. KOH & rinse with water

19% outcome Si, Ge, AgCl, Cu, Pb, Ga, In,Selenium oxide etc.

- Method is not sufficient as it takes long time
- Energy consumption is very less
- High chemical additives are used, environmentally not a favorable method.
- Outcome is very of low purity & economic aspect is very high
- Less gaseous emission is released
- Utilized for obtaining scarce & hazardous materials like Cd, Te, In, Ga.

Fig. 4.4 Chemical Method

Table 4.2 gives a comparative analysis of the above-described methods of recycling photovoltaic modules. An overall comparison shows that a combination of mechanical and thermal methods is good for the recycling process.

Table 4.2 Comparative Analysis of the Thermal, Chemical, and Mechanical Method

		Recycling methods		
S. No.	**Property**	**Thermal**	**Chemical**	**Mechanical**
1	Efficiency	Sufficient	Insufficient	Insufficient
2	Time period	Short	Long	Intermediate of the previous two methods
3	Energy consumption	High	Very little	Low
4	Outcome	High purity product	Low	Less purity
5	Economic aspect	Lesser in cost than chemical method	High cost	Least costly
6	Emission	Gaseous emission	Very less gaseous emission	No gaseous emission
7	Utilized for	Valuable materials like Si, Ag, etc.	Scarce & hazardous materials like Cd, Te, In, Ga	Glass, Aluminium frame, etc.
8	Chemical additives	No additives	High chemical additives	No additives
9	Environmental behaviour	Environmentally puts a burden	Environmentally harmful	Environmentally friendly

Table 4.3 Silicon Solar Modules Recycling Processes

Process	**Merits**	**Demerits**
Dissolution in Organic Solvent	Less cell damage Quick access to EVA Glass can be recovered	Deadly emissions and wastes Delamination time depends on the area
Ultrasonic irradiation & orgnaic solvent	Easy access to the EVA Quite more effective than the solvent dissolution procedure	Harmful emissions and wastes Expensive machines
Electro-Thermal Heating	Quick removal of glass	The treatment is slow
Mechanical separation by hot wire cutting	Low cell damage Recovery of glass	Complete removal of EVA requires different methods
Pyrolysis	Separate 80% of wafers and almost 100% of the glass sheets Cost-effective industrial recycling process	Slightly worse texturization (damage to the cell surface)
Solvent (Nitric acid) dissolution	Complete removal of EVA and metal coating on the wafer It is possible to recover intact cells	It can cause cell defects due to inorganic acid Generates harmful emissions and wastes
Physical disintegration	Capable of treating waste	Other separation processes required for full EVA removal Dust containing heavy metals Breakage of solar cells Equipment corrosion
Dry and wet mechanical process	No process chemicals Equipment widely available Low energy requirements	No removal of dissolved solids
Thermal heating (two steps)	Full removal of EVA Possible recovery of intact cell Economically feasible process	Harmful emissions High energy requirements Cell defects and degradation due to high temperature
Chemical etching	High purity materials are recovered Simple & efficient method	Use of chemicals

Table 4.4 Thin-film Solar Modules Recycling Processes

Process	**Merits**	**Demerits**
Organic solvent dissolution	Easy access to the encapsulant Less cell damage Recovery of glass	The time for delamination depends on the area Harmful emissions and wastes
Irradiation by laser	Easy access to encapsulant	Slow process Highly expensive equipment
Mechanical separation & hot wire cutting	Low cell damage Recovery of glass	Other separation processes required for encapsulant
Vacuum blasting	Removal of semiconductor layers without chemicals Recovery of clean glass	Relatively slow process Emission of metals Further chemical/mechanical treatments
Attrition	No usage of chemicals Recovery of clean glass	Further chemical or mechanical treatments needed
Flotation	Relatively simple process Low use of chemicals	High losses of valuables during the rinsing and sieving process Flotation process required
Dry etching	Simple process	High energy demand High effort for purification
Physical disintegration	Capable of treating waste	Other separation processes required for encapsulant Dust containing heavy metals Breakage of solar cells Equipment corrosion
Dry and wet mechanical process	No process chemicals Equipment widely available Low energy requirements	No removal of dissolved solids
Chemical etching	High purity materials Simple and efficient process	Use of chemicals
Thermal treatment	Complete removal of encapsulant Recovery of intact cell Simple & economical	Harmful emissions High energy requirement Cell defect & degradation
Leaching	Complete removal of metals	High use of chemicals Generation of acidic fumes Complex control of chemicals

Analysis of recycling methods requires the determination of the economic feasibility of crystalline silicon and polycrystalline silicon photovoltaic panels. The recycling process of thin film photovoltaic panels involves smelting of, an acid bath for the recovery of elements like Ga, Se, and In. Glass can also be removed by decomposition through high temperature, and acid dissolution can also be used for the removal of EVA polymer layer (Granata et al., 2014; Klugmann-Radziemska, 2012; Mahmoudi, Huda, Alavi, et al., 2019). Stripping with the help of chemicals is processed in the case of cadmium telluride panels for the removal of metals.

Further separation of these metals can be done by precipitation, electrodeposition, and evaporation (Marwede & Reller, 2012; Paiano, 2015). Due to maximum installations of crystalline silicon photovoltaic modules in India emphasis is laid on its economic recycling analysis and also on the solar panels containing elements of economic benefit like Gallium, Indium, Silicon, Cadmium, Tellurium, Aluminium, etc. (Kim et al., 2014). Frame made of glass and aluminum separated by the physical process isn't taken into consideration for economic recycling analysis. For the determination of the economic feasibility of recycling various generations of solar cells like a-Si, c-Si, CIGS, CdTe, and GaAs an analysis is carried out.

The analysis is carried out on a $1m^2$ area of the solar panel (Deng et al., 2019). The recovered product mass is depicted as

$m_r = At_s\rho_sZ_s$ [g/module] (1)

m_r = recovered product mass

A= area in cm^2

t_s= thickness in cm

ρ_s= semiconductor material density in g/cm^3

Z_s = material recovered in %

The profit made from the selling of the recovered semiconductor is estimated by

$P_s=m_rv_s$[\$/module] (2)

v_s = money earned by reselling

Other than semiconductor materials, profit can also be earned by recovering the glass

$m_{g.r}=At_g\rho_gZ_g$ [g/module] (3)

$m_{g.r}$ = recovered product mass

A= area

t_g= thickness of glass in cm

ρ_g= glass density in g/cm^3

Z_g = glass recovered, it is taken as 100 %

$P_g=m_g v_g$ [\$/module] (4)

P_g = profit from recycling glass

v_g = money earned by selling recovered glass

Along with recycling the disposal cost for landfill can be calculated depending on the waste generated by a module.

$W = AEw / N_p$ [kg/module] (5)

E = power of each module in per unit area in W/ m^2

w = weight of module in Kg

Np = nominal power in Watt

The overall disposal cost (D) is calculated as

D= WT [\$/module] (6)

W = solar module waste mass

T= tipping fees paid for the disposal site. The cumulative profit (P_c) earned by the recycling

$P_c=(P_s+P_g) + D-C$ [\$/module] (7)

C = recycling cost of the material prevailing in the market

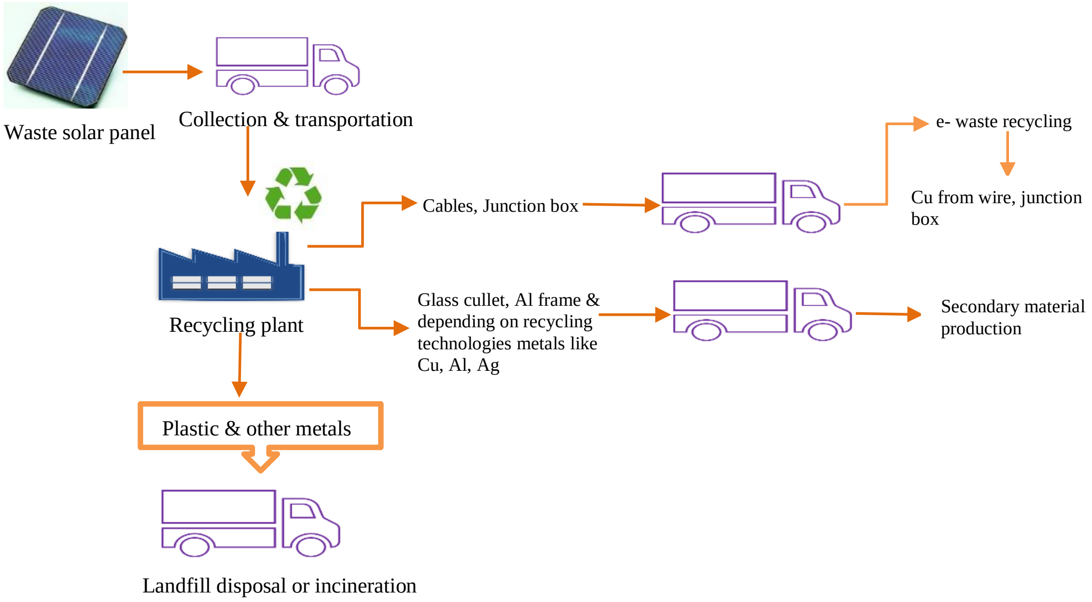


Fig.4.5 System Boundary in Recycling

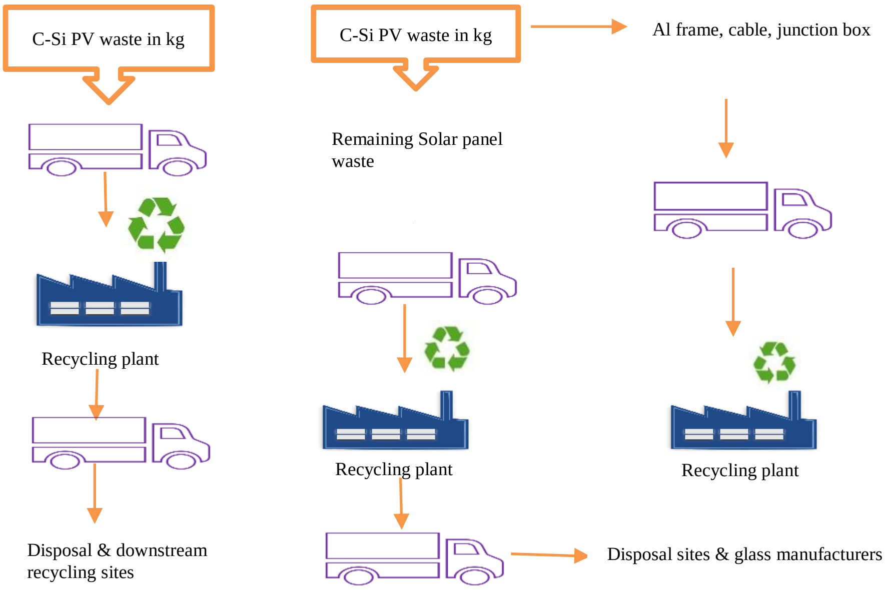


Fig. 4.6 Centralized & Decentralized Recycling Scenario

4.2.1 Current Solar Photovoltaic Recycling Firms:

The under-mentioned recycling firms are involved in regions of the world. 3R recycling, Cleanlites Recycling, CMK Recyclings, Dynamic Lifecycle Innovations, Echo Environmental, First Solar, Green Lights Recycling, Interco Trading Company, Solar Sun’s Recycling, Recovery, We Recycle Solar, etc. are the companies involved in the recycling of the solar panels in the United States. CMK Recycling and Dynamic Lifecycle Innovations are involved in the recycling of Junction boxes, frames, cable, and back sheets other than solar panel recycling. Out of all these waste recycling companies; First Solar is more prominent in this process of recycling.

In China Bocai E-Energy, Chaoqiang Silicon Material, Jiangsu Juxin Energy Silicon Technology, Kunshan Suda Jingwel Electronic Technology, Suzhou Hedeying Metal, Suzhou Huizhijie PV Technology, Suzhou Sangyunda, Suzhou Sunhui New Energy Technology, YCJ Solar, Yuepyeng New Energy are the companies which are involved in the recycling of solar panels. In Germany Envaris, Loser Chime, Reiling Glass Recycling, Rinivasol, etc. are involved in the recycling of solar panels. In United Kingdom H&H Pro, Panoramic Resource Partner, Recycle Solar Technologies, and Solar2Recycle are recycling solar panels, cables, junction boxes, connectors, and glass. GVS, Immark, and Sens Foundation are recycling solar panels in Switzerland. PV Techno Cycle and Trinity are involved in the recycling of solar panels in Japan.

Inactive, and Reclaim PV Recycling are involved in the recycling of solar panels in Australia.

In Italy Experia Solutions and La Mia Energia are involved in recycling solar panels, Junction boxes, cables, etc. In Ireland, only one recycling firm The Recycling Village is performing solar panel recycling. In Taiwan, Get Green Energy is involved in recycling solar panels. Silcontel-Israel is involved in the recycling of solar panels. Solar recycling is involved in the recycling of solar panels in Spain. REMA PV system is involved in the recycling of Solar panels in the Czech Republic. Other solar recycling firms like Deutsche, Solar AG, Solar world AG, Solar cell Inc. (SCI), Pillington Solar Int. (PSI) are also involved in the recycling business. Some of the firms have taken action on the recycling procedure. PV CYCLE program is also being run for this procedure. The ultimate objective is to assure sustainable, clean, and economic recycling all over the globe.

The thin film panels were recycled by the First Solar Company under its recycling program. This firm was established in the year 1999 in America. This company started manufacturing the CdTe films in the year 2002. They have provided solar installations to more than 35 countries in the world. Fabrication of the solar modules is achieved here. Emissions occurring during the PV manufacturing process, end-life treatment, and other steps are made sure to have low carbon concentration. The carbon footprint of First Solar is the lowest among all the other renewable energy technologies. In 2005 the very first voluntary recycling practice of solar panels was initiated. With the expanding installations of the solar PV in every sector, First Solar continued to receive the waste volume of the photo voltaic solar panels. Other firms of First Solar are operating in Malaysia. Germany, the U.S. For the last ten years, First Solar is the leading recycler of photovoltaic technologies.

By the recycling processes continuing in First Solar 90% of glass and semiconductor materials are taken out from the discarded solar panels. Modules are crushed and chemically treated to break the lamination covers and recover the materials. Recovered materials are further packed and processed to further use in the market. Shoe-soles handles of bicycles, and mats of rubber can be made from solar waste. This is practiced in Malaysia. The material is supplied from the First Solar Panel operating in Malaysia.

The remaining unrecoverable amount of the material is accumulated as waste, which needs an effective disposal strategy to avoid detrimental effects on the ecosystem. Material losses occur due to the involvement of steps like shredding, crushing, and heating during the recycling stages of the solar panels.

Recycling at the Solar World AG:

This firm is involved in the manufacturing of silicon wafers and solar modules. It was established in March 1999 in Germany. It is involved in the production of mono-crystalline silicon solar cells. All kinds of solar PV modules are recycled here despite the differences in their size and weight. Solar recycling occurring in Deutsche Solar, Solar World, SCI, PSI

PV Cycle

Industries in the European region set up a PV recycling program known as PV CYCLE in the year 2007. The establishment of this program was an outbreak of the consciousness toward recycling solar PV panels during their early life and at their end life. It aimed to the liability of manufacturers towards sustainable assistance for the PV waste handling; this is yet to be practiced around the PV-rich corners of the globe. Countries in different parts of the world have become members of this initiative. The rate of recycling has also increased to the compilation of a greater volume of PV waste. The acquisition of enhanced PV waste is possible due to increased installations. 96% of the total material composition in silicon PV modules was recycled in 2016. Laminate sheets, metallic parts, and semiconductor materials were effectively recovered through this initiative. Due to its effectiveness, it is implemented and put into work aggressively all over Europe. Tenders were provided by PV CYCLE to France for further contribution to the solar waste recycling field.

Various research and development programs were also initiated under the PC CYCLE. In 2012 Eco-Innovation Programme provided funds for the creation of PV More, for the establishment of a device capable of recycling PV waste in a mobile manner. Direct recycling treatment can be completed at the installation site only. FP7 program launched by European Union has also undertaken a CU-PV recycling project which is concerned with the Research and Development program for solar PV recycling.

Through this project initiative were specialized for the reduction of lead and silver in the manufacturing of photovoltaic panels, establishing environment-friendly designs. Such designs also possess high material recovery during their end-life treatment. This project proved to be an excellent recovery program for the PV modules made of silicon.

Various PV firms like First Solar, Deutsche Solar, Solar cells Inc. (SCI), Pillington Solar International (PSI) have initiated the PV reclaiming programs. SCI is indulged in recovering the backing film, EVA by pyrolysis at 500°C. The first solar has developed methods to reclaim the CdTe panels by acid treatment and precipitation reactions. Deutsche Solar operated on the damaged panels through thermal treatment followed by chemical treatment. Reducing the PV waste material from faulty solar panels is the foremost step of recycling. The Solar panels are recycled across the market by different companies as depicted below:

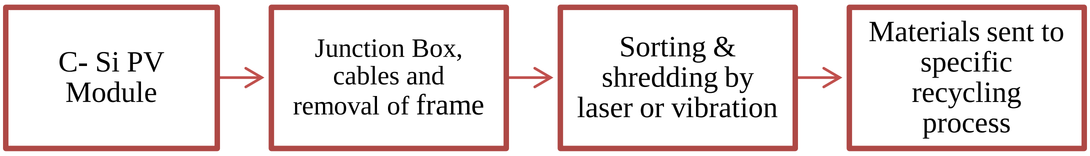


Fig.4.7 PV Recycling Process for c-Si Module

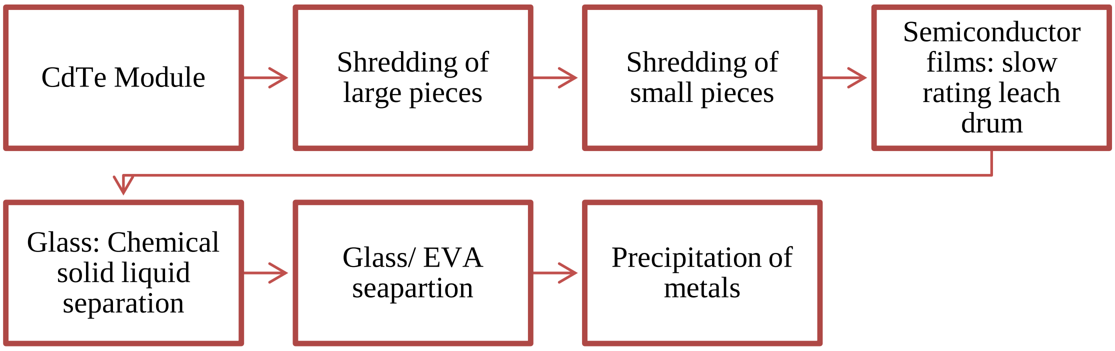


Fig.4.8 CdTe Recycling Module Process of First Solar Recycling Company

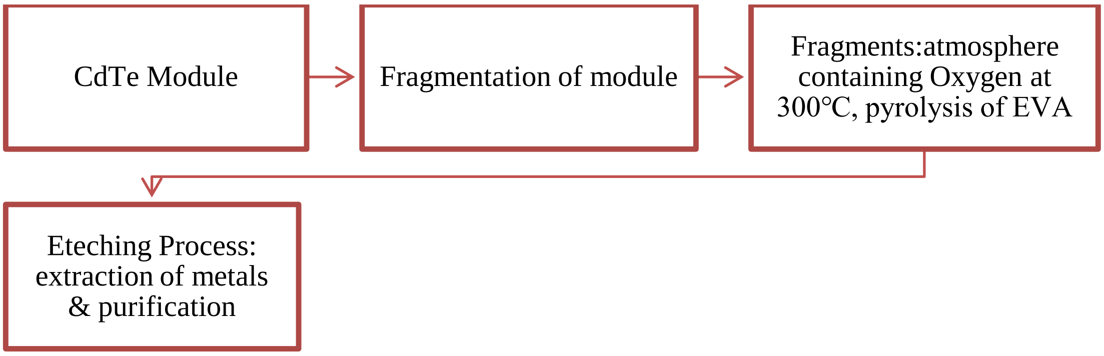


Fig.4.9 CdTe Recycling Module Process of ANTEC Solar GmbH Recycling Process

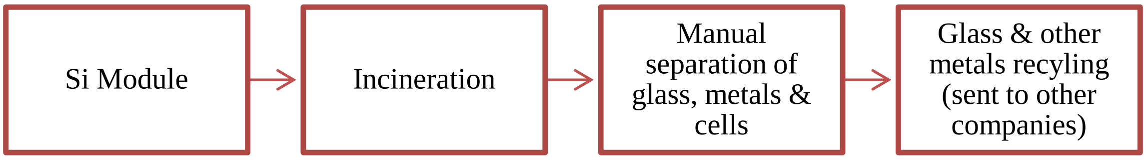


Fig.4.10 PV Recycling Process for Si Module of SolarWorld

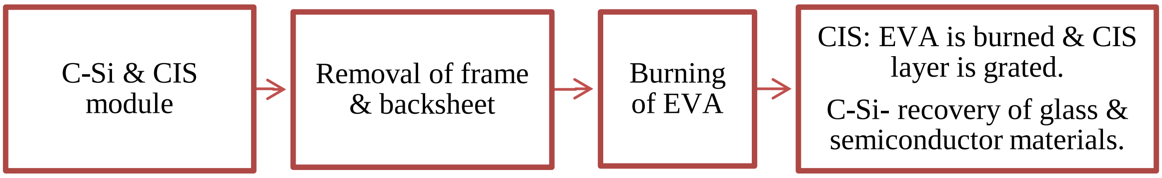


Fig.4.11 PV Recycling Process for Si Module of NEDO

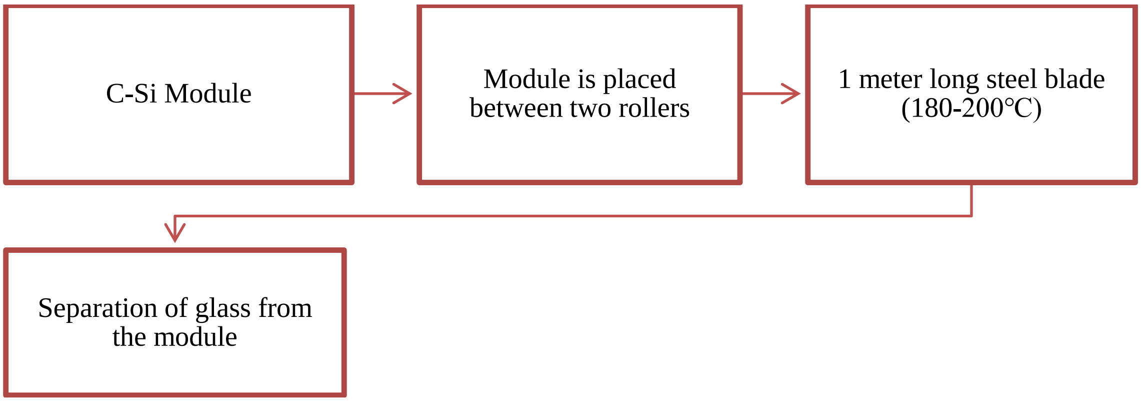


Fig.4.12 Hot Knife Recycling Process for c-Si Module

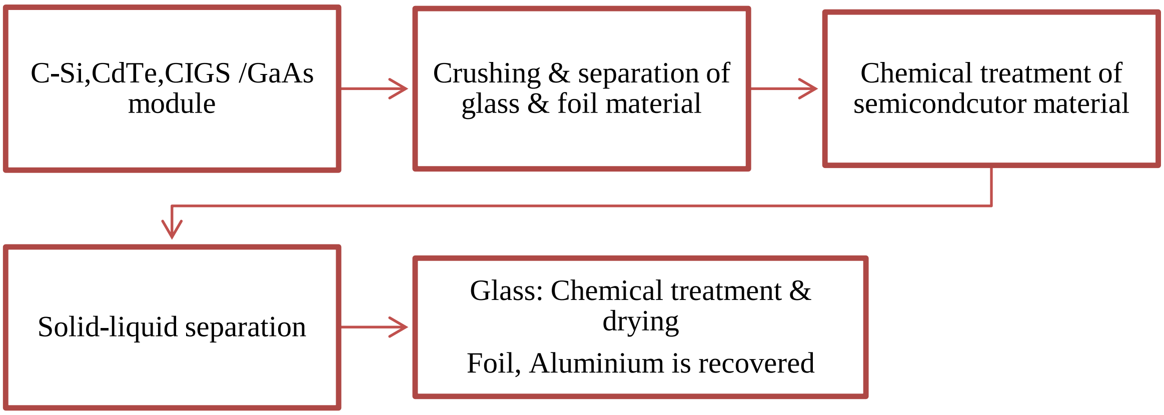


Fig.4.13 Loser Chemie Recycling Process of Different PV Modules

4.2.2. Economic Analysis of the Reclaimed Materials

It is well recognized that raw material quantity and price changes are always difficult tasks while conducting effective production. As a result, secondary materials for PV modules would provide a cost benefit to makers. Almost 90 percent of the initial raw material investment cost may be recouped by recovering the primary constituents of crystalline silicon PV modules (D’Adamo et al., 2017). PV modules have an estimated life of 20-30 years and include a considerable quantity of copper, aluminum, silver, and glass waste. Until recently, the average metal recovery yield might reached 94 percent, and there are limited locations for this recovery, mostly in the United States (US), the European Union (EU), and some regions of Asia (Domínguez & Geyer, 2017)

As a result, there are two critical approaches to assessing these recycled materials. For starters, recycling them to invest in duplicating next-generation PV modules is a significant cost saving. Second, metal excavations and glass fabrication augment the primary resource requirements of the PV module manufacturing process, which results in massive energy consumption and GHG emissions, raising the level of carbon in the atmosphere and causing climate change in the long term.

4.3. Hazardous Materials Used in Solar Panels

Crystalline silicon, derived from quartz or sand, is the most often utilized material. Although it is not inherently dangerous, aspects of the production process do include toxic chemicals, which must be carefully managed and regulated to avoid environmental damage. Mines are used to extracting quartz. Crystalline silica dust is a potentially hazardous byproduct of quartz mining and processing. The initial refining process converts quartz into metallurgical-grade silicon, which is primarily used to harden steel and other metals. The metallurgical-grade silicon is subsequently turned into polysilicon, a purer type of silicon. Hydrochloric acid is combined with metallurgical-grade silicon during the refining process to produce tri-chloro-silanes. Tri-chloro-silanes then react with hydrogen to form polysilicon and liquid silicon tetrachloride. Silicon tetrachloride is extremely toxic.

Manufacturers of solar cells refine polysilicon pieces into brick-like ingots, which are subsequently sliced into wafers. The wafer is then heated at high temperatures in the presence of phosphorous oxy-chloride to develop the physical qualities needed to generate electricity. To reduce reflection and boost light absorption efficiency, a silicon nitride anti-reflective coating is placed on the top surface of the cell. Finally, metallic electrical wires are screen printed onto the surface wafer to allow electricity to be transported away from the cell. Individual solar cells are commonly soldered together using tin-coated copper wire. Some solar panel manufacturers use soldiers that include lead and other metals that, if discharged into the environment, can be hazardous to both the environment and human health.

Although polysilicon is used in more than 90% of photovoltaic panels today, there is a fresh approach: thin-film solar-cell technology. Thin-film solar cells are expected to gain market share over the next decade because they can be just as efficient as silicon-based solar cells while being less expensive to manufacture due to the usage of less energy and material. Thin-film cell manufacturers put layers of semiconductor material directly on glass, metal, or plastic substrate rather than slicing wafers from a silicon ingot. This creates less waste and eliminates the laborious melting, drawing, and slicing processes needed to create standard cells. In essence, a piece of glass enters one end of the factory and emerges as a completely working solar module at the other. Because there is no need for certain hazardous chemicals-no hydrofluoric acid, no hydrochloric acid-moving to thin-film solar cells avoid many of the environmental and safety problems associated with manufacturing. However, this does not imply that thin-film solar cells are environmentally friendly.

Cadmium telluride and a more contemporary rival, copper indium gallium selenide, are the dominating thin-film technology today. The first semiconductor layer in the former is cadmium telluride, while the second is cadmium sulfide. The primary semiconductor material in the latter is CIGS, although the second layer is often cadmium sulfide. As a result, each of these methods makes use of compounds containing the heavy metal cadmium.

Table 4.5 Potential Toxicity of Materials Utilised in Solar Photovoltaic Panels (Bakhiyi et al., 2014)

Chemical	**Utilization**	**Hazard category**				
		Asphyxiant	**Corrosive**	**Irritating**	**Flammable**	**Explosive**
Argon gas	Thin film deposition			■		■
Ammonia	Anti-reflective coating	■				
Diborane	a-Silicon dopant			■	■	
Helium gas	Thin film deposition	■				
Boron Trifluoride	Dopant		■	■		
Hydrochloric Acid	x-raw material etching and cleaning		■	■	■	
Hydrofluoric Acid	x-cleaning and etching		■	■	■	
Hydrogen Selenide	CIS sputtering			■	■	
Hydrogen gas	a-deposition				■	■
Hydrogen Sulphide	CIS sputtering			■	■	
Nitrogen Trifluoride	Si wafer plasma etching	■				
Methane gas	a-Si & GaAs manufacturing	■			■	■
Phosphine gas	Thin film dopant			■	■	■
Phosphorous Oxychloride	x-Si dopant			■		
Selenium	CIS & CIGS raw material			■		
Silane gas	An intermediate product in x-Si production			■		■
Silicon Tetrachloride	x-Si & a-Si deposition		■	■		
Tellurium	CdTe & CIS raw material			■		■
Trichlorosilane	x-Si & a-Si deposition			■		
Alkali	Cleaning		■	■		

4.4. Environmental Impact of Solar Modules

Detrimental eventuality caused by the use of conventional resources and the growing energy needs marked the boom of the solar PV industry. Endorsed by the bureaucratic undertaking and declining expenses, solar firms are thriving promptly in India and around the world. At the initial stages of their wheel of life, PV panels account for no ambiance spoliation. Through life cycle analysis, the environmental effect of c-Si and thin film PV modules is examined. GaBi is used to evaluate the LCA model, and the CML 2001 baseline technique is used to evaluate the modules' environmental impact. Although CdTe modules require less material input than c-Si technology, their disastrous consequences are far worse than those caused by c-Si.

Health and safety are important considerations in all aspects of energy production. Nonrenewable energy resources are frequently contrasted. However, what health risks does the solar industry pose? Aside from batteries, the amount of hazardous elements in off-grid solar systems is negligible. Material extraction and landfilling might endanger dismantlers who are exposed to the environment. Although the material extraction from PVs is minimal, continual exposure results in the materials being absorbed in the body. Researchers also discovered that persons who are directly exposed to disassembling PVs had a greater concentration of PAH (Polycyclic aromatic hydrocarbon metabolites) than people who are indirectly exposed, putting them at risk of lung infections. Because certain PV modules include hazardous compounds such as Cadmium, Selenium, Tellurium, and Lead, most nations have rigorous laws in place owing to the toxicity of these materials to fish, animals, and humans. For example, because of Cadmium-control rules, the sale of PV is prohibited in several areas.

Cadmium, a recognized long-term environmental contaminant, has been linked to a variety of disorders including high blood pressure, peripheral artery disease, pulmonary impairment, renal failure, and bone alterations (Alfred, 2008). Because the recycling process requires cleaning, the water used for cleaning may contain cadmium, which leaches into the groundwater. This can then enter incinerators and be absorbed into the atmosphere (V. M. Fthenakis, 2000; V. Fthenakis & Zweibel, 2003).

Untreated garbage placed in water or landfills may create a severe risk to water resources owing to leachate entering groundwater or surface water and contaminating the water. The leachate produced is determined by the aforementioned criteria and is expected to differ among nations, with low-income countries offering the greatest danger. Exposure to this contaminated water source may hurt childhood development as well as other diseases such as coughing and chest discomfort (Feldt et al., 2014).

Lead (Pb) poisoning can cause a variety of issues, including eye, kidney, and brain damage, burns, and reproductive problems (Balasubramanian et al., 2017). When solar PV trash is burnt in the open, it can add to other risk factors such as disease vectors, exposing sellable items, and causing airborne pollutants that can cause lung issues, among other things (Hu et al., 2016). The more challenging component is the possibility of exposure to heavy metals, polychlorinated biphenyls, polyvinyl chloride, wire casings, and circuit board contents during product disassembly or burning.

Many harmful and carcinogenic compounds are found in solar panels, posing major hazards to the environment and living beings. Ingestion of these compounds can cause bone damage and have a negative influence on the functioning of important organs such as the kidney and liver. Some of these compounds can cause lung cancer if inhaled. Many rare metals, such as indium and gallium, are employed in solar panels. If these rare metals are not collected at the end of their useful life, they may be permanently deleted.

Silica dust has been linked to silicosis, a lung condition in which scar tissue accumulates in the lungs and impairs breathing. Chronic obstructive lung disease, rheumatoid arthritis, scleroderma, Sjogren's syndrome, lupus, and renal illness are all linked to high levels of exposure regularly. When exposed to humid air, silicon tetrachloride, which is manufactured alongside polysilicon, degrades into acids and toxic hydrogen chloride gas. This might cause dizziness and cause the chest to constrict. Silicon tetrachloride is a skin irritant as well as an eye and respiratory irritant. Kerf dust, a byproduct of cutting silicon ingots into wafers, can be toxic to living beings if breathed.

Chemical burns can result from exposure to solvents used in wafer etching and reactor cleanings, such as nitric acid, sodium hydroxide, and hydrofluoric acid. Hydrofluoric acid must be handled with extreme caution and disposed of correctly. Silane, which is utilized in the deposition of anti-reflective coatings, is very combustible and must be handled carefully. Lead in soldiers is extremely harmful to the central nervous system, the endocrine system, the cardiovascular system, and the kidneys. Because lead accumulates in landfills, abandoned solar PV panels containing lead have the potential to contaminate drinking water. In one investigation, solar PV panels made with lead solder surpassed the maximum permitted lead contents by 30% in the Toxicity Characteristic Leaching.

4.4.1. Impact on Human Health:

Solar Cells Made of Crystalline Silicon: Wafer-based Solar Cells composed of crystalline silicon are known as crystalline silicon solar cells. As these substances are used to clean wafers and reactors, HNO_3, HF, and NaOH are linked to chemical burns. When the aforementioned compounds' fumes are inhaled, the nasal passages and lungs get irritated. The elements used in the doping procedure in the gaseous phase like B_2H_3, $POCl_3$ also pose threat to the respiratory system as $POCl_3$ can produce P_2O_5 and Cl_2 hazards associated with the respiratory tract can be controlled by adequate ventilation system designing of a solar photovoltaic manufacturing firm.

The health conditions mentioned above were connected to persons working in the industry that produces solar photovoltaic panels. Due to waste creation in the gaseous and liquid states, environmental challenges arise throughout the wafer slicing, etching, cleaning, processing, and assembly of the solar cells. However, steps have been done to reduce waste and the use of environment amiable materials for solvents and soldiers (B. Huang et al., 2017; Latunussa et al., 2016). The act of etching can lessen the amount of caustic waste. Additionally, soldiers employ toxic materials like lead. By advancing their production technology, several businesses are utilising lead-free troops.

Solar Cells Made of Amorphous Silicon: Silane is used in the production of amorphous silicon. Due to its flammability as a gas and the usage of its derivatives in the deposition of silicon nitride, it is also dangerous. When silane is exposed to ambient air, it can catch fire. Silane's ability to ignite relies on how much of the carrier gas it contains; the concentration should be between 2 and 3%. Silane is made with the help of hydrogen, which is likewise explosive. In the gas handling system, safety precautions are taken to prevent mishaps caused by gas leaks. Instead of replacing the cylinders, safety is also guaranteed by keeping the explosive components in tube trailers with valves for restricting gas flow and PH_3 also pose toxic effects upon exposure to the environment.

To avoid any form of risk in the manufacturing company, constant caution is required. The significant usage of silane in the production of silicon raises environmental concerns as well. When handling silane on a big scale in solar panel production facilities, extreme caution should be used. The facilities should be set apart from habitats to prevent any extra dangers.

Cadmium Telluride Solar Cell, CdTe: Materials including CdS, $CdCl_2$, and CdTe are utilised in the production of CdTe panels; cadmium poses a concern owing to breathing its vapours. In extreme situations, it might result in pneumonitis, pulmonary edoema, and even death. Due to the lungs' high absorption capacity and subsequent transmission to the gastrointestinal system, inhaling these compounds results in the harmful consequences. The greater risk to the employees at the solar power plant comes from the leakage of vapours, the etching of materials from the panels, the cleaning and scrapping of materials during maintenance, as well as the handling of waste produced by solar panels during the solar power plant's life cycle or after it has finished.

To guarantee there are no health concerns among the personnel, a mask must be given to prevent dangerous emissions of cadmium from adhering to the employees' respiratory tracts. Additionally, routine staff health checks must be carried out (Peng et al., 2013). The broken and retired solar panels cause the leaching of pollutants as Cd, In, Pb, etc. The subsequent destiny of the leachate from emission to transport is shown in Fig. 4.14.

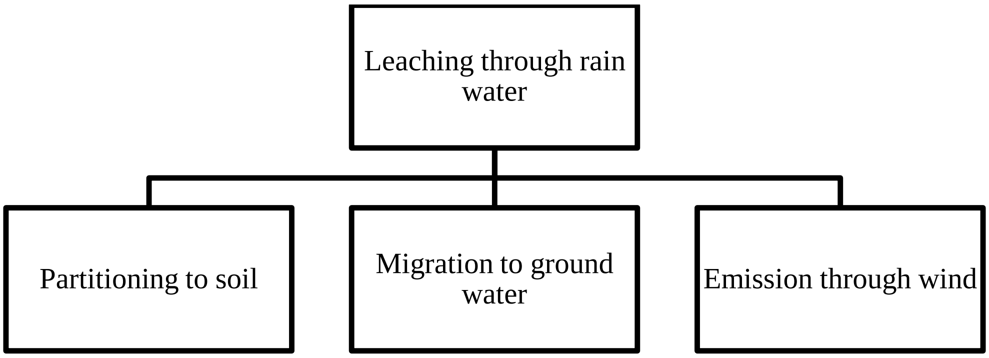


Fig.4.14 Emission and Transport Schemes

Solar Cell Made of Copper Indium Selenide: Hg_2Se medium is used to deposit selenium during the production of CIS solar cells. Copper, indium, and selenium are employed in the vapour form. CIS has an extremely low level of toxicity for animals. Despite being extremely hazardous, selenium becomes selenium hydroxide when mixed with hydrogen. At concentrations of 1 ppm, selenium hydroxide poses a hazard to the life of living things. To reduce the likelihood of any risks in the depositing system, a scrubber must be employed in conjunction with an emergency control system. To protect the individuals in the working environment, proper monitoring must be exercised and administrative control must be maintained. Due to the risks and health concerns involved with hydrogen selenide storage units, safety precautions must be followed, including the installation of restriction valves to stop the gas flow (Bakhiyi et al., 2014).

Gallium Arsenide Solar Cells: These are made using toxic gases including phosphine, arsine, and hydrides as the feedstock gases. Unintentional exposure to them can be a risk. Hydrogen is utilized in amounts of 23 metric tons, 0.7 tons, 7 tons, and 1500 tons, respectively, along with AsH_3, PH_3, and metal organics (Tammaro et al., 2015). Alternative chemicals can be used in place of toxic chemicals to reduce risks. In place of the aforementioned compounds, tertiary butyl arsine and tertiary butyl phosphine can be used to make these solar panels. Since nitrogen is less reactive than hydrogen, it may also be used to substitute hydrogen in solar panels.

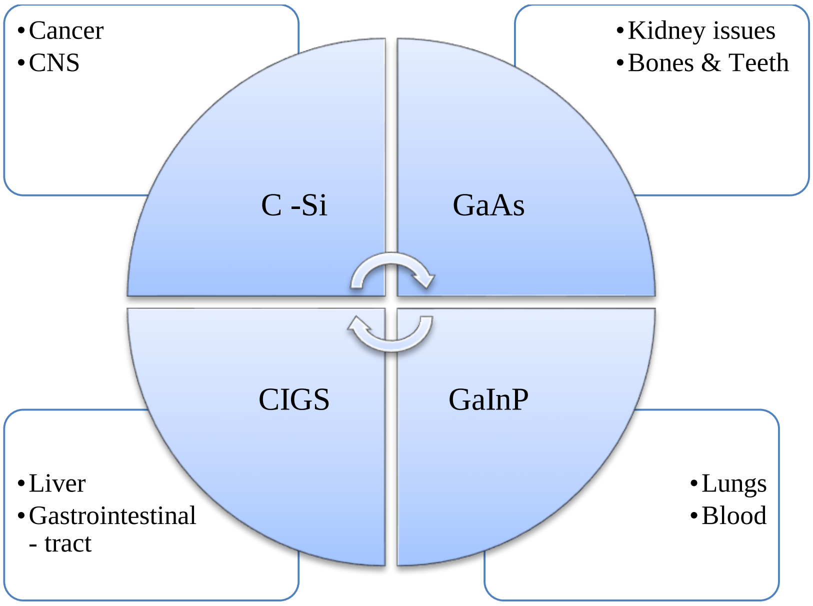


Fig.4.15 Effects on Health due to Solar Photovoltaic Materials

4.4.2. Air and Soil pollution:

Lead is a heavy metal with a high potential for accumulation in humans and the environment. When lead enters the body, it circulates in the blood and accumulates in the bones. Lead can harm the nervous system, kidney function, immune system, reproductive and developmental systems, and cardiovascular system depending on the level of exposure. Ecosystems near lead sources experience a variety of negative effects, including biodiversity loss, decreased growth and reproductive rates in plants and animals, and neurological effects in vertebrates.

The use of first-generation crystalline silicon (c-Si) solar panels has been connected to lead leaching. While lead leaching is minimal if the lead contained in a c-Si photovoltaic panel is kept at the same pH as the panel, exposure to low pH, such as nitric acid or rain, causes leaching of up to 90% of the amount of lead contained in an average c-Si photovoltaic panel. An average c-Si panel (which weighs around 22 kg) contains approximately 12.67 g of lead, resulting in a potential for lead leaching into the environment of between 1.64 g and 11.4 g per panel, or 75 g and 518 g per t of panel disposed of**.**

Cadmium is a heavy metal that accumulates in living organisms and has a biological half-life of 30 years; serious symptoms caused by low-level cadmium poisoning can take up to 10 years to manifest. Cadmium has high acute toxicity and a high propensity for accumulation in people. Cadmium is a known carcinogen that can induce major pathophysiological alterations when exposed repeatedly.

Cadmium leaching is a danger that only 2nd generation thin film solar panels face (particularly CdTe and CIGS technologies). If retained at the panel's pH, cadmium leaching for CdTe PV is on average 7% of the volume of cadmium contained in a solar panel. However, when exposed to a lower pH, such as nitric acid or rain, as in a landfill, cadmium leaching increases to between 29 and 40 percent. An average CdTe panel (weighing around 12 kg) contains roughly 4.60 g of cadmium, implying a potential for cadmium leaching into the environment of 0.32 g to 1.84 g per panel, or 27 g to 153 g per t of panel disposed of.

4.5. Regulatory Measures of Hazardous Materials

To protect against silica dust, one should monitor air quality, automate operations to reduce human exposure, implement dust suppression methods, and provide employees with personal protective equipment such as respirators. Because these recovery systems are required for the economic operation of a facility, the facilities should utilize a closed-loop process that captures system wastes for recycling and reuse inside the process loop. Furthermore, any waste gases that cannot be recycled are routed via a variety of pollution control systems (e.g., wet scrubbers) before being released into the environment. Very low quantities of particulate matter, hydrogen chloride, and silicon tetrachloride have been released into the environment**.** All of the materials used in solar panels have been listed, along with their impacts and disposal methods.

Encapsulant**:** Typically, the ethylene vinyl acetate encapsulant and polyvinyl butyral substrate are not recoverable and must be removed thermally. Lead-containing soldiers pose the largest end-of-life health risk from crystalline solar modules if not properly retired. Under the correct conditions, lead may seep into waste soils and subsequently into water bodies. The by-product ash from a thermal process is land-filled.

Methods of Disposal: Vacuum Blasting: Vacuum blasting is a process that replaces air pressure with a vacuum.

Thermal dismantling entails heating ethylene-vinyl acetate molecules to their melting point, which is 1,472 degrees Fahrenheit.

Attrition Wet Mechanical Treatment: Mixing equipment with revolving agitators is commonly used to separate soil from harmful chemicals. Chemicals are rarely used because simply the addition of water is necessary.

Hydro Cyclones: When ethylene vinyl acetate molecules are burned, poisonous and carcinogenic chemicals are released into the environment. As a result, density cyclone separation technologies have become popular. These methods rely on plastic particles floating or sinking in a separation medium of a specific density, generally under the influence of gravity. These technologies may be used to recycle huge amounts of plastic materials such as ethylene vinyl acetate in various sizes.

Tedlar film**:** Polyvinyl fluoride is used to manufacture it. The Tedlar film is not hazardous in and of itself, but when burned, it releases hydrogen fluoride. Choking, coughing, and severe eye, nose, and throat distress may occur from breathing this. Overexposure to this can potentially endanger the kidneys and liver. It also has dimethyl acetamide, which can cause a variety of skin disorders.
Methods of Disposal: A landfill is the preferable method of disposal. It can also be smoked if the incinerator can remove hydrogen fluoride and other acidic components.

Solar Cell: Wafer-Based Solar cell: These materials and disposal procedures are briefly discussed in the following portion:

a. CdS, CdSe: These are utilized to improve the efficiency of solar cells. This can induce nausea, respiratory issues, stomach pain, and cancer if you are subjected to it.

b. CuO : It is an efficient absorbing layer due to its strong solar absorption and low thermal emittance. It can harm the endocrine and central neurological systems. Contact with the eyes or skin might irritate them.

c. FeS_2: It shows very promising results when used as the active layer in solar photovoltaic and photo electrochemical cells. Sulfate generated by dissolving pyrite reacts with water to form sulfuric acid, resulting in acidic rock drainage and even acid rain.

d. Mg_2Si: Due to the challenges in crystal formation, magnesium silicide is typically employed in thin film applications.

e. (Tin Sulfide) SnS: A large band gap absorption layer in n-type solar cells. Tin Sulfide is not hazardous to humans or the environment.

f. ZnSe: A buffer layer with total area efficiencies of up to 9.6 percent (under air mass 1.5 illumination), an open circuit voltage of 482 mega Volt, a short circuit current of 31.0 milliampere /cm^2, and a fill factor of 64 percent.

g. $CuInSe_2$: In the absorber layer, $CuInSe_2$ is employed.

h. Mangnese Sulphide (MnS): is a dilute magnetic semiconductor utilized as a window/buffer layer in solar cells. When manganese permeates the soil, it disrupts the plant's system. It interferes with the separation of water into hydrogen and oxygen, as well as their distribution in the plant

i. Polybrominated biphenyls (PBBs) and brominated diphenyl ethers (PBDEs) are brominated flame retardants used in solar panel inverters and circuit boards (which convert DC to AC power). PBDEs, which bioaccumulate in fatty tissues, have been identified as hazardous and carcinogenic, as well as endocrine disruptors.

j. Crystalline Silicon (c-Si): Crystalline silicon is produced using silane gas, which produces harmful waste silicon tetrachloride. It can be recycled into new silane gas, although it may cause injury.

k. GaAs: If GaAs crystals are deposited in landfills, they will produce arsine or arsenic. Arsenic is an extremely poisonous and carcinogenic substance. The scant toxicological data on GaAs indicate that it may have serious consequences for the lung, liver, immunological, and blood systems. There is no recycling method available.

Sulfur Hexafluoride is used to clean the silicon manufacturing reactor. If it got out, it would be an extremely powerful greenhouse gas. It may also combine with silicon to form a variety of different compounds. According to the Intergovernmental Panel on Climate Change, SF_6 is 22,800 times more hazardous to the environment than CO_2.

Methods of Disposal: As previously stated, toxic elements including lead, brominated fire retardants, and hexavalent chromium are included in c-Si PV circuits and inverters. Toxics included in the modules themselves are below EPA limit limits. Options for recycling: Used silicon (Si) wafers can be melted into Si ingots and then sliced into fresh wafers.

Thin-film Solar cell: Thin film silicon decreases the amount of material needed to cover a surface with a thin layer of silicon, potentially reducing effects and waste. A portion of the thin film cell includes cadmium telluride, a very hazardous chemical that should not be exposed to the elements. It must be collected and recycled. To circumvent the onerous recycling procedure, most firms avoid employing the material in the first place.

Instead, most people use crystalline silicon, which is composed of easily recyclable elements such as glass, aluminum, copper, and plastic foil, in addition to silicon. These are also less difficult to dispose of.

Copper Indium Gallium Selenide (CIGS) and Copper Indium Selenide (CIS) thin-film PV modules rely on novel semiconductor materials. CIS and CIGS are substantially less costly than c-Si because they can be printed onto glass, and, as thin films, needs less material. The primary semiconductor material in this is CIGS, although the second layer is usually cadmium sulfide. Companies in California and Massachusetts are employing nanotechnology to boost CIGS efficiency, but the use of nanotechnology brings with it uncertainties regarding environmental, health, and safety risks.

Selenium is a controlled chemical that bioaccumulates in food webs and is classified by the EPA as very hazardous and carcinogenic. CdTe is frequently utilized as a buffer material in these modules, which raises the aforementioned CdTe toxicity problems. With the inclusion of gallium, which is linked with low toxicity, CIGS has toxicity levels similar to CIS. CIS and CIGS employ CdS (cadmium sulfide) as a buffer layer. As a result, each of these technologies makes use of compounds containing the heavy metal cadmium, which is both a carcinogen and a genotoxin, which means it may induce inheritable mutations. Researcher evaluated the acute toxicity of CdTe, CIS, and CIGS and discovered that CIGS had the lowest toxicity while CdTe had the highest.

Methods of Disposal: The easiest method to prevent exposing employees and the environment to harmful cadmium is to use as little as possible or none at all. Already, two large CIGS-photovoltaic producers, Avancis and Solar Frontier are replacing cadmium sulfide with zinc sulfide, a more environmentally friendly substance. Researchers from the Universities of Bristol and Bath in England, as well as the University of California, Berkeley, and many other academic and government laboratories, are attempting to develop thin-film photovoltaics that does not rely on toxic elements like cadmium or rare elements like tellurium.

4.6. Discussion

Some features of solar PV production and disposal procedures are explored in this work. Without a doubt, solar power will play a major part in the next generation's power sector, and we cannot prevent further penetration of solar PV cells, both on a small and big scale. It does, however, come at a cost. Technologies for efficient recycling and disposal of solar panels, as well as leading research in manufacturing processes, must advance for the world to be ready when the time for huge disposals approaches. We cannot afford to put off answers or turn a blind eye to the problem since it exists and its nature is exceedingly dangerous if not addressed appropriately.

Broken, faulty, and retired solar PV equipment will enter the waste stream if recycling processes are not successful and safe. It will wind up in landfills or incinerators where dangerous substances might escape into groundwater and where burning could discharge them into the air. Recycling solar PV panels at existing responsible e-waste recycling facilities or facilities that recycle batteries containing lead and cadmium is one disposal alternative, keeping toxins out of municipal incinerators and landfills. However, these hazardous waste recovery plants frequently employ substandard technology and require significant R&D to enhance their environmental footprint. Most recycling facilities, for example, smelters, which are known to increase the risk of lung cancer, to process metals due to cadmium exposure in neighboring communities and the workplace.

When solar photovoltaic materials reach the end of their useful lives, transition metals like cadmium and copper as well as other elements like tellurium, selenium, and silicon raise serious concerns for human health and the environment. 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 Arsine 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.

If solar panels are not recycled and reused, key materials such as glass and aluminum will be lost over time. Because solar panels include rare metals such as indium and gallium, not collecting them at the end of their useful life may result in their irreversible depletion. Non-recycled materials are either burnt or disposed of in landfills. This has negative consequences since these compounds can enter any living entity via groundwater, soil, absorption by nearby plants, and so on.