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A review of solar photovoltaic waste management in India

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ABSTRACT

Energy plays a crucial role for the development of a country. Production of electricity takes place using both conventional and non-conventional methods. Sunlight is converted into solar energy through a solar panel, also called a photovoltaic module or PV module. "The National Solar Mission" is one of the primary missions of India's National Action Plan on Climate Change, which places solar energy at the centre. "The National Solar Mission" was launched on January 11, 2010.There is a 26.53% share of renewable energy in total installed generation capacity in India, while solar energy's contribution is 3.6% of total energy generation in year 2019-20. The solar energy installation capacity of India was 40085 MW in 2021 and will increase to 100 GW in 2022. By 2030, India's PV waste generation is predicted to reach 200,000 tonnes, and by 2050, 1.8 million tonnes. Solar PV waste collected from their facility at the EOL should disposed of in line with the central government's "E-waste (Management and Handling) Rules," as updated frequently. Unexpectedly, the electronic-waste restrictions do not apply to PV module waste. As a result, no formal procedure for disposing of Photovoltaic waste occurs in India. The current study intends to fill technological gaps in Photovoltaic waste management, recycling and outline a framework for the future to develop effective regulations and policies in India for EOL Photovoltaic waste generated.

Keywords: PV waste, Photovoltaic, Waste management, EOL.

1. Introduction:

The contribution of solar energy is increasing rapidly in worldwide energy market. Sun light is the resources of solar energy easily and free available everywhere in the world. The main reason behind it to easily acceptable is green and clean energy (Domínguez et al., 2018). PV systems for solar energy have become a possible option for power generation in order to decrease greenhouse gas emissions (Daniel et al., 2021). the solar PV module directly convert solar energy into electricity (Santos et al., 2018). India has rich resource of solar energy, it's have more than 250–300 sunshine days with regular solar radiation of 200 MW / km^2 (Solangi, 2011). India has a satisfactory level of solar radiation, getting around 5 trillion MW of solar energy every year. The sun radiation impacting on the surface are around 4 and 7 kWh/m^2 on a day with 2300 to 3200 hours of sunlight each year. The sun's

Nomenclature or Abbreviation

End-Of-Life (EOL)

Extended -Producer -Responsibility (EPR)

International Renewable Energy Agency (IRENA)

Photovoltaic (PV)

Waste Electrical and Electronic Equipment (WEEE)

Mega Watt (MW)

Giga Watt (GW)

International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS)

Institute for Energy Economics and Financial Analysis (IEEFA)

National Solar Energy Federation of India (NSEFI)

Ministry of New and Renewable Energy (MNRE)

European Union (EU)

total radiation varies from 1600 to 2200 kWh/m^2.for a period of a year. The energy output is around 6000 million GWh per year (Sharma, 2011). The application of solar energy was started a long year ago but significant work started from 2010 When the national solar project was initiated. The cumulative solar energy capacity of India is increasing rapidly as shown in Figure1. The demand of PV cell is increasing day by day to worldwide (Xu et al., 2018). So, there must be a solid future plan for PV waste management. "The International Renewable Energy Agency" (IRENA) and the "International Energy Agency Photovoltaic Power Systems Programmed" (IEA-PVPS) collaborated on this paper, which is the first to forecast PV panel waste amounts until 2050. By 2050, it is anticipated that recycling PV module at the end of life will release 60-78 million tonnes of raw materials and other important components globally. By 2050, the recovered material might be worthy to put back into the economy.

"The Institute for Energy Economics and Financial Analysis" (IEEFA) found in their study that renewable energy target of India is about 175GW by 2022. From which 100 GW by solar PV system.

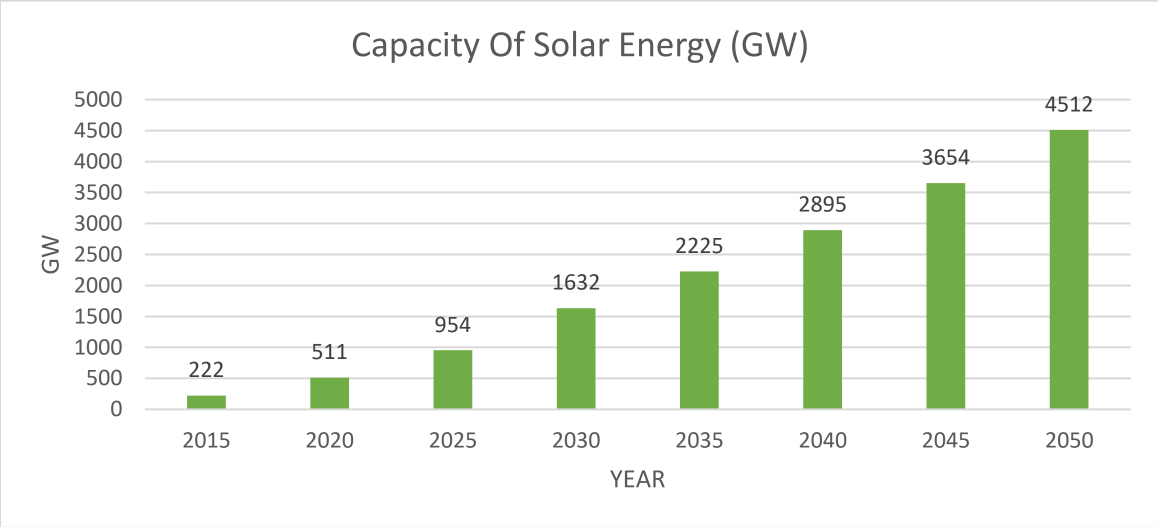

Fig-1: Projection of Cumulative PV capacity of world (IRENA, 2016)

Now India has 84.75GW renewable energy installed capacity out of which 34.40GW is from solar PV system capacity (Solangi., 2011). "The National Solar Energy Federation of India" (NSEFI) collaboration with the "EU India Technical Cooperation Project", European solar trade body Solar Power Europe, recycling association PV Cycle, If India reaches a cumulative 280 GW of installed solar cumulative capacity by 2030 from 40 GW in 2020, it might produce 21 Kt. of solar PV module waste from new-fangled solar capacity installations. Early failures or damage during transit, installation, and operation will be the source of PV waste. In another study It is found that EOL PV waste will be 2.95 billion tonnes between 2020 and 2047, and it would be dangerous to manage such huge amount of PV waste in India so a technical and a strategic management approach will be required (Gautam et al., 2021). There are so many factors in India to increase high demand of solar power i.e., modernization, government planning in rural areas of country. Solar manufacturing in India is yet not on commercial scale its extremely depends on imports from other countries (Weckend et al., 2016). It's increased the overall cost of PV module. PV module consists metals like as steel, Aluminum, copper, Silicon, Lithium, germanium, silver etc. These metals can be recovered by recycling of PV waste at EOL. In present scenario recyclability of metals are 60% to 90% (Sahoo, 2016). In India there is no any formal recycling facility available for PV waste (MNRE, 2021). The existing e-waste management Rules 2016 is also applicable for solar Photovoltaic waste generated in country which imposed the responsibility of e-waste disposal on manufacturer. Due to unavailability of specific regulations, it is difficult to restructure of Recovery, Collection and Recycling of solar Photovoltaic waste in India (Balls, 2020: koroigwe et al, 2020; Chaudhary et al, 2020). So due to lack of regulations and guidelines generally PV waste are dumped in landfills without following any scientific method (Chakankar et al., 2019; Sica et al, 2019). Due to absence of liability and direction between solar industry Stakeholders, tendering authorities, producers, and Suppliers making difficult to administer the guidelines (Sica et al., 2018). A systematic Reverse Supply Chain Management needed to convert linear economy to circular economy of PV waste in India (Sharma et al., 2021; Rathore & Panwar 2021; Mahmoudi et al., 2021). Stakeholder responsibility, EPR, joint waste collecting policy with recycling could be best strategy for PV waste management. An effective and economical Reverse Supply chain should be developed for PV waste in India.

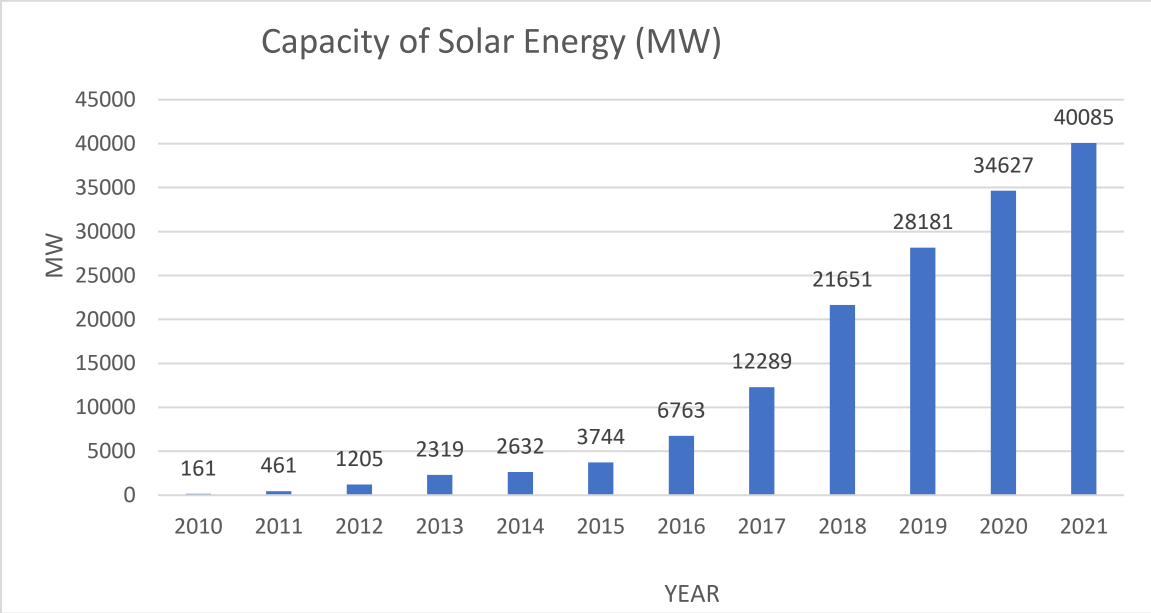

Fig-2: Yearly Variation of cumulative capacity of solar energy in India (MW)

2. Literature Review

The normal life span of a solar PV module is between 25 to 30 years. hence, this large scale of PV panel installation will responsible for a large amount of PV waste generation in India in the future. The total EOL solar PV panel waste of 2.95 billion tonnes will be expected by 2047 (Gautam et al., 2021). According to the NITI Aayog's Energy Security Scenarios 2047, solar PV might reach 479 GW in 2047. According to a report released by the National Solar Energy Federation of India, India will generate approximately 34,600 tonnes of cumulative solar PV waste by 2030. Only 2% of India’s total e-waste gets recycled due to poor infrastructure, lack of legislation and framework which leads to a waste of diminishing natural resources in India (Chaudhary et al.,2017) The exponential increase in the PV panel waste is anticipated to reach over 60 to 70 million tonnes by 2050. PV waste contains hazardous elements that imperil human health as well as the environment (Mahmoudi et al., 2018). These PV waste contains Cadmium, Lead, Selenide etc. (Mahmoudi et al., 2021). The high recyclability rates of solar PV waste can reduce PV module waste upto 90% (Domínguez & Geyer., 2019). From the viewpoints of environmental and resource management, it is necessary to have specialized solar PV waste management, recycling programs and policies in India (Farrell et al., 2020). The management of solar power waste, on the other hand, is a neglected issue in India, where it is treated in an unorganized, unscientific, and informal manner. (Sheoran et al., 2020; Weckend et al., 2016). Under the Ministry of Environment, Forest and Climate Change, solar waste is now classified as ordinary electronic waste. there is a space for the development of a consistent policy approach to controlling this PV waste which may result a long-term environmental advantage as well as economically strengthen country's resources. By 2021–22 about 50 solar parks with a total capacity of 40 GW are expected to be completed in country. This reveals that, at the EOL stage, the country's primary focus is on promoting solar energy deployment rather than developing a waste disposal and management strategy (Suresh et al., 2019; Rathore & Panwar, 2021). The identification and control of present and future amount of PV waste can be assisted by intensive care and reporting systems at the central and local levels (Mahmoudi et al., 2019). In India, there is no any written norm that the solar PV makers are responsible for the end-of-life or disposal of their products. Even if it is stated in the tender document, it is not mentioned in the e-waste guidelines, and as a result, no one is held responsible (Suresh et al., 2019).

3. Photovoltaic Waste

The electronic waste generated by abandoned solar panels is known as solar panel e-waste or PV waste or PV e-waste. Generally, three types of approaches are used to predict the PV waste, that generated in India. Firstly, is the cumulative and annually installed PV capacity, secondly is assumptions to PV module weight; rate of replacement due to damage during transportation and installation, and third is early failure or damage i.e., optical failure, glass breakage, delamination etc as shown in Fig-3. The PV waste generated as a result of the end of life of PV modules will start to increase only after 2040, and will swiftly become the most relevant waste source. India should focus its efforts on developing comprehensive solar panel waste management regulations. The majority of waste will be generated during shipment, installation, or operation as a result of damage or early failures (IRENA, 2016). PV modules will be the most wasteful components, although inverters are substantially lighter. Ballasts, mounting structures, wires, and other are less likely to be damaged and fail early than other components. Fig-3 shows the percentage of involvement of factors causing damage of PV panel.

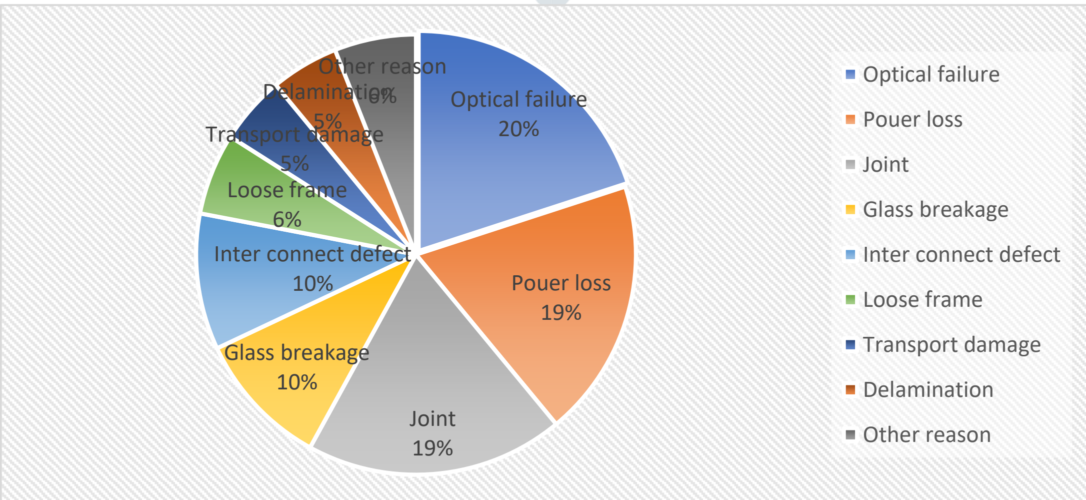

Fig-3: Factors responsible for damage of PV panel (IRENA 2016)

PV panel waste output is expected to increase to 200,000 tonnes by 2030 and 1.8 million tonnes by 2050 in India. Glass, metal, silicon, and polymer fractions make up the majority of a PV module. Aluminum with glass, they make up about 80% of the overall weight and are non-hazardous. However, Polymers, metals, and metallic compounds are among the various materials used. And alloys have been labelled as possibly dangerous (IRENA, 2016 & IEA-PVPS, 2016). Fig-4 shows the estimated PV module waste volume at the end of life in India.

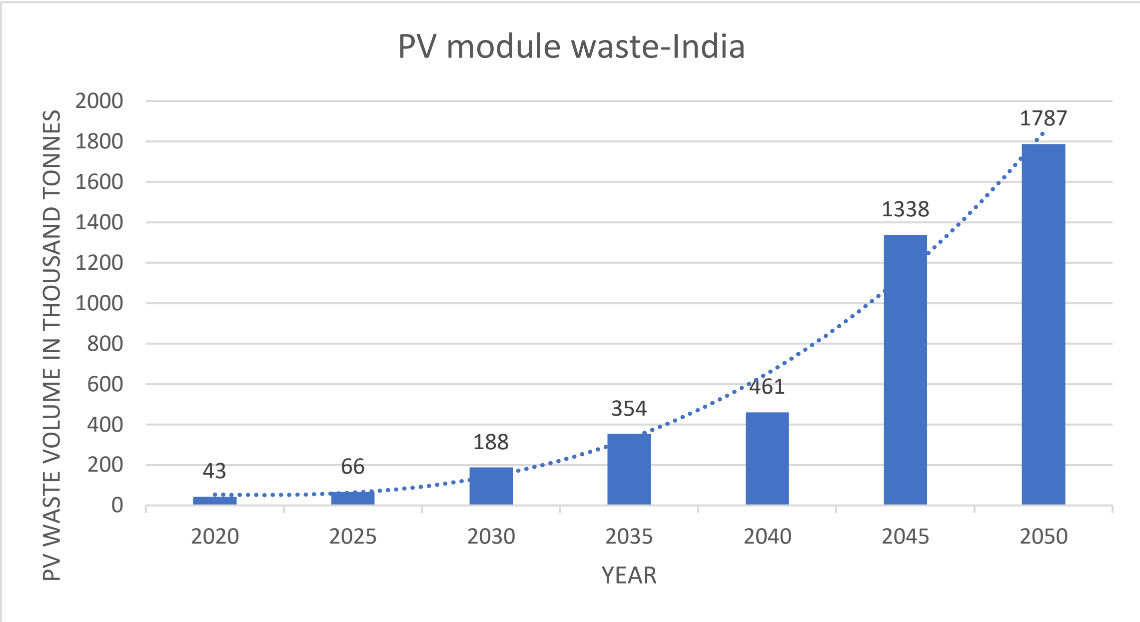

Fig-4: Estimated PV module waste volume, thousand tonnes at the EOL in India

PV panel waste was 43,500 tonnes at the end of 2016 and its projection is 1.7 million tonnes by 2030, under the regular-loss scenario. By 2050 the increase might be even more dramatic, reaching upto 60 million tonnes, and in the early-loss scenario overall PV waste streams was 250000 tonnes, at the end of 2016, and in 2030 this figure is expected to climb to 8 million tonnes with a total of 78 million tonnes by 2050 (IRENA, 2016 & IEA-PVPS, 2016). Because the early-loss scenario predicts a higher rate of early PV panel failure than the regular-loss scenario, the early-loss scenario is more expensive. The real future PV panel waste will be between these two. Figure-5 shows cumulative PV module waste volume at regular loss scenario projected up to 2050.

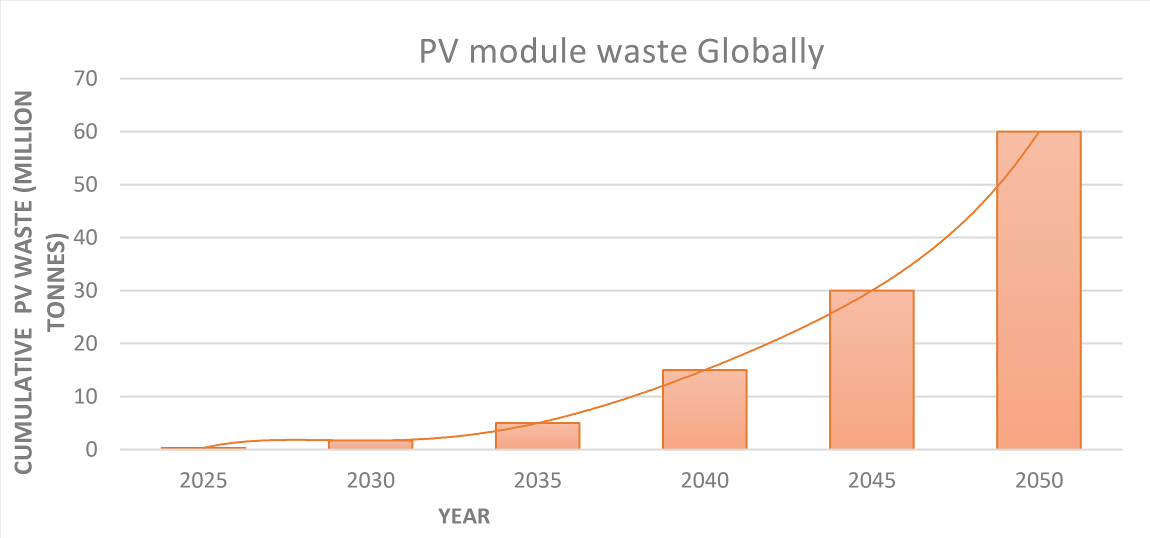

Fig-5: Cumulative PV module waste volume, million tonnes at the regular-loss scenario globally.

On his report IRENA, projected that highest PV waste will be generated in Asia, by 2030, which will be around 3.5 million tonnes, and it may be vary on regular or early loss scenario. Regional Asian Champions in renewable energy deployment also support the above prediction of highest PV waste in Asia. China will have cumulative PV capacity of 420 GW in 2030 which generate PV waste between 200000 tonnes to 1.5 million in 2030, and India will generate between 50000 tonnes to 325000 tonnes cumulative PV waste while Japan will have 200000 tonnes to 1 million tonnes estimated PV waste in 2030 respectively. In 2030, the top three PV waste countries will be China, Germany and Japan while in 2050, the top five PV waste generating countries expected are China, US, Japan, Germany and India.Fig-6, shows the cumulative PV waste volume of top five countries of world in 2050.

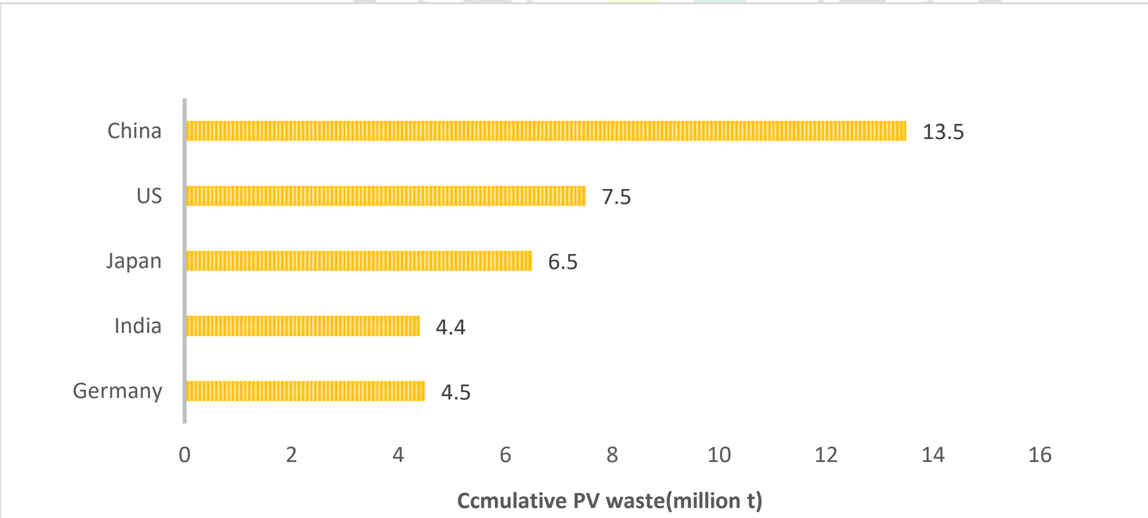

Fig-6: Projection of cumulative PV waste volume of top five countries of World in 2050.

Solar PV module generate two types of PV waste, primary and secondary before and after their EOL. The PV system components make up the primary stream. The toxins of resources utilized to manufacturing and disposal system, such as Inverters, and cables are represented in the secondary stream (Okoroigwe et al., 2020).

Solar module waste is divided into three categories based on its environmental impact, recyclability, and commercial worth, (Balaji & Rahul, 2021)."Management and Transboundary Movement Rules 2016" of the "Ministry of Environment, Forest and Climate Change" Indian Government, serve as the basis for environmental classification. Hazardous waste is defined as any waste that poses a threat to human health or the environment due to their physical condition, chemical reaction, poisonous and combustible qualities.

4. International regulatory frameworks for PV Waste

Solar photovoltaic waste is categorised as industrial waste or electronic waste in many countries. It is classified as solar PV waste in some parts of Europe, although it still ends up in standard metal and glass recycling facilities. The "European Union" was the first to implement solar PV rules and framework, with Policies and Measures for Sustainable Management of Solar Panel End-of-Life in Italy being the first (Malandrino et al., 2017). Italy is the first to develop WEEE directions on EPR to manage Photovoltaic waste (Weckend et al., 2016). Table-1 shows the summarized way of existing rules and regulations in worldwide for PV waste management and disposal.

S.NO	Country	Regulation	Feature of PV waste management approach
1	European Union	WEEE Directive	i. Makers and traders must bear responsibility for the EOL treatment of their products or face stiff penalties. ii. All 28 member countries are forced to maintain the rules. iii. After decommissioning, state members accountable for establishing a system for collecting and treating Photovoltaic panel waste. iv. European R&D efforts are encouraging the development of recycling technology to lower treatment costs.
2	United States	The Resource Conservation and Recovery act,1976	i. There are no specific regulations in place to deal with EOL solar PV waste. ii. There is no legal structure for waste management at the national level. Different states have the freedom to establish their own regulatory standards for determining the toxicity of solar PV waste. iii. First Solar, based in the United States, is one of only two manufacturing companies in the world to have commercialised solar PV recycling on a large scale. iv. Through its corporate responsibility committee, the Solar Energy Industries Association of the United

			States (SEIA) examines PV recycling process on a regular basis.
3	JAPAN	Waste management and cleaning act	i. There is no regulatory or legal structure in place to manage end-of-life solar panel waste, classified as e-wastes. ii. The "Ministry of Economy, Trade and Industry" and the "Ministry of Environment" in collaboration to design a framework for regulating the country's end-of-life PV waste in 2015.
4	CHINA	No Regulatory approach	i. There is no framework to managing end-of-life PV module waste. ii. The progress for particular regulations for Photovoltaic panel waste recycling, and the establishment to a relevant economic context, are all priorities.
5	India	No regulation	i. The PV waste are considered as e-waste in India. ii. MNRE's rules are the only place wherein recycling is addressed. iii. The Indian E-waste Handling Rules, 2016 are in effect and are based on the EPP.

Table-1: Existing rules and regulation on worldwide for PV waste disposal.

4.1 European Union

The EU is one of the first countries to implement policy frameworks for solar PV waste at end-of-life management. The EU's ″Waste Electrical and Electronic Equipment (WEEE)" directive was first enlisted in 2002 and updated in 2012 to cover Photovoltaic waste chain management. After the implementation of the "WEEE Directive 2012/19//UE" by the ″European Parliament and the Council" in 2012. the recycling of PV panels at their end-of-life was mandated in the EU (Chowdhury et al., 2020; Sica at al., 2018; Weckend at al., 2016; Malandrino at al., 2017). This directive promotes resource efficiency by encouraging reuse, recycling, and reducing waste (including hazardous materials) dumping in landfills (Farrell. et al., 2020) The ERP based regulation, includes targets for solar PV module collection, recovery, and recycling at their end of life. The WEEE directive took effect on 13.08 2012, and all 28 E U member states were required to comply by 14.02 2014, it requires all member states to put effort together for PV module waste management in legal framework.

4.2 Germany

Germany revised their e-waste policy "EEE Act of 2005" in 2015, and it has started to follow the WEEE directive. According to new regulation, collection on appropriate way, their exclusion and proper disposal is mandatory. In the German electronic-waste is regulated by the ″National Register for Waste Electrical Equipment (De Boeck et al., 2016), it keeps records of all e-waste producers.it secure the responsibilities and accountabilities of proper disposal of e waste generated at the end of life and advance repairing & recycling of damage product at early loss scenario. (Goe et al., 2015). Generally, in Germany there are multiple PV waste collection centres are available throughout country where any one can give PV waste for disposal in a separate and proper manner, Mostly of German people trailed it (Mehta, 2017). Collection centre send PV waste to dismantle unit for repair or recycle.

4.3 USA

In the United States no existence of advance directives solar panel waste management. To manage it, regulations are made at state level. Manufacturers are asked to submit a plan for PV waste recycling at end-of-life up to 2021 in Washington, which initiated the first solar recycling measure. California and New York are also considering legislation to hold manufacturers accountable for module trash and prohibit it from being disposed of in landfills. The drawback of rules is that PV waste can be moved to anywhere there where is no any restrictions. A lot of projects are in effect, either individual or groups. First Solar, a thin-film module manufacturer, is the most well-known of these.

Recycling programmed at First Solar in 2005, a pre-paid, take-back was first model to develop first solar programme in the United States, Germany, Malaysia, and Vietnam, the corporation operates dedicated recycling facilities. In the EU, the industry continues to offer multiple versions of its take-back service, which are tailored to country-specific restrictions.

4.4 U. K.

As per European Union Directive, the United Kingdom is a futuristic market with adequate solar photovoltaic waste relevant policies and regulations. The WEEE directive was enacted on January 1, 2014, to ensure correct disposal of PV waste through collection, segregation, and recycling. Prior to this regulation, the unwritten norm was that the producer was responsible for the disposal of solar PV modules, which they did voluntarily (Reid & Wynn, 2015). Prior to the establishment of a formal policy in 2014, the majority of E-O-L issues were covered by the manufacturer's warranty and returned through the B2B channel. The government of the United Kingdom has established some guidelines for defining a solar photovoltaic manufacturer. As a UK producer, a solar photovoltaic module maker must adhere to this policy.

4.5 Japan

Because there are no policies or procedures to manage the disposal of solar PV panels, all e-waste, including solar PV panels, is dealt standard under the Waste Management and Public Cleansing Act, which covers all e-waste (Mansouri & Kacha, 2017). The Japan Photovoltaic Energy Association (JPEA) has developed optional guidelines to ensure appropriate recycling of solar PV modules. In addition, the New Energy and Industrial Technology Development Organization (NEDO), a national research organization, has undertaken considerable R&D efforts to produce cost-effective recycling solutions.

4.6 China

The government currently lacks a formal policy to regulate the disposal and recycling of waste PV panels, however a 2011 rule requires e-waste to be recycled and collected in a centralized manner. By 2050, it is expected that 13.5-19.9 million tonnes of PV modules would have been discarded (Weckend et al., 2016). China has invested much in solar photovoltaic module research and development, with an emphasis on two recycling processes. From 2012 to 2015, these studies were funded by China's National High-tech R&D Program, Solar PV Recycling and Safety Disposal Research (Hong et al., 2016).

4.7 India

In India, currently there are no specified regulations for the disposal or recycling of solar PV waste at EOL, Hence, there is no mandated collection or disposal of solar photovoltaic panels, which means that the waste created by solar PV waste modules is only subject to normal e-waste regulations (Sheoran et al., 2020). MNRE's facilities contain sole mention of recycling. In 2030, India is expected to have 1.7 million tonnes of PV waste and 60 million tonnes in 2050, The PV waste management scenario in India and the European WEEE directives have a lot in common. The new laws are based on the EPR concept, with different kinds of producers (maker, distributor, dealer, and re-furbisher) having different obligations and liabilities., the prevalence of illegal and informal sector of PV waste reverse supply system, which hinders circularity so its needs developed structure (Dwivedy et al., 2015), is one of the major challenges in India. Another distinction is the presence of BOS in the PV management systems. The European WEEE directives, as well as the Indian "E-waste Handling Rules 2016", are based on EPR and are mainly concerned with "consumer-based electronic waste", one product and one equipment' in both the EU and India, which means that waste management rules do not apply to various PV system components (EU-India TCP, 2021).

Producers can employ a variety of tools to assure compliance, including PROs, e-waste swaps, and deposit refund schemes, responsible for raising customer knowledge about recycling choices and ensuring that PV waste is not disposed of as e-waste by labelling items with a "crossed-out bin sign. "Each producer has their own collection goals target. “The first's objective Developers are responsible for disposing of PV waste, according to the guidelines," The e-waste regulations are not applicable to PV wastes. As a result, there is no specific process or standard in place in India for the disposal of PV waste. "Construction and Demolition Waste Management Rules16" and "Solid Waste Management Rules17" Solid or semi-solid household waste, sanitary waste, commercial waste, institutional waste, catering and market waste, and other non-residential wastes, street sweepings, silt removed or collected from surface drains, horticulture waste, agriculture and dairy waste, and treated bio-medical waste are all covered by these "Solid Waste Management Rules". Industrial trash, biomedical waste, e-waste, lead-acid battery waste, and radioactive crap are all excluded. "The 2016 Construction and Destruction Managing Waste Rules" apply to waste containing building materials, debris, and rubble generated during the construction, remodeling, repair, neither of these two Rules apply to PV modules or other equipment used in a PV system (Weckend et al., 2016; EU-India TCP, 2021). Thus, India has to develop an integrated framework that incorporates the EU's strategy to handling PV waste management system. The recommended regulatory framework has the potential to effectively control India's future PV waste related issues.

5. Conclusion

The amount of PV waste produced is quickly increasing, and India must be ready to deal with it. The EU serves as a useful worldwide benchmark point. Its rigorous strategy is yielding positive market results. Over time, we expect worldwide PV waste laws to tighten. PV waste management should be addressed by the Indian government as soon as possible. Existing e-waste regulations provide a rudimentary starting point for developing PV waste treatment regulations., policymakers and private stakeholders must work together to develop an effective framework. The government is building capacity and certifying technicians for personnel interfere in the end-of-life management of PV waste. For Indian residents, includes instructional programs related to appropriate end-of-life reverse supply chain management of PV waste. Provides for the enhancement of PV waste as an important R&D for introducing technical breakthroughs after solar PVs have reached their end of life.

6. Consideration of Framing regulation for Management of PV waste in India

The current review aims to find out the research gaps in solar PV waste management and to outline a regulatory framework for future to develop an effective regulation and policies for EOL solar PV waste in India. Following Feature should be considered for developing regulation and policies for PV waste management in India:

i. Technical expert should also be part of regulatory committee, to advice for formulate & planning a standard procedure for recycling and treatment of PV waste at the end-of-life
ii. Impose a penalty on improper landfill for solar PV modules.
iii. In review we found that, normally 10% PV module damages occurs before EOL due to various factors in a supply chain process, improper handling and unscientific installation, so that in supply chain process inspection by experts should regularized.
iv. By recovering materials in a sustainable and ecologically acceptable manner, a scientific recycling process must be in practice.so that it is possible to reduce the hazardous material amount of solar PV waste that ends up in landfills.
v. Barriers must be identified in reverse supply chain of PV waste, so we can develop a resilient framework.
vi. Fee for dumping and disposing of PV waste should mention in regulation.

vii. Recycling process of PV waste should be monitor, regularly by technical expert committee and advice to adopt latest advanced available technology.

viii. Policymakers and private stakeholders must take proactive measures against huge amount of PV waste which will generate in incoming days.

ix. Provision must be kept of incentives and tax relaxation for PV waste recycling units.

7. Future scope of research in the area of PV waste management

Since there is no any separate specific provision for handling PV waste in India, the responsibilities of researchers increase, to work more on advance research, in the area of disposal, recycling process etc. of PV waste. Some research scopes in the area of PV waste management are suggested in future are Framing a formal recycling structure & its impact on circular economy, barriers in Reverse Supply Chain for collecting PV waste at the EOL of PV module, Optimization of PV waste handling management process and Impact on Environment of informal working practices of PV waste treatment in India etc.

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