

Photovoltaic waste assessment in india and its environmental impact

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Abstract. An increased energy demand of the world is met by the renewable sources of energy. In this solar photovoltaic technology has turned out as a major contributor. In India solar photovoltaic sector has enhanced from 1 GW to 28 GW from 2012 to 2018 and reached 32.627 GW on 30 March 2020 as reported by the MNERA. With the soaring installations, solar photovoltaic waste has also been increasing. 200,000 million tonne of waste solar photovoltaic will be assembled in India till 2030 and approximately 1.8 million tonne by 2050. Solar photovoltaic technology includes crystalline silicon panels, amorphous silicon panels, CdTe, CIGS, GaAs panels. Among these crystalline silicon panels are used in India on a larger scale upto 93% . Life cycle assessment methodology is utilised. Environmental effects of c-Si, a-Si, CdTe, GaAS, CIGS on public health are assessed. Major health effects pertaining to different human body organs are also mentioned. The article also targets apparently thriving social, economic influence of the recycled solar photovoltaic panels. Interest of the society and recycling companies is also mentioned in the paper to highlight economic benefits that can be availed from the end life of the photovoltaic panels.

Keywords: Solar photovoltaic waste; Human health impact; End life management.

1. Introduction

Solar photovoltaic technology has emerged as a great environment rescuer after the extinction of fossil fuels and in curbing down the global warming [1]–[3]. As reported by the Ministry of New and Renewable Energy in 2012 the solar photovoltaic installation was only 1 GW which got hiked to 32.627GW by March 2020 and with this the solar waste accumulation is also escalating high [4]. It is estimated that 200,000 tonnes of photovoltaic waste will be accumulated by the year 2030 and 1.8 million tonnes by 2050 [5]. Photovoltaic technologies like first generation crystalline silicon panels, second generation Cadmium Telluride panels and CIS panels, amorphous silicon, Gallium Arsenide panels etc. and third generation solar cells are considered in this article. The different solar panels contain variety of elements like Cd, Pb, Sn, In, Se, etc. which are regarded as hazardous. During operation phase solar photovoltaic technology is completely environmental friendly as it is free of toxic gaseous emissions and other emissions responsible for greenhouse effect. In manufacturing phase of solar photovoltaic modules, some hazards are associated to environment, safety and health [6]. Toxic and flammable elements are used in minute quantities in the photovoltaic industry, which holds environmental hazards during the panel manufacturing. National Photovoltaic Environment Health Safety Assistance Centre along with the photovoltaic industry of the United States has taken wise concern for hazards associated with here mentioned commercial solar panels crystalline silicon, CIS, GaAs, CdTe, amorphous silicon [7]. The potential risk posed by the photovoltaic panels to human health is due to exposure through air, water and soil in the industry or nearby inhabited areas [8]. For risk assessment of hazards caused by the solar photovoltaic panels the mechanism of released chemicals and their transport through air, water, soil is to be studied. Exposure can be through dermal



contact, inhalation by respiratory tract during installation and transportation due to damage to the solar panels [9], [10].

2. Solar panels and their health effects

2.1. Crystalline silicon solar cell

These are the wafer-based solar cells made up of silicon which is of crystalline nature. Chemical burns are associated with the use of HNO_3 , HF , NaOH as these are utilised for cleaning wafer and reactor [11]. Fumes upon inhalation causes irritation to the nasal tract and lungs. The elements used in the doping procedure in 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 [12]. Hazards associated with the respiratory tract can be controlled by adequate ventilation system designing of solar photovoltaic manufacturing firm. The above were the health issues related to those involved in the occupation of solar photovoltaic panel manufacturing. In the wafer slicing, etching, cleaning, processing, assembling of the solar cells environmental issues are into effect due to waste generation in gaseous and liquid state. However, initiatives have been taken for waste reduction and use of environment amiable materials for solvents and solders [2], [13]. Caustic waste can be reduced by the process of etching. Lead is also used in the solders that possess hazardous effects. However, some of the companies are using lead free solders by bringing advancement in their manufacturing technologies.

2.2. Amorphous Silicon solar cells

In the manufacturing of amorphous silicon Silane is used. It also possesses hazards as it is a flammable gas and its derivatives are used in the deposition of silicon nitride. Silane is liable to spark when exposed to atmospheric air. The ignition property of Silane depends upon its proportion with the carrier gas; its concentrations should be from 2-3%. Hydrogen is also utilized in the manufacturing of Silane and it is explosive in nature. Safety measures are used in the gas handling system so as to avoid the accidents by the leakage of gas. Safety is also ensured by storing the explosive components in tube trailers equipped with valves for the restriction of gas flow instead of changing the cylinders. Dopant gases like AsH_3 , GeH_4 , PH_3 also pose toxic effects upon exposure to environment. Continuous circumspection is needed to avoid any kind of hazard in the manufacturing firm. Environmental issues also pertain with the large use of silane in manufacturing of a-silicon [14]. Utmost care should be taken while handling silane on large scale in the solar panel manufacturing plants, the manufacturing plants should be away from the habitats to avoid any further hazards.

2.3. Cadmium Telluride solar cell, CdTe

In the manufacturing of the CdTe panels materials like CdS , CdCl_2 , CdTe are used and out of these cadmium possess risk due to inhaling of its vapours. It can cause edema in pulmonary, pneumonitis and death in severe cases. The toxicity effects of these materials is due to its inhalation as the lungs have high efficiency of absorption and further sending it to the gastrointestinal tract. Health risks come into light during the preparation of the components in the panel manufacturing [15]. Leaking of the vapours, etching of materials from the panels, cleaning and scrapping of the materials in maintenance process and also in handling the waste culminated by solar panels during life cycle of the solar power plant or after its life cycle completion possess greater risk to the workers at manufacturing site. Eye should be kept upon the hazards posed in manufacturing process and provision of equipment's for individual protection should be ensured to maintain the safety at the occupational site for the workers

[14]. Mask is to be provided for the prevention of adsorbing harmful emissions of cadmium in respiratory tract of workers and routine health check-up is also to be ensured of the staff so as to ensure the zero health risks among the workforce [16]. As such no human health issues are in record in context of CdTe solar panels however the problem arises in disposal and the end life management of these [7], [17]. Leaching of chemicals like Cd, In, Pb etc. occurs from the broken and decommissioned solar panels [18]–[20]. The leachate further has its fate from emission to transport as depicted in Fig. 1.

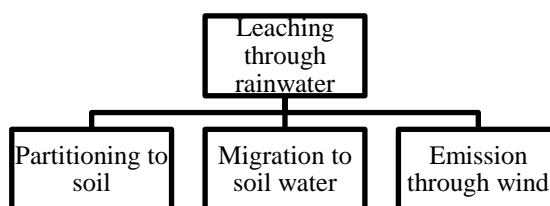


Fig.1 Fate and transport scheme from emission to exposure stage [19]

2.4. Copper Indium Selenide solar cells

In the manufacturing of CIS solar cells copper, indium, selenium is used in the vapour state, Hg_2Se medium is used for depositing Se. CIS shows very mild effect in terms of toxicity towards the animals. Though selenium is very toxic on combining with hydrogen it leads to formation of selenium hydroxide [21]. Selenium hydroxide possesses threat to survival of living beings in the concentration range of 1 ppm. It is similar to arsine in terms of physical properties but it gets oxidized and it affects the mucous membrane. An emergency control system is to be used with a scrubber so as to prevent the chances of any hazards in the depositing system. Proper vigilance is to be taken and control at the administrative level should be established to safeguard the people in the working area. Health issues and hazards are associated with the hydrogen selenide storage units henceforth safety measure are to be taken in by the use of restricting valves which prevent the flow of the gas [22]. Further the hazards can be prevented by using wet and dry scrubbing in case of sudden emission of the gas. Further environmental hazards are associated with the disposal and end life management of these solar panels [23]–[25].

2.5. Gallium Arsenide solar cells

Toxic gases like phosphine, arsine, and hydrides are used as the feedstock gases for making of this kind of solar cells. Accidental exposures of these can lead to a hazard [26]. AsH_3 , PH_3 , metal organics and hydrogen are used in quantity of 23 metric tons, 0.7 tons, 7 tons and 1500 tons respectively. Hazards can be avoided by the use of alternative chemicals instead of harmful chemicals. Tertiary butyl arsine and tertiary butyl phosphine can be used in the manufacturing of these solar panels instead of above mentioned chemicals. Nitrogen being less reactive in comparison to hydrogen can also be used to replace it from the solar panels [25], [27]. Table 1 summarizes the overall potential toxicity of materials utilized in solar panels. Fig. 2 highlights the human health effects from various chemicals used in solar photovoltaic panels.

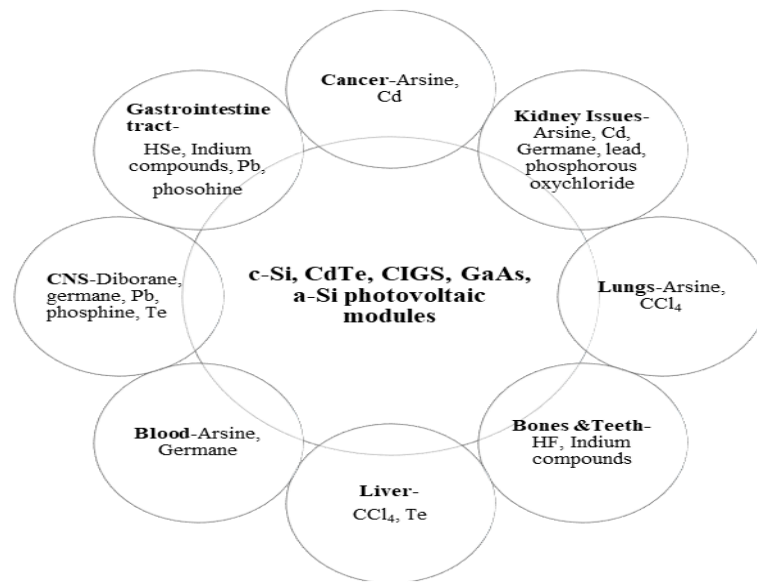


Fig.2 Human health effects from c-Si, CdTe, CIGS, GaAs, a-Si solar photovoltaic panels

2.6. *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)
2. Concentrated solar cells (CSC)
3. Dye sensitized solar cells (DSC)
4. Solar cells based on pervoskite
5. Nano crystal based solar cells

3. **Methodology**

Life cycle assessment is done to study environmental repercussions involved throughout fabrication, positioning and knocking down conditions. 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 three areas - (1) Design & outlook (2) Reservoir assay (3) Effect analysis. On the basis of above areas an entire outline of the LCA can be shaped as in Fig.3.

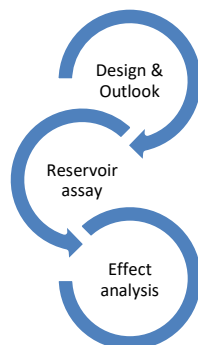


Fig.3 Outline of Life Cycle Assessment

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 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. Life cycle assessment of the solar panel waste based on the end life is essential as it analyses the product after its life cycle completion when it turns out as waste [28]. Profitable elements like silver, aluminium, copper etc. can be utilised for making of new solar panels [29]. Life cycle management based on reduce, reuse, recycle and recovery is to be practiced [30]–[32].

Dumping into land is the least preferred option for the treatment of solar photovoltaic waste [33]. Photovoltaic panels consist of materials like silicon cadmium, selenium, tetrachloride, sulphur hexafluoride, aluminium, silicon wafers, Indium, Tin, Nickel, Zinc, CdTe filter cake, Silver, plastic, glass, CIGS filter cake etc. On attainment of end life, the materials can be used again to gain economic benefit [13], [34]. Recycling is also to be performed on different solar panel to again utilise their components and materials [35]. Solar panel components are separated by shredding, detaching, solubilising, chemical bath and material sorting; further recycling can be achieved by processing panels in dedicated glass [36], [37]. Hazardous and non-hazardous materials are to be recovered which either can be reused or dumped into land so as to prevent the piling up of the waste.

Chemical	Utilisation	Hazard category				
		Asphyxiant	Corrosive	Irritating	Flammable	Explosive
Argon gas	Thin film deposition					
Ammonia	Antireflective coating					
Diborane	a-Silicon dopant					
Helium gas	Thin film deposition					
Boron trifluoride	Dopant					
Hydrochloric acid	x-ray 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	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					

Table.1 Potential toxicity of materials utilized in solar photovoltaic panels [22]

4. End life cycle management of Solar photovoltaic panels

Dumping of waste or burying them into land is the least preferred option for waste treatment [32], [38].

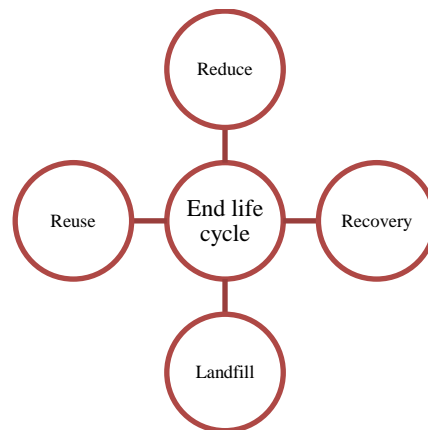


Fig. 4 End life cycle management of the solar photovoltaic waste

End life assessment of the solar photovoltaic modules holds importance for recycling companies and society on below mentioned criteria (Table. 2) as it prevents the environment and enhancement of economy [13], [39]. USD 15 billion worth raw material can be generated from the 60-78 million tons solar waste pile up from all over the world by 2050 which will give boon to new employment sector. Also in India the 1.8 million tons waste generated by 2050 will be of due economic worth to harness new employment industry [37], [40]. Value can be generated from the solar photovoltaic waste by their recycling at end life. Recycling techniques needs to be practiced at commercial scale so as to recover the valuable materials as it will boon the employment sector by establishing recycling industry and further new industry will be set up to utilize the recycled materials. Construction industry can utilize the recovered aluminium in making doors, window panes and floor tiles. Automotive industry can utilise Al, Cu, glass etc. Packaging industry can also utilize the recycled solar panel parts.

Criteria	Interest of society (%)	Interest of recycling companies (%)
Valuable materials	5	35
Hazardous materials	5	15
Average weight	0	25
Market share	0	25
Energy efficiency	20	0
Life duration	20	0
Production cost	5	0
Light absorption	10	0
Energy payback time	20	0
Greenhouse gas emission	0.15	0

Table.2 Interest of society and recycling companies [36]

5. Conclusion

Manufacturing of the solar photovoltaic panels requires use of hazardous chemicals that pose threat to health and safety of the people involved in the solar panel manufacturing. Hazard category of solar photovoltaic panels is also categorised. This negative impact upon health of the people and surroundings can be compacted by taking proper safety measures in the manufacturing firm. Further the use of hazardous materials needs to be replaced by the environmentally amiable substances so as to eradicate the root cause. Life cycle assessment of solar photovoltaic technology also emphasis on

environment and human health impact from origin to cradle and is proving to be a great savior in environmental impact analysis of this emerging technology. Accurately designed working infrastructure furnished with proper engineering system, imparting proper training to the employees for safety sustainment can lead to the reduction in the risk at manufacturing level and it will curb the detrimental effects of the solar manufacturing. Though crystalline silicon panels contain majority of the safe metals in comparison to CdTe, CIS, GaAs and amorphous silicon panels but the manufacturing procedure utilises harmful chemicals and further the disposal of these photovoltaic panels possess greatest risk to the environment. Among all the generations of solar cells health issues were more reported from CdTe, CIS, GaAs while lesser from c-Si, a-Si. Crystalline silicon panels though contain fewer amounts of valuable materials other than silver are non-toxic to environment. Recycling should be taken ahead with focusing on both environmental and economic benefit to attain sustainability in terms of development. Gaseous emissions released in the environment during manufacturing also pose harmful impact. This article also highlights comparative recycling interest of society and recycling companies as solar panel recycled material holds great economic benefit. Utmost caution needs to be practiced for reducing human health hazards and establish solar photovoltaic technology as completely eco-friendly.

References

- [1] S. Sen, S. Ganguly, A. Das, J. Sen, and S. Dey, 'Renewable energy scenario in India: Opportunities and challenges', *Journal of African Earth Sciences*, vol. 122, pp. 25–31, Oct. 2016, doi: 10.1016/j.jafrearsci.2015.06.002.
- [2] B. Huang, J. Zhao, J. Chai, B. Xue, F. Zhao, and X. Wang, 'Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process', *Solar Energy*, vol. 143, pp. 132–141, Feb. 2017, doi: 10.1016/j.solener.2016.12.038.
- [3] G. Giacchetta, M. Loporini, and B. Marchetti, 'Evaluation of the environmental benefits of new high value process for the management of the end of life of thin film photovoltaic modules', *Journal of Cleaner Production*, vol. 51, pp. 214–224, Jul. 2013, doi: 10.1016/j.jclepro.2013.01.022.
- [4] A. Paiano, 'Photovoltaic waste assessment in Italy', *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 99–112, Jan. 2015, doi: 10.1016/j.rser.2014.07.208.
- [5] K. Komoto *et al.*, 'End-of-life management of photovoltaic panels: trends in PV module recycling technologies', NREL/TP-6A20-73847, 1561523, Jan. 2018.
- [6] D. Strachala, J. Hylský, J. Vaněk, G. Fafílek, and K. Jandová, 'Methods for recycling photovoltaic modules and their impact on environment and raw material extraction', *Acta Montanistica Slovaca*, vol. 22, no. 3, pp. 257–269, 2017.
- [7] Md. S. Chowdhury *et al.*, 'An overview of solar photovoltaic panels' end-of-life material recycling', *Energy Strategy Reviews*, vol. 27, p. 100431, Jan. 2020, doi: 10.1016/j.esr.2019.100431.
- [8] M. Goe and G. Gaustad, 'Estimating direct human health impacts of end-of-life solar recovery', *Golisano Institute for Sustainability*, 2016.
- [9] M. Marwede, W. Berger, M. Schlummer, A. Mäurer, and A. Reller, 'Recycling paths for thin-film chalcogenide photovoltaic waste – Current feasible processes', *Renewable Energy*, vol. 55, pp. 220–229, Jul. 2013, doi: 10.1016/j.renene.2012.12.038.
- [10] V. Fthenakis and M. Raugei, 'Environmental life-cycle assessment of photovoltaic systems', in *The Performance of Photovoltaic (PV) Systems*, Elsevier, 2017, pp. 209–232.
- [11] T. Markvart and L. Castañer, Eds., 'Overview of potential hazards', in *Practical handbook of photovoltaics: fundamentals and applications*, New York: Elsevier Advanced Technology, 2003.
- [12] L. Karthikeyan, V. Suresh, V. Krishnan, T. Tudor, and V. Varshini, 'The Management of hazardous solid waste in India: An Overview', *Environments*, vol. 5, no. 9, p. 103, Sep. 2018, doi: 10.3390/environments5090103.

- [13] C. E. L. Latunussa, F. Ardente, G. A. Blengini, and L. Mancini, 'Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels', *Solar Energy Materials and Solar Cells*, vol. 156, pp. 101–111, Nov. 2016, doi: 10.1016/j.solmat.2016.03.020.
- [14] M. Vellini, M. Gambini, and V. Prattella, 'Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels', *Energy*, vol. 138, pp. 1099–1111, Nov. 2017, doi: 10.1016/j.energy.2017.07.031.
- [15] C. C. Faircloth, K. H. Wagner, K. E. Woodward, P. Rakkwamsuk, and S. H. Gheewala, 'The environmental and economic impacts of photovoltaic waste management in Thailand', *Resources, Conservation and Recycling*, vol. 143, pp. 260–272, Apr. 2019, doi: 10.1016/j.resconrec.2019.01.008.
- [16] J. Peng, L. Lu, and H. Yang, 'Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems', *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 255–274, Mar. 2013, doi: 10.1016/j.rser.2012.11.035.
- [17] V. M. Fthenakis, 'End-of-life management and recycling of PV modules', *Energy Policy*, vol. 28, no. 14, pp. 1051–1058, Nov. 2000, doi: 10.1016/S0301-4215(00)00091-4.
- [18] A. Ramos-Ruiz, J. V. Wilkening, J. A. Field, and R. Sierra-Alvarez, 'Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions', *Journal of Hazardous Materials*, vol. 336, pp. 57–64, Aug. 2017, doi: 10.1016/j.jhazmat.2017.04.052.
- [19] P. Sinha, R. Balas, L. Krueger, and A. Wade, 'Fate and transport evaluation of potential leaching risks from cadmium telluride photovoltaics', *Environmental Toxicology and Chemistry*, vol. 31, no. 7, pp. 1670–1675, Jul. 2012, doi: 10.1002/etc.1865.
- [20] R. Zapf-Gottwick *et al.*, 'Leaching hazardous substances out of photovoltaic modules', *International Journal of Advanced Applied Physics Research*, vol. 2, no. 7–14, p. 8, 2015.
- [21] 'Health-and-Safety-Impacts-of-SolarPhotovoltaics2017_white-paper-1.pdf', N.C.Clean Energy Technology Center, May 2017.
- [22] B. Bakhiyi, F. Labrèche, and J. Zayed, 'The photovoltaic industry on the path to a sustainable future — Environmental and occupational health issues', *Environment International*, vol. 73, pp. 224–234, Dec. 2014, doi: 10.1016/j.envint.2014.07.023.
- [23] F. Ardente, C. E. L. Latunussa, and G. A. Blengini, 'Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling', *Waste Management*, vol. 91, pp. 156–167, May 2019, doi: 10.1016/j.wasman.2019.04.059.
- [24] V. Fiandra, L. Sannino, C. Andreozzi, and G. Graditi, 'End-of-life of silicon PV panels: A sustainable materials recovery process', *Waste Management*, vol. 84, pp. 91–101, Feb. 2019, doi: 10.1016/j.wasman.2018.11.035.
- [25] F. Corcelli, M. Ripa, and S. Ulgiati, 'End-of-life treatment of crystalline silicon photovoltaic panels. An emergy-based case study', *Journal of Cleaner Production*, vol. 161, pp. 1129–1142, Sep. 2017, doi: 10.1016/j.jclepro.2017.05.031.
- [26] M. Tamaro, A. Salluzzo, J. Rimauro, S. Schiavo, and S. Manzo, 'Experimental investigation to evaluate the potential environmental hazards of photovoltaic panels', *Journal of Hazardous Materials*, vol. 306, pp. 395–405, Apr. 2016, doi: 10.1016/j.jhazmat.2015.12.018.
- [27] M. F. Azeumo, C. Germana, N. M. Ippolito, M. Franco, P. Luigi, and S. Settimio, 'Photovoltaic module recycling, a physical and a chemical recovery process', *Solar Energy Materials and Solar Cells*, vol. 193, pp. 314–319, May 2019, doi: 10.1016/j.solmat.2019.01.035.
- [28] K. Tasnia, S. Begum, Z. Tasnim, and Md. Z. R. Khan, 'End-of-life management of photovoltaic modules in Bangladesh', in *2018 10th International Conference on Electrical and Computer Engineering (ICECE)*, Dhaka, Bangladesh, 2018, pp. 445–448, doi: 10.1109/ICECE.2018.8636782.
- [29] L. Rocchetti and F. Beolchini, 'Recovery of valuable materials from end-of-life thin-film photovoltaic panels: environmental impact assessment of different management options', *Journal of Cleaner Production*, vol. 89, pp. 59–64, Feb. 2015, doi: 10.1016/j.jclepro.2014.11.009.
- [30] M. Lunardi, J. Alvarez-Gaitan, J. Bilbao, and R. Corkish, 'Comparative life cycle assessment of end-of-life silicon solar photovoltaic Modules', *Applied Sciences*, vol. 8, no. 8, p. 1396, Aug. 2018, doi: 10.3390/app8081396.

- [31] P. Stolz and R. Frischknecht, 'Life cycle assessment of current photovoltaic module recycling', life cycle assessment T 12-13, 2018.
- [32] W. D. Cyrs, H. J. Avens, Z. A. Capshaw, R. A. Kingsbury, J. Sahmel, and B. E. Tvermoes, 'Landfill waste and recycling: Use of a screening-level risk assessment tool for end-of-life cadmium telluride (CdTe) thin-film photovoltaic (PV) panels', *Energy Policy*, vol. 68, pp. 524–533, May 2014, doi: 10.1016/j.enpol.2014.01.025.
- [33] P. IEA, 'Snapshot of Global PV Market', International Energy Agency, Spain, Snapshot T1:35, 2019.
- [34] D. Sica, O. Malandrino, S. Supino, M. Testa, and M. C. Lucchetti, 'Management of end-of-life photovoltaic panels as a step towards a circular economy', *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2934–2945, Feb. 2018, doi: 10.1016/j.rser.2017.10.039.
- [35] J. Zhang, F. Lv, L. Y. Ma, and L. J. Yang, 'The status and trends of crystalline silicon PV module recycling treatment methods in Europe and China', *Advanced Materials Research*, vol. 724–725, pp. 200–204, 2013, doi: 10.4028/www.scientific.net/AMR.724-725.200.
- [36] M. Masoumian and P. Kopacek, 'End of life of management of photovoltaic modules', presented at the IFAC, 2015, vol. 48–24, pp. 162–167.
- [37] S. Weckend, A. Wade, and G. A. Heath, 'End of life management: solar photovoltaic panels', NREL/TP-6A20-73852, 1561525, Aug. 2016.
- [38] Y.-S. Zimmermann, A. Schäffer, P. F.-X. Corvini, and M. Lenz, 'Thin-film photovoltaic cells: long-term metal(loid) leaching at their end-of-life', *Environ. Sci. Technol.*, vol. 47, no. 22, pp. 13151–13159, Nov. 2013, doi: 10.1021/es402969c.
- [39] R. Deng, N. L. Chang, Z. Ouyang, and C. M. Chong, 'A techno-economic review of silicon photovoltaic module recycling', *Renewable and Sustainable Energy Reviews*, vol. 109, pp. 532–550, Jul. 2019, doi: 10.1016/j.rser.2019.04.020.
- [40] S. Suresh, S. Singhvi, and V. Rustagi, 'Managing India's PV Module Waste', Bridge To India, India, Analytical, 2019.

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