

# **End Life Cycle Recycling Policy Framework For Commercially Available Solar Photovoltaic Modules And Their Environmental Impacts**

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**Abstract:** Increasing changes in weather conditions like up surged global temperature, pollution, population explosion and economic backwardness being the major problems faced by our society in the present century. The natural resources have been exploited to their peak by the increasing population. Emerging industries and enhancement of lifestyle of people across the globe has further exhausted the conventional sources of energy with mother Earth being in its usual form. The growing taste of urbanization and modernization in developing countries is causing major repercussions for the environment and energy sector. The requirement of energy and its associated amenities indulges humankind into the blooming of social, economic and health benefits. To meet these requirements the necessity of renewable energy sources was emphasized. With ubiquitous presence of Sun solar energy proved to be an inexpensive and versatile source of energy. Further provision of governmental subsidies the solar photovoltaic power bloomed across the world. Using the Life Cycle Assessment (LCA) approach, an in-depth study of the various inputs and outputs in solar PV system is studied. Though with increasing agitation in climate perturbedness a sustainable and greener route to decrease the green house gaseous emissions is mandatory. Use of renewable source of energy in a clever mode will be bringing drastic changes in the improvement of energy issues in a greener way. The clean and green way of renewable energy resources has to be applied in every niche of the world. Solar energy proved to be a major contributor in this task. The governmental initiative of more PV installations is leading to macroscopic proliferation of solar photovoltaic waste accumulation in the country, which has become an utmost issue of the hour to be handled by PV scrap management and recycling policy. Existing PV technologies will be evaluated and their effects on environment, human health, social and economic aspects will be analyzed in depth. Major PV module recycling methods are evaluated and the material recovery in economic terms is recorded. With the sky rocking PV scrap, India is obligate for inclination towards the PV recycling policy framework. The main focus of present work is towards the effective remedy of the environmental and socio-

economic impact arising in the life cycle assessment of c-Si, CdTe, CdS, CIGS. A sustainable policy is to be put forward to potentially tackle the upcoming problems from the PV waste generation and accumulation.

**Key Words:** Life Cycle Assessment, Solar Energy, Environmental impact, Solar e-waste, Policy

### **Introduction:**

Ever since the homosapiens came on this planet they have been using energy in one form or the other. For the very time they used fire originated from rubbing of stones together to cook flesh. But with passage of time the process of manipulating the sources of energy came into emergence. To further meet the demands of food cultivation of land was initiated and further energy was generated from water, wind, Sun. The use of fossil fuels is increasing the environmental problems like acid rain, air pollution, global warming. To avoid these environmental problems a migration towards the sustainable energy resource is required and solar PV energy has the capability to full fill this need. PV converts the solar energy directly from the sun into the electric energy by the photo-voltaic effect. During the operational phase of the solar photo-voltaic system there is no utilization of the conventional energy sources and there is no emission of greenhouse gases, hence this technology is guided as environmentally friendly.

With the growing population the energy requirements of the world is continuously increasing. Urbanization further added to this demand. Energy from the solar radiations can be converted into consumable form by the use of various tools and techniques. Mainly three techniques can be applied to fulfill the solar energy conversion:

- 1) Solar energy can be converted into electricity by using photovoltaic technology.
- 2) Solar energy can be converted into heat energy by using solar thermal technology.
- 3) Solar energy can be directly transmitted to buildings using non-mechanical methods.

Environmental effect of the photovoltaic panels is divided into two categories:

- 1) Advantageous impact
- 2) Disadvantageous impact

The advantageous impact is assessed by the use of Photovoltaic technology to combat the harmful effects of the conventional resources on the environment like pollution, increased global temperature. The disadvantageous impact is due to the decommissioning and manufacturing of the photovoltaic panels. Increasing energy demands all over the world has

led to the discovery of new energy sources after uncontrolled use of conventional energy sources. Solar photovoltaic technology has emerged as a most promising technology to improve the energy security and to mitigate the climate changes. PV technology has emerged as clean energy source, so its proper end of life treatment is a concerning issue migration towards an environmentally friendly resource from the conventional resource is the key step for the putting an end to the greenhouse gaseous emissions..

### **Methodology:**

Total installed capacity at the end of 2018 was 500 GW globally, by 2023 the global PV installations will reach to 1296 GW as mentioned in IEA- PVPS 2019 and further by the end of 2050 it will reach to 4500 GW as quoted in IRENA 2016. India will attain a total installation of 28 GW as on March 2019 as mentioned in IRENA. With the increasing over exploitation of conventional energy sources and degradation of earth's life support system, many industries and businesses have started to assess their product's environmental impact. One such tool used for this is LCA i.e. Life cycle assessment. A life cycle assessment is performed to understand the cumulative input and output<sup>1,2</sup>.

LCA is a tool to assess the environmental impacts and resources used throughout a product's life cycle and consider all attributes or aspects of natural environment, human health, and resources and can be defined as a method for analyzing and assessing environmental impacts of a material, product, or service along its entire life cycle (ISO 2005). Thus, ISO14040 defined LCA as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 2006). For further classification of it into environmentally friendly technology the whole life cycle assessment of the PV technology is taken into analysis. Utilization of solar energy came out to be a very alluring option. With the increasing population and economy of the world the traditional sources of energy have failed to full-fill the demands of energy. And the greenhouse gaseous emissions have also increased and this is causing environmental deteriorations. Therefore a sustainable energy resource is strictly required to accomplish the needs of energy and to combat the environmental deteriorations<sup>3,4</sup>. Various types of harnessing systems are developed for solar energy like building integrated PV and building applied this includes facade, sloped or pitched, submerged PV, floating PV, solar tree etc. Among these Solar PV tree are eventually being trendy for the generation of electricity because of lesser requirements of land area. SPTV are being more prominent in urban areas due to lesser availability of space. Moreover these resemble like a natural tree.<sup>5</sup>

The complete life cycle involves the manufacturing steps, assemblage steps, processing of components of photo-voltaic system, transportation of required materials, installation and furnishing of the solar PV system and finally the disposal after the complete utilization of the product<sup>6,7</sup>. Consequently the life cycle assessment is brought out. Through this an exact and accurate study is shaped which considers all aspects of environment from manufacturing to its payback time of energy.

LCA is defined as the accumulation and interpretation of the inputs required and the outcome of the technology during the overall lifetime. LCA is comprised of four areas:

- 1) Design & outlook
- 2) Reservoir assay
- 3) Effect/impact analysis

On the basis of above areas an entire outline of the LCA can be shaped.

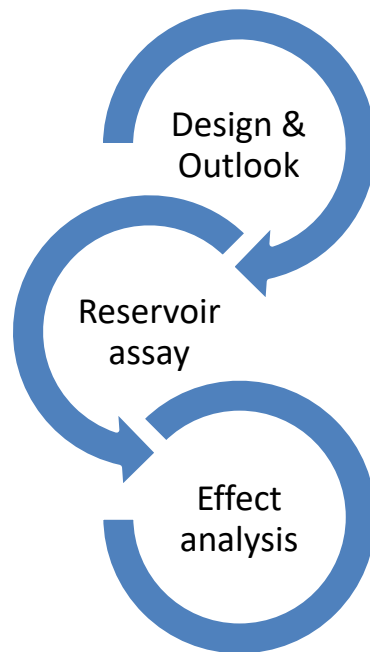


Fig.1 : Outline of Life Cycle Assessment

The design and outlook of LCA considers the manufacturing stage means from cradle to gate and end life stage means cradle to grave. Hence LCA speculates the entire stages of life cycle of the product. All the stages from raw material acquisition to assemblage process to the operational phase are all veiled into the life cycle assessment of the PV technology. Reservoir assay deals about the raw material extraction for the input<sup>8,9</sup>. It also includes the cost inclusion of all the input steps and the output steps of the life cycle of photovoltaic panels; transportation cost is also included here. Effect analysis inculcates the entire assessment of the photovoltaic panels. All the inputs from the surroundings and the output going to the

various other sources like air, water, land are analysed by the approach of raw material flow. Climate change, human toxicity, depletion of ozone, eutrophication, depletion of water resources, acidification etc. are all included under the effect analysis<sup>10,11</sup>.

Electricity producing systems based on photo-voltaic phenomenon impart lower emissions of greenhouse gases in comparison to systems generating energy from the conventional sources. If this energy generation based on PV system is attached to the grid than the greenhouse emissions will be high<sup>12</sup>. For further analysis of the environmental impacts caused by the electricity generation LCA will be deeply studied and EPBT is taken as the index.

Air emission, water use and land use are considered as the indicators of life cycle. All over the environmental attributes are examined. LCA analyzes the environmental burden of products from cradle to grave, from raw material acquisition, manufacturing of product, use and maintenance of product and finally to its end of life management, either by reuse, recycle or reducing<sup>13</sup>. Input is analysed in terms of amount of energy, the energy payback time is also given which ensures that solar energy is a clean energy source and the operation period is assumed to be of 27-30 years, hence its more environmental friendly than fossil fuels.

The life cycle stages of solar PV are depicted in Figure 2.

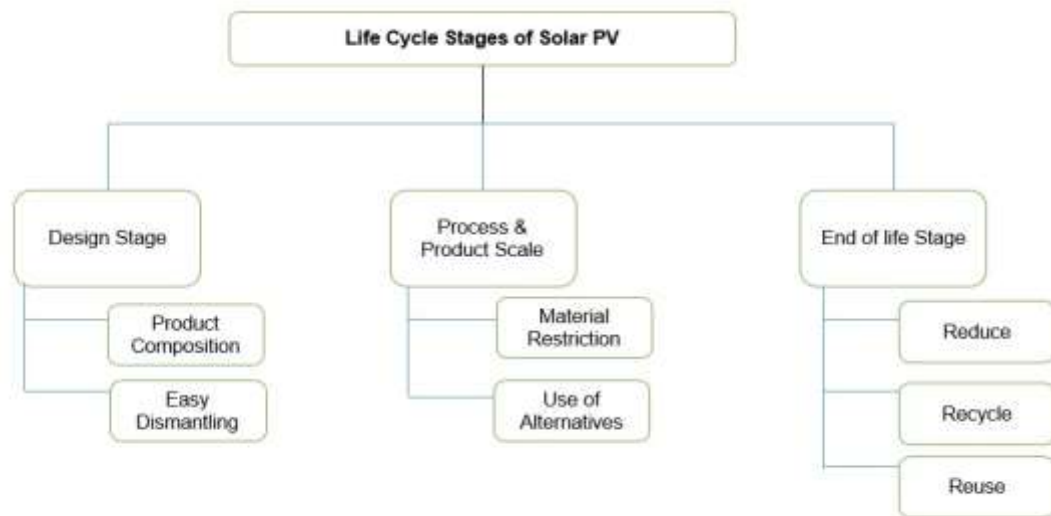


Fig.2: Life cycle stages of solar PV

A photovoltaic module consists of assembly of solar cells packed into protective multilayer structure consisting of front cover, electrical circuit interconnecting solar cells, encapsulant layer, backsheet and metal frames for support<sup>14</sup>. Major share is of glass and aluminium. With the growing PV technologies the use of metals like Cd, Te, Sn, In, Ga, Se is increasing and they possess toxicity effects<sup>15,16</sup>. Most materials other than glass and aluminum are usually

recovered in less quantity <sup>17</sup>. Some existing PV recycling methods are shown in Figures 3, 4, 5.

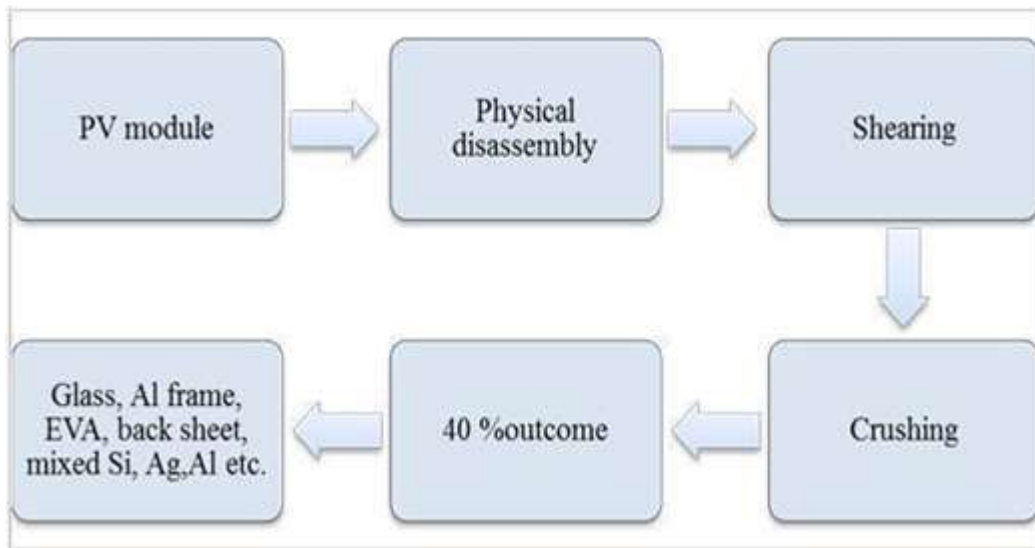


Fig. 3: Mechanical recycling method

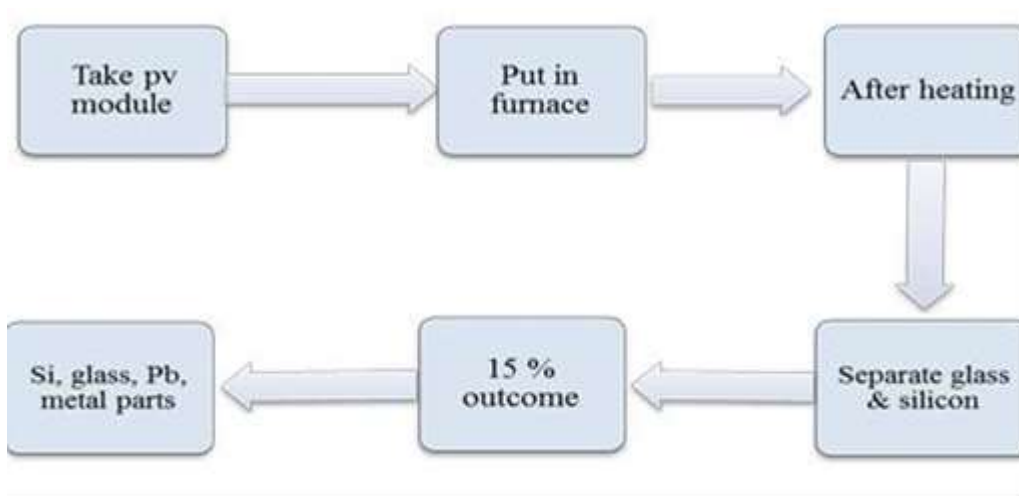


Fig. 4: Thermal method of recycling

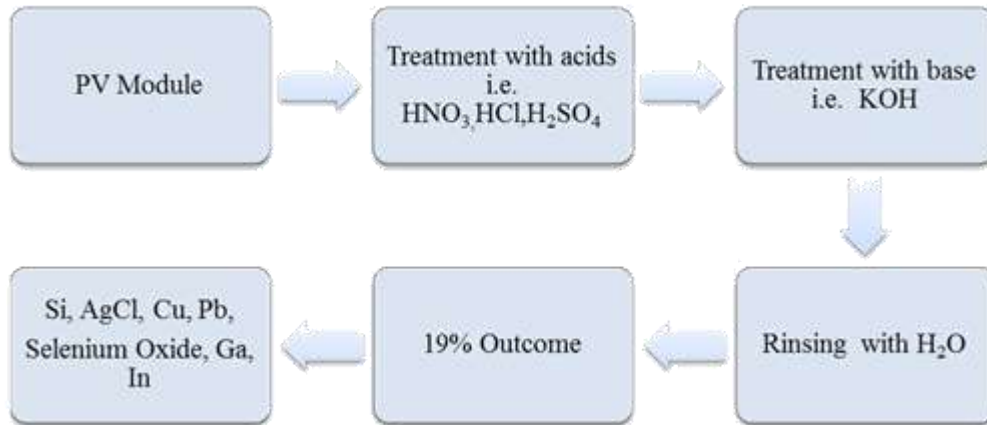
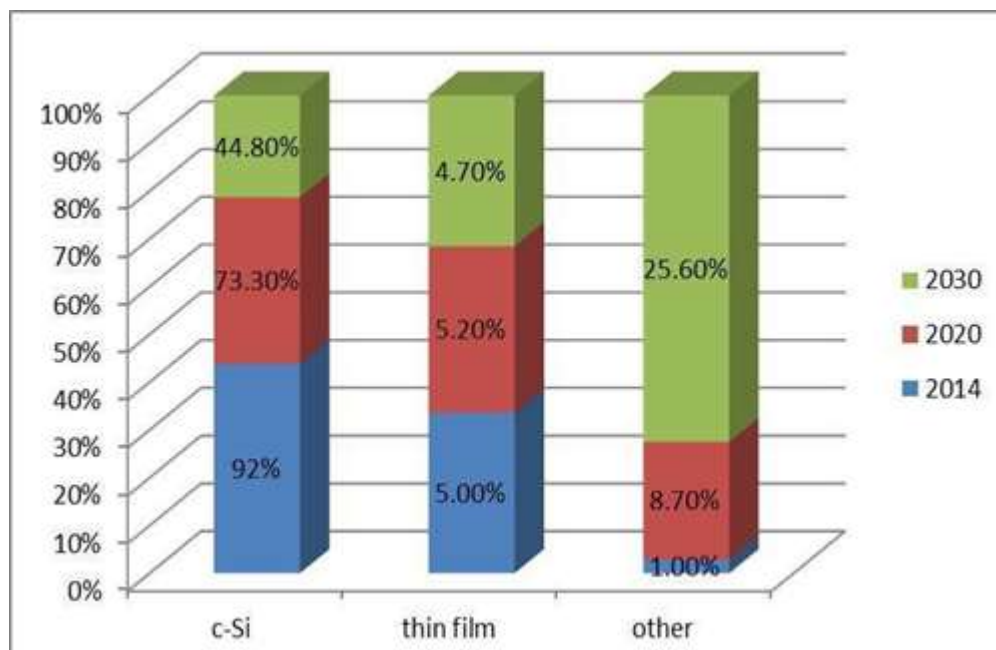


Fig. 5: Chemical recycling method

Solar modules waste has detrimental effects on environment, humans, ecosystem and biodiversity. Major aftereffects on humans included the carcinogenic effects of Cd, Te, Se, effects of Germane, Indium compounds on gastrointestinal tract etc<sup>18,19</sup>. The following is the current market share of the various solar PV technologies (2014-2030):



Source: IRENA 2016<sup>20</sup>

Fig. 6: Market share of PV panels (2014-2030)

With increasing PV installations the amount of PV waste proliferation is increasing and the recycling process is still at nascent stage<sup>20</sup>. The completion of the life cycle of solar photovoltaic module after 25-30 years has scope of recycling but the estimation of the total outcome of recycling is a complication. Thermal and chemical based end life treatment

methods are used to curb this complication<sup>21,22</sup>. Further the total material input is analysed and then compared with the output after recycling. The outcome ratio of elements like aluminum, silver, copper are assessed and other materials like steel and glass are also assessed<sup>23-25</sup>.

Till the present hour the largest fraction of waste PV materials are dumped in landfill. Though recycling could result in less environmental burden than landfilling but at an added monetary cost. So the need of the hour is to build up an effective PV waste management<sup>26</sup>.

## Solar cell

Solar cell is a photovoltaic device that converts the light energy into electrical energy based on the principles of photovoltaic effect. The generation of voltage across the PN junction in a semiconductor due to the absorption of light radiation is called photovoltaic effect. The device based on this effect is called photovoltaic device. The working of a solar cell is shown in Figure 7. The movement of the electrons takes place from the n region to the p region across the depletion region and an electric field is generated. The n and p region are further connected to the finger electrodes to collect the electrons and are further supplied to the load.

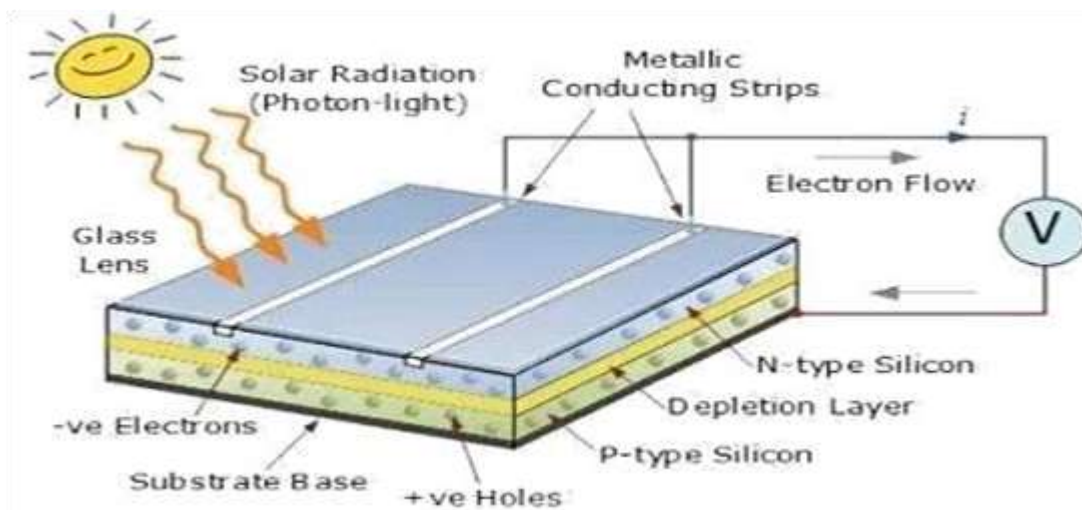


Fig. 7: Working of solar cell

Categorization of the solar photovoltaic solar cells is done on the basis of type of materials used and is discussed below<sup>9,27</sup>.

### First Generation Solar Cell—Wafer Based

These types of solar cells are made by using wafers of silicon. It's the most famous technology because of its high efficiency and being the most primitive. It is further divided into two types:

1. Single crystalline silicon solar cell.

2. Multi-crystalline silicon solar cell.

1. Single Crystalline Silicon Solar Cell: Single crystal of silicon is used in making this type of solar cell and their efficiency is of the order of 17 % to 18%.

2. Multi-crystalline Silicon Solar Cell: Different crystals are combined together to make a cell. In the present time it's the most popular. These are also cheap to compile in comparison to single crystal solar cells and their efficiency is less to nearby 12% to 14%<sup>12,16</sup>.

### **Thin Film based Solar Cells**

In comparison to wafer based silicon cells thin film solar cells have more economical aspects as 350 micro-meter layer is present for absorbing the incident photons. Whereas only one micro-meter thick layer is present in wafer based cell.

Solar cells made of thin film are further divided into -

1. Amorphous Silicon (a-Si)
2. Cadmium telluride (CdTe)
3. Copper indium gallium di-selenide (CIGS)

1. Amorphous silicon thin film (a-Si) solar cell: The atoms of silicon are arranged in a haphazard manner in the lattice of crystal. It is the most elementary solar cell which was firstly prepared at industrial scale. It is relatively having nominal cost and extensively available. Its efficiency is low from 4% to 8%.

2. Cadmium telluride (CdTe) thin film solar cell: From the rest of the thin film solar cells cadmium telluride solar cells are the most prominent type. These are feasible in terms of cost also. Their cost is much more reasonable in comparison to other solar cells. Their working efficiency is from 9% to 11%.

In spite of the above favorable reasons to utilize more CdTe solar cells the transition element Cadmium present in it imparts detrimental effect on the living beings of the ecosystem i.e. plants, animals, humans etc. The reclaiming process of Cadmium is also cost demanding and output ratio is also not much feasible. Transition elements also have low availability in nature. The threatening effect of Cadmium on the surroundings is also an issue of concern.

3. Copper indium gallium di-selenide (CIGS) solar cell: Such type of solar cell contains a combination of tetra elements comprising of representative elements and transition elements. These solar cells possess greater efficiency of 10% to 12% in comparison to CdTe solar cells. In terms of cost also these solar cells are relatively cheap in comparison to their other thin film solar cell counterparts<sup>28,29</sup>.

### **Third Generation Solar Cells**

This generation of solar cells is the emerging one in the latest hour in both industry level and research level. Various types included in this category are:

1. Polymer based solar cell (PSC) - This type of solar cell is made up of a thin layer of polymer wrapped on the absorbing layer.
2. Concentrated solar cells (CSC) - This is the modern photovoltaic technology. In this technology the incident energy of the photons is converged into a small area.
3. Dye sensitized solar cells (DSC) – This technology utilizes dye molecules in between the collecting electrodes.
4. Solar cells based on pervoskite - In this type of solar cells halogen ions like iodide, bromide, chloride, and two different cations i.e. A and B of variable radius are present. Usually  $ABX_3$  formula compounds are included. This pervoskite solar technology is the recent advancement in photovoltaic industry.
5. Nano crystal based solar cells - This category of solar cell consists of semiconductor material in nanometer range. Elements of transition group are also present. Solar cells based on nano crystals are also known as quantum dot cells.

All these above mentioned solar photovoltaic panels contains the various elements as mentioned below in the table I along with their production and their reserves in million tons from worldwide as documented by the U.S department of the Interior U.S Geological Survey in the Mineral Commodity Summaries 2019.

Table I: Production & Reserve of elements used in PV panels

Element	Mine Production		Reserves
	2017	2018	
Copper	20000	21000	830000
Aluminum	59000	60000	80300
Arsenic	34600	35000	N.A

Cadmium	25400	26000	N.A
Gallium	320000	410000	N.A
Germanium	106000	120000	N.A
Indium	714	750	N.A
Selenium	2710	2800	99000
Silver	26800	27000	560000
Silicon	6580	6700	N.A

The first shipment of the PV installations from the early 1980 has already withdrawn from their active life. And there is an urgency to handle the PV waste generated. The waste so generated at the end is of two types:

- 1) Manufacturing waste generated in plant
- 2) Waste generated at the end life

By 2030, 1.7 million tons and by 2050, 60 million tons of PV waste will be generated. Analytical studies put forward on thin film solar cells showed that 97% percent of the materials used in their manufacturing can be removed from the whole<sup>26,30,31</sup>. However solar energy is taken as the most reassuring technology for cleaner energy production. Further the performance of the PV technology is assessed in terms of environmental conduct.

### **Environmental repercussion:**

Environmental impact of the c-Si and thin film PV modules are analyzed through the life cycle assessment. GaBi is used for the LCA model assessment, CML 2001 baseline method is utilized for the assessment of the environmental effects of the modules. CdTe modules though require less material input than c-Si technology but the catastrophic aftermath of the CdTe modules is much greater than that laid out by the c-Si<sup>32</sup>.

Using transition metals like cadmium, copper and other elements like tellurium, selenium, silicon in the manufacturing of bulk and thin film solar photovoltaic materials causes major concern for health and environment at their end of life phase<sup>22</sup>. During the operation phase, bulk and thin film solar photovoltaic panels cause no harm to the environment. Exposure to arsine, cadmium, germane, lead, phosphorous oxychloride causes issues related to kidney which can further lead to nephrotoxicity<sup>15,33,34</sup>. Arsine and carbon tetrachloride can cause severe effect on lungs. Hydrogen fluoride and compounds of indium used in the manufacturing of thin film photovoltaic materials cause detrimental effects on bones and teeth. Deposition of fluoride and indium compounds on bones and teeth causes skeletal and

dental fluorosis. Exposure to phosphine causes cardiovascular dysfunction, gastrointestinal disorder; it can also act as pulmonary irritant. Phosphine can also catch fire due to sudden rise in the ambient temperature, which can lead to hemorrhage, neuropsychiatric disorders, respiratory and renal failures within few hours of exposure<sup>35</sup>. Inhalation of germane during the manufacturing of thin film photovoltaic materials can lead to dizziness, abdominal pain and headache. Germane catches fire quickly on exposure to air; it can also lead to an explosion on exposure to high temperature and can also cause a hazard. Long term exposure to germane and arsine causes lesions of blood cells which result in decreased efficiency to carry blood. Indium compounds can also cause irritation to the eyes, skin and oesophagus. Silane, selenium oxides and selenium hydroxides on inhalation can cause irritation to the skin, eyes and mucous membrane<sup>22,36</sup>. Major emphasis in this section is given on human health during the manufacturing and after the recycling process. 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 are shown in Figure 8.

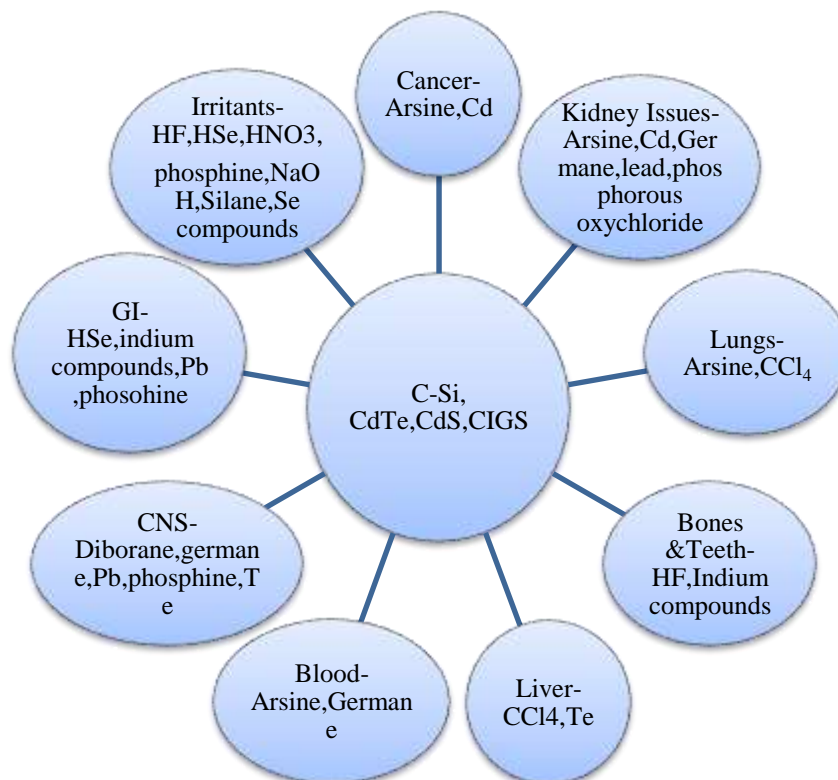


Figure 8: Effects on health by solar PV modules

## **Legislative framework for solar PV recycling in India**

With macroscopic proliferation of photovoltaic solar panel waste (PV material waste) in our country it has become an utmost need of the hour to establish a PV scrap management and recycling policy. In India the solar photovoltaic material recycling is still at its infancy<sup>37</sup>. In the present time India is not having any law making for the compulsory assemblage, resumption and recycling of life span of PV material. Bridge to India managing committee aforementioned that while the solar sector lengthens to heighten greatly from bare 3 gigawatt in 2014 to around 28 gigawatt in 2019.

Currently in India, there is lack of transparency on solar waste management. Endowment of sustainable energy pillar act is required, so that the PV scarp is extracted out from the general waste systemization. Solar PV material recycling is still not with peculiar laws<sup>38</sup>. WEEE published a Directive 2002/19/EC in the official journal of the European Union on 4 July 2012. The above directive was retrieved from the 2002/96/EC directive, this directive includes the Photo-voltaic panels into the electrical and electronic equipment catalog. From past ten years the European Union policy accords emphasis on recycling and resumption of the material and least on landfilling. Under 2016 solid waste management rules and trans boundary movement rules, ministry of environment forest and climate change is managing the other waste and hazardous waste. Solar PV material manufacturing utilizes the hazardous compounds, if these are left without treatment or recycling would cause adverse environment impact<sup>39</sup>.

At present, India neither possesses a policy guideline nor the least operational groundwork to safeguard recycling of PV scrap by traditional recycling process. With the sky rocking PV scrap India is obligate for inclination towards solar PV recycling policy framework. Solar PV recycling legislatives recommendations can be urged from members across the globe. Below are the ideas for the Indian government to tackle the inevitable PV scarp dilemma by applying the recycling legislative strategy in the detailed manner:

### **a) Regulative framework:**

- The manufacturing firm should be registered with a license.
- Constituent components utilization should also be familiarized.
- Prohibit the use of low abundant elements.
- Warranty of accomplishing environmentally loyal materials

- Provision of end life sketch for retiring panels.
  - Comprehensively manufacturing should be amiable to nature.
  - Provision of analytical testimony from birth to retirement.
  - Gross production & import of all PV material trading routes should be monitored.
- b) Layout the accountability & obligation of the collaborator for scrap handling & operation:**
- Establishment of a joint collection ventures across India for the retired and distorted solar panels between the producer and the recycler<sup>40</sup>.
  - Consumers should be provided some incentives for waste deposition in collection centers.
  - Collected waste material can then be auctioned for the recyclers or tenders can be directed.
  - Collection centers should have familiarity with waste disposal regulations<sup>20</sup>.
  - Alimony to such joint ventures should be provided
- c) Compose model for PV waste compilation:**
- B2B (Business to Business) and B2C (Business to consumer) firms should be utilized.
  - A municipal collection point is utilized.
- d) Launch of treatment method:**
- A combination of both mechanical & thermal method should be registered commercially.
  - Method should deal with hazardous & non- hazardous waste.
  - Risk factors of treatment of the wastes should be established to the recyclers
  - Standardized infrastructure for the treatment should be available.
- e) Disposition Corporation Endowment:**
- Survey usual recycling methods.
  - Analyze the expenditure and the industrial need for the efficient PV recycling system.
  - Develop units to accumulate recycling materials.
  - Supply recycled products to related industries for further profit gain.
- f) Manufacturer Liability System (MLS) constitution:**
- Abide the manufacturer to ensure lesser impact of hazardous materials.
  - Utmost stringent responsibility of producer to take back its product from the market after its complete life end.
- g) Set up of a head body over all the solar PV industry:**
- Monitor the overall activity of the solar firms and knock out offenders from registration.
  - This organization should also promote the use of sustainable materials in the designing.

#### **h) Financial aid:**

- A federal government agency should be set up for the financial assessment to PV industry.
- Indian government should inculcate various monetary schemes for recyclers.
- These way hazardous effects of the clean energy source are totally culminated out from the environment.

#### **i) Recycling institution set up:**

- India should establish institutes which will impart professional skills among the people involved in this field.
- It will also be a boon for employment.

#### **Conclusion:**

The paper presents a policy framework for solar PV recycling in both rural and urban India. With everyday target achievement of new solar PV plant the waste accumulation has reached to an estimated amount of 6096508 tons. Till now the recycling methods have received very less emphasis. Treacherous planetary waste spawned by the decommissioning of solar PV materials can't be thrown in garbage. There has to be a stringent plan for their management. The implementation of a legislative PV recycling structure in emergent nations especially in Indian scenario will be a great life savior to tackle the havoc which is to be originated in times to come. Comprehensive analysis is carried out on existing PV recycling methods out of them thermal method is good enough with some demerits. The scrutiny of LCA methodology of PV comprehends the three phases: 1) Manufacturing 2) Utility 3) End life Manufacturing phase is more influential for the environmental perspective, as it holds the involvement of various substances in all states of matter which can produce endangerment to the health of humans. The utility phase can also add to the harmful emissions due to fire hazard which can further cause harm to the land. The end life phase accumulates the waste pile up. This paper also emphasizes on the environmental and socio economic tremor bumped by the clean energy source due to increasing market share of PV technology. An affirmative response to this policy from Indian government will effectively curb the future forecast of the PV scrap disaster. Harmful gaseous emissions are released into the environment during the process of manufacturing, utility phase and end life phase. Further not only the manufacturing process but also the resource consumption is also considered and the impact is evaluated in context to environment. A complete interpretation is made for the disposal and

end life plot of c-Si and CdTe panel. Recycling of the solar photovoltaic modules at the end life plays an important role in the restoration of the materials used. Recycling is veiled up by the complications encountered during the procedure like lack of collection point of the waste and proper recycling technology. Inadequacy of the material availability is paving way towards the recycling of the material from the PV modules. Recycling of the solar panels can help in abstaining the material wastage.

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