SHIKSHA SAMVAD
International Open Access Peer-Reviewed & Refereed
Journal of Multidisciplinary Research
ISSN: 2584-0983 (Online)
Volume-1, Issue-2, Oct-Dec- 2023
www.shikshasamvad.com

SUSTAINABLE MANAGEMENT OF WASTE IN SOLAR ENERGY INDUSTRY

Dr. Nomita Gowan
Assistant Professor
Lucknow Christian (Degree)College, Lucknow.
Email:dr.nomitagowan@gmail.com

Abstract:

The rapid expansion of the solar energy industry has heralded a promising era of sustainable energy production. However, this developing sector has not been immune to the generation of waste materials, raising questions about its overall sustainability. This paper explores the sustainability of waste management in the solar energy industry. It investigates the challenges, opportunities, and environmental impact of handling waste generated by solar energy technologies.

The paper categorizes the wastes generated by solar energy technologies, encompassing discarded solar panels, electronic waste stemming from inverters and controllers and explores the pressing challenges associated with the disposal, recycling, and repurposing of these materials, such as environmental concerns, technological limitations, and regulatory complexities. Key aspects covered include recycling innovations, policy implications, economic viability, and case studies of successful waste management initiatives. Moreover, the economic viability of sustainable waste management strategies is assessed, highlighting not only their potential for reducing environmental harm but also their capacity to foster new industries and employment opportunities.

This study employs secondary data analysis methodology to explore the sustainability of waste management in the renewable energy industry. It underscores the imperative for sustainable waste management within the solar energy industry. It underscores that addressing waste challenges is integral to ensuring that solar energy technologies continue to contribute significantly to a sustainable energy future while minimizing their environmental footprint.

Keywords: *Waste, Solar Energy, Sustainability, Extended Producer Responsibility.*

INTRODUCTION

In the ever-evolving landscape of the 21st century, India stands at a crossroads, poised for a transformative journey that encompasses economic prosperity, social equity, and environmental sustainability. Amidst global challenges like climate change, resource depletion, and pollution, sustainability has become essential. India, with its diverse issues, including environmental concerns and social challenges, relies on solar energy for solutions.

Solar energy, a cornerstone of sustainability to power India's growth. This industry plays a vital role in fighting climate change and reshaping energy towards eco-friendly options. Its swift growth redefines energy, providing cleaner alternatives to fossil fuels. As solar power expand, we envision a future with lower emissions and reduced reliance on finite resources. As the solar energy sector expands globally, it faces an unexpected challenge: waste generation. While cleaner energy sources bring environmental benefits, they also introduce a complex issue—the management of waste from solar energy technologies.

The significance of this inquiry becomes evident when one considers the sheer scale of the solar energy industry and its expansion. With the global solar energy capacity steadily increasing year by year, the volume of waste generated is set to grow in tandem. Addressing this issue is not merely a matter of environmental responsibility; it is a fundamental aspect of ensuring the long-term sustainability and viability of the entire sector.

As the solar energy industry continues to evolve, the challenge of waste management remains a significant piece of the sustainability puzzle. Addressing this challenge is paramount, as it will determine whether solar energy technologies can continue to thrive as key contributors to a more sustainable and environmentally responsible future. Through a thorough examination of the issues, opportunities, and solutions surrounding waste management in the solar energy industry, this paper seeks to contribute to the ongoing dialogue on sustainable energy and environmental stewardship.

LITERATURE REVIEW

Markvart & Castañer (2003)[1] draws attention to the critical issue of hazardous materials used in the production of solar panels. These materials, including HF, SiH4, Cd, H2Se, and AsH3, have been associated with various health and safety risks, such as cancer, explosions, and detrimental effects on the liver, CNS, sense organs, and kidneys. Importantly, these risks extend to all three generations involved in the solar PV industry.

Gottesfeld & Cherry (2011)[2] make a compelling case for investing in environmental controls, particularly in industries related to lead smelting, battery manufacturing, and recycling. They advocate for improvements in battery take-back policies to mitigate the negative impacts of lead pollution that may arise alongside the growth of solar PV systems.

McDonald & Pearce (2010)[3] advocate for recycling policies that not only focus on economic benefits but also place a strong emphasis on Extended Producer Responsibility to address the environmental impacts of hazardous materials. This approach recognizes that environmental concerns should not be overlooked in the pursuit of economic gains.

Ardente et al. (2015)[4] highlight the need for a comprehensive approach to the end-of-life phase of solar technologies. They emphasize that this phase, while still relatively limited in terms of waste compared to other sectors, must not be ignored. A holistic lifecycle perspective is essential to ensure that environmental burdens are not shifted from one phase to another.

This paper provides a well-rounded examination of the risks posed by hazardous materials in the renewable energy industry. It offers valuable recommendations for mitigating these risks, from environmental controls to recycling policies, ultimately contributing to the promotion of sustainable practices and responsible waste management within the renewable energy sector.

RESEARCH OBJECTIVES

- To identify and explore the challenges and obstacles associated with the disposal, recycling, and repurposing of waste materials generated by solar energy systems.
- To analyze the environmental consequences of improper waste disposal in the solar energy sector.
- To assess the role of policy and regulation in shaping sustainable waste management practices within the solar energy industry.

METHODOLOGY

For this research, we gathered secondary data from a range of reputable sources such as government reports and international reports and Information was collected from trusted websites, including government portals and news sources, to gather current data and insights on solar energy, environmental policies, and sustainability initiatives.

EMPOWERING INDIA’S SUSTAINABLE FUTURE

Sustainability, at its core, embodies the responsible utilzation of natural resources to ensure the well-being of both present and future generations. The United Nations Brundtland Commission defines sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability balances environment, economy, and equity. Neglecting the environment for short-term economic gains harms long-term prosperity. The three pillars—social, environmental, and economic—are interdependent, as recognized by the 2005 UN World Summit Outcome.

India's journey towards sustainable development embodies a crucial synergy between the well-being of its people and environmental preservation. Indian government involve efforts to enhance solar energy efficiency.

India is not merely focusing on its domestic efforts; it is also positioning itself as a leader on the global stage in shaping sustainability. Prime Minister Modi's address to G20 energy ministers underscored the pivotal role of energy in shaping the future sustainability, growth, and development of both individuals and nations[5].

India's commitment to sustainability is evident in a series of concrete actions and policy measures. One notable example is **India's ambitious plan to achieve 50% non-fossil fuel installed capacity by the year 2030[6]**. This commitment reflects the recognition that transitioning to cleaner energy sources is vital for long-term sustainability.

INDIA'S LEADERSHIP IN SOLAR ENERGY

India currently holds the **fourth position globally in terms of installed solar capacity[7]**, a testament to its commitment to sustainable energy. The nation aims to achieve ambitious targets, including producing 50% of its energy requirements from renewable sources by 2030 and installing 500 GW of non-fossil energy capacity by the same year. Cumulative achievement in solar power is shown in Table 1.

Table 1: Cumulative achievements in Solar Power.

Sector	Installed Capacity (GW)	Under Implementation (GW)	Tendered (GW)	Total Installed/Pipeline (GW)
Solar Power	63.30	51.13	20.34	134.77

Source: Ministry of New and solar energy, Annual Report (2022-23).

India's impressive strides in the realm of solar energy position it as a global leader in sustainable power solutions.

"India's Solar Power Leadership: Targets and Achievements[8]"

- **Ranked 4th globally in installed solar capacity.**
- **Total installed solar capacity as of 31.DEC 2022: 63.30GW.**
- **Target for 2022: 100GW.**
- **Ambitious goal for 2030: 300GW, including utility-scale and rooftop projects."**

India's estimated solar energy potential stands at approximately 750 GWp, determined by factors like available land and solar radiation. Table 2 provides state-wise details of this solar potential. On the other hand, Table 3 outlines the cumulative solar installed capacity by state as of December 31, 2022.

TABLE 2: State wise estimated solar energy potential in the country

Sl. No.	States/UTs	Solar Potential (GWp)
1	Andhra Pradesh	38.44
2	Arunachal Pradesh	8.65
3	Assam	13.76
4	Bihar	11.20
5	Chhattisgarh	18.27
6	Delhi	2.05
7	Goa	0.88
8	Gujarat	35.77
9	Haryana	4.56
10	Himachal Pradesh	33.84
11	Jammu & Kashmir	111.05
12	Jharkhand	18.18
13	Karnataka	24.70
14	Kerala	6.11
15	Madhya Pradesh	61.66
16	Maharashtra	64.32
17	Manipur	10.63
18	Meghalaya	5.86
19	Mizoram	9.09
20	Nagaland	7.29
21	Odisha	25.78
22	Punjab	2.81
23	Rajasthan	142.31
24	Sikkim	4.94
25	Tamil Nadu	17.67
26	Telangana	20.41
27	Tripura	2.08
28	Uttar Pradesh	22.83

Sl. No.	States/UTs	Solar Potential (GWp)
29	Uttarakhand	16.80
30	West Bengal	6.26
31	UTs	0.79
Total		748.98

Source: Ministry of New and solar energy, Annual Report (2022-23).

Table 3: State-wise cumulative solar installed capacity in the country (as on 31-12-2022)

Sl. No.	State/Uts	Cumulative Capacity till 31-12-2022 (MW)
1	Andaman & Nicobar	29.91
2	Andhra Pradesh	4524.72
3	Arunachal Pradesh	11.52
4	Assam	147.93
5	Bihar	192.88
6	Chandigarh	58.69
7	Chhattisgarh	944.22
8	Dadra & Nagar Haveli	5.46
9	Daman & Diu	41.01
10	Delhi	211.48
11	Goa	26.40
12	Gujarat	8500.74
13	Haryana	990.67
14	Himachal Pradesh	87.39
15	Jammu & Kashmir	48.90
16	Jharkhand	94.90
17	Karnataka	7885.56
18	Kerala	688.34
19	Ladakh	7.80
20	Lakshadweep	3.27
21	Madhya Pradesh	2774.78
22	Maharashtra	3646.13

Sl. No.	State/Uts	Cumulative Capacity till 31-12-2022 (MW)
23	Manipur	12.28
24	Meghalaya	4.15
25	Mizoram	8.02
26	Nagaland	3.04
27	Odisha	452.71
28	Puducherry	35.53
29	Punjab	1153.21
30	Rajasthan	16340.75
31	Sikkim	4.69
32	Tamil Nadu	6412.36
33	Telangana	4650.93
34	Tripura	16.67
35	Uttar Pradesh	2485.16
36	Uttarakhand	575.46
37	West Bengal	179.82
38	Others including NABARD	45.01
Total		63302.47

Source: Ministry of New and solar energy, Annual Report (2022-23).

In 2022, solar PV power generation surged by 270 TWh, marking a 26% increase from 2021[9]. Solar PV now constitutes 4.5% of the world's total electricity generation, ranking as the third-largest solar energy source after hydropower and wind.

India has embarked on several groundbreaking projects and initiatives that exemplify its dedication to sustainability. The **Pavagada Solar Park and Modhera Solar Village** are notable examples of how India is harnessing solar energy on a large scale. These projects not only contribute to clean energy production but also serve as models for sustainable development.

Various key initiatives and schemes are National Solar Mission, PM Kusum, Atal Jyoti Yojana, Solar Transfiguration of India (SRISTI), Suryamitra program, grid-connected solar rooftop program, solar parks, and ultra-mega solar power projects collectively form the backbone of India's clean energy agenda. Furthermore, India's holistic approach extends to international collaborations, most notably the International Solar Alliance (ISA) and its visionary "One Sun One World One Grid" initiative.

The ISA, a collaborative effort between India and France, is dedicated to combating climate change through widespread solar energy deployment. **Its mission encompasses mobilizing $1,000 billion in solar energy investments by 2030**, providing clean energy access to a billion people, and installing a staggering 1,000 GW of solar energy capacity[10]. ISA's priority areas include capacity building, programmatic support, and readiness, reinforcing its commitment to clean energy solutions.

A standout achievement within the ISA's endeavours is the **"One Sun One World One Grid"** initiative, a groundbreaking project aiming to create the world's first interconnected network of solar power grids. This visionary undertaking integrates various solar energy sources, such as large-scale solar power stations, wind farms, rooftop solar installations, and community-based initiatives. Its ultimate goal is to ensure a resilient, reliable, and affordable supply of green energy, thereby solidifying India's position as a global leader in sustainable energy solutions.

The **"Lifestyle for Environment"** mission seeks to channel individual and community efforts into a global mass movement of positive behavioral change. This initiative acknowledges the potential of traditional practices and lifestyles in contributing to a more sustainable future.

WASTE ARISING FROM SOLAR ENERGY SECTOR

India's relentless pursuit of solar energy is poised to make a significant global impact. According to a report by the International Energy Agency, by the year 2040, India is projected to account for a remarkable 30% of the world's installed solar capacity. The National Solar Mission has firmly established India as a trailblazing leader in the solar energy arena. However, amid this remarkable progress, the challenge of managing and mitigating the rising waste generated from solar energy sources has come to the forefront.

Additionally, the International solar Energy Agency (IRENA) forecasts that the volume of photovoltaic waste will soar to a substantial 78 million tonnes by the same year[11]. Notably, India is positioned among the top five contributors to this mounting wave of photovoltaic waste.

Solar Panel Waste:

- Solar panels typically have a lifespan of 25 to 30 years, but a staggering 90% of used solar panels end up in landfills without adequate planning for waste management[12].
- These panels contain toxic metals and minerals such as arsenic, lead, zinc, cardium that can leach into the ground, posing environmental hazards.
- A report by the National Solar Energy Federation of India estimates that India could accumulate over 34,600 tonnes of solar waste by 2030.
- India's significant solar PV deployment, ranking fourth globally with an installed capacity of nearly 62GW in November 2022, contributes to the substantial amount of solar PV waste.

- The recovery rate for both crystalline silicon (c-Si) and cadmium telluride thin-film modules is approximately 85-90%.

NEED FOR WASTE MANAGEMENT FOR A CLEANER INDIA

India, while striving to achieve ambitious solar power installation targets, currently lacks a comprehensive solar waste management policy. Solar waste, arising from discarded solar panels, is often sold as scrap within the country. This issue is poised to grow significantly in the next decade, potentially expanding four to five times its current size. Therefore there is need for effective waste management in India for solar panel to ensure a cleaner and more sustainable environment. solar panels are considered e-waste, and their improper disposal can have detrimental consequences. E-waste can contaminate soil, water sources, and air through leaching, water pollution, and hazardous gas emissions. It contains toxic substances like lead, cadmium, mercury, beryllium, and hexavalent chromium, posing risks to the health and safety of workers and communities. Inadequate e-waste treatment, such as landfill fires, emits toxic gases like formaldehyde and hydrogen cyanide, polluting the air and groundwater. Such pollutants are linked to severe health issues, including birth defects and low birth weight, particularly in nearby areas. It becomes imperative for India to focus its efforts on formulating robust regulations to address the challenges posed by solar waste.

Although photovoltaic account for only around 3% of global electricity generation, they are notable consumers of critical resources. This includes 40% of the world's tellurium, 15% of its silver, substantial quantities of semiconductor-grade quartz, as well as lesser but still significant amounts of indium, zinc, tin, and gallium.

The potential for reusing these materials extracted from solar panels is significant. By 2030, the market value of raw materials recoverable from solar panels could reach up to USD 450 million equivalent to the resources needed to build 60 million new solar panels or generate 18 GW of electricity[13]. Looking further into the future, it is projected that the value of these recoverable materials could exceed USD 15 billion by 2050, an amount sufficient to generate 630 GW of power using two billion solar panels.

Globally, there is a growing expectation that the End-of-Life (EoL) phase of solar panels will become a key driver of the solar panel recycling industry in the coming 10-20 years. It is crucial for India, with its burgeoning solar energy sector, to address these impending challenges proactively and lay the groundwork for effective solar waste management. This not only aligns with sustainable practices but also presents economic opportunities in the emerging recycling sector.

The responsible management of e-waste, including that from solar panels is essential to safeguard both the environment and human health. It helps prevent soil contamination, water pollution, air pollution, and related health risks, contributing to a cleaner and more sustainable India.

INDIA'S CURRENT RECYCLING POLICY

India's current photovoltaic (PV) recycling policy has brought solar waste under the umbrella of Electronic Waste Management rules, 2022 subjecting PV modules to the Extended Producer Responsibility (EPR) framework. EPR extends the producer's responsibility for a product beyond its useful life, addressing its disposal and recycling.

Solar Waste Management has been added in chapter 5 of E-waste management rules,2022. As per the rules the manufacturer of PV module cell shall: ensure their registration in the portal, store solar waste upto 2034-2035 according to the guidelines of Central pollution Board, file annual return before the end of year according to the form laid down on the portal, ensure processing of waste of solar PV cells, ensure the inventory of solar photo voltaic panels and comply with standards. [14]

CHALLENGES

However, there are some issues with the current policy. Around 50% of the materials within a PV module can be recovered, but in India, only about 20% of PV waste is properly recovered. The remaining waste is informally treated, leading to accumulations in landfills that contribute to environmental pollution. Moreover, incinerating PV waste releases harmful substances like sulphur dioxide, hydrogen fluoride, and hydrogen cyanide into the atmosphere.

One of the main issues is the classification of PV waste alongside other e-waste. The characteristics of solar panel materials are distinct from other electronic wastes, particularly because PV cells contain monocrystalline or multi-crystalline silicon. This silicon requires different recovery methods than the focus on metal recovery in regular e-waste recycling.

Another challenge is the lack of economic viability in recycling PV waste. According to the National Renewable Energy Laboratory, recycling a solar panel can cost between $20 and $30, while sending it to a landfill only costs $1-2. The absence of government incentives for recycling further exacerbates the situation.

REMEDIAL MEASURES AND SUGGESTION

To address these issues, India should consider specific provisions for PV waste treatment within the framework of e-waste guidelines. Establishing a central regulatory body could protect against financial losses associated with waste collection and treatment. An awareness campaign emphasizing the hazardous nature of PV materials is essential. Furthermore, India should invest in domestic research and development efforts, especially given the limited capacity for local solar PV-panel manufacturing. These measures are crucial for sustainable and responsible management of PV waste in the country.

Implement robust e-waste or Renewable Energy Waste Laws, such as Extended Producer Responsibility (EPR), where manufacturers and developers bear the responsibility for the end-of-life management of solar panels. The European Union's Waste Electrical and Electronic Equipment (WEEE) regulations serve as an example, offering financing options for waste management.

Reducing recycling costs requires investments in recycling infrastructure. Collaboration between the energy and waste sectors is crucial for efficient renewable energy waste handling. This includes establishing more recycling facilities to prevent solar panels from ending up in landfills.

Include provisions for environmental disposal and recycling of solar waste in power purchase agreements between organizations like SECI, DISCOMS, and the government and project developers.

Consider imposing bans on landfills for solar panel waste. Solar panels contain toxic metals and minerals that can leach into the ground, making landfill disposal environmentally harmful.

Introduce new business models and incentives, such as green certificates, to motivate the recycling industry's greater involvement in managing renewable energy waste.

Encourage innovation in panel design to reduce waste generation. Advancements in technology can significantly reduce the impact of renewable energy waste; for instance, newer panels use less silicon and produce less waste during manufacturing.

These strategies are essential for a sustainable approach to handling the waste generated by the solar energy industry, safeguarding the environment and maximizing resource efficiency.

CONCLUSION

The rapid proliferation of renewable energy technologies presents an invaluable opportunity for transitioning towards a more sustainable and eco-friendly energy future. However, this promising path towards cleaner power sources is not without its challenges, particularly in the management of the waste generated by photovoltaic (PV) modules.

As the photovoltaic industry continues to expand, the issue of solar waste becomes increasingly critical. It is evident that addressing this challenge is essential, not only from an environmental perspective but also for unlocking economic potential. The potential recovery of valuable materials from end-of-life PV modules, estimated to reach billions of dollars, underscores the economic opportunities in responsible waste management.

Internationally, there are clear precedents for dealing with renewable energy waste, from Extended Producer Responsibility (EPR) regulations in the European Union to industry-led recycling schemes in the United Kingdom and proactive state-level initiatives in the United States.

These examples demonstrate the viability of implementing structured approaches to waste management in the renewable energy sector.

While the road ahead may be demanding, incorporating solar waste management into the policy framework is a pivotal step towards building a sustainable renewable energy ecosystem. Proactive measures should include the establishment of strong regulatory frameworks, investments in recycling infrastructure, and the inclusion of environmental disposal provisions in power purchase agreements. Moreover, initiatives like banning landfills for solar waste, offering business incentives, and promoting research and development in panel design are indispensable components of a comprehensive strategy.

The challenges posed by renewable energy waste should not overshadow the immense potential of clean energy sources. By implementing sustainable waste management practices and integrating them into the renewable energy agenda, nations like India can not only mitigate environmental harm but also harness the economic prospects within this growing recycling industry. This proactive approach not only safeguards the environment but also paves the way for a more sustainable and resource-efficient renewable energy future.

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SHIKSHA SAMVAD
An Online Quarterly Multi-Disciplinary
Peer-Reviewed / Refereed Research Journal
ISSN: 2584-0983 (Online)
Volume-01, Issue-02, Oct-Dec- 2023
www.shikshasamvad.com
Certificate Number-Dec-2023/26

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"SUSTAINABLE MANAGEMENT OF WASTE IN SOLAR ENERGY INDUSTRY"

Published in 'Shiksha Samvad' Peer-Reviewed / Refereed Research Journal and E-ISSN: 2584-0983(Online), Volume-01, Issue-02, Month December, Year- 2023.

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