A novel policy to tackle life span reassessment of existing bulk and thin-film photovoltaic materials

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Abstract: With the growing planetary demands of clean energy, solar photovoltaic system electricity generation has become mandatory in today's world. At the same time, when we look towards photovoltaic waste volume in India, it is estimated to burst forth to 200,000 by 2030 and around 1.8 million tons by 2050. Therefore, there is a dire need to scale up the PV recycle method from lab to full-fledged industry. Most of the developed countries such as China, UK, Japan, etc. have ensued their PV scarp management policies but in context to Indian prospective, it is yet to be established. The paper focuses on the effective remedy of environmental and socio-economic impact arising during the life span fulfilment of c-Si, CdTe, CdS and CIS. Over here, a sustainable novel policy framework is put forward to potentially tackle the above-mentioned problem which is still to be adopted by the Indian Government for further implementation.

Keywords: life span reassessment; photovoltaic system; recycling policy; environmental impact; socio-economic impact.

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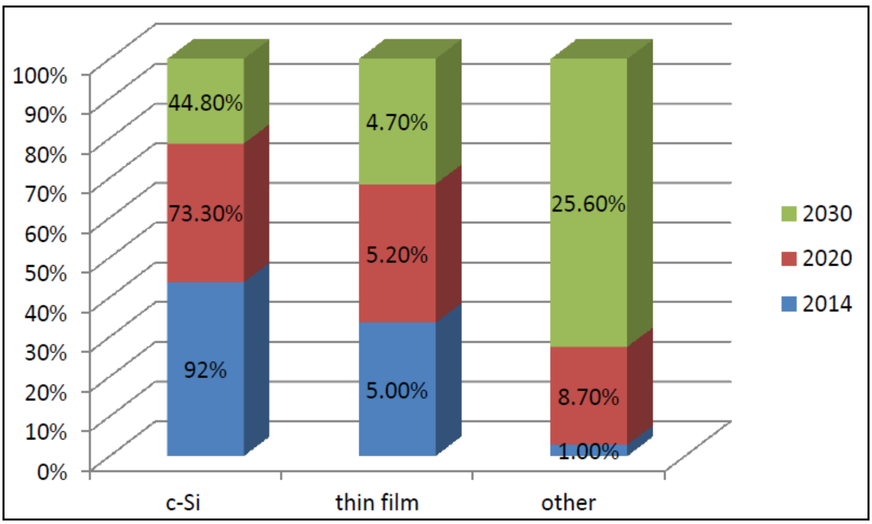
1 Introduction

With the flourishing of the solar PV system, the installation will reach to gross 637–653 GW by the edge of 2019. IEA anticipated solar hike to 4.7 terawatts (4,674 GW) by the extreme of 2050 with major setup in China and India. The comprehensive surge of PV materials is remarkably diversified across countries. The maximum installation of the solar PV system in 2017 was in China (53 GW), the USA (10.6 GW), India (9 GW) and Japan (7 GW) (Suresh et al., 2019). Expanding installation is proliferating the PV waste. India will attain a total installation of 28.18 GW as of March 2019. India as an economically emerging country has a huge population density in comparison to land availability. By the end of 2050, 1.8 million tons of PV solar waste will be assembled across India. In such a scenario, recycling of solar PV material becomes obligatory with a legitimate policy framework (Li et al., 2020; Xu et al., 2018). Current recycling techniques, i.e., thermal, chemical, mechanical (Strachala et al., 2017) are analysed and their environmental and socio-economic repercussions are emphasised.

A number of literature has 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 in the recycling strategy of PV materials. Till the present hour's, largest fraction of the PV materials is dumped to landfills recycling processes are yet not monetary. The amount of PV material scrap reaching to the recyclers is still negligible due to the fair life span of 25–30 year of the solar PV system (Granata et al., 2014) because of this, the recycling of PV scrap lacks in bringing forth a lucrative turnout.

Figure 1 Market share of PV panels (2014–2030) (see online version for colours)



The market composition of c-Si is reducing from 2014 to 2030, while the thin-film technologies showed an increase in market share from 2014 to 2020 whereas a decrease in market share is estimated from 2020 to 2030 (Weckend et al., 2016) as shown in Figure 1. This decline is due to the toxicity effects of cadmium, tellurium, selenium, etc. Other emerging technologies like pervoskite solar photovoltaic, concentrated solar photovoltaic, dye-sensitised solar photovoltaic, etc. were not in a significant quantity till 2014 due to stability issues, but in later years, they will show an increase in market share due to more advances in photovoltaic technologies stability. Moreover, till now, recycling strategies are build-up only for the multi-crystalline silicon, recently First Solar developed a recycling process for thin-film PV systems too (Sinha and Wade, 2015). Sometimes, the scarp volume gets reduced after further recycling which increases the economic losses (Faircloth et al., 2019). Recyclers also lack the provision of incentives for the various inputs involved (Goe and Gaustad, 2016). Various recycling methods like thermal, chemical, and mechanical are used and their comparative analysis is ruled out

(Zhang et al., 2013). At the level of manufacturing various hazardous substances are involved in both c-Si, CdTe, CIS which accord health detriments to biotic components (Fthenakis and Kim, 2011), and their disposal is also a tedious task (Sen et al., 2016) because of greater risk of leaching from both the demolished and worn out solar panels.

2 Methodology

The life span reassessment methodology has been applied for the bulk and thin-film solar photovoltaic material (Cyrs et al., 2014; Wu et al., 2017). This methodology analyses the complete cradle to the grave framework of the solar photovoltaic system. Through life span reassessment, the environmental impacts of the photovoltaic technologies can be analysed on human health, natural resources, ecosystem, biodiversity, environmental toxicity, etc. Life span reassessment can be further studied by two approaches, i.e., cut-off approach and end of life approach (Deng et al., 2019). In the cut-off approach, the recycling benefits in terms of environmental impacts and the worth of the recovery materials are included in the recycling processes total cost. Whereas at the end of life approach, the total worth of recovery materials to be gained after recycling and the total cost which is to be invested are taken in a separate way (Mathur et al., 2020). In this approach, the benefits occurring in the environment due to recycling are studied in a detailed manner.

The eminent focus of reprocessing of the existing bulk and thin-film photovoltaic material is to bring down the quantity of leftover scrap and escalate the quantity of material obtained after recycling. The material obtained from the recycling can also be used for the manufacturing process of the photovoltaic modules. Recycling of photovoltaic material is essential for profit-making and keeping the mother Earth's ambiance clean. With the rapid installations from the 1980s to the present hour, the amount of photovoltaic materials to be used in making solar photovoltaic modules is increasing. These solar photovoltaic modules consist of various solar cells made up of silicon, tellurium, cadmium, copper, selenium, etc.

For the recycling of the photovoltaic materials, the exact composition of the various solar photovoltaic modules should be analysed (Latunussa et al., 2016). Recycling of photovoltaic materials is being eminent because of the increasing demands of the PV materials like silicon, tellurium, copper, cadmium, gallium, germanium, etc. Two stages of photovoltaic material recycling are important (Stolz and Frischknecht, 2018):

a Segregation of photovoltaic cell: This can be done by either using the thermal recycling method or the chemical method of recycling.

b Washing of the top layer of the photovoltaic cell: In the course of the recycling procedures, the outcome of each of the recycling methods should be sterilised either the use of laser technique or by the help of chemicals. The undesirable coatings on the surface of the photovoltaic cells like the anti-reflection layer, metal coating layer, etc. can be easily detached.

For effective recycling methods, all the laminating layers should be removed. Glass, aluminium frames, copper, Tedlar sheets, ethylene-vinyl acetate sheet, plastic components, polymer sheets all are to be completely detached. The existing market scenario of the photovoltaic materials is captured by the bulk photovoltaic materials, i.e., c-Si technology comprising of both monocrystalline silicon solar cells and multi-crystalline silicon solar cells. Monocrystalline silicon solar cells are more used due to their higher efficiency and single electron layer in comparison to multi-crystalline silicon solar cells. With increasing efficiency criteria and the use of lesser materials in the manufacturing of the solar photovoltaic cells, new technologies in the market have flourished (IEA, 2019).

The foremost target of reprocessing the PV materials is to dwindle the demolished and faulty modules. With the increasing efficiency of the modules, the likely existing ones have to be taken over with the brand new. Up to now trivial mechanical, thermal and chemical methods of recycling are used (Klugmann-Radziemska, 2012; Maani et al., 2020). Silicon can be obtained through the laser method as manufacturing units of silicon are absent in India, therefore it has to be mandatorily recycled, moreover its transportation to China for recycling is not economically feasible (Hałacz et al., 2020). Intrinsic proportions of c-Si, CIS photovoltaic panels are depicted in Figures 2 and 3.

Figure 2 C-Si component proportion (%) (see online version for colours)

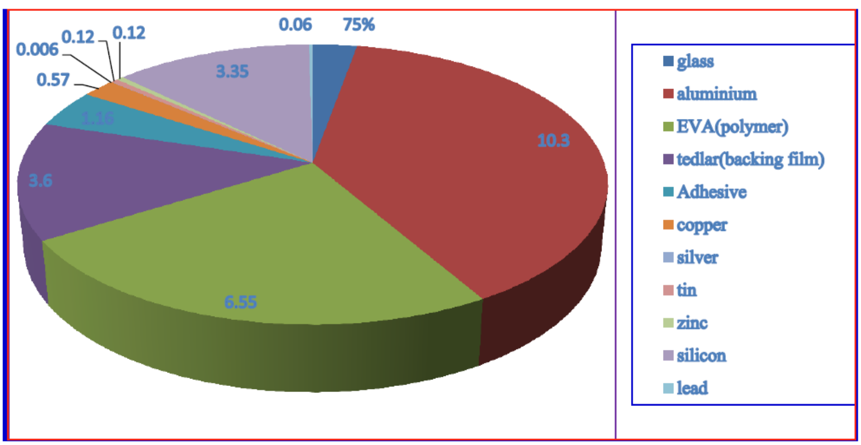
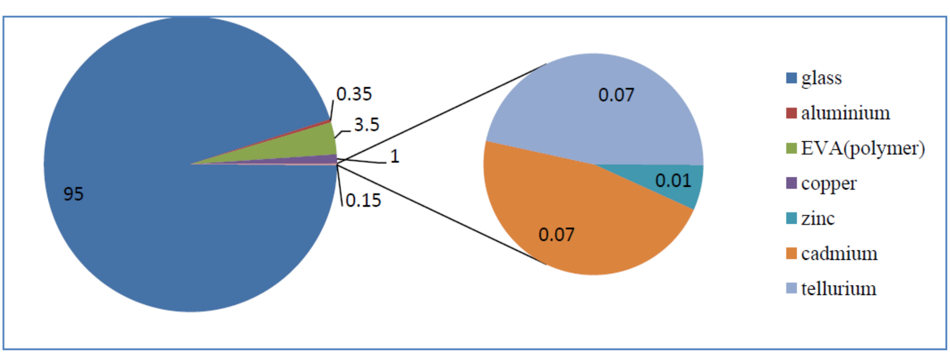


Figure 3 CdTe component proportion (%) (see online version for colours)



At present strong regulatory framework to support recycling should be framed (Chowdhury et al., 2020; Ranasinghe and Athapattu, 2020). The existing recycling procedures adopted in various countries are mentioned here. In the USA, recycling method consists of three main steps. The first step is disassembly, second is delamination and third is disposal. Disassembly includes the removal of aluminium frame, copper wires and junction box. Further, the coverings of glass, EVA, etc. are removed by the existing recycling methods like mechanical, thermal and chemical. Further, hazardous and non-hazardous materials are disposed. Whereas in Europe, some guidelines for solar panel waste disposal are put forward according to the Legislations of Waste of Electrical and Electronics Equipment. Washington State in July 2017 passed the Solar Stewardship Bill for the producers of solar photovoltaic materials to take the recycling methods into account for the reassessment of their product. California's Government is also encouraging the appropriate and safe handling of retired and worn-out panels. California Government is also planning to categorise solar waste as universal waste due to the worldwide installations of the solar photovoltaic system. New York is also planning to merge the agencies working for environmental protection and solar panel manufacturers (McElligott, 2020). They will be building-up a program for the PV waste collection, transportation, recycling of the decommissioned solar panels. The overall benefits of recycling methods can be estimated by analysing the expenses occurring at each step.

Various PV firms like First Solar, Deutsche Solar, Solar cells Inc. (SCI) and Pillington Solar International (PSI) have initiated the PV reclaiming programs. SCI is indulged in recovering the backing film, i.e., EVA by the pyrolysis at 500°C. 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. Existing recycling methods, i.e., thermal, mechanical and chemical methods are summarised in Figures 4, 5 and 6.

For thermal treatment, photovoltaic modules to be recycled are placed in a muffle furnace, heated to high temperatures of 400°C to 500°C in approximately 20–25 minutes.

Photovoltaic modules can be completely recycled to a larger extent by the use of mechanical method of recycling.

Figure 4 Thermal recycling method (see online version for colours)

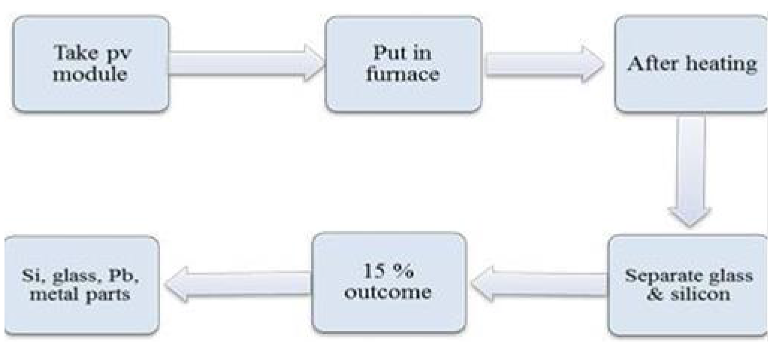


Figure 5 Mechanical recycling method (see online version for colours)

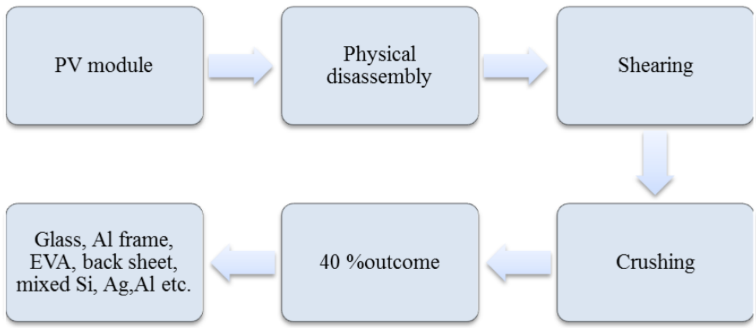


Figure 6 Chemical recycling method (see online version for colours)

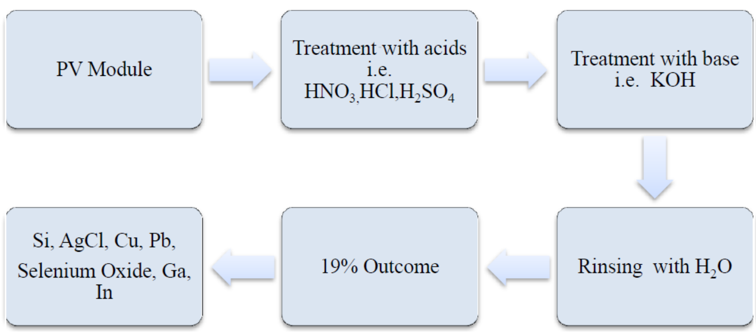


Table 1 Comparative analysis of the thermal, chemical and mechanical method

		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	Utilised for	Valuable materials like Si, Ag, etc.	Scarce and 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

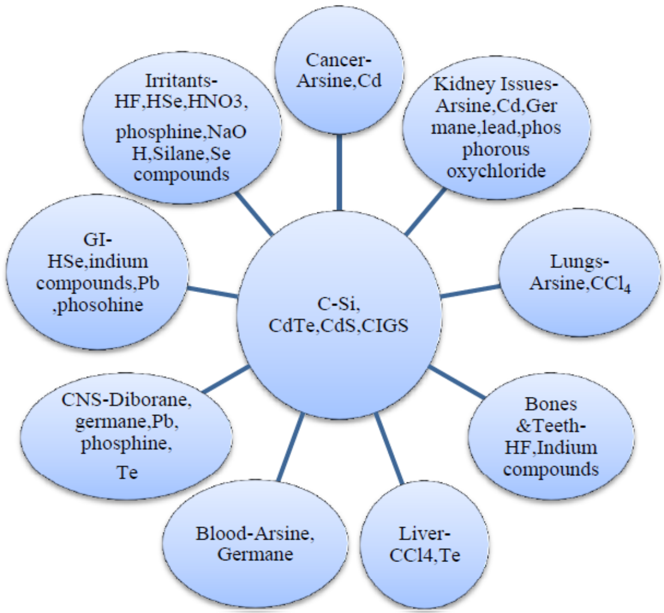
This method is not very much efficient as it takes a long time for the action of the chemicals; moreover, it has an additional cost factor added to it due to the chemicals used. This method can be utilised for obtaining scarce and hazardous metals like cadmium, tellurium, indium, gallium, etc. The chemicals used in this method for recycling purposes can also pose an environmental threat when disposed of (Huang et al., 2017).

Table 1 gives a comparative analysis of the above-described methods of recycling of photovoltaic modules. An overall comparison shows that a combination of mechanical and thermal methods is good for the recycling process.

3 Environmental repercussion

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 the environment at their end of life phase (Quek et al., 2019). 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 the kidney which can further lead to nephrotoxicity (Nkuissi et al., 2020). Arsine and carbon tetrachloride can cause a severe effect on the lungs. Hydrogen fluoride and compounds of indium used in the manufacturing of thin-film photovoltaic materials cause detrimental effects on bones and teeth. The 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 a pulmonary irritant. Phosphine can also catch fire due to a sudden rise in the ambient temperature, which can lead to haemorrhage, neuropsychiatric disorders, respiratory and renal failures within a few hours of exposure. Inhalation of germane during the manufacturing of thin-film photovoltaic materials can lead to dizziness, abdominal pain and headache (Grant, 2020). Germane catches fire quickly on exposure to air; it can also lead to an explosion on exposure to high temperatures 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 irritate the eyes, skin, and oesophagus. Silane, selenium oxides, and selenium hydroxides on inhalation can irritate the skin, eyes and mucous membrane (Kwak et al., 2020). The major emphasis in this section is given on human health during manufacturing and after the recycling process. The environmental after-effects 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 7.

Figure 7 Effects on health by solar PV modules (see online version for colours)



4 Socio-economic impact

Prominent worth can be assessed by recovering materials from the recycling of waste solar photovoltaic materials. Eminent profit attained from recycling can be estimated by taking the value of the recovered material from the market. The estimated waste generated by 2050 will be 7,278,167 tons (Paiano, 2015). The major portion of the waste accumulated will be shared by glass, aluminium, silicon, tellurium, and other representative group elements like indium, gallium, germanium, etc. With the existing recycling methods of solar photovoltaic materials, the recovery rate of aluminium is 100%, followed by the glass with a recovery rate of 95%, silicon with 81%, tellurium 87.5% recovery rate is obtained. The representative group elements like germanium, gallium, and indium account for only a 30% recovery rate. The maximum amount of glass is recovered from the accumulated solar photovoltaic waste, followed by aluminium, silicon, transition group elements, and representative group elements. Increasing recycling technologies will also open a new job employment sector across the globe (Komoto et al., 2018). Moreover, the interest of the society and the recycling companies is also incorporated into recovering the valuable materials like Cu, Ag, etc. from the decommissioned and retired panels (Masoumian and Kopacek, 2015), especially Si is estimated to be recovered to a quantity of 30,000 tons by 2030. The overall waste generated up to 2050 and its percent recovery rate along with total waste recovered is depicted in Figures 8, 9 and 10, respectively.

Figure 8 Material and waste generated (in tons) by 2050 (see online version for colours)

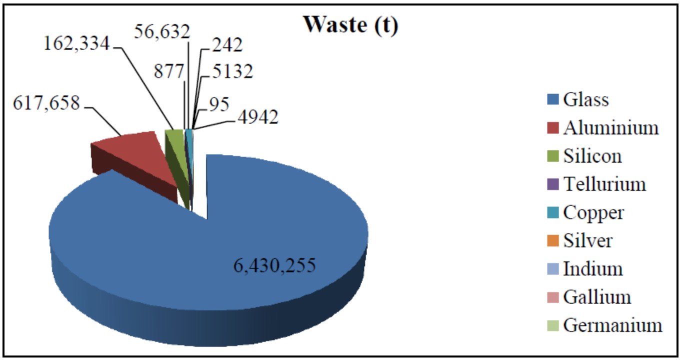


Figure 9 Recovery rate of waste material (see online version for colours)

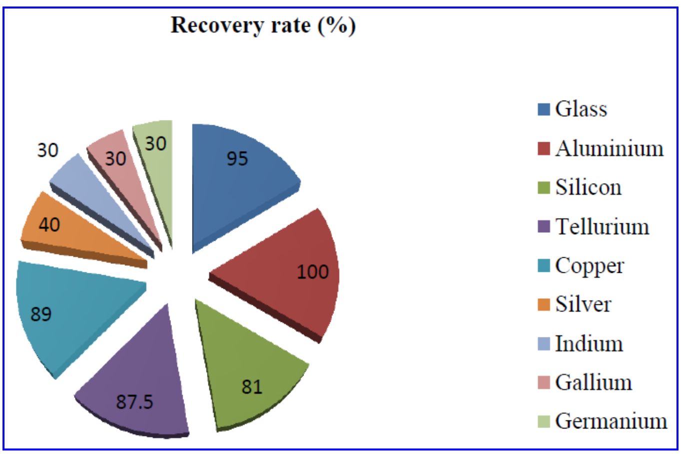
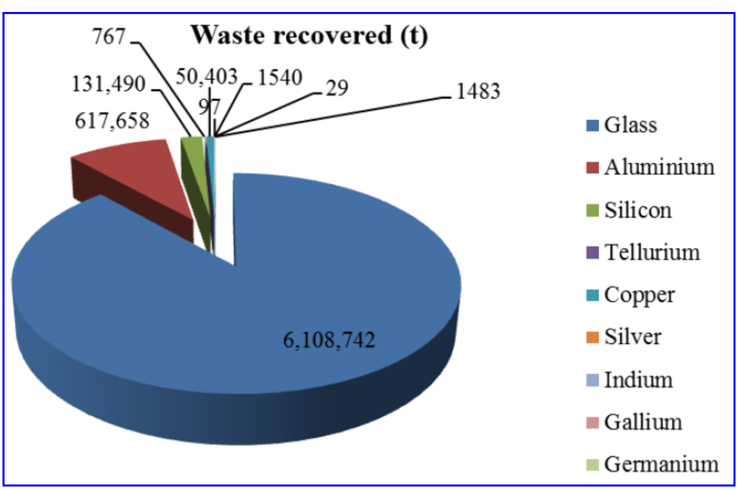


Figure 10 Waste (in tons) recovered after recycling (see online version for colours)



5 The legislative framework for solar PV recycling in India

With the 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. In the present time, India is not having any lawmaking 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 gigawatts in 2014 to around 28 gigawatts in 2019.

Currently, in India, there is a lack of transparency in solar waste management. An endowment of a sustainable energy pillar act is required so that the PV scarp is extracted out from the general waste systemisation. Solar PV material recycling is still not with peculiar laws (Karthikeyan et al., 2018). Under the 2016 Solid Waste Management Rules and Transboundary Movement Rules, the Ministry of Environment Forest, and Climate Change is managing the other waste and hazardous waste. Solar PV material manufacturing utilises hazardous compounds, if these are left without treatment or recycling would cause adverse environmental impact.

At present, India neither possesses a policy guideline nor the least operational groundwork to safeguard the recycling of PV scrap by the traditional recycling process. With the sky rocking PV scrap, India is obligate for inclination towards solar PV recycling policy framework. Solar PV recycling legislative 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 a detailed manner:

a Regulative framework:
   - The manufacturing firm should be registered with a license.
   - Constituent components utilisation should also be familiarised.
   - 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 and import of all PV material trading routes should be monitored.

b Layout the accountability and obligation of the collaborator for scrap handling and operation:
   - Establishment of joint collection ventures across India for the retired and distorted solar panels between the producer and the recycler (Xu et al., 2018).
   - Consumers should be provided some incentives for waste deposition in collection centres.
   - Collected waste material can then be auctioned for the recyclers or tenders can be directed.
   - Collection centres should have familiarity with waste disposal regulations.

- Alimony to such joint ventures should be provided

c Compose model for PV waste compilation:
- Business-to-business (B2B) and business-to-consumer (B2C) firms should be utilised.
- A municipal collection point is utilised.

d Launch of treatment method:
- A combination of both mechanical and thermal methods should be registered commercially.
- The method should deal with hazardous and non-hazardous waste.
- Risk factors of treatment of the wastes should be established to the recyclers
- Standardised infrastructure for the treatment should be available.

e Disposition corporation endowment:
- Survey the usual recycling methods.
- Analyse 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 a lesser impact of hazardous materials.
- Utmost stringent responsibility of the producer to take back its product from the market after its complete life end.

g Setup 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 organisation should also promote the use of sustainable materials in designing.

h Financial aid:
- A federal government agency should be setup for the financial assessment of the PV industry.
- Indian Government should inculcate various monetary schemes for recyclers.
- These ways of hazardous effects of the clean energy source are culminated out from the environment.

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

6 Conclusions

The paper presents a novel policy framework for solar PV recycling in both rural and urban India. With everyday target achievement of a new solar PV plant, the waste accumulation has reached an estimated amount in tons. Till now, the recycling methods have received very little emphasis. Treacherous planetary waste spawned by the decommissioning of solar PV materials cannot be thrown in the garbage. There has to be a stringent plan for its management. The implementation of a legislative PV recycling structure in emergent nations especially in the Indian scenario will be a great life saviour to tackle the havoc which is to be originated in times to come. A comprehensive analysis is carried out on existing PV recycling methods out of the thermal method is good enough with some demerits. This paper also emphasises the environmental and socio-economic tremor bumped by the clean energy source due to the increasing market share of PV technology. An affirmative response to this policy from the Indian government will effectively curb the future forecast of the PV scrap disaster.

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