Enhancing Photovoltaic Waste Management in India: A Comparative Study with International Practices and Strategic Suggestions

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***Abstract*—The exponential growth of solar photovoltaic (PV) installations across the globe has dramatically changed the energy landscape worldwide, but it has also posed a significant environmental challenge: effective management of PV waste. India, being a leader in the renewable energy sector with ambitious solar capacity goals, is at a critical juncture in addressing this issue. This review critically compares India's photovoltaic waste management practices with established frameworks and technologies in countries like Germany, Japan, the United States, and China, where PV waste management systems are more advanced. The study assesses the lifecycle of PV modules, identifies key sources of waste generation, and examines the existing regulatory landscape, recycling infrastructure, and market dynamics in India. It discusses global best practices in the domains of EPR, advanced recycling technologies, and circular economy models to depict their applicability and potential to be adapted within the Indian framework. The critical gaps in the Indian approach are further identified as there is no separate PV waste policy, lack of advanced recycling facilities, and too little public-private partnerships. Based on these conclusions, actionable recommendations are proposed for improving India's PV waste management strategy, such as the establishment of strict regulations, development of domestic recycling technologies, financial incentives for stakeholders, and increased awareness among consumers and manufacturers. The study highlights the importance of aligning India's policies with global best practices to ensure sustainable growth in the solar energy sector. By creating a circular economy for photovoltaic materials, India would be able to reduce environmental risk, maximize recovery of resources, and become a global leader in sustainable development of solar energy.**

Index Terms- Circular Economy, Environmental Risk Mitigation, Extended Producer Responsibility (EPR), Global Best Practices, India Solar Energy Sector, Photovoltaic Waste Management, PV Module Lifecycle, Recycling Technologies, Renewable Energy Policy, Solar Energy Sustainability

I. INTRODUCTION

It is in the recent past that adoption of solar energy at a global level has significantly increased, and at a declining cost, for its environmental-related benefits. Today, solar photovoltaic is a part of the renewable energy mix in many nations, as it is an alternative, clean source of energy, as opposed to fossil fuel. Global solar capacity touched 1,000 GW by 2020 [1], and it continues to grow rapidly, at a pace that is unprecedented, according to the International Renewable Energy Agency, IRENA. India has particularly played a pivotal role in expanding solar energy by announcing ambitious goals for increasing solar capacity and reaching 500 GW of non-fossil fuel-based energy by 2030 [2]. Already, over 50 GW of solar power have been installed, making India one of the forerunners in developing renewable energy. But while solar installations have grown in recent years, an even greater challenge has appeared alongside it. Typically, a solar panel has a life of about 20 to 25 years, and the sheer number of decommissioned panels around the world will eventually add up in volumes. IRENA estimates that the world would generate up to 78 million metric tons of solar waste by 2050 [3]. If it is not well managed, the impact would be enormous and devastating for the environment as well as to human health, which calls for developing proper methods of disposal and recycling of the solar panels. Management of solar PV waste remains an emerging issue in India. Although the country is at the forefront of solar energy adoption, it has no comprehensive framework for handling the waste generated by decommissioned solar panels. Most of the solar panel waste is either dumped in landfills or recycled informally, which can lead to hazardous materials such as cadmium, lead, and silicon leaching into the environment [4]. This poses a risk to both soil and water quality and could potentially harm human health. [5] indicated that the specialized materials in solar panels are yet to be

managed by India's waste management infrastructure. Although the Indian government has started recognizing the need to act, the regulatory framework of PV waste management is still at its infancy stage. The Ministry of New and Renewable Energy has issued voluntary guidelines. Notwithstanding that, there is no mandatory standard for solar panel recycling or its disposal [6]. In the absence of a clear and mandatory policy for PV waste, India stands at considerable risk of environmental degradation with the rising quantum of solar waste. Given the reliance of the country on informal methods and the lack of infrastructure, there is a pressing need to implement an organized structure of PV waste management. Even though India is just at the threshold of having an organized formal strategy, many other countries have evolved advanced systems to address solar panel wastes. In Europe, manufacturers are held liable for the collection and recycling and proper disposal of solar panels after they have attained the end-of-life stage under the WEEE Directive. In fact, through this policy, European countries were able to evolve their recycling schemes into efficient ways and minimize PV waste environmental damage [7]. Japan also was able to make an example for others by applying the same kinds of regulations with regards to solar panel recycling. The country has developed sophisticated technologies to recover valuable materials such as silicon, silver, and aluminium from old panels. These efforts not only reduce waste but also create economic opportunities in the recycling sector [8]. These examples show that with the right regulatory frameworks, PV waste management can be both environmentally sustainable and economically viable. Adopting such strategies in India could significantly improve the management of PV waste. Experts like Suresh et al. [9] argue that India could benefit from policies like Extended Producer Responsibility (EPR), which would require manufacturers to manage the entire lifecycle of their products, including recycling. This would encourage manufacturers to design panels that are easier to recycle and would help create a sustainable recycling infrastructure in the country. Although India has made great progress in expanding solar energy, the absence of a clear legal framework for PV waste management presents a major obstacle. The government's current voluntary guidelines are insufficient, and there is a need for comprehensive, enforceable policies that address the growing challenge of solar waste. Scholars like Hossain and Islam [10] advise that India institute mandatorily the recycling targets; introduce a take-back scheme on the national level for the used panels, as well as frame rules on guidelines to be strictly followed by producers. Apart from the above-mentioned policy level efforts, India would need to seriously invest in setting up its proper recycling infrastructure. With increasing generation of PV wastes, more solar panel recycling plants and material recovery would be required by the country. Public-private partnerships (PPPs) could be the key mechanism for developing such infrastructure, bringing government agencies, private companies, and research institutions together to address this challenge [11]. Another step is to create awareness about the proper disposal and recycling of solar panels. Singh and Singh [12] recommend that the government organize public education programs to ensure all stakeholders, such as manufacturers, consumers, and waste management companies, understand the importance of proper waste management. Public awareness initiatives should also include partnerships with global organizations like IRENA for best practices in other parts of the world. Technological advancements will be pivotal in solving the problems of PV waste management. India can be at the forefront globally in solar panel recycling by investing in R&D to develop low-cost and efficient recycling technologies. New technologies to recycle silicon, silver, and cadmium telluride materials are crucial in reducing the costs of recycling and making it an economically viable activity [10]. Collaboration between the government, industry, and academia will be vital in driving such innovations. By offering incentives to investment in recycling technologies and establishing R&D hubs that can focus on solar waste, the country can ensure a very strong recycling industry that not only can serve its renewable energy goals but also propel the economic growth of the nation. This review will first begin with the state of PV waste management in India and globally, then outline the technological and policy frameworks required to address this emerging PV waste challenge.

II. SOLAR POWER PRODUCTION IN INDIA AS OF 2024

India has made remarkable progress in solar power generation. The states are contributing differently due to regional policies, resources, and infrastructure. Here is a list of the states with the highest to the lowest contribution, along with their respective capacities.

Rajasthan is the largest contributor to India's solar power generation. With its vast desert landscapes and high solar insolation, Rajasthan has become a key state for large-scale solar parks. By 2023, Rajasthan's installed solar power capacity had crossed 14 GW, accounting for over 25% of India's total solar capacity. Badla Solar Park in Jodhpur is one of the largest solar parks in the world and holds a significant place in the state's solar power generation [13]. Karnataka ranks second in the list of states with the highest installed capacity for solar power generation, which was 9.5 GW by 2023 and contributed around 18% to India's total solar energy generation. Karnataka's sunny climate and large, open areas have supported the development of several major solar parks, among them is Pavagada Solar Park in Tumkur district, one of the largest in India [14]. Andhra Pradesh developed its solar power infrastructure very quickly and by 2023 has reached an installed capacity of 7 GW that contributes around 13% of the total solar power generation in India.

The state's major solar parks, such as the Kurnool Ultra Mega Solar Park, have significantly increased its solar energy production, helping it to become one of the major contributors to the national solar grid [15]. Tamil Nadu is another major player in India's solar power production, with an installed capacity of 6.5 GW by 2023, representing about 12% of India's total solar power generation. The state has been in the lead in rooftop solar installation and utility-scale projects, and important solar parks like the Kanchipuram Solar Park contributed to growth [16]. Gujarat, with an installed capacity of 5.5 GW, contributes approximately 11% to India's total solar power generation. Known for its early adoption of solar energy, Gujarat was the site of India’s first large-scale solar park, the Charanka Solar Park, and continues to be a significant player in India’s solar power generation [17]. Madhya Pradesh has made considerable progress in solar energy production, with an installed capacity of 5 GW by 2023, contributing around 10% to India’s total solar capacity. One of India's largest and most important solar projects is located in the state: the Rewa Ultra Mega Solar Park [18]. With an installed capacity of about 3 GW, Uttar Pradesh has been growing steadily as a solar energy-producing state, adding about 6% to the solar generation of India. It has been looking to increase the number of both large-scale solar parks and rooftop solar installations across the state [19]. Maharashtra has a smaller share of the total solar power generation in India, which reached 2.5 GW by 2023, about 5% of the solar power generation in India. Although it is less compared to other states, the state has been very keen on investing in solar energy in the industrial sectors [20]. Haryana's solar power generation capacity is at around 2 GW and is contributing approximately 4% to the national grid.

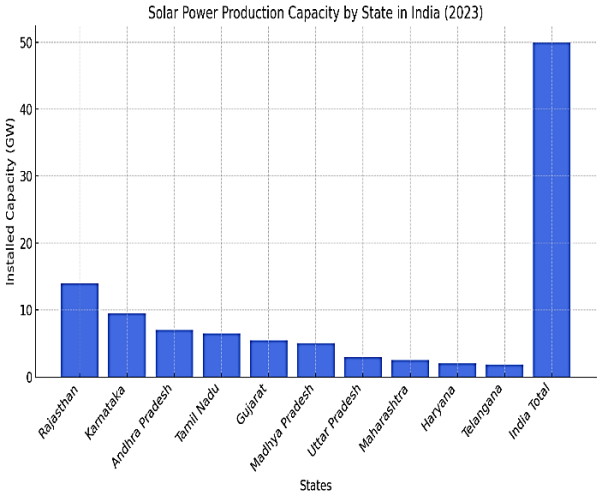

Figure 2.1: - solar power generation capacities across different states in India

The state of Haryana has been promoting rooftop solar installations, which have increased its share [21]. Telangana has an installed solar capacity of 1.8 GW, contributing around 3% to India's total solar power generation. The state is becoming a major player with the initiatives it is taking for solar parks, such as the Kollapur Solar Park [22]. India's Total Solar Power Generation Capacity By 2023, India's total solar power generation capacity crossed over 50 GW. India is now one of the top three producers of solar power in the world. With future projections, India is expected to achieve 100 GW by 2025 and 500 GW of non-fossil fuel-based power by 2030, and solar will contribute a significant amount to this ambitious goal [23]. Figure 2.1: Installed Solar Power Generation Capacities in Various States of India, Including Total National Capacity at the End of 2023. Values indicate installed capacities in GW for the respective states as well as India as a whole.

III. SOLAR POWER PRODUCTION AND WASTE MANAGEMENT IN OTHER COUNTRIES EXCEPT INDIA

In such a rapid worldwide deployment of photovoltaic (PV) systems, end-of-life (EOL) management of solar panels is an emerging concern as the global solar capacity continues to rise. Germany tops the list of PV waste management, with

about 70 GW installed solar power capacity by 2025, which has implemented extended producer responsibility under the Waste Electrical and Electronic Equipment (WEEE) Directive. Germany aims to recover up to 85% of module materials from recycling practices, and it is estimated that by 2050, there will be 400,000 tonnes of PV waste [24, 25]. Japan has 80 GW of solar power capacity and utilizes its Waste Management and Public Cleansing Law combined with guidelines by the Japan Photovoltaic Energy Association (JPEA). This means modules are safely recycled, with the estimated volumes of waste amounting to 10,000 tonnes by 2030 [26, 27]. The challenge for China, which boasts over 400 GW of installed solar capacity worldwide, is handling the largest anticipated PV waste volume at 20 million tonnes by 2050. The country addresses this using the National Solid Waste Law and a comprehensive recycling framework [28]. The United States, with a capacity of over 150 GW, relies on the Resource Conservation and Recovery Act (RCRA) and state-level policies to regulate hazardous and non-hazardous PV waste. However, waste volumes are expected to rise to 10 million tonnes by 2050, posing a challenge for a harmonized approach [29]. Australia, with a capacity of nearly 30 GW, has focused on innovation and industry collaboration, which has been supported by the Australian Renewable Energy Agency. The country predicts that by 2030, PV waste will be about 1,500 tonnes, which is being focused on developing advanced recycling technologies [30]. France has a solar capacity of 16 GW and applies an EPR system under the WEEE Directive, where producers are made responsible for financing the recycling. France estimates to generate 5,000 tonnes of waste by 2030, reflecting its structured and well-regulated approach [31]. Lastly, South Korea, with a capacity of 25 GW, enforces mandatory recycling targets through the Act on Resource Circulation of Electrical and Electronic Equipment. The country is expecting to manage 2,000 tonnes of waste by 2030, having dedicated recycling centers and strong regulatory oversight [32]. These countries have different strategies for dealing with PV waste. Germany has exceptional leadership through high recycling targets and advanced technologies. Japan and South Korea focus on secure waste disposal and legislatively obliged recycling to maximize producer responsibility. China and the USA pay special attention to building up infrastructure for large solar capacities. Australia and France do this through innovation and extended producer responsibility. Together, these countries exhibit a very best combination of regulatory compliance, recycling innovation, and producer responsibility as part of sustainable PV waste management systems. Figure 3.1: PV production capacity, projected waste for 2030 and 2050, and waste management scores for seven countries. Germany, Japan, and France have good waste management practices, with high scores, as a result of robust recycling policies, such as EPR systems. Germany is the leader in recycling innovation, while it is managing an estimated 400,000 tonnes of waste by 2050 (red points), along with its 70 GW production capacity (blue bars). China, with the largest solar capacity of 400 GW, faces a significant challenge with projected waste of 20 million tonnes by 2050. The United States, despite its high capacity of 150 GW, shows weaker waste management integration. Australia and South Korea continue with moderate production but have innovative and regulatory-driven approaches to PV waste management, thus ensuring smaller volumes of waste by 2030 (orange bars). Overall, the graph depicts the relationship between solar deployment, waste projections, and the effectiveness of waste management systems in addressing sustainability challenges. The table 3.1 gives an overview of the global photovoltaic (PV) waste management practices, covering production capacity, projected waste, waste management efficiency, and treatment methods in seven countries.

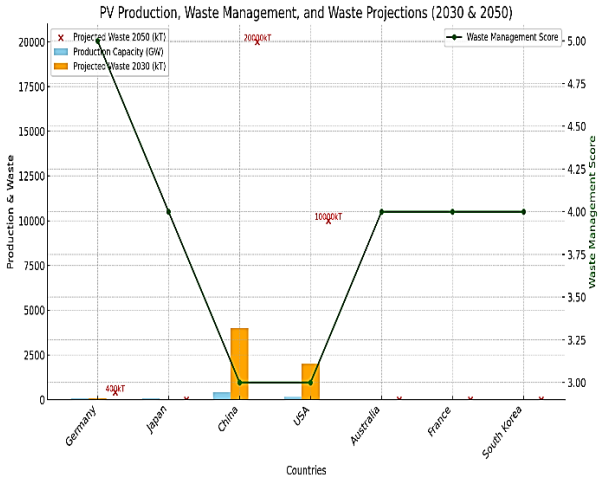

Figure 3.1: - Photovoltaic (PV) production capacity, projected waste for 2030 and 2050, and waste management

Table 3.1: - Photovoltaic (PV) waste management across countries except India

Country	Production Capacity (GW)	Projected Waste (2030, kT)	Projected Waste (2050, kT)	Waste Management Score (1-5)	Waste Treatment Methods
Germany	70	80	400	5	Advanced recycling under WEEE Directive, Extended Producer Responsibility (EPR), recovery of 85% material.
Japan	80	10	-	4	Recycling under Waste Management and Public Cleansing Law, supported by Japan Photovoltaic Energy Association (JPEA).
China	400	4,000	20,000	3	Recycling under National Solid Waste Law, large-scale recycling infrastructure with focus on scaling efforts.
USA	150	2,000	10,000	3	State-level policies and federal Resource Conservation and Recovery Act (RCRA), mixed approach to hazardous and non-hazardous waste.
Australia	30	1.5	-	4	Industry-led innovations supported by the Australian Renewable Energy Agency (ARENA), advanced recycling technologies.
France	16	5	-	4	Recycling under WEEE Directive, producer-financed recycling under EPR system, and structured waste handling.
South Korea	25	2	-	4	Recycling under Act on Resource Circulation of Electrical and Electronic Equipment, mandatory recycling targets.

IV. SOLAR WASTE PRODUCTION AND MANAGEMENT IN INDIA

Being the largest and fastest-growing solar market in the world, India is facing extreme difficulties in managing PV waste. It has been estimated that by 2030, India will produce around 200,000 tonnes of PV waste. This number will increase tremendously to 1.8 million tonnes by 2050, with the large installation of solar panels under its ambitious renewable energy targets [33]. However, a dedicated framework of PV waste management is not there in India similar to Germany, Japan, or China. Rather, the e-waste management policies of this country are as general as The E-Waste (Management) Rules, 2016 and the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016, and are not proper for handling issues specific to PV waste [34]. In terms of waste management techniques, India's approach is currently dominated by informal recycling sectors, where unregulated practices pose risks to both the environment and human health. Minimal efforts have been made to recover valuable materials like silicon, silver, and aluminium from end-of-life (EOL) PV modules. Countries like Germany actually implement EPR under WEEE Directive that makes producers pay for the collection, recycling, and recovery of PV waste. Japan resorts to strict guidelines coming from the Japan Photovoltaic Energy Association (JPEA), while China makes use of the National Solid Waste Law to enable huge-scale recycling [35][36]. The same countries also heavily invest in the latest technologies in material recovery, with recycling efficiencies reaching as high as 85%. India does not have this. India has started pilot projects and research on PV recycling by organizations such as NISE and private companies but are still at a small scale and impact. To match the global best practices, India must implement a robust PV-specific waste management framework that includes mandatory EPR, recycling targets, and investment in advanced recycling technologies. Additionally, public-private partnerships and capacity-building initiatives can help address the growing PV waste challenge and align India with global leaders in sustainable PV waste management. Figure 4.1 shows the PV waste generation rate in India and how it is increasing with each passing year. The bar graph compares the recycling efficiencies of various countries, pointing out that India needs to shift towards advanced recycling techniques to bring it at par with the international level. The table 4.1 highlights the growth of PV waste, along with the waste management techniques used in India, which also point out its limitations. It depicts the requirement of having PV-specific frameworks and advanced technologies to address the increasing waste issues effectively.

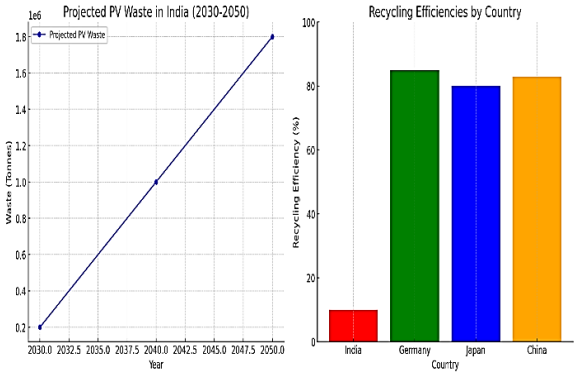

Figure 4.1: - Photovoltaic (PV) waste production and management in India

Table 4.1: - Photovoltaic (PV) waste management in India

Year	Projected PV Waste (Tonnes)	Waste Management Technique	Drawback
2030	200,000	Informal recycling	Unregulated, harmful to environment and health
2040	1,000,000	Generic e-waste management rules	Inadequate for PV-specific challenges
2050	1,800,000	Limited pilot projects	Small-scale impact, lacks advanced technology

V. MANDATORY RECYCLING TARGETS AND THEIR IMPACT

To improve photovoltaic waste management in India and attain a higher waste management score, the

following multiple measures need to be adopted with proven effectiveness based on global best practices. The very first one among them is implementing Extended Producer Responsibility, where it is mandatory that producers finance the collection, recycling, and recovery of PV waste. EPR successfully operates in such countries as Germany through the implementation of the WEEE Directive with significant reduction at a level of about 60-70% to the unprocessed wastes. Producers take responsibility to ensure that such materials are placed under EOL management, allowing higher recycling and recovery of resource value. Crucially important also is making an investment into high-tech waste recycling technologies using thermal, chemical, and mechanical recycling to achieve extraction of expensive resources like silicon, silver, and aluminium. These technologies achieve efficiencies of up to 85% recycling by separating high-value components from PV modules, reducing the requirement for raw material extraction and minimising landfill waste. Public-private partnerships can scale up the recycling infrastructure significantly in India. PPPs are a means to foster collaboration between government bodies and private firms, encouraging financial investments, innovation, and operational efficiency. This has already been adopted in countries such as China to expand their recycling framework and the recycling capacity up to 50%. For starters, the legal recycling targets like those established through the WEEE Directive in Europe can ensure diversion of 70-85% of PV waste away from landfills and into properly regulated recycling. This will ensure a well-planned handling of the growing volumes of wastes and recovery of critical resources. This can further increase the recycling efficiency by 15% by implementing capacity-building activities to train the informal sector workers in safe handling and efficient recycling techniques. Currently, the informal sector is responsible for handling a large percentage of PV waste in India in unregulated manners that pose environmental risks and health concerns. Offering subsidies to large-scale PV waste recycling facilities can also help encourage private investment and establish large-scale plants in this regard. This can increase recycling levels by 25–40% due to a decrease in the financial burden on companies and deployment of state-of-the-art technology. By integrating all these strategies, India can bring down its expected PV waste volume up to 70% by 2030. India will become in line with global leaders, such as Germany, Japan, and China. Table 5.1 Summarizes a variety of techniques that can help improve PV waste management in India and the respective impact on reducing waste. Each technique, from EPR to advanced recycling technologies, offers a clear path to significantly increase recycling efficiency and reduce environmental impact.

Table 5.1: - Suggested recycling methods and their impact

Suggested Technique	Description	Reduction Potential
Extended Producer Responsibility (EPR)	Mandate producers to finance PV waste collection, recycling, and recovery, aligning with global practices.	Reduces waste by up to 60–70% as producers ensure efficient recycling processes.
Advanced Recycling Technologies	Invest in thermal, chemical, and mechanical recycling technologies to recover high-value materials (e.g., silicon, silver).	Reduces waste by an additional 20–30%, achieving up to 85% recycling efficiency.
Public-Private Partnerships (PPP)	Encourage collaborations between government and private companies to scale recycling infrastructure.	Could improve waste management capacity by 50% through enhanced funding and innovation.
Mandatory Recycling Targets	Set legally binding recycling targets for PV modules, similar to the WEEE Directive in the EU.	Ensures that 70–85% of PV waste is diverted from landfills to recycling facilities.
Capacity Building and Training	Train informal recycling workers in safe and efficient practices to integrate them into formal systems.	Reduces hazardous handling and increases recycling efficiency by up to 15%.
Subsidies for Recycling Facilities	Provide financial incentives to establish advanced PV recycling plants across the country.	Can boost recycling rates by 25–40%, depending on the scale of implementation.

The figure 5.1 visualizes the reduction potential of various PV waste management techniques. Mandatory Recycling Targets stands out as the most effective approach, offering the highest potential for waste reduction at 85%, followed by techniques like Extended Producer Responsibility (EPR) and Public-Private Partnerships (PPP). This highlights the importance of legally binding recycling targets for achieving significant improvements in waste management.

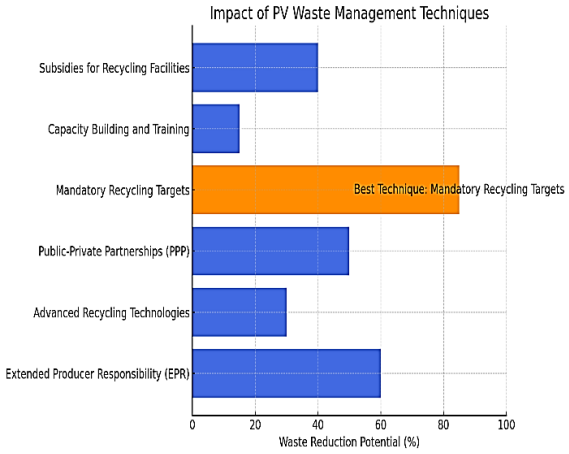

Figure 5.1: - Techniques for improving waste management

VI. CONCLUSION

India has achieved a fast pace of development in solar power generation, and thus this country is holding the top spot in the world in renewable energy. As of 2024, India has acquired remarkable growth, with states such as Rajasthan, Karnataka, and Andhra Pradesh making significant contributions to solar power production. However, the increasing number of photovoltaic (PV) installations also pose a major management headache that relates to the growing volume of solar waste. Projections suggest that India's PV waste will shoot up drastically, reaching 1.8 million tonnes by 2050, creating a pressing need for effective waste management solutions. At present, India's approach to PV waste management is fragmented and insufficient, primarily relying on generic e-waste policies and informal recycling practices. The need is to use a focused plan for PV waste management incorporating global best practices such as EPR, advanced recycling technologies, and recycling targets. These measures would not only make recycling more efficient but also would help in reducing environmental and health risks associated with improper handling of wastes. PPP and capacity-building initiatives can be used to upscale recycling so that large-scale, regulated recycling operations may work. India can reduce its projected PV waste volume significantly by investing in modern technologies and fostering innovation, thereby bringing itself at par with global leaders like Germany, Japan, and China, which have successfully integrated advanced recycling practices into their solar industries. In conclusion, by adopting comprehensive and forward-thinking policies, India can ensure the sustainable management of PV waste, supporting its transition to a greener, more circular economy while meeting its ambitious renewable energy targets. This holistic approach will help India mitigate the growing environmental impact of solar waste and enhance its position as a global leader in both solar power production and sustainability.

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