ANALYSIS OF SOLAR PHOTOVOLTAIC MODULE WASTE

A COMPARATIVE ANALYSIS OF INDIA AND GLOBAL BEST PRACTICES

by

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Dedication

This thesis is dedicated to my beloved parents, whose endless love, support, and sacrifices have been the foundation of all my achievements. Your belief in my potential has been my greatest motivation.

To my mentors and academic advisors, I express my deepest gratitude for your guidance, encouragement, and the invaluable knowledge you imparted. Your insights have shaped not only this work but also my growth as a researcher and individual.

To my friends and colleagues, who provided constant support, camaraderie, and encouragement, thank you for making this journey more meaningful and less arduous.

To the pioneers of sustainable energy and environmental stewardship, whose relentless efforts have paved the way for a greener and more sustainable world, this work is dedicated to you. It is my hope that this analysis contributes to the ongoing discourse on solar photovoltaic module waste management, offering valuable insights that will help bridge the gap between India and global best practices.

Lastly, to all those who envision a future where technology and nature coexist harmoniously, may this thesis be a small step towards realizing that vision.

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A special thanks to my family, whose unconditional love and support have been my greatest source of strength. To my friends and colleagues, your camaraderie and encouragement have made this journey all the more meaningful and enjoyable.

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ABSTRACT

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While instrumental in advancing global sustainability efforts, the proliferation of solar photovoltaic (PV) technology has introduced significant challenges related to managing solar PV module waste. This thesis presents a rigorous comparative analysis of India's solar PV waste management practices, benchmarked against global best practices. The study systematically examines the awareness, practices, and challenges associated with solar PV waste management among key stakeholders in India, including manufacturers, regulators, and waste management professionals. The research is structured around critical questions concerning stakeholder awareness of the risks associated with solar PV waste, familiarity with recycling methods, and the efficacy of existing waste management systems. Furthermore, the study explores the influence of demographic variables—such as age, gender, industry affiliation, and years of experience—on these dimensions, testing a series of hypotheses to assess the significance of these relationships. Findings from this research reveal that, while demographic factors influence awareness and perceptions, they are not robust predictors of the challenges encountered in solar PV waste management. The challenges identified are pervasive across the industry, underscoring systemic issues that transcend specific demographic or industry segments.

The study highlights substantial areas for improvement in India's current waste management infrastructure, regulatory frameworks, and technological capabilities. These gaps present significant barriers to effective solar PV waste management and suggest an urgent need for comprehensive policy reforms and the adoption of more sustainable practices. This study contributes to the broader discourse on environmental sustainability by offering a nuanced understanding of the complexities surrounding solar PV waste management in India. It also provides actionable recommendations for aligning India's practices with global standards, thereby enhancing the overall effectiveness of solar PV waste management efforts.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I:

INTRODUCTION

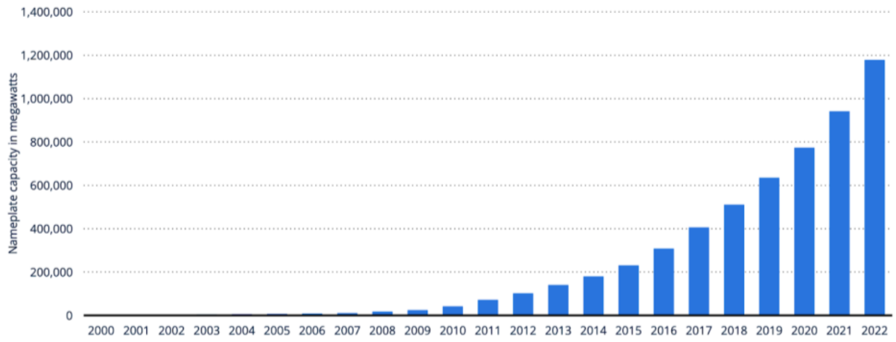
1.1 Introduction

Solar photovoltaic (PV) technology, as described by Zweibel (1990), involves using solar cells to convert sunlight into electricity without direct pollution or noise. This technology has seen significant advancements with the emergence of photovoltaic thermal (PVT) modules that simultaneously produce electricity and heat (Shakouri, 2020). The solar photovoltaic cell, a vital component of this technology, captures light photons to generate an electric current (Breeze, 2016). The process is based on the photovoltaic effect, where solar cells, typically made of semiconductor materials, create an electric field to convert light energy into electrical energy (Bayod-Rújula, 2019). India has made significant progress in adopting solar photovoltaic (PV) systems, with a target of 100 GW by 2022 (Saravanan, 2022). India's solar photovoltaic (PV) program has evolved through four distinct phases since 1947, influenced by scientific, technological, economic, and political factors (Devaraj & Haribabu, 2015). Despite being one of the largest national programs globally, with significant potential due to unelectrified villages and households (Sastry, 2002), India has faced challenges in indigenous PV technology development (Devaraj & Haribabu, 2015). The country has implemented comprehensive programs for research, development, and utilization of solar PV, providing subsidies for various applications (Sastry, 2002). Solar PV is recognized as a promising energy source for India, offering advantages such as direct power conversion and environmental friendliness (Anantha, 1997). Recently, India has shown interest in floating photovoltaic (FPV) technology, utilizing large water bodies for power generation. The country has the potential to develop 38.88 GW capacity using 35 large water bodies, although technical and economic barriers persist (Misra, 2020).

The country's vastness and rural electrification need to make SPV a particularly attractive renewable energy source (Dutta, 2006). However, challenges such as the reliance on fossil fuels and the need for stable, sustainable energy remain (Manju, 2017). The management of end-of-life solar PV systems is also a growing concern, with a need for proper waste management and recycling strategies (Pankadan, 2020). The global solar PV market has experienced significant growth and evolution over the past decade. This growth has been driven by various factors, including technological advancements, cost reductions, and supportive public policies (Zheng, 2014; Comello, 2018; Barker, 2005). The industry has seen a substantial increase in installations, focusing on grid-connected configurations and a shift towards distributed power generation (Wilhelm, 2011). Despite approaching $100 billion in value, the industry remains heavily subsidized and policy-driven (Morgan et al., 2012). Key factors influencing PV grid parity include solar resources, module costs, electricity prices, and environmental costs (Kamran et al., 2019). The market has been shaped by various actors, with politicians playing a crucial role through legislation and funding (Kaartemo, 2016). China has emerged as the leading PV market, surpassing Germany due to policy changes (Kamran et al., 2019). In 2017, global PV installations exceeded 98 GW, bringing cumulative capacity to approximately 402 GW (Masson et al., 2018). The Paris Agreement (COP21) is expected to provide long-term support for the solar PV market, even during economic downturns and low fossil fuel prices (Kaartemo, 2016). Standardization and technology advancements remain critical for reducing industry barriers and accelerating market adoption (Morgan et al., 2012).

The expenditure on solar PV has dropped significantly, making it a more competitive energy source (Barker, 2005). Despite these improvements, the industry still encounters challenges, such as surplus and the need for continued innovation (Zheng, 2014). Various factors influence the projected growth trends for solar PV installations in India and globally. Chaurey (2001) and Goel (2016) both highlight the role of government initiatives and policies in driving growth, with India aiming to install 100 GW of solar energy capacity by 2022, including 40 GW of grid-connected solar PV rooftop. Pandey (2022) underscores the potential impact of COVID-19 on solar energy installations, with a projected 450 GW of absolute renewable energy capacity, of which solar energy is expected to contribute over 60% by 2030 (Refer to Figure 1.1).

Figure 1.1: Cumulative installed solar PV capacity worldwide from 2000 to 2022 (in megawatts)



Source: Statista (2022)

Jager-Waldau (2012) emphasizes the rapid growth of the global PV industry, particularly in Asia, and the need for smaller competitors to specialize in niche markets or offer advanced and cost-effective solar cell concepts to survive in the competitive market. Solar PV modules predominantly consist of semiconductor materials, with silicon being the most widely employed due to its tetravalent nature and ability to bind with other atoms (Labouret, 2010). Other commonly used materials include compounds of cadmium sulfide, cuprous sulfide, and gallium arsenide (Kalogirou, 2009). These materials are arranged in various structures, with the most common being single-crystalline, multi-crystalline, and amorphous silicon, as well as polycrystalline thin films like copper indium diselenide and cadmium telluride (Addeo et al., 1983). Additionally, ongoing research is being done on using organic PV cells and dye-sensitized solar cells (Addeo, 1983).

The average lifespan of a solar PV module is around 25 years, with some studies suggesting it could be longer. Tan (2022) emphasizes the need for responsible end-of-life management, while Dunlop (2005) indicates that current module technologies may exceed the 20-year lifetime. Laronde (2013) presents a methodology for estimating the lifetime of a PV module, considering factors such as corrosion. Ross (1984) discusses the progress in achieving a 30-year helpful life for photovoltaic modules. These studies collectively highlight the potential for longer lifespans and the importance of considering various factors in estimating module lifetime. The common reasons for solar PV module failure or end-of-life (EOL) include environmental factors such as high UV irradiation, humidity, and temperature, which can lead to module degradation (Nain 2020). Intrinsic failure reasons, such as material defects, can also contribute to module failure (Ferrara 2012). Delamination and electromigration are two significant failure modes that can cause output power losses in PV modules (Hasan 2021).

The lack of recycling infrastructure, incentives, and environmental awareness can also influence the management and recycling of EOL modules (Nain 2020). It is crucial to develop suitable systems for the collection and management of EOL modules to prevent environmental damage (Tan 2022). The estimated volume of solar PV module waste generated annually in India is projected to be significant, with 200,000 tonnes expected by 2030 and 1.8 million tonnes by 2050 (Sheoran

2021, Morone 2023, Rathore 2021). This waste is a result of the increasing use of solar photovoltaic technology in the country, which has been driven by the need to meet the growing energy demand and mitigate climate change (Sheoran 2021, Morone 2023, Rathore 2021). The management and recycling of this waste are crucial to prevent environmental damage, and various techniques for recycling solar waste have been discussed (Morone 2023, Rathore 2021). The volume of solar PV module waste in India is projected to increase significantly in the coming years, with estimates ranging from 200,000 tonnes by 2030 to 1.8 million tonnes by 2050 (Sheoran 2021, Rathore 2021). This is a significant concern, as the proper disposal and recycling of this waste is crucial to prevent environmental damage. However, India currently lacks a concrete strategy for managing this waste (Gautam 2021). In comparison to other leading solar markets, such as Germany, the UK, and the US, India's policies and guidelines for recycling solar PV modules are still in the early stages of development (Sharma 2019). Therefore, there is a need for India to focus on developing a robust regulatory framework and innovative business models to address the challenges of PV recycling. Improperly disposed solar PV modules can have significant environmental impacts, including releasing hazardous contaminants, water pollution, and air emissions during manufacturing (Tawalbeh, 2020). However, recycling these modules can result in net environmental advantages, mainly in downsizing greenhouse gas emissions (Komoto, 2018; Tawalbeh, 2020). Despite these benefits, the environmental impacts of PV module production, use, and disposal are only sometimes considered in market valuations

(Srinivasan, 2018). To address these issues, high-value closed-loop recycling is recommended, along with the implementation of extended producer responsibility principles and suitable infrastructure (Yu, 2022). Solar PV modules possess hazardous materials such as cadmium, copper, gallium, and lead, posing risks to human health and the environment (Fthenakis, 2003; Nain, 2020). These risks are particularly evident during fires, where toxic materials can be released and pose health hazards (Moskowitz, 1990). The flammability of PV modules also presents a potential fire hazard, with the critical heat flux being a key factor (Yang, 2015). However, there needs to be more data to understand the release of these hazardous materials into the environment, highlighting the need for further research in this area (Nain, 2020). The disposal and recycling of solar PV modules in India are currently a matter of concern, with the country's rapid increase in solar power plant installations leading to a potential accumulation of waste (Sharma, 2019; Sheoran, 2020).

The need for a comprehensive policy framework to address this issue is emphasized, focusing on the economic, environmental, and social benefits of effective recycling (Sharma, 2019; Sheoran, 2020). Hazardous materials in these modules further underscore the importance of safe disposal and recycling practices (Jayapradha, 2023). Implementing high-value closed-loop recycling is recommended, focusing on extended producer responsibility, infrastructure, and research and development (Yu, 2022). India's existing waste management systems for solar PV module waste are currently inadequate, with a lack of effective disposal and recycling methods (Rathore, 2021; Gautam, 2021). The country is projected to generate a significant amount of solar PV e-waste, highlighting the urgency of addressing this issue (Gautam, 2021). While some countries have established policies and guidelines for PV recycling, India is still in the early stages of addressing this challenge (Sharma, 2019). There is a need for further research and development in this area, particularly in assessing the recycling potential and emissions from current solar PV modules (Oteng, 2021). The management of end-of-life solar PV modules is a growing concern, with a need for sustainable solutions. Research and development priorities include reducing recycling costs and environmental impacts, maximizing material recovery, and planning adaptable recycling infrastructure (Heath, 2020). High-value closed-loop recycling is preferred, but its implementation faces challenges (Yu, 2022). The EU and some PV manufacturers have established policies and programs for PV recycling, but there is a need for a system-level approach and capacity building (Sharma, 2019). The repair, refurbishment, and re-certification of decommissioned PV modules present both environmental challenges and value creation opportunities, with a need for standardized best practices and commercial services (Tsanakas, 2019).

A range of regulatory approaches to managing solar PV module waste are evident across different countries. In the EU, for instance, PV panels are classified as e-waste, while other countries generally treat them as general waste (Bajagain, 2020). However, there is a growing recognition of the need for more sustainable management, with a shift towards high-value closed-loop recycling (Yu, 2022).

This is particularly important given the increasing volume of PV waste, which is expected to reach 4% of installed capacity by 2030 (Sharma, 2019). The EU has taken the lead in establishing a PV module collection and handling regime, focusing on recycling (Sharma, 2019). The cumulative volume of the waste is estimated to vary from 25 to 28.5 million tons from 2001 to 2058 (Mahmoudi et al., 2021). Recycling solar PV modules has seen significant technological advancements, although challenges remain. Gerold (2024) emphasizes the need for stakeholder collaboration and the adoption of circular economy principles to drive the development of efficient and sustainable PV module recycling practices.

Tao (2015) highlights the exploration of recycling technologies for PV manufacturing waste and end-of-life modules, focusing on process efficiency, reduction in complexity, and economic viability. Moskowitz (1992) discusses the potential need for recycling specific PV module materials, such as cadmium and selenium, and the exploration of technical and institutional options for their recycling. These studies collectively underscore the importance of continued technological innovation and policy support in recycling solar PV modules. The economic benefits of recycling solar PV modules are significant, with recovering and recycling valuable metals presenting environmental and financial advantages (Smith, 2018). Despite some ecological burdens, the net environmental benefits of recycling these modules are positive (Komoto, 2018). However, the economic viability of PV module recycling is still a challenge, with the need for policies to encourage producer responsibility and an efficient collection network (Tao, 2015).

A cost-benefit analysis of waste photovoltaic module recycling in China found a positive net benefit, with the sale benefits of recycled materials and tax being the most sensitive factors affecting the project's economy (Liu, 2020). The improvement of solar PV module recycling rates in India is a vital matter that requires instantaneous attention. Sheoran (2020) emphasizes the need for effective policy measures to address this challenge, particularly considering the increasing installation of solar power plants in the country. Sharma (2019) underscores the importance of end-of-life management policies and regulations, drawing on global examples to highlight the potential for economic value creation from PV waste. Rathore (2021) further underscores the urgency of managing and recycling solar panel waste, particularly in the context of India's expected waste production. Finally, Tao (2015) provides a comprehensive review of feasible recycling pathways and technologies for solar PV modules, highlighting the need for policies to encourage producer responsibility and an efficient collection network.

The barriers to effective solar PV module recycling in India are multifaceted. Technological complexities, such as varying module compositions and recycling processes, pose significant challenges (Gerold, 2024). Inadequate infrastructure, regulatory gaps, and limited awareness hinder progress (Gerold, 2024; Ansari, 2013). The need for a compatible standard policy measure to tackle solar PV waste is emphasized, focusing on the hazardous effects of the waste and the importance of reclaimed material (Sheoran, 2020). The development of regulatory frameworks/guidelines and innovative business models are essential for PV end-of-life management systems (Sharma et al., 2019). Even with the ongoing advances, there is a fair chance that Photovoltaic electricity can be generated in India today (Singh et al., 2012). Various social and cultural factors influence the management of solar PV module waste in India. Sheoran (2021) highlights the increasing volume of waste and the potential for economic benefits from recycling. Padmanathan (2019) identifies barriers to adopting solar PV systems, which may impact waste management practices. Walzberg (2021) emphasizes the role of social factors in the success of reuse and recycle programs, suggesting that changing customer attitudes can boost module reuse. Ulsrud (2011) underscores the importance of considering both technical and non-technical factors in implementing and using solar PV technology, which can also impact waste management practices. Manufacturers play a crucial role in the lifecycle management of solar PV modules, as highlighted by Keoleian (1997). They are responsible for the material production, manufacturing, and assembly of the modules, which significantly impact their energy performance and environmental footprint.

Heath (2020) and Fthenakis (2000) emphasize the importance of end-of-life management, particularly module recycling, to support a circular economy and minimize environmental impact. This underscores the need for manufacturers to prioritize sustainable design and production practices, as well as invest in research and development for efficient recycling processes. The commission of extended producer responsibility (EPR) in the solar PV industry can be coaxed by a range of factors, including the dearth of a pre-established collection network, weak institutional capacity, and the need for specific domestic regulations (Kabir, 2023). In Korea, the government has proposed classifying solar PV panels as an EPR item, making manufacturers and importers responsible for their recycling (Lee, 2019). However, the cost efficiency of EPR implementation is a key concern, and cost allocation mechanisms that induce participation in collective systems and maximize cost efficiency have been proposed (Gui, 2016). These studies collectively highlight the importance of handling typical domestic crises, such as the absence of a pre-existing waste take-back system and the need for cost-efficient EPR implementation in the solar PV industry. The potential markets for recovered materials from recycled solar PV modules are significant, with valuable metals such as silicon, silver, copper, and aluminum being key targets (Yi 2014). The recovery of these materials is feasible through various methods, including thermal treatment (Wang 2012), two-step leaching and dissolving of impurities (Chen 2021), and thermal pyrolysis and chemical etching (Nagarajan 2020). These methods can produce high-purity silicon, glass, and metals, which can be used to produce new solar PV modules, creating a closed-loop system that reduces the industry’s environmental impact.

A range of studies have highlighted the need for improved public awareness and education about solar PV waste management in India. (Dr. Brahampal Singh (2017) emphasizes the role of higher education in promoting awareness of solar energy devices, while Yadav (2020) suggests that locally organized and delivered campaigns could be more effective in rural areas. Baloat (2023) and Pankadan

(2020) both underscore the importance of proper waste management and recycling strategies, with Baloat (2023) specifically addressing the need for scientific disposal and recycling of solar waste. These studies collectively point to the potential for a multi-faceted approach to improving public awareness and education, including higher education initiatives, locally targeted campaigns, and effective waste management and recycling strategies. Given the country's rapid urbanization and increasing energy demand, improving public awareness and education about solar PV waste management in India is crucial (Nixon, 2015; Pankadan, 2020). Key challenges include poor waste segregation, lack of government support, and the need for technology that can handle domestic waste characteristics (Nixon, 2015). To address these challenges, there is a need for improved education at institutional levels, better policies and regulations, and financial support from the government (Nixon, 2015).

Developing a compatible standard policy measure for solar PV waste management is also essential (Sheoran, 2020). The Indian government should consider implementing effective and eco-friendly recycling methods for end-of-life solar panels (Rathore, 2021). The economic costs associated with solar PV module waste management are a crucial consideration in the industry. Markert (2020) found that the private cost of end-of-life management of c-Si PV modules is USD 6.7/m2, with a net benefit of USD 1.19/m2 when considering externality costs. Liu (2020) conducted a cost-benefit analysis of waste PV module recycling in China, revealing a unit net benefit of 0.57 USD/kW. D'Adamo (2017) focused on the financial feasibility of crystalline Si PV module recycling processes, highlighting the absence of valuable materials and the critical role of process costs. Miah (2023) emphasized the need for a successful waste management plan in Bangladesh, where PV waste recycling could generate an economic value of USD 65.8 million and reduce CO2 emissions by 63 million tonnes.

A range of policy incentives can also be designed to promote sustainable disposal and recycling practices. Krozer (2003) suggests that subsidies for investments in re-design and deposit-refund for low-price elasticity products are effective in fostering design for recycling. Zhou (2021) proposes an innovative incentive-based recycling system using the Internet of Things and data analysis technologies to improve household waste recycling. Walls (2000) argues that downstream waste disposal policies, such as disposal fees, can encourage upstream "design for the environment" by sending signals to producers. Murakami (2015) further emphasizes the role of public policies, including tax exemptions, sanctions, and incentives for technological development, in inducing recycling and saving public funds. International organizations play a crucial role in shaping solar PV waste management policies by providing data, projections, and recommendations. They highlight the potential value of recycling and repurposing PV panels (Weckend, 2016) and emphasize the need for policy action to address the challenges ahead (Sharma, 2019).

These organizations also stress the importance of a holistic, multi-strategic approach to environmental management (Tudor, 2011) and the need for an enabling framework adapted to each region or country (Weckend, 2016). Furthermore, they underscore the significance of international cooperation in maintaining the PV waste stream at an economically feasible scale (Kim, 2018). Managing solar PV module waste in India significantly impacts global environmental goals. Baloat (2023) and Rathore (2021) highlight the potential for toxic waste from end-of-life solar panels if not correctly disposed of. India is expected to produce a substantial amount of this waste in the coming years. Sheoran (2021) underscores the need for effective and eco-friendly recycling methods, particularly given India's increasing installation of solar PV systems. Pankadan (2020) further emphasizes the importance of a waste management strategy to address the growing PV waste generation and reclaim valuable materials. These studies collectively underscore the critical role of India's solar PV waste management in mitigating environmental impact and contributing to global sustainability. The recycling and disposal of solar PV modules can have significant health impacts on workers. The manufacturing process involves using toxic, flammable, and explosive chemicals, posing a health hazard to workers (Dubey, 2013). In particular, using cadmium compounds in thin film PV modules can raise health, safety, and environmental concerns (Patterson, 1994). Workers may be exposed to hazardous materials such as lead, cadmium, and silicon and face risks of falls and electrical hazards during installation and maintenance activities (Ninduwezuor-Ehiobu, 2024). However, recycling PV modules can result in net environmental benefits, although there are still some environmental burdens (Komoto, 2018). A range of case studies offer valuable insights into effective waste management practices. Silva (2017) highlights the importance of transitioning from waste prevention to sustainable materials management, as seen in San Francisco, Flanders, and Japan. Storey (2015) emphasizes the need for partnerships in waste-to-resource initiatives, as demonstrated in Sri Lanka and Vietnam. Coban (2018) underscores the significance of multi-criteria decision-making methods in solid waste management, as applied in Istanbul, Turkey. Aziz (2022) discusses the challenges and potential solutions in waste-to-energy policies, drawing on the experiences of Indonesia and benchmark countries in the EU. The management of solar PV module waste differs significantly between urban and rural areas in India. Urban areas tend to have a more proactive approach, focusing on increasing the efficiency of solar PV panels (Nathan, 2015).

In contrast, rural areas need more resources and skilled human power (Nathan, 2014). This is particularly concerning given India's expected increase in solar PV waste production (Baloat, 2023). There is a need for a more balanced and sustainable approach to solar PV module waste management that considers the specific challenges and needs of both urban and rural areas. The improper management of solar PV module waste can have significant environmental and economic impacts. Gönen (2019) and Faircloth (2019) both highlight the potential for environmental benefits and economic recoveries through recycling, with Faircloth (2019) explicitly noting that recycling can result in less environmental burden than landfilling. However, the economic viability of recycling is a concern, as noted by Faircloth (2019) and Dubey (2013). The presence of toxic materials in PV modules and the competition for land are also potential issues (Dubey, 2013). Yu (2022) emphasizes the importance of high-value closed-loop recycling to mitigate these issues and calls for implementing sustainable management practices and regulatory frameworks. Advancements in material science can significantly reduce the environmental impact of solar PV modules. Tawalbeh (2020) emphasizes the importance of optimized design, novel materials, and reduced use of hazardous materials in mitigating environmental challenges. Sekhar (2021) highlights the role of technological advancements and material cost reduction in improving the efficiency of solar cells. Mohr (2009) and Scholten (2005) underscore the potential of using solar electricity in the production of PV modules and the importance of reducing silicon consumption and implementing environmental improvement options in module manufacturing. These studies collectively suggest that advancements in material science, particularly in developing novel materials and reducing hazardous and energy-intensive processes, can significantly reduce the environmental impact of solar PV modules. The potential for a circular economy in the solar PV industry is significant, with opportunities for waste reduction, resource recovery, and economic growth.

Mathur (2020) and Dancza (2022) highlight the importance of effective end-of-life management and the potential for new industries and revenue streams. Franco (2021) emphasizes the need for circular strategies throughout the PV value chain, including circular design and business models. Farrell (2020) discusses the technical challenges and opportunities in realizing a circular economy, particularly in recycling end-of-life modules. The studies collectively underscore the potential for a circular economy in the solar PV industry, focusing on waste reduction, resource recovery, and implementing circular strategies throughout the value chain. Supply chain dynamics significantly impact the lifecycle management of solar PV modules. Ishak (2020) and Marsillac (2012) highlight the need for sustainable supply chain management in the solar PV industry, proposing a conceptual framework for this purpose. Sandor (2018) emphasizes the role of global trade in critical materials like polysilicon, which can lead to price fluctuations and affect manufacturing capacity. Tsanakas (2019) underscores the importance of a circular supply chain for PV modules, particularly in recycling, refurbishment, and re-certification. These studies underscore the complex and multifaceted nature of supply chain dynamics in the solar PV industry and the need for strategic management to ensure sustainability and efficiency.

A range of partnerships and collaborations are necessary to improve India's solar PV module waste management. Sharma (2019) emphasizes the need for a system-level approach, suggesting partnerships between regulatory bodies, PV manufacturers, and local institutions. This is supported by Yu (2022), who highlights the importance of extended producer responsibility (EPR) and suitable infrastructure, which could be achieved through collaboration between the government and private sector. Sinha (2012) underscores the need for effective R&D strategies, indicating potential partnerships between research institutions and industry. Rathore (2021) further emphasizes the importance of eco-friendly recycling technologies, suggesting partnerships between technology developers and waste management companies. These partnerships and collaborations are crucial for addressing the growing challenge of solar PV module waste management in India. India can enhance its solar PV module waste management strategy by leveraging global best practices. Critical areas for improvement include the development of a regulatory framework and guidelines, establishing a PV recycling industry, and adopting a system-level approach (Sharma, 2019). The country should also focus on the disposal and recycling of solar waste, considering the significant increase in waste generation expected in the future (Rathore, 2021). Furthermore, there is a need to assess the issue's magnitude and explore the potential for a circular economy-based supply chain (Gautam, 2021). Finally, India should consider the challenges and prospects of PV materials disposal and recycling, including implementing high-value closed-loop recycling and promoting the extended producer responsibility principle (Yu, 2022).

The effectiveness of solar PV waste management practices can be evaluated using a range of metrics. Oteng (2021) suggests assessing the recycling potential and emissions from current solar PV modules and the remanufacture, recovery, and reuse of future modules. Rediske (2022) emphasizes the importance of operation and maintenance (O&M) practices, proposing 33 key performance indicators (KPIs) to evaluate O&M performance. Hoang (2014) highlights the need for a comprehensive sustainability assessment, including responsible resource management, recyclability, and social indicators. Bang (2018) recommends a comparative assessment of PV panels based on hazardous waste, resource depletion, and toxicity potentials, focusing on recycling and managing waste from polycrystalline Si and CIGS PV panels. Current research on solar PV module waste management has focused on recovery and recycling, particularly silicon-based modules (Mahmoudi, 2019; Oteng, 2021; Xu, 2018; Heath, 2020). However, there is a need for further exploration in several key areas. These include forecasting waste streams, developing recycling technologies, and addressing the lack of dedicated recycling plants (Mahmoudi, 2019; Xu, 2018). Electronic waste management, including photovoltaic (PV) panels, is a growing concern globally due to rapid technological advancements and increasing e-waste generation (Andeobu et al., 2021). Recycling PV panels at installation sites could offer economic and environmental benefits by reducing transportation costs (Chrzanowski & Zawada, 2023). However, many countries, particularly in Asia, lack effective e-waste management practices and face challenges in implementing proper recycling programs (Andeobu et al., 2021; Houéssionon et al., 2021).

Developed countries lead research in most recycling areas, while developing nations focus on using recycled plastics in construction (Tsuchimoto & Kajikawa, 2022). To improve e-waste management, countries must enhance knowledge, attitudes, and practices among healthcare professionals and waste management workers (Bhagavathula et al., 2016; Singh et al., 2021). Additionally, implementing sustainable management strategies, such as promoting circular economic behaviour and addressing behavioural spillovers, could help mitigate the environmental impact of e-waste (Newaz & Appolloni, 2023; Zarzavilla et al., 2022). The rapid growth of renewable energy, particularly solar photovoltaics (PV) and wind power has raised concerns about waste management and its environmental impact. By 2050, an estimated 78 million tonnes of PV waste will need recycling (Chrzanowski & Zawada, 2023). Wind turbine blade waste also poses challenges due to composite materials (Sorte et al., 2023). Recycling techniques for PV and wind turbines are being explored, with microwave pyrolysis showing promise for wind blades (Sorte et al., 2023). For PV, on-site recycling could reduce transportation costs and environmental impacts (Chrzanowski & Zawada, 2023). Despite technological improvements, PV manufacturing still has environmental hotspots (Blanco et al., 2020). To address these issues, circular economy strategies are being developed for offshore wind (Velenturf, 2021). In India, green bonds could help finance renewable energy projects but face challenges such as high transaction costs and lack of awareness (Abhilash et al., 2023). The global increase in photovoltaic (PV) usage has led to concerns about e-waste management and environmental impacts (Chrzanowski & Zawada, 2023; Andeobu et al., 2021). While PV technology offers sustainability benefits, its lifecycle environmental footprint requires careful consideration (Blanco et al., 2020). Standardized metrics for quantifying solar energy-land relationships are crucial for assessing impacts (Cagle et al., 2023). Implementing environmental management systems, such as ISO 14001, can improve operational efficiencies and stakeholder relations despite potential challenges (Camilleri, 2022).

Environmental Impact Assessments (EIA) and Life Cycle Assessments (LCA) are valuable tools for evaluating PV projects' impacts (Zarzavilla et al., 2022). Smart city initiatives are integrating innovative waste management solutions to address sustainability challenges (Szpilko et al., 2023). However, gaps in knowledge, attitudes, and practices regarding environmental management persist among professionals, highlighting the need for education and awareness programs (Bhagavathula et al., 2016). Recent research highlights the growing challenge of managing solar PV and electronic waste, particularly in developing countries. Studies emphasize the need for effective recycling processes to mitigate environmental and health risks associated with e-waste (Andeobu et al., 2021; Chrzanowski & Zawada, 2023). Policy frameworks and legal enforcement are crucial for improving waste management practices (Hirpe & Yeom, 2021). Factors influencing household waste sorting participation include attitudes, moral norms, and perceived behavioral control (Rousta et al., 2020). Smart city initiatives are integrating innovative technologies for efficient waste management (Szpilko et al., 2023). The circular economy concept is gaining traction, promoting reuse, recycling, and recovery in municipal solid waste management (Khatiwada et al., 2021). Sustainable waste management companies are adopting intelligent solutions, though more focus on user awareness and education is needed (Farooq et al., 2022).

Multi-criteria decision-making frameworks incorporating social indicators and stakeholder involvement are emerging as valuable tools for sustainable waste management (Gutierrez-Lopez et al., 2023). The emerging trends in photovoltaic (PV) technology, including thin-film and organic PV, are expected to reduce environmental impacts through material savings and improved efficiency (Weyand et al., 2019; Blanco et al., 2020). To address this, circular economy approaches and innovative waste management solutions are being explored (Khatiwada et al., 2021; Farooq et al., 2022). Smart city initiatives also incorporate advanced waste management technologies to improve efficiency and sustainability (Szpilko et al., 2023). However, challenges remain, particularly in developing countries like India, where e-waste management practices need enhancement (Andeobu et al., 2021). The Paris Agreement 2015 set ambitious targets for limiting the rise of global temperature, necessitating transformative changes across various sectors. Achieving net-zero emissions in buildings and industry requires overcoming economic, knowledge, and technical barriers (Mahmoodi et al., 2024). The circular economy concept has gained traction as a potential mitigation strategy, with the highest savings potential in the industry, energy, and transport sectors (Cantzler et al., 2020). However, current efforts are insufficient to meet the 1.5°C target (Samadi et al., 2018). Addressing climate change requires considering deep structural factors beyond individual behavior change (Hirth et al., 2023). The banking system is crucial in supporting the transition to a low-carbon economy, with research focusing on climate-related prudential regulation tools (Hidalgo-

Oñate et al., 2023). Local sustainability processes, such as Local Agenda 21, have evolved to encompass environmental, economic, and social aspects (Echebarria et al., 2018). The Paris Agreement's key objectives, particularly concerning renewable energy and sustainability goals, have spurred global efforts to transition from fossil fuels to renewable energy sources by 2050 (Holechek et al., 2022). This transition requires a multifaceted approach, including improving energy efficiency, increasing conservation, and implementing carbon taxes (Holechek et al., 2022). Adopting renewable energy in various sectors, such as hotels, promotes sustainability practices (Ghimire et al., 2023). Machine learning is enhancing the efficiency of renewable energy systems, particularly in Latin America (Hernández-Palma et al., 2024). However, challenges remain, including structural changes in consumption patterns (Hirth et al., 2023) and addressing barriers to renewable energy development in countries like Nepal (Adhikari et al., 2024). Business schools play a crucial role in achieving Sustainable Development Goals by creating awareness and fostering stakeholder cooperation (García-Feijoo et al., 2020). The global shift towards renewable energy aligns with the Paris Agreement's goals and the 2030 Agenda for Sustainable Development (Seminario-Córdova, 2023). The Paris Agreement has spurred research into clean energy transitions and circular economy strategies to mitigate climate change (Zhang et al., 2021; Cantzler et al., 2020). Solar energy has emerged as a promising solution, with studies exploring various technologies and their potential for decarbonization (Nikolaidis, 2023). However, deploying solar installations raises concerns about land use and environmental impacts (Cagle et al., 2023; Zarzavilla et al., 2022). Research indicates that wind and solar energy have the highest potential for contributing to a decarbonized energy supply (Shaw et al., 2023). As solar panel usage increases, effective recycling processes are crucial to manage the anticipated waste (Chrzanowski & Zawada, 2023). Smart city initiatives are incorporating innovative waste management solutions, including those for solar panel recycling, to promote sustainability and circular economy principles (Szpilko et al., 2023). These studies highlight the need for balanced approaches that maximize clean energy benefits while minimizing environmental impacts. The Paris Agreement aims to limit global temperature rise to 1.5°C above pre-industrial levels, requiring significant reductions in greenhouse gas emissions (Samadi et al., 2018). Achieving this target necessitates a rapid transition to renewable energy sources, with wind and solar power identified as the most significant contributors to decarbonizing the energy supply (Shaw et al., 2023). Solar energy technologies have shown immense potential in shaping a cleaner future (Nikolaidis, 2023). However, challenges remain in delivering net-zero emissions buildings (Mahmoodi et al., 2024) and replacing fossil fuels entirely by 2050 (Holechek et al., 2022). A combination of strategies is needed to meet these targets, including improving energy efficiency, increasing conservation, and implementing carbon taxes (Holechek et al., 2022). Additionally, negative emissions technologies may play a role, with various options, such as BECCS and afforestation, offering different potentials and costs

(Fuss et al., 2018). Accurate scenario generation methods are crucial for planning and optimizing solar power integration (Kousounadis-Knousen et al., 2023).

The Paris Agreement's goals have spurred research into environmental impacts and lifecycle management of renewable energy technologies, including solar photovoltaics (PV) and wind turbines. Life cycle assessments (LCA) of PV systems reveal that emerging technologies like organic PV show promise for reduced environmental impacts (Weyand et al., 2019). However, end-of-life management remains challenging, with an estimated 78 million tonnes of PV waste expected by 2050 (Chrzanowski & Zawada, 2023). For wind energy, blade recycling is a key concern, with microwave pyrolysis emerging as a promising technique for large-scale recycling (Sorte et al., 2023). The circular economy concept offers potential solutions for both sectors, with strategies such as design for circularity, maintenance, and recycling (Velenturf, 2021). Despite these efforts, implementing circular economy principles in renewable energy needs to be stronger, highlighting the need for further research and policy development (Cantzler et al., 2020). These papers must address the Paris Agreement's mechanisms for monitoring and reporting progress in renewable energy adoption and sustainable waste management. However, the studies highlight various aspects of sustainable waste management that contribute to climate change mitigation. Innovative city technologies and circular economy approaches are emphasized to improve waste management efficiency (Szpilko et al., 2023; Cantzler et al., 2020). IoT-enabled systems and smart bins are proposed to optimize waste collection and reduce emissions (Sosunova & Porras, 2022; Farooq et al., 2022). Sustainability reporting and collaborative frameworks are important for tracking progress and promoting transparency (Job & Khanna, 2024). Universities are identified as critical players in developing sustainable waste management practices (Giurea et al., 2024). The studies also highlight challenges in medical waste management, particularly during the COVID-19 pandemic (Singh et al., 2021) and emphasize the need for circularity in municipal solid waste management (Khatiwada et al., 2021). The Paris Agreement has influenced national policies on sustainable disposal and recycling of solar photovoltaic (PV) modules by driving research and implementing circular economy principles. Studies highlight the need for effective legislation to manage the projected 78 million tonnes of PV waste by 2050 (Chrzanowski & Zawada, 2023). Circular economy strategies in the PV industry show potential for climate change mitigation, particularly in the energy and transport sectors (Cantzler et al., 2020). Research emphasizes the importance of life cycle and environmental impact assessments in PV projects (Zarzavilla et al., 2022). Policy recommendations include carbon pricing, behavioral change, and technological solutions (Ottelin et al., 2019). The circular economy approach facilitates more efficient public policies for renewable energy (Nunes et al., 2023). Automated disassembly processes are crucial for improving the recycling efficiency of PV modules (Wu et al., 2023). Overall, technological innovations in PV show positive environmental sustainability trends (Blanco et al., 2020). The Paris Agreement has driven innovations in managing solar PV module waste to ensure sustainable renewable energy expansion. Research indicates that recycling PV panels at installation sites can reduce economic and environmental costs associated with transportation (Chrzanowski & Zawada, 2023). Life cycle assessments reveal that larger PV plants have shorter emission payback times, suggesting improved sustainability (Zarzavilla et al., 2022). Innovative waste management solutions, including smart bins and recycling technologies, are being developed to address sustainability goals (Farooq et al., 2022). The circular economy concept shows potential for climate change mitigation, particularly in the industry, energy, and transport sectors (Cantzler et al., 2020). Critical factors for selecting PV project sites include solar irradiation, proximity to infrastructure, and land use considerations (Rediske et al., 2018). Smart city approaches to waste management integrate technological solutions with community engagement to promote sustainable urban living and contribute to the circular economy (Szpilko et al., 2023). The rapid expansion of solar energy to meet Paris Agreement commitments is creating a growing challenge in photovoltaic (PV) waste management, with 78 million tonnes predicted by 2050 (Chrzanowski & Zawada, 2023). While solar PV offers climate benefits, its variable nature affects energy yield and economic viability (Iheanetu, 2022). Countries face difficulties in implementing effective e-waste management practices (Andeobu et al., 2021), and the environmental impacts of large-scale solar installations are significant (Cagle et al., 2023). Standardized metrics for quantifying solar energy-land relationships are needed to understand better these impacts (Cagle et al., 2023). Environmental impact assessments and life cycle analyses are crucial for evaluating the sustainability of solar projects (Zarzavilla et al., 2022). As countries balance solar expansion with waste management, they must also consider recycling technologies for other renewable energy components, such as wind turbine blades (Sorte et al., 2023), and utilize Earth system models for long-term energy resource projections (Chen & Ji, 2024). The global management of photovoltaic (PV) module waste presents challenges and opportunities for achieving environmental and climate targets. Studies highlight the need for effective recycling processes to handle the projected 78 million tonnes of PV waste by 2050 (Chrzanowski & Zawada, 2023). Implementing circular economy principles in waste management can contribute to climate change mitigation, with the highest potential in the industry, energy, and transport sectors (Cantzler et al., 2020). Life cycle assessments reveal positive trends in PV environmental sustainability, though hotspots remain for specific technologies (Blanco et al., 2020). In regions like Castilla-La Mancha, Spain, environmental impact assessments of large-scale PV projects provide valuable insights for policymakers (Zarzavilla et al., 2022). Universities play a crucial role in developing sustainable waste management practices through research, education, and implementation (Giurea et al., 2024). Innovative smart solutions and marketing initiatives by waste management companies can further enhance sustainability efforts (Farooq et al., 2022). International collaborations under the Paris Agreement are crucial in developing sustainable solar PV waste management solutions for large-scale solar economies. The increasing use of photovoltaics is expected to generate 78 million tonnes of waste by 2050, necessitating effective recycling processes (Chrzanowski & Zawada, 2023). Circular economy strategies can contribute to climate change mitigation, with the highest potential in the industry, energy, and transport sectors (Cantzler et al., 2020). Innovative waste management solutions, such as smart bins and recycling technologies, are being implemented globally (Farooq et al., 2022; Szpilko et al., 2023). Standardized metrics for quantifying solar energy-land relationships are crucial for understanding environmental impacts (Cagle et al., 2023). Technological advancements in PV are improving environmental sustainability, but potential hotspots remain (Blanco et al., 2020). Higher education institutions are key in transitioning to a circular economy, particularly in Latin American countries (Salas et al., 2021). Managing solar PV module waste is becoming increasingly important as the industry proliferates. By 2050, an estimated 78 million tonnes of PV waste will need recycling (Chrzanowski & Zawada, 2023). While PV energy offers environmental benefits, concerns remain about its impact (Zarzavilla et al., 2022). Effective e-waste management, including PV modules, is crucial to prevent environmental and health issues (Andeobu et al., 2021). Smart city initiatives are integrating innovative waste management solutions, including those for PV waste (Szpilko et al., 2023; Farooq et al., 2022). Technological advancements in PV are improving environmental sustainability, but potential hotspots remain for specific technologies (Blanco et al., 2020). Recycling PV modules faces challenges similar to those of electric vehicle batteries, including the dismantling complexity and the materials' diversity (Zhang et al., 2018). Integrating recycled materials and new technologies in various industries can significantly reduce CO2 emissions (Yaro et al., 2023). Federal and state-level policies are crucial in achieving U.S. Paris Agreement targets, particularly in managing renewable energy waste like solar PV modules. The circular economy concept is gaining traction, combining economic development with environmental benefits (Nunes et al., 2023). However, implementation remains weak, with the highest potential for climate change mitigation in the industry, energy, and transport sectors (Cantzler et al., 2020). The Strategic Energy Technology Plan (SET-Plan) has shaped multi-level energy policies in Europe, facilitating synergies among governance levels and stakeholders (Manni et al., 2020). For solar PV, key considerations include environmental impact assessments (Zarzavilla et al., 2022), power forecasting techniques (Iheanetu, 2022), and standardized metrics for quantifying solar energy-land relationships (Cagle et al., 2023). Recycling PV panels at installation sites shows potential economic and environmental benefits (Chrzanowski & Zawada, 2023), while factors like solar irradiation and infrastructure proximity are crucial for site selection (Rediske et al., 2018). The U.S. faces challenges balancing solar energy growth with environmental concerns, particularly regarding photovoltaic (PV) waste management. By 2050, an estimated 78 million tonnes of PV waste will require recycling (Chrzanowski & Zawada, 2023). While solar energy offers environmental benefits, its total impact remains a concern (Zarzavilla et al., 2022). Standardized metrics for quantifying solar energy-land relationships are crucial for understanding environmental impacts (Cagle et al., 2023). Emerging PV technologies may have lower environmental impacts due to material savings (Weyand et al., 2019), but their performance varies (Blanco et al., 2020). Improved efficiency, lifetime, and manufacturing processes can enhance environmental performance (Weyand et al., 2019). Site selection for PV projects is critical, with factors such as solar irradiation, substation distance, and land use being key determinants (Rediske et al., 2018). Accurate solar PV power forecasting is essential for addressing variability issues (Iheanetu, 2022). Decoupling economic growth from resource use and emissions remains a challenge for sustainable development (Wiedenhofer et al., 2020). The rapid growth of global photovoltaic (PV) installations has raised concerns about the environmental impact of end-of-life PV waste (Chrzanowski & Zawada, 2023). While solar energy offers environmental benefits, its total impact remains a concern (Zarzavilla et al., 2022). As a significant player in the PV industry, China faces challenges in green building development, including a lack of policy guidance and environmental awareness (Wu et al., 2019). The circular economy concept has gained popularity for combining economic development with environmental benefits, but its mitigation potential varies across sectors (Cantzler et al., 2020). E-waste management practices in Asia-Pacific countries, including China, need improvement to address environmental and health concerns (Andeobu et al., 2021).

Technological innovations in PV are primarily driven by cost considerations, potentially overlooking environmental impacts (Blanco et al., 2020). Decoupling economic growth from resource use and emissions is crucial for sustainability, but evidence of absolute decoupling is scarce (Wiedenhofer et al., 2020). The circular economy (CE) approach is gaining traction globally to address resource scarcity and environmental issues while promoting economic development (Min et al., 2021). In waste management, CE strategies offer potential for climate change mitigation, particularly in the industry, energy, and transport sectors (Cantzler et al., 2020). Integrating CE principles in offshore wind energy infrastructure is also emerging as a crucial area for sustainable development (Velenturf, 2021). However, barriers to implementing CE and green building practices persist, including lack of policy guidance, immature market environments, and insufficient environmental awareness (Wu et al., 2019). Coordinated policies promoting innovative circular businesses and technologies are necessary to accelerate the transition to a CE and achieve net-zero emissions by 2050 (Khalifa et al., 2022). Recent research highlights China's efforts in advancing recycling technologies and policies for solar energy and waste reduction. Studies indicate a growing focus on recycling photovoltaic panels, with potential economic and environmental benefits from on-site recycling (Chrzanowski & Zawada, 2023). China is implementing circular economy practices in renewable energy sectors, emphasizing the 3Rs (reduce, reuse, recycle) to address environmental challenges (Nunes et al., 2023). Chinese SMEs are adopting circular economy principles, though barriers like lack of resources persist (Min et al., 2021). Advancements in recycling technologies for carbon fiber-reinforced plastics and batteries are also being explored (Chen et al., 2023; Toro et al., 2023). China is a pivotal contributor to research on low-carbon pavement using recycled materials (Yaro et al., 2023). However, challenges remain in e-waste management, requiring enhanced practices (Andeobu et al., 2021). Overall, China is making significant strides in integrating recycling technologies with its renewable energy leadership, though continued efforts are needed for comprehensive waste reduction. The reviewed papers highlight various aspects of solar energy and battery recycling, but only one directly addresses Japan's measures for managing solar PV module disposal. Several studies emphasize the importance of recycling photovoltaic panels to mitigate environmental impacts and recover valuable materials (Chrzanowski & Zawada, 2023; Zarzavilla et al., 2022). Research gaps exist in recycling potential at installation sites and standardized recycling methods (Chrzanowski & Zawada, 2023; Zhang et al., 2018).

The environmental sustainability of PV technologies is improving, but potential hotspots remain (Blanco et al., 2020). Automated disassembly processes for lithium-ion batteries could enhance recycling efficiency (Wu et al., 2023). E-waste management practices in Asia-Pacific countries, including Japan, need improvement (Andeobu et al., 2021). Standardized metrics for quantifying solar energy-land relationships are proposed to facilitate a better understanding of environmental impacts (Cagle et al., 2023). However, the papers do not specifically address Japan's measures for PV module disposal concerning the Paris Agreement. Recent research highlights the importance of circular economy (CE) and intelligent waste management (SWM) strategies in achieving climate goals and sustainable urban development. CE approaches in various sectors, particularly industry, energy, and transport, show potential for significant greenhouse gas reductions

(Cantzler et al., 2020). Intelligent cities implement innovative SWM systems using IoT technologies, sensors, and data analytics to optimize waste collection and disposal (Szpilko et al., 2023; Sosunova & Porras, 2022). These systems can contribute to sustainability goals by improving efficiency and reducing environmental impacts (Farooq et al., 2022). However, challenges remain in transitioning to renewable energy and implementing CE principles in sectors like offshore wind (Velenturf, 2021). Achieving fossil fuel independence by 2050 will require the aggressive application of multiple pathways, including renewable energy development and energy conservation (Holechek et al., 2022). Also, proper medical waste management, particularly during pandemics, presents challenges and opportunities for sustainable resource recovery (Singh et al., 2021). Recent research highlights the growing challenges and opportunities in waste management, particularly in smart cities and developing countries. Studies emphasize the importance of integrating innovative technologies, such as IoT-enabled smart bins and waste collection systems, to improve efficiency and sustainability (Szpilko et al., 2023; Farooq et al., 2022; Sosunova & Porras, 2022). The COVID-19 pandemic has exacerbated medical waste management issues, necessitating better strategies for disposal and recycling (Singh et al., 2021). Circular economy principles are increasingly crucial for transforming traditional linear waste management approaches (Khatiwada et al., 2021). Developing countries face unique challenges, including a need for more policy enforcement and public awareness (Hirpe & Yeom, 2021). E-waste management in the Asia Pacific requires significant improvement (Andeobu et al., 2021). For renewable energy projects, such as solar photovoltaics, careful site selection considering factors like solar irradiation and infrastructure proximity is essential (Rediske et al., 2018). The growth of solar energy in Germany has increased concerns about the sustainable management of photovoltaic (PV) waste. While specific German regulatory frameworks still need to be directly addressed, several studies highlight the importance of adequate legislation and recycling processes for end-of-life PV panels (Chrzanowski & Zawada, 2023). Germany has been a leading contributor to research on renewable energy policies and circular economy practices (Nunes et al., 2023). Various recycling techniques for PV panels and wind turbine blades have been explored, with considerations for economic and environmental impacts (Sorte et al., 2023; Blanco et al., 2020). Life cycle and environmental impact assessments have been used to evaluate the sustainability of PV power plants (Zarzavilla et al., 2022). The integration of circular economy principles in renewable energy infrastructure, including offshore wind, has been proposed as a framework for sustainable development (Velenturf, 2021). Standardized metrics for quantifying solar energy-land relationships have also been suggested to improve understanding environmental impacts (Cagle et al., 2023). Managing electronic and photovoltaic waste presents significant challenges and opportunities for sustainable development. E-waste generation is increasing rapidly in Asia Pacific countries, necessitating improved recycling practices to mitigate environmental and health risks (Andeobu et al., 2021). Recycling photovoltaic panels, particularly at installation sites, offers economic and environmental benefits by reducing transportation costs (Chrzanowski & Zawada, 2023). Medical waste management faces challenges, with only 38.9% of waste properly segregated and 41% of workers trained in disposal practices (Singh et al., 2021). Intelligent cities are integrating innovative technologies for effective waste management, focusing on sustainability and community engagement (Szpilko et al., 2023). The circular economy concept can transform traditional linear approaches to waste management, promoting reuse, recycling, and recovery (Khatiwada et al., 2021). Additionally, renewable energy development, including solar PV, requires quality human resources (Udin, 2020) and improved forecasting techniques to address variability in energy yield (Iheanetu, 2022). Studies highlight the need for improved e-waste management practices in Asia Pacific countries (Andeobu et al., 2021) and emphasize the potential for recycling PV panels at installation sites to reduce transportation costs and environmental impacts (Chrzanowski & Zawada, 2023). Circular economy strategies show promise for climate change mitigation across various sectors, including industry and energy (Cantzler et al., 2020). Smart city approaches to waste management, incorporating innovative technologies and community engagement, are emerging as crucial for urban sustainability (Szpilko et al., 2023). Researchers stress the importance of circularity in municipal solid waste management (Khatiwada et al., 2021) and the need for sustainable waste management companies to focus on technological solutions and user awareness (Farooq et al., 2022). Additionally, the wind energy sector faces challenges in recycling turbine blades, with various techniques being evaluated for sustainability (Sorte et al., 2023).The concept of "net-zero" targets under the Paris Agreement drives countries to address solar PV waste as part of their sustainability strategies. As the use of photovoltaics increases, the need for effective recycling of end-of-life panels becomes crucial (Chrzanowski & Zawada, 2023). Transitioning to a circular economy is essential for achieving net-zero emissions, requiring attention to energy- and non-energy-related GHG emissions (Khalifa et al., 2022). While decoupling economic growth from resource use and emissions is necessary, evidence for absolute decoupling is scarce (Wiedenhofer et al., 2020). Cities play a vital role in achieving net-zero carbon, which requires systemic transformation (Seto et al., 2021).

Technological developments in PV are improving environmental sustainability, though potential hotspots remain (Blanco et al., 2020). Smart city approaches to waste management, including PV waste, are emerging as crucial components of urban sustainability (Szpilko et al., 2023). Accurate solar PV power forecasting is essential for addressing variability challenges (Iheanetu, 2022). Recent developments in carbon credit markets and solar PV waste reduction highlight the growing importance of sustainable practices in the renewable energy sector. The increasing adoption of photovoltaics has led to concerns about end-of-life panel recycling, with an estimated 78 million tonnes of PV waste expected by 2050 (Chrzanowski & Zawada, 2023). Recycling efforts focus on fraction separation at installation sites to reduce transportation costs and environmental impacts (Chrzanowski & Zawada, 2023). Life cycle assessments of various PV technologies show positive trends in environmental sustainability, though potential hotspots remain (Blanco et al., 2020). Green finance mechanisms are emerging as practical emissions reduction tools, with carbon markets identified as a significant research topic (Zhang et al., 2022). The integration of circular economy principles across sectors, including agriculture, industry, and energy, is crucial for achieving net-zero emissions by 2050 (Khalifa et al., 2022). However, challenges persist in implementing efficient recycling techniques for renewable energy components, such as wind turbine blades (Sorte et al., 2023). Recent research highlights the growing importance of circular economy (CE) principles in addressing global challenges, particularly in waste management and sustainability. The increasing adoption of photovoltaics is expected to generate significant waste by 2050, necessitating effective recycling strategies (Chrzanowski & Zawada, 2023). CE initiatives are driven by various factors, including technological advancements, policy frameworks, and economic incentives (Aloini et al., 2020). Imaginative city concepts are integrating innovative waste management solutions (Szpilko et al., 2023), while the COVID-19 pandemic has impacted progress toward Sustainable Development Goals, emphasizing the need for CE approaches (Martín-Blanco et al., 2022). Studies suggest CE strategies can mitigate climate change, particularly in industry, energy, and transport sectors (Cantzler et al., 2020). However, transitioning to a CE faces barriers such as limited practical implementation and the need for coordinated policies (Tan et al., 2022; Khalifa et al., 2022). Effective CE implementation requires a multifaceted approach encompassing technology, finance, ecosystem considerations, and behavioral changes (Khatiwada et al., 2021). The circular economy (CE) model, including solar PV modules, is increasingly recognized as a crucial approach to sustainable waste management. CE strategies encompass the 3Rs (reduce, reuse, recycle) and extend to 12Rs, emphasizing resource efficiency and waste reduction (Onungwe et al., 2023). Recycling at installation sites for PV panels shows potential economic and environmental benefits by reducing transportation costs (Chrzanowski & Zawada, 2023). The offshore wind sector also explores CE integration, with 18 strategies identified across the lifecycle (Velenturf, 2021). Higher education institutions play a vital role in CE implementation, particularly in Latin America, through research, industry collaboration, and policy support (Salas et al., 2021). Public policies are crucial for promoting renewable energy and CE practices (Nunes et al., 2023). CE assessments at various scales, from neighbourhoods to global, are being developed to monitor performance and guide implementation (Bueren et al., 2021).

Additionally, there is a need for more research on the recycling potential and emissions from current solar PV modules and the remanufacture recovery, and reuse of future modules (Oteng, 2021). Lastly, research and development priorities should focus on reducing recycling costs and environmental impacts, maximizing material recovery, and planning adaptable recycling infrastructure (Heath, 2020). India's solar PV industry can align with the United Nations' Sustainable Development Goals (SDGs) through policy, investment, and technology. Srikanth (2018) emphasizes the need for a policy framework that integrates low-carbon energy technologies with coal, while Kar (2016) suggests strategic steps such as creating an investment climate and developing domestic component manufacturing. Rajshree (2021) underscores the business feasibility of solar energy in India and the role of government policies in promoting PV installations. Finally, Caldés (2018) highlights the potential contributions of concentrated solar power (CSP) in meeting the SDGs, including access to basic services, human health improvement, and sustainable economic growth. These studies collectively underscore the importance of policy support, investment, and technology innovation in aligning India's solar PV industry with the SDGs. The current management of end-of-life (EoL) solar PV modules, which often involves disposal in landfills or bulk recycling, poses significant environmental and sustainability challenges (Yu, 2022). To address these issues, there is a need for high-value closed-loop recycling, which requires research and development to reduce costs and environmental impacts (Heath, 2020). This approach, however, has yet to be widely implemented, and there needs to be more consideration for environmental effects in decision-making (Deng et al., 2019). The emerging field of solar PV waste management research focuses on the performance and efficiency of polymer solar cells. However, there is a need for more attention to be given to recycling, recovery, and policy and regulation (Oteng, 2021).

1.2 Research Problem

Despite the growing adoption of solar photovoltaic (PV) systems as a sustainable energy solution, the management of solar PV waste presents significant environmental and logistical challenges. The lack of comprehensive awareness and effective practices in solar PV waste management among stakeholders, coupled with the absence of robust infrastructure and regulatory frameworks, exacerbates these challenges. This research aims to address the gaps in awareness, practices, challenges, and the overall effectiveness of solar PV waste management in India, highlighting the role of sustainable practices and government intervention.

1.3 Purpose of Research

The purpose of this PhD research is to systematically investigate and evaluate the awareness, practices, and challenges associated with solar photovoltaic (PV) waste management among various stakeholders in India. By leveraging theoretical frameworks such as the Theory of Planned Behavior, Sociological Models, Altruism Models, the DPSIR Framework, and Multi-Criteria Decision-Making models, this research aims to:

1. **Assess Stakeholder Awareness and Practices:**

- Evaluate the level of awareness and current practices related to solar PV waste management among different stakeholders, including manufacturers, installers, policymakers, and consumers.
- Analyze how demographic factors (age, gender) and industry-specific characteristics (type of industry, years of experience) influence awareness and practices.

2. **Identify Key Challenges:**

- Identify and categorize the main challenges faced by stakeholders in managing solar PV waste, including infrastructural, regulatory, technological, and economic barriers.

3. **Evaluate Sustainable Practices and Government Roles:**

- Assess the perceived importance of sustainable practices and the role of government in promoting and implementing effective solar PV waste management strategies.

- Explore how existing policies and regulatory frameworks impact the effectiveness of waste management practices.

4. **Analyze Demographic and Industry-Specific Trends:**

- Investigate how various demographic factors and industry-specific characteristics shape solar PV waste management practices and challenges.

1.4 Significance of the Study

The significance of this study lies in its potential to provide comprehensive insights into the multifaceted issue of solar photovoltaic (PV) waste management in India. As the adoption of solar PV systems continues to grow exponentially, the management of resulting waste becomes increasingly critical. This research addresses key areas of awareness, practices, challenges, and the role of government and sustainable practices in managing solar PV waste. The findings of this study will contribute to:

1. **Enhanced Awareness**: By assessing the level of awareness among stakeholders, this study will highlight knowledge gaps and provide a basis for targeted educational programs and awareness campaigns.
2. **Improved Practices**: Identifying current practices and their effectiveness will help in developing best practices for solar PV waste management, thereby improving environmental sustainability.

3. **Addressing Challenges**: Understanding the specific challenges faced by stakeholders will inform the development of more effective policies and frameworks to mitigate these issues.
4. **Policy Development**: Evaluating the role of government and the importance of sustainable practices will offer valuable insights for policymakers to enhance regulatory and incentive structures.
5. **Strategic Recommendations**: The study's analysis of demographic and industry-specific trends will enable tailored strategies that consider the unique needs and challenges of different stakeholder groups.
6. **Sustainable Development**: Ultimately, this research will contribute to the broader goals of sustainable development by promoting more efficient and responsible management of solar PV waste.

1.5 Research Questions

The objectives of the study are:

1. To evaluate the level of awareness and the current practices related to solar PV waste management among different stakeholders.
2. To identify the key challenges faced by stakeholders in managing solar PV waste.
3. To assess the perceived importance of sustainable practices and the role of government in solar PV waste management.

4. To analyze how demographic factors and industry-specific characteristics influence solar PV waste management practices and challenges.
5. To assess the Effectiveness of Solar PV Waste Management Practices in India

CHAPTER II:

REVIEW OF LITERATURE

2.1 Current state of solar PV waste generation globally and specifically in India

Solar photovoltaic (PV) waste generation is becoming a significant global concern, with projections estimating 60 million tonnes worldwide by 2050 (Rathore & Panwar, 2021). In India, the rapid growth of solar energy installations is expected to generate approximately 200,000 tonnes of PV waste by 2030 and 1.8 million tonnes by 2050 (Rathore & Panwar, 2021). More recent estimates suggest even higher figures, with 6.64 million tonnes of waste projected by 2040 in India alone (Sharma et al., 2023). The absence of adequate regulations and infrastructure for PV waste management in India poses environmental and health risks (Jain et al., 2022). Recycling end-of-life PV panels can reduce environmental impacts by up to 70% compared to landfilling (Sharma et al., 2023). To address this challenge, researchers propose implementing a regulatory framework based on Extended Producer Responsibility and a multi-stakeholder approach for effective solar PV waste management in India (Jain et al., 2022; Sheoran et al., 2022).

2.2 Existing methods and technologies for managing solar PV waste

The management of solar photovoltaic (PV) waste is becoming increasingly important as global PV deployment grows. By 2050, solar waste could reach 60-78 million tonnes globally (Komoto et al., 2018; Rathore & Panwar, 2021). Various recycling methods have been explored, including crushing, high-voltage pulse, laser irradiance, and hot knife processes (Ali et al., 2024). By 2030, India is expected to generate approximately 200,000 tonnes of PV waste, increasing to 1.8 million tonnes by 2050 (Rathore & Panwar, 2021). Improper disposal of PV waste poses environmental and health risks, necessitating effective management strategies (Suresh Jain et al., 2022). Proposed solutions include developing a regulatory framework based on Extended Producer Responsibility (EPR) and a participatory approach involving multiple stakeholders (Suresh Jain et al., 2022; Gautam et al., 2022). Implementing circular economy principles, such as recycling and remanufacturing, can help manage PV waste efficiently (Gautam et al., 2022). Additionally, cost-benefit analysis of recycling processes could attract SME investors to the sector (Gautam et al., 2022). Policymakers should consider these approaches when developing or modifying regulations for PV waste management in India (Pankadan et al., 2020; Gautam et al., 2022).

These techniques aim to recover valuable materials such as silicon, metals, glass, and encapsulants. The European Union's Waste Electrical and Electronic Equipment (WEEE) Directive sets recycling targets for PV modules, with rates expected to reach 85%/80% (recovery/recycling) (Komoto et al., 2018). In India, where solar capacity has grown rapidly, a regulatory framework based on Extended Producer Responsibility (EPR) has been proposed to manage PV waste (Jain et al., 2022). Effective end-of-life management of PV modules is crucial for maintaining the environmental benefits of solar energy and recovering valuable materials.

2.3 Main environmental and health risks associated with improper management of solar PV waste

Improper management of solar PV waste poses significant environmental and health risks. Hazardous metals like lead and cadmium in PV panels can contaminate soil and groundwater when improperly disposed of (Bajagain et al., 2020; Nain & Kumar, 2020). Children are particularly vulnerable, with lead presenting the highest risk (hazard quotient 1.2-2.6) (Nain & Kumar, 2020). Occupational hazards during manufacturing, installation, and decommissioning include exposure to hazardous materials and workplace accidents (Ninduwezuor-Ehiobu et al., 2024). Large-scale solar installations may also lead to land use changes and habitat disruption (Ninduwezuor-Ehiobu et al., 2024). To address these concerns, countries are developing regulatory frameworks for PV waste management, with the EU classifying PV panels as e-waste under the WEEE Directive (Bajagain et al., 2020). India is also working on a multi-stakeholder approach to manage this emerging waste stream (Jain et al., 2022). Advancements in recycling technologies and improved manufacturing processes are crucial for mitigating these risks (Ninduwezuor-Ehiobu et al., 2024).

2.4 Awareness of the stakeholders about the risks and best practices for managing solar PV waste

The growing deployment of solar photovoltaic (PV) systems has raised concerns about end-of-life waste management. Stakeholders' awareness of risks and best practices varies globally. In Europe, PV recycling is regulated, with manufacturers motivated by profit and image (Auer, 2015). India lacks a regularized strategy, prompting the proposal of a multi-stakeholder regulatory framework (Jain et al., 2022). The United States lacks federal PV waste regulations, potentially leading to significant landfill disposal, while the European Union has adopted specific directives (Nain & Anctil, 2024). A survey of industry stakeholders revealed limited engagement with end-of-life module management, with only 20% of manufacturers responding to questions on this topic (Nain & Kumar, 2020). The study also identified a lack of recycling infrastructure, incentives, and environmental awareness as factors influencing recycling practices. These findings highlight the urgent need for improved PV waste management strategies and increased stakeholder awareness.

2.5 Regulatory frameworks and policies currently govern solar PV waste management in India and other key regions

Solar photovoltaic (PV) waste management is an emerging challenge in India due to the rapid growth in solar capacity (Jain et al., 2022). By 2040, India is projected to generate 6.64-5.48 million tonnes of PV waste (Sharma et al., 2023). Currently, India lacks adequate regulations, guidelines, and infrastructure for PV waste management, risking improper disposal (Sharma et al., 2023). Several countries, including EU members, have implemented policies and guidelines for PV recycling, with the EU's WEEE Directive serving as a model (Sharma et al., 2019). Recycling PV modules can reduce environmental impacts by up to 70% compared to landfilling (Sharma et al., 2023). To address this issue, researchers propose regulatory frameworks based on Extended Producer Responsibility and multi-stakeholder approaches (Jain et al., 2022; Sheoran et al., 2022). These frameworks aim to create economic value from PV waste while mitigating environmental and health risks associated with improper disposal (Sharma et al., 2019; Jain et al., 2022).

2.6 Key challenges and barriers faced by stakeholders in implementing effective solar PV waste management practices

The key challenges in implementing effective solar PV waste management practices include technological complexities, economic hurdles, inadequate infrastructure, and regulatory gaps (Gerold & Antrekowitsch, 2024). Stakeholders face issues such as varying module compositions, limited recycling processes, and insufficient awareness (Gerold & Antrekowitsch, 2024). Both China and the USA struggle with harmonizing federal and local regulations (Ali et al., 2023). In India, unscientific dumping poses environmental and health risks, necessitating a regularized management strategy (Jain et al., 2022). Brazil faces similar challenges, including material design issues, lack of incentives, and absence of specific policies (Souza et al., 2024). To address these barriers, stakeholders should adopt a multi-sectoral approach based on Extended Producer Responsibility (Jain et al., 2022), promote collaboration among policymakers and industry stakeholders (Ali et al., 2023), and invest in research and development for cost-effective recycling options (Ali et al., 2023; Souza et al., 2024).

2.7 Impact of demographic factors (age, gender) and industry-specific characteristics (industry type, years of experience) influence solar PV waste management practices

Solar photovoltaic (PV) waste management is an emerging concern due to the rapid growth of the industry and increasing end-of-life (EOL) waste (Oteng et al., 2021). Studies estimate that between 2025 and 2050, the US and EU will generate 24.93 and 36.23 million tonnes of PV waste, respectively, with significant economic value (Nain & Anctil, 2024). While the EU has adopted specific regulations like the Waste Electrical and Electronic Equipment Directive, the US lacks federal PV waste-specific management regulations, leading to potential landfill disposal (Nain

& Anctil, 2024; Ali et al., 2023). Key challenges include harmonizing federal and local/state-level policies, developing cost-effective recycling options, and promoting collaboration among stakeholders (Ali et al., 2023). Future research should focus on recycling potential, emissions from current modules, and easy remanufacture, recovery, and reuse of future modules (Oteng et al., 2021). Additionally, incorporating emerging contaminants in regulations and waste characterization methods is crucial for responsible management (Nain & Anctil, 2024).

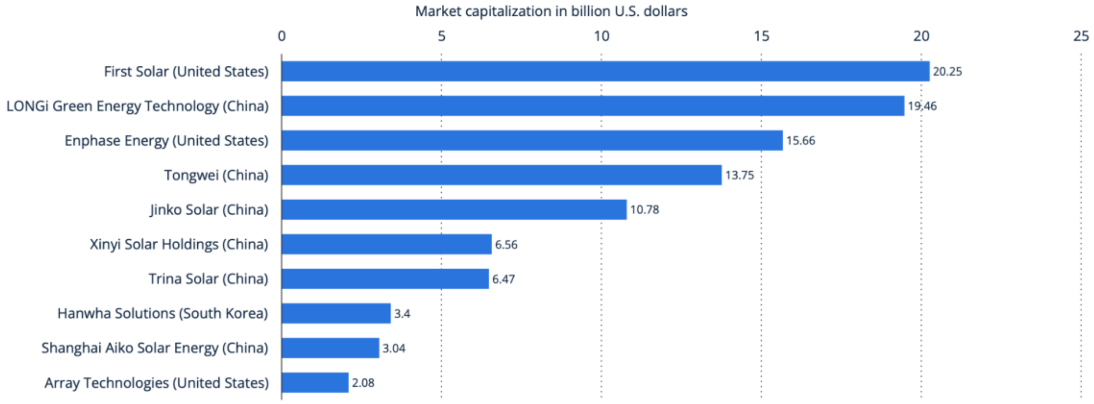
2.8 Role of Government Interventions and Policies in promoting sustainable solar PV waste management practices

Government interventions and policies play a crucial role in promoting sustainable solar PV waste management practices. Studies highlight the importance of subsidies and penalties in encouraging the formal treatment of waste PV modules (Zhang et al., 2023). Both China and the USA have implemented regulations for managing PV end-of-life waste but face challenges in harmonizing federal and local policies (Ali et al., 2023). Australia lacks specific regulations for PV waste management, leading to unregulated movement and tracking of solar PV waste (Oteng et al., 2022). To establish sustainable PV waste management frameworks, experts recommend implementing extended producer responsibility (EPR) principles, developing suitable infrastructure, and fostering cooperation between governmental and private bodies (Yu et al., 2022). Additionally, continued research and development efforts are crucial for exploring cost-effective and environmentally responsible recycling options (Ali et al., 2023). These interventions are essential for addressing the growing concern of PV waste and its potential environmental impacts.

2.9 Financial and economic factors impact the adoption of sustainable waste management practices in the solar PV industry

The adoption of sustainable waste management practices in the solar PV industry is influenced by various financial and economic factors. While the economic contribution of solar and wind energy is minimal, the solid waste generation is substantial, with associated abatement costs impacting Green-GDP estimates (Prabhu & Mukhopadhyay, 2023). Extended producer responsibility (EPR) has been identified as a crucial policy tool for managing solar PV waste, but its implementation faces challenges such as the absence of pre-established collection networks and weak institutional capacity (Kabir et al., 2023). Economic considerations, including performance, module composition, and emerging recycling technologies, play a significant role in asset management decisions and recycling practices (Libby & Shaw, 2019). The adoption of circular economy solutions for PV waste management requires regulations and incentives, including fiscal incentives, to unlock end markets for second-life PV panels and recovered materials (Madrigal et al., 2023). Furthermore, the development of a sustainable and circular PV industry business model addressing environmental, economic, social, and technical factors is essential (Refer to Figure 2.1) for optimizing the industry's sustainability and transitioning towards a circular economy (Rabaia et al., 2022).

Figure 2.1: Global solar firms based on market capitalization 2024



Source: Statista

2.10 Best practices and successful case studies in solar PV waste management from other countries or regions

Solar photovoltaic (PV) waste management is becoming a critical issue as the industry grows. The European Union has implemented the Waste Electrical and Electronic Equipment (WEEE) Directive, categorizing PV panels as e-waste (Bajagain et al., 2020). In contrast, the United States lacks comprehensive federal regulations, with varying requirements across states (Nain & Anctil, 2024). China has established national policies but lacks local-level regulations (Amjad Ali et al., 2023). Estimates suggest that by 2050, the US and EU will generate 24.93 and 36.23 million tonnes of PV waste, respectively, with significant economic value (Nain & Anctil, 2024). Recycling PV modules is more cost-effective than manufacturing new ones (Al-Aqqad & Menyhárt, 2023). To improve PV waste management, experts recommend harmonizing federal and local/state-level policies, promoting collaboration among stakeholders, investing in research and development, and implementing take-back programs by leading manufacturers (Amjad Ali et al., 2023; Nain & Anctil, 2024).

Table 2.1: Countries and Existence of Waste Management Policies

Country	**Sustainable Waste Management Policy**
United States	Yes
China	Yes
Japan	Yes
Germany	Yes
United Kingdom	Yes
India	Partial
France	Yes
Italy	Yes
Canada	Yes
South Korea	Yes

Source: Author

2.11 Theoretical Frameworks

The literature presents several theoretical models and frameworks to explain stakeholder awareness and behavior in environmental management, including solar PV waste. The Theory of Planned Behavior is widely used to explore pro-environmental behavior, considering attitudes, subjective norms, and perceived behavioral control (Kepatuhan et al., 2008). Other frameworks include linear progression models, altruism models, and sociological models (Kollmuss & Agyeman, 2002). For solar PV waste management specifically, the DPSIR framework has been applied to understand challenges and barriers in India (Jain et al., 2022). Decision support models, such as life-cycle assessment, cost-benefit analysis, and multi-criteria decision-making, are commonly used in solid waste management (Karmperis et al., 2013). Game-theoretic approaches can also model decision-making with multiple stakeholders (Karmperis et al., 2013). These frameworks consider various factors influencing pro-environmental behavior, including demographic, external, and internal factors, highlighting the complexity of stakeholder awareness and behavior in environmental management (Kollmuss & Agyeman, 2002).

The management of end-of-life solar photovoltaic (PV) waste presents significant environmental and economic challenges globally. Key issues include inadequate infrastructure, lack of specific regulations, and economic unfeasibility (Souza et al., 2024; Ali et al., 2023). To address these challenges, several strategies have been proposed, including the implementation of Extended Producer Responsibility (EPR) policies, the development of circular economies, and investment in research and development (Souza et al., 2024; Yu et al., 2022). Countries like China and the USA have enacted various policies and regulations but face difficulties in harmonizing federal and local/state-level approaches (Ali et al., 2023). In India, a multi-stakeholder regulatory framework based on EPR has been proposed to manage the increasing solar PV waste (Jain et al., 2022). Globally, there is a need for comprehensive legislation, improved recycling technologies, and collaboration among stakeholders to establish sustainable PV waste management practices and mitigate potential environmental and health risks (Yu et al., 2022; Ali et al., 2023). The theoretical perspectives for analyzing demographic and industry influences on waste management practices encompass various approaches. Complexity theory and neoclassical economics offer frameworks for examining innovation in solid waste management (SWM) industries, considering market, firm, and social perspectives (Gaeta et al., 2020). Demographic factors such as household size, education levels, and presence of senior citizens significantly impact waste segregation awareness and adoption (Kaur et al., 2023). Workplace waste recycling behavior is influenced by demographics, situational variables, past behavior, incentives, and attitudes (Oke, 2015). Systems analysis models, including systems engineering, analysis platforms, and assessment tools, provide interdisciplinary support for policy analysis and decision-making in SWM (Chang et al., 2011). These perspectives highlight the complexity of waste management challenges and the need for multifaceted approaches considering technical, socioeconomic, legal, ecological, and cultural components to develop effective strategies for sustainable waste management practices.

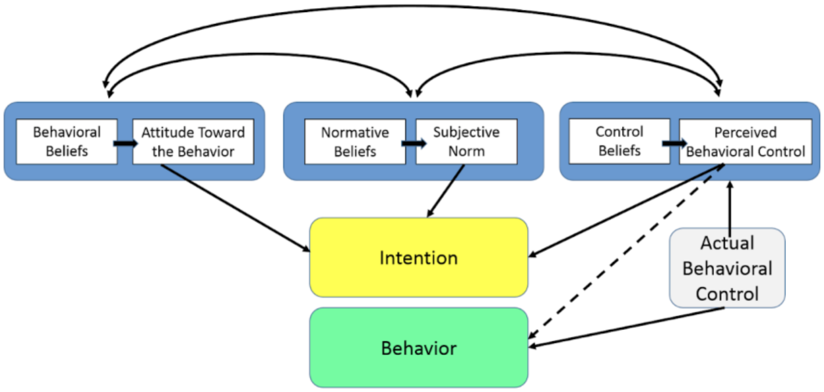
The solar PV industry faces challenges in sustainable waste management, particularly with end-of-life modules. The economic viability of recycling is a key concern, with process costs and reverse logistics being major factors (Choi, 2017; D'Adamo et al., 2017). Despite environmental benefits, financial feasibility remains uncertain, with negative net present values reported for recycling plants (D'Adamo et al., 2017). Circular economy strategies could enable PV adoption in organizational markets, but their implementation is limited by market development and organizational constraints (Opstal & Smeets, 2022). Challenges include infrastructure, technology, economic unfeasibility, and lack of specific regulations (Souza et al., 2024). Potential strategies involve partnerships, extended producer responsibility, market development, awareness programs, R&D investment, financial incentives, and targeted regulations (Souza et al., 2024). Optimizing recycling center locations and developing automated processes could improve economic viability (Choi, 2017).

Several frameworks and models have been proposed to evaluate the effectiveness of government policies for sustainable solar PV waste management. The DPSIR framework was used to analyze challenges in India's solar PV waste sector, leading to a proposed regulatory framework based on Extended Producer Responsibility (EPR) (Jain et al., 2022). Life cycle assessment (LCA) was employed to evaluate the environmental impacts of different management options in Australia, considering factors like transport distances (Oteng et al., 2023). The Fuzzy Delphi Method (FDM) was applied to gather expert opinions on end-of-life PV management in Australia, resulting in a conceptual framework for current treatment practices (Oteng et al., 2022). Globally, implementing high-value closed-loop recycling faces challenges, and various countries have adopted different regulatory frameworks. Recommendations include promoting EPR, developing suitable infrastructure, investing in R&D, and fostering cooperation between governmental and private entities to establish sustainable PV waste management systems (Yu et al., 2022).

2.12 Theory of Planned Behavior (TPB)

The Theory of Planned Behavior (TPB) is a social-psychological model that predicts and explains human behavior (Al-Lozi & Papazafeiropoulou, 2012). Developed by Icek Ajzen in 1985, TPB posits that behavior is driven by intentions influenced by personal, social, and situational factors (Bellová & Špírková, 2021). The theory suggests that behavioral intentions can be predicted from attitudes, subjective norms, and perceived behavioral control, which collectively account for significant variance in actual behavior (Wen, 2008). TPB has been widely applied across multiple disciplines, including information systems and tax research (Al-Lozi & Papazafeiropoulou, 2012; Bellová & Špírková, 2021). While well-supported by empirical evidence, the theory continues to evolve, with ongoing research addressing unresolved issues and potential improvements (Wen, 2008).

Figure 2.2: Theory of Planned Behavior



Source: Sun et al.

Studies have applied the Theory of Planned Behavior (TPB) to understand factors influencing stakeholders' intentions and behaviors toward sustainable practices. Sun et al. (2023) found that waste management literacy positively affects waste sorting intentions. Garg et al. (2023) extended TPB to include factors like government policy and financial benefits in e-waste management among young consumers. Tanveer et al. (2021) explored factors influencing consumers' willingness to adopt solar PV, including perceived risk and self-efficacy. Widayati et al. (2023) used TPB to study waste separation in traditional markets, showing that attitudes, subjective norms, and perceived behavioral control influence waste separation intentions and behaviors, emphasizing the importance of sustainable waste management practices.

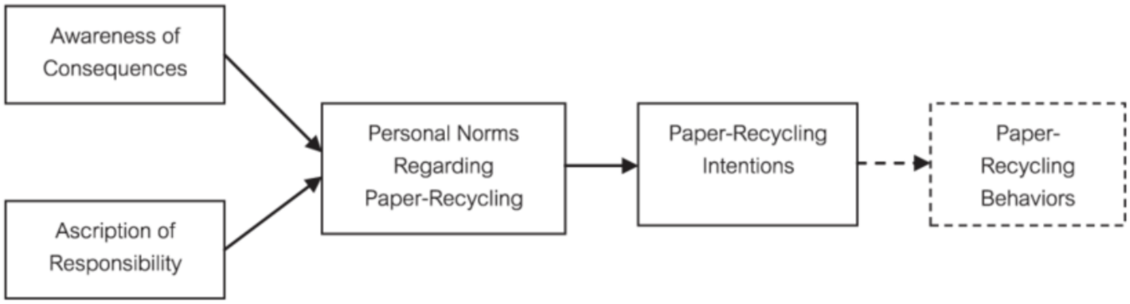
2.13 Sociological Model

Sociological models aim to explain human behavior and social processes. The homo sociological model, focusing on normative behavior, faces limitations in explaining non-normative or deviant actions and resolving norm conflicts (Opp, 1986). Mathematical and computational approaches offer alternative tools for modeling social phenomena, including stochastic and deterministic models, as well as fuzzy cognitive modeling for information interaction (Bulatetskaya, 2019). Dynamic sociological system models can integrate economic input-output analysis with social stratification and mobility concepts (Mickle & Vogt, 1973). In software engineering, formal sociological models help reveal laws and principles of cooperative work organization, exploring how group structures impact behavior, productivity, and performance (Wang, 2005). These diverse approaches to sociological modeling demonstrate the field's evolution in addressing complex social dynamics and their applications in various domains, from economics to software development. The social dynamics and cultural factors influencing stakeholder awareness and practices in solar PV waste management are complex and multifaceted. Stakeholder engagement is crucial in developing effective product stewardship schemes for end-of-life PV panels (Salim et al., 2021). Social networks, including family, neighbors, and friends, play a significant role in PV adoption decisions, with trust and perceived closeness affecting influence levels (Scheller et al., 2020). Socio-cultural dimensions, such as geographic and market factors, shape market development and technology uptake by different consumer groups (Elmustapha et al., 2018). Agent-based modeling incorporating social factors alongside techno-economic considerations provides a more realistic assessment of PV circularity potential, revealing that customer attitudes significantly impact module reuse (Walzberg et al., 2021). However, reuse alone cannot meet demand, necessitating complementary recycling efforts. These findings underscore the importance of considering social dynamics and stakeholder perspectives in developing effective PV waste management strategies and policies.

2.14 Altruism Model

Altruism, defined as an act benefiting others at one's own expense, is a fundamental human behavior with implications for personal and societal welfare (Bati & Singh, 2018). Recent research has explored various aspects of altruism, including its modeling and impact on consumer behavior and peer-to-peer networks. Mobile phone data can be used to predict altruistic propensities more effectively than demographic information (Bati & Singh, 2018). In peer-to-peer networks, altruism can lead to substantial peer contributions even without incentive mechanisms (Vassilakis & Vassalos, 2007). Altruism also provides a framework for understanding consumer product choices in a global economy (Hopkins & Powers, 2015). A hierarchical model of prosocial behavior has been proposed to address the varying definitions of altruism across disciplines, encompassing different levels from general helping behavior to specific motivational aspects (Rodrigues & Hewig, 2021). This model aims to create a common ground for communication and highlight the hierarchical differences in altruism definitions across research fields.

Figure 2.3: Altruism Model



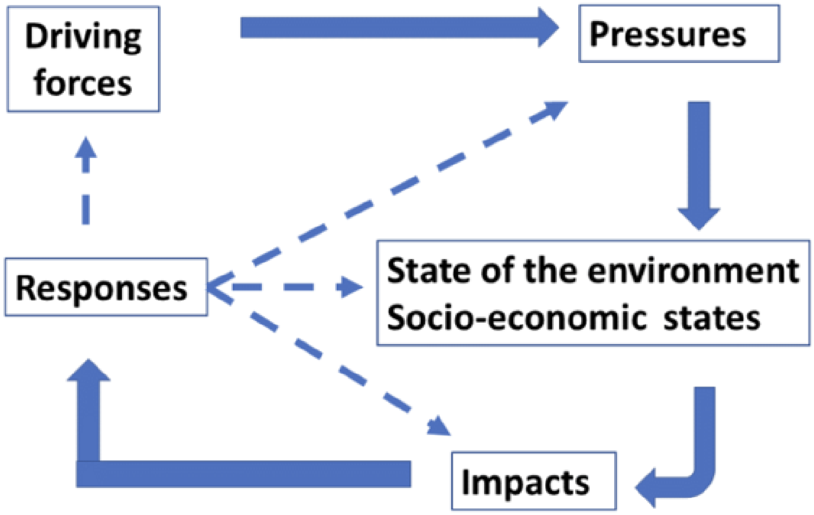
Source: Chaisamrej & Zimmerman, 2014

The Altruism Model plays a significant role in understanding stakeholders' engagement in sustainable practices, including solar PV waste management. While rational choice factors are primary determinants of household waste separation behavior, altruism correlates with attitudes towards such practices (Yin & Ma, 2022). Personal norms and perceived behavioral control are key predictors of waste prevention behavior, with subjective norms having a weaker influence (Bortoleto et al., 2012). In the context of solar PV waste management, a shared responsibility system can balance stakeholders’ techno-economic motivations across the supply chain, encouraging participation in recovery schemes (Salim et al., 2021). This approach allows for gradual changes in regulatory requirements, promoting industry and market development. Overall, integrating altruism factors with rational choice models may provide a more comprehensive framework for analyzing and promoting sustainable behaviors in waste management initiatives (Yin & Ma, 2022; Bortoleto et al., 2012).

2.15 DPSIR Framework

The DPSIR (Drivers-Pressures-State Changes-Impacts-Responses) framework is a widely adopted tool for assessing and managing environmental issues, particularly in marine contexts (Atkins et al., 2011; Patrício et al., 2016). Originally developed for environmental problem reporting, it has evolved to facilitate stakeholder engagement and communication (Atkins et al., 2011). Despite its popularity, DPSIR faces criticisms for oversimplification and varying interpretations of its components (Patrício et al., 2016). When applied to sustainable development, it may perpetuate existing inequalities due to its implicit hierarchy of actors (Carr et al., 2007). However, DPSIR's resilience and adaptability have been demonstrated through its integration with other methodologies, such as the "Imagine" approach in coastal management projects (Bell, 2012). While DPSIR has limitations, its widespread use suggests a convergent evolution in ecosystem management approaches, particularly in European marine contexts (Patrício et al., 2016). To address complex environmental issues, more sophisticated, nested models are needed to adequately assess pressure-state change relationships in marine ecosystems (Patrício et al., 2016).

Figure 2.4: DPSIR Framework



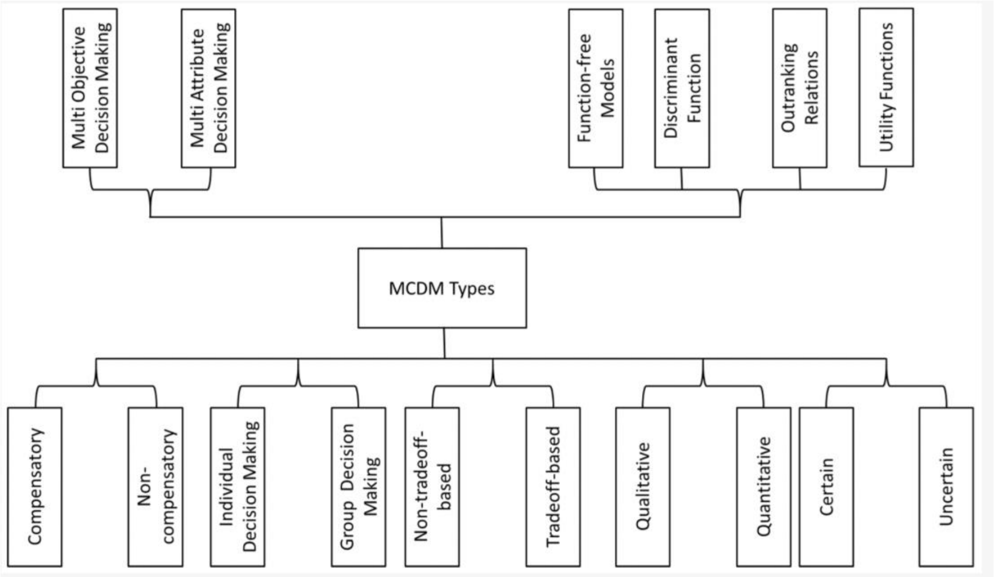
Source: Allen, 2017

The DPSIR (Drivers-Pressures-State-Impact-Response) framework has been applied to analyze various environmental challenges, including solar PV waste management and hazardous waste management. In India, the rapid growth of solar energy has led to increasing concerns about PV waste management (Jain et al., 2022). The DPSIR approach has been used to identify challenges and propose regulatory frameworks for managing this emerging waste stream (Sheoran et al., 2022). Similarly, in China, the DPSIR framework has been employed to examine hazardous waste management, revealing the complex interplay between drivers, pressures, and responses (Kanwal et al., 2021). However, critics argue that applying DPSIR to sustainable development may perpetuate existing inequalities and fail to address informal responses adequately (Carr et al., 2007). Despite these limitations, the DPSIR framework remains a valuable tool for analyzing environmental and socio-economic factors in waste management and sustainable development contexts.

2.16 Multi-Criteria Decision-Making

Multi-criteria decision-making (MCDM) is a technique used to select the optimal alternative when multiple, often conflicting criteria must be considered (Majumder & Saha, 2016; Azzabi et al., 2020). It is a sub-discipline of operations research that provides objectivity in comparing alternatives and estimating their priority values (Majumder & Saha, 2016; Azzabi et al., 2020). MCDM encompasses various methods, including ELECTRA, PROMETHEE, TOPSIS, and AHP, with AHP, TOPSIS, and MAUT being the most used (Bhole, 2018). These methods have diverse applications across fields such as location selection, finance, bankruptcy prediction, construction, and waste management (Bhole, 2018). While MCDM has traditionally been considered a poorly regulated technique, recent developments have seen the emergence of hybrid or integrated methods, which are creating new opportunities in MCDM research and application (Azzabi et al., 2020; Bhole, 2018).

Figure 2.5: Classification of MCDM



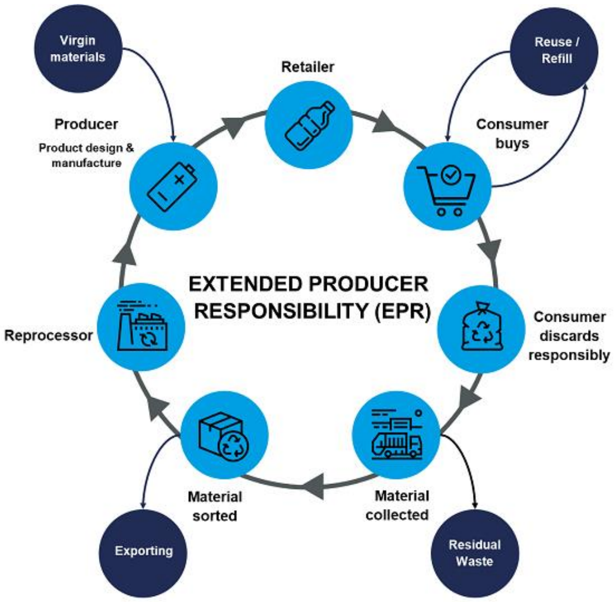
Source: Taherdoost & Madanchian, 2023

Multi-criteria decision-making (MCDM) models have emerged as valuable tools for evaluating and prioritizing strategies in solar PV waste management. The Analytic Hierarchy Process (AHP) has been applied to rank end-of-life (EOL) disposition alternatives based on environmental, economic, social, policy, and technical criteria (Alzahmi & Ndiaye, 2023). MCDM approaches are particularly useful in solid waste management due to their ability to handle complex problems with multiple dimensions and conflicting criteria (Coelho et al., 2017). These models can be combined with spatial tools to inform siting decisions for PV material recovery infrastructure, considering social, environmental, and economic factors (Goe et al., 2015). Additionally, an Anticipatory Life Cycle Analysis (a-LCA) framework has been developed to assess the sustainability of various EOL management options for PV panels, incorporating stakeholder input to prioritize economic, environmental, and social indicators (Ganesan & Valderrama, 2022).

2.17 Extended Producer Responsibility

Extended Producer Responsibility (EPR) is an environmental policy approach that holds manufacturers accountable for the entire lifecycle of their products, including disposal and recycling (Agamuthu, 2010). EPR aims to improve the environmental and social performance of products by extending producers' responsibilities beyond the point of sale (Clift & France, 2006). This approach creates incentives for manufacturers to consider post-consumer waste management costs when making product design and marketing decisions (Smith, 2005). In the United States, EPR policies have primarily been implemented at the state level, with over 70 EPR laws enacted between 1991 and 2011 (Nash & Bosso, 2013). While some manufacturers have implemented voluntary recycling programs, these efforts have generally been ineffective in capturing significant quantities of waste products (Nash & Bosso, 2013). To evaluate the effectiveness of EPR programs, policymakers must weigh the costs of implementation against the benefits of reduced social costs and environmental impacts associated with waste management (Smith, 2005).

Figure 2.6: Extended Producer Responsibility



Source: The Food and Drink Federation, 2022

Extended Producer Responsibility (EPR) is increasingly recognized as a crucial policy tool for managing end-of-life solar photovoltaic (PV) panels. Studies from various countries highlight the importance of EPR in addressing the growing challenge of PV waste ((Lee & Cha, 2019), Jain et al., 2022). EPR implementation requires a multi-stakeholder approach and context-specific adaptations, particularly in developing countries (Kabir, Mondal, et al., 2023).

Key factors for successful EPR adoption include establishing waste collection networks, strengthening institutional capacity, and gaining user acceptance (Kabir, Mondal, et al., 2023). Government subsidies can serve as incentives in EPR-based recycling models (Wu et al., 2019). However, challenges such as the absence of pre-existing take-back systems and weak regulatory frameworks must be addressed (Kabir, Mondal, et al., 2023). Overall, EPR is seen as essential for the sustainable management of PV waste, but its implementation requires careful consideration of local contexts and potential barriers (Jain et al., 2022; Kabir, Mondal et al., 2023).

2.18 Complexity Theory

Complexity theory is a branch of computer science and mathematics that focuses on classifying and analyzing the computational resources required to solve problems (Aho, 2011; Curlee & Gordon, 2006). It aims to understand the structure and behavior of complex systems, which are characterized by emergent properties resulting from interactions among their components (Levy, 2014). The field provides mechanisms for measuring computational resources, explaining why certain problems lack practical solutions, and anticipating difficulties in problem-solving (Curlee & Gordon, 2006). Researchers in complexity theory often use abstraction and computer simulations to derive steady-state information about systems, such as invariants and attractors (Koliba et al., 2022).

The subject has broad applications in real-world systems and remains an active area of research with some of the deepest unsolved problems in mathematics and computer science (Aho, 2011; Koliba et al., 2022). Complexity theory is central to understanding how complex systems both within and outside of computer science behave and compute (Aho, 2011). The management of solar photovoltaic (PV) waste is becoming increasingly important as PV installations grow globally. Complexity in PV waste management arises from interactions between various stakeholders, regulatory frameworks, and environmental concerns (Jain et al., 2022; Yu et al., 2022). A systems approach reveals the need for comprehensive national product stewardship schemes, landfill restrictions, and industry incentives to promote recovery activities (Salim et al., 2020). Effective waste management requires industry participation through regulation, specified targets, and sustainable funding models (Salim et al., 2020). Circular economy strategies, such as the 10 R's of circularity and the ReSOLVE framework, can minimize waste across PV lifecycle stages (Madrigal et al., 2023). Implementation of these strategies depends on establishing regulations and incentives, including fiscal measures (Madrigal et al., 2023). Extended Producer Responsibility (EPR) is a key concept in developing regulatory frameworks for PV waste management (Jain et al., 2022; Yu et al., 2022).

2.19 Neoclassical Economic Theory

Neoclassical economic theory, emerging in the 1870s, is characterized by its focus on individual economic behavior, free competition, and limited government intervention (Gasanov et al., 2022; Gasanov, 2021). It emphasizes the efficient use of limited resources at the microeconomic level and employs quantitative analysis and mathematics (Gasanov et al., 2022). The theory is built on principles of rational egoism and the "invisible hand" (Gasanov, 2021). Revealed Preference Theory attempted to establish economics as an empirical science by removing psychological concepts, but it faces challenges due to its reliance on rationality assumptions (Keita, 2012). Neoclassical economics differs from classical political economy by shifting focus from growth and distribution to subjective utility theory and marginal calculus (Caporaso & Levine, 1992). Some argue that neoclassical economics should be viewed as an ideology underpinning modern capitalism and neoliberal economics rather than a purely scientific endeavor (Keita, 2012).

The adoption of sustainable solar PV waste management practices is influenced by economic incentives and market behaviors. Studies suggest that circular economy solutions and regulatory frameworks are crucial for effective PV waste management (Nunez Madrigal et al., 2023).

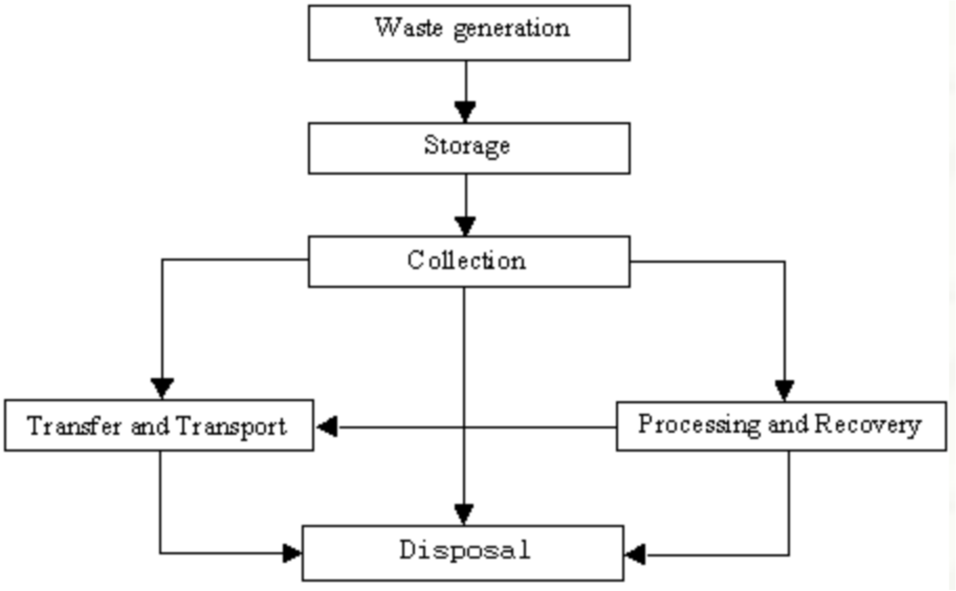
Economic factors, such as upfront costs and investment returns, play a significant role in household adoption of solar panels, while social learning mechanisms also influence adoption rates (Eslami & Krishnan, 2023). Government interventions, including subsidies and penalties, can impact the investment and pricing decisions in PV recycling supply chains (Zhang et al., 2023). The profitability of PV recycling systems depends on factors like reverse logistics costs, optimal location of take-back centers, and market prices of reclaimed materials (Choi, 2017). To ensure the long-term sustainability of the PV industry, it is essential to develop cost-effective recycling technologies and infrastructure alongside the commercialization of PV technologies (Choi, 2017; Nunez Madrigal et al., 2023).

2.20 Solid Waste Management (SWM) Theory

Decision-making in Solid Waste Management (SWM) theory often employs Multi-Criteria Decision Analysis (MCDA) frameworks to address complex environmental, economic, and social challenges (Goulart Coelho et al., 2017; Soltani et al., 2015). These frameworks, including life-cycle assessment, cost-benefit analysis, and multi-criteria decision-making, help evaluate conflicting criteria and rank SWM strategies (Karmperis et al., 2013).

The involvement of multiple stakeholders, such as governments, municipalities, industries, experts, and the public, is crucial in the decision-making process (Soltani et al., 2015). Recent studies emphasize the importance of incorporating social indicators and sustainability aspects into MCDA models (Gutierrez-Lopez et al., 2023). The Analytic Hierarchy Process (AHP) is commonly used when considering multiple stakeholders (Soltani et al., 2015). Game-theoretic approaches have also been proposed to model decision-making situations with multiple stakeholders (Karmperis et al., 2013). Overall, effective SWM decision-making requires a comprehensive understanding of local contexts and community consultation to address potential challenges and improvements (Gutierrez-Lopez et al., 2023).

Figure 2.7: Solid Waste Management (SWM) Theory



Source: India Institute of Science, 2024

Decision-making in solid waste management, including solar PV waste, involves multiple stakeholders and criteria. Multi-criteria decision analysis (MCDA) is widely used to evaluate conflicting criteria and rank management strategies (Soltani et al., 2015). The Analytic Hierarchy Process (AHP) is particularly popular for considering multiple stakeholders, with governments and experts being the most common participants (Soltani et al., 2015). For solar PV waste, AHP has been applied to analyze end-of-life disposition strategies based on environmental, economic, social, policy, and technical criteria (Alzahmi & Ndiaye, 2023). Game-theoretic approaches can also model decision-making with multiple stakeholders, considering environmental, economic, and social aspects (Karmperis et al., 2013). Recent research emphasizes the importance of including social indicators and stakeholder involvement in decision-making frameworks for sustainable waste management (Gutierrez-Lopez et al., 2023). Understanding the local context and community consultation are crucial for recognizing challenges and improvements in solid waste management systems (Gutierrez-Lopez et al., 2023).

2.21 The circular economy Theory

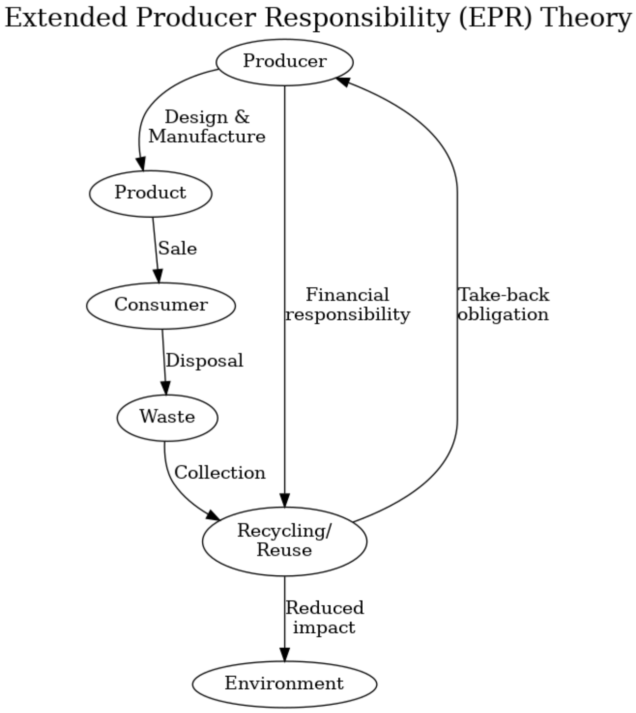
The circular economy (CE) The circular economy is gaining attention as a sustainable approach to resource management, including in the context of solar PV modules. CE strategies can be applied throughout the lifecycle of PV panels, from design to end-of-life management (Chrzanowski & Zawada, 2023). Key aspects include designing for circularity, data management, maintenance, reuse, recycling, and energy recovery (Velenturf, 2021). Transitioning to CE faces various drivers and barriers, including technological, financial, and behavioral factors (Tan et al., 2022; Aloini et al., 2020). Implementing CE principles in supply chain management can enhance corporate sustainability (Theeraworawit et al., 2022). However, the potential for CE to contribute to climate change mitigation varies across sectors, with industry, energy, and transport showing the highest potential (Cantzler et al., 2020). Despite growing interest, practical implementation of CE in many sectors, including PV, remains limited and requires further research and policy support (Centobelli et al., 2020; Khalifa et al., 2022). The circular economy

(CE) approach significantly benefits solar PV waste management, enhancing resource efficiency and sustainability. CE strategies in the energy sector show high potential for climate change mitigation (Cantzler et al., 2020). Recycling solar PV panels at installation sites can reduce transportation costs and environmental impacts (Chrzanowski & Zawada, 2023). CE principles applied to renewable energy infrastructure, including solar, can address challenges like resource exploitation and end-of-use solutions (Velenturf, 2021). Implementing CE in waste management requires effective policies, stakeholder involvement, and sufficient funding (Tleuken et al., 2022; Onungwe et al., 2023). For businesses, adopting CE practices can improve innovation, reputation, and network opportunities (Min et al., 2021). CE integration in supply chain management promotes redesign, reuse, and product transformation (Theeraworawit et al., 2022). Public policies supporting renewable energy and CE practices are crucial for sustainable development and reducing environmental degradation (Nunes et al., 2023). Governments and industries can collaborate by implementing effective legislation and recycling processes for end-of-life PV panels (Chrzanowski & Zawada, 2023). Recycling at installation sites shows potential economic and environmental benefits (Chrzanowski & Zawada, 2023). Life cycle assessments reveal positive trends in environmental sustainability across the PV sector, though some hotspots remain (Blanco et al., 2020). Industrial symbiosis tools can promote resource sharing and waste reduction (Yeo et al., 2019). Harmonizing key performance characteristics in life cycle greenhouse gas emission studies can provide more consistent results for decision-making (Hsu et al., 2012). Barriers to circular economy development in Central Asian countries include fossil fuel dependence and ineffective waste management, while opportunities exist in sustainable development orientation and green financing (Tleuken et al., 2022). Accelerating the transition requires integrating technology, finance, ecosystem, and behavioral studies across various sectors (Khalifa et al., 2022). The circular economy (CE) is emerging as a solution for sustainable economic development within environmental boundaries (Bueren et al., 2021). CE frameworks are being applied across various sectors, including offshore wind (Velenturf, 2021), photovoltaics (Chrzanowski & Zawada, 2023), and construction (Gasparri et al., 2023). While CE strategies show potential for climate change mitigation, implementation must be more robust (Cantzler et al., 2020). The highest saving potential is observed in industry, energy, and transport sectors (Cantzler et al., 2020). Research on CE has identified numerous associates, with business, economics, environment, and resource management being the most explored (Ghosh et al., 2022). Technology is a crucial accelerator for CE transition, but more studies are needed on ecosystem, financing, and behavioral aspects (Khalifa et al., 2022). The Theory of Planned Behavior is extensively used in e-waste management research (Newaz & Appolloni, 2023). Future research should address knowledge gaps across economic, environmental, governmental, methodological, societal, sectoral, and technological dimensions (Gasparri et al., 2023).

2.22 Extended Producer Responsibility (EPR) Theory

Extended Producer Responsibility (EPR) theory is not directly addressed in these papers, but they cover related concepts in environmental sustainability and consumer behavior. Green supply chain management practices aim to reduce environmental impacts through innovation, performance, and management dimensions (Assumpção et al., 2019). Consumer green purchase decisions are influenced by individual factors, product attributes, and social factors (Zhang & Dong, 2020). Environmentally sustainable consumer behavior is driven by green image, environmental knowledge, and social norms (Han, 2021). Integrating green and lean Six Sigma approaches can facilitate waste minimization, emission reduction, and resource conservation (Farrukh et al., 2020). Eco-innovation, while risky, can improve organizational performance and address stakeholder concerns (Munodawafa & Johl, 2019).

Figure 2.8: Extended Producer Responsibility (EPR) Theory



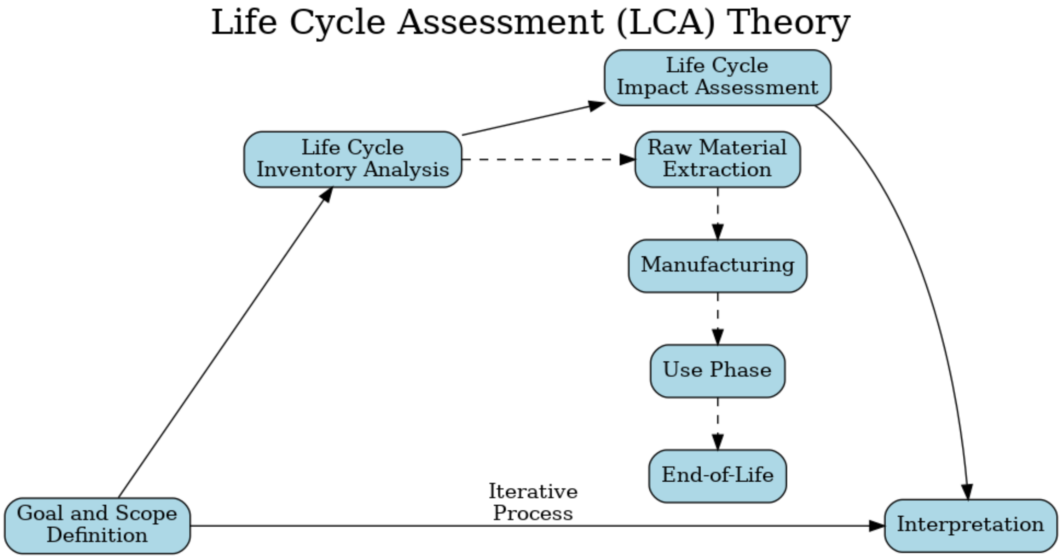
Source: Author

Research on environmental sustainability increasingly employs behavioral theories to understand and influence consumer actions (Scherrens et al., 2018; Newaz & Appolloni, 2023). Extended Producer Responsibility (EPR) theory has gained prominence in research on environmental sustainability and circular economy. Studies have explored its application in e-waste management (Newaz & Appolloni, 2023) and green supply chain practices (Assumpção et al., 2019). The theory of planned behavior emerges as a core framework for understanding consumer behavior toward environmental sustainability (Han, 2021; Zhang & Dong, 2020). Researchers have also investigated the design of circular business models (Centobelli et al., 2020) and the use of life cycle assessment in evaluating the environmental impacts of consumer electronics (Subramanian & Yung, 2016). The goal-framing theory has been applied to analyze pro-environmental behaviors, considering conflicting motivations and situational factors (Canto et al., 2022). The integrated and sustainability reporting field has applied various theories, including legitimacy, stakeholder, and institutional theories (Lakhani & Herbert, 2022). Extended producer responsibility (EPR) for solar PV manufacturers can improve end-of-life waste management through various strategies. Recycling PV panels at installation sites shows potential economic and environmental benefits by reducing transportation costs and impacts (Chrzanowski & Zawada, 2023). Life cycle assessments reveal positive trends in environmental sustainability across PV technologies, though some hotspots remain (Blanco et al., 2020). Innovative waste management solutions, including smart technologies and user education, can enhance sustainability (Farooq et al., 2022). Environmental impact assessments of PV plants provide valuable information for policymakers and technicians (Zarzavilla et al., 2022). Circular economy strategies, such as design for circularity, maintenance, reuse, and recycling, can be integrated throughout the lifecycle of offshore wind infrastructure and potentially applied to PV (Velenturf, 2021). Emerging PV technologies show promise for reduced environmental impacts, with organic PV demonstrating competitive performance (Weyand et al., 2019). These approaches can guide EPR implementation for improved PV waste management. Extended Producer Responsibility (EPR) incentivizes manufacturers to design more durable and recyclable solar PV modules by addressing end-of-life management challenges. The growing PV industry is expected to generate 78 million tonnes of waste by 2050, necessitating effective recycling processes (Chrzanowski & Zawada, 2023). EPR encourages manufacturers to consider the entire lifecycle of their products, including recycling potential and environmental impacts (Zarzavilla et al., 2022; Blanco et al., 2020). This aligns with circular economy principles, which promote resource efficiency and waste reduction (Tan et al., 2022). Ecodesign tools can help manufacturers incorporate environmental considerations into product design (Lee et al., 2023), while Industry 4.0 technologies can enhance sustainable manufacturing practices (Machado et al., 2019). Implementing circular business models (Centobelli et al., 2020) and identifying critical success factors (Aloini et al., 2020) are crucial for transitioning to a more sustainable PV industry that prioritizes durability and recyclability. The transition to circular economy (CE) models for solar PV modules presents challenges and opportunities for manufacturers. Key drivers include environmental sustainability, resource scarcity, and potential economic benefits (Aloini et al., 2020; Tan et al., 2022). However, barriers such as high initial investment costs and complex business restructuring exist, particularly for smaller companies (Gonçalves et al., 2022). Recycling end-of-life PV panels is crucial, with an estimated 78 million tonnes of waste expected by 2050 (Chrzanowski & Zawada, 2023). On-site recycling shows promise in reducing transportation costs and environmental impacts (Chrzanowski & Zawada, 2023). Implementing CE principles requires redesigning business models, value networks, and supply chain relationships (Centobelli et al., 2020). Leveraging technology in circular supply chains can help build innovative, sustainable business models (Abideen et al., 2021). Overall, transitioning to CE-driven models for PV modules demands a holistic approach, considering economic, environmental, and technological factors.

2.23 Life Cycle Assessment (LCA) Theory

Life Cycle Assessment (LCA) is a widely used methodology for evaluating products, services, and systems' environmental impacts throughout their life cycle (Medina et al., 2023; Yang, 2022). It has been applied to various fields, including road pavements (Medina et al., 2023), furniture design (Dongfang Yang, 2022), ocean energy technologies (M. Paredes et al., 2019), consumer electronics and protected agriculture (Villagran et al., 2023). LCA studies typically focus on impact categories such as climate change, with raw material extraction and manufacturing often identified as critical stages (Paredes et al., 2019; Go et al., 2024). Researchers have noted the need for standardized methodologies and assumptions to ensure robust results (Villagran et al., 2023; Zamagni et al., 2012). Recent developments include the application of LCA to organizational sustainability (Wafa et al., 2022) and using meta-analysis to identify research directions (Zamagni et al., 2012). Life Cycle Assessment (LCA) is a widely used methodology for evaluating the environmental impacts of products and processes throughout their entire life cycles (Medina et al., 2023; Zamagni et al., 2012). LCA applications span various sectors, including furniture design (Yang, 2022), road pavements (Medina et al., 2023), consumer electronics (Subramanian & Yung, 2016), ocean energy technologies (Paredes et al., 2019), and protected agriculture (Villagran et al., 2023).

Figure 2.9: Life Cycle Assessment (LCA) Theory



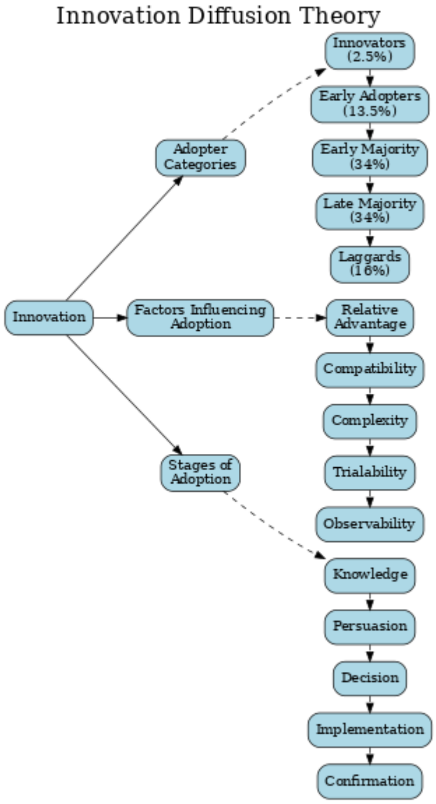
Source: Author

Recent research has focused on incorporating waste reuse (Medina et al., 2023) and assessing carbon footprints (Zhong et al., 2019). Meta-analyses and systematic reviews have been conducted to identify research trends and methodological challenges (Go et al., 2024; Zamagni et al., 2012). Key issues include standardized approaches, considering context-dependent factors, and integrating circular bioeconomy strategies (Villagran et al., 2023). Climate change and global warming potential are consistently important impact categories across studies (Zhong et al., 2019; Paredes et al., 2019), with use phase, end-of-life, and production phase often identified as dominant contributors to environmental impacts (Subramanian & Yung, 2016). Life Cycle Assessment (LCA) is widely used to quantify the environmental impacts of solar PV modules throughout their lifecycle. Studies have focused on various PV technologies, including crystalline silicon, thin-film, and emerging technologies like organic and perovskite cells (Weyand et al., 2019; Blanco et al., 2020). LCA helps identify environmental hotspots in PV lifecycles, with manufacturing, raw material extraction, and end-of-life stages often significant contributors (Zarzavilla et al., 2022; Hsu et al., 2012). Harmonization approaches have been developed to address variability in LCA results and improve comparability across studies (Blanco et al., 2020; Hsu et al., 2012). Recent research has also explored absolute environmental sustainability assessment methods based on LCA, which compare impacts to environmental carrying capacities (Andersen et al., 2020). While LCA has proven valuable for assessing PV technologies, challenges remain in benchmarking due to differences in functional units, data usage, and assumptions (Subramanian & Yung, 2016). Ongoing research aims to improve LCA methodologies and increase their applicability in decision-making processes. Life Cycle Assessment (LCA) is a valuable tool for evaluating the environmental impacts of photovoltaic (PV) technologies and informing policy decisions to minimize end-of-life waste (Blanco et al., 2020; Weyand et al., 2019). LCA studies have identified potential environmental hotspots in emerging PV technologies and highlighted the importance of improving efficiency, lifetime, and manufacturing processes (Blanco et al., 2020; Weyand et al., 2019). Recycling PV panels at installation sites shows promise for reducing transportation-related environmental impacts and costs (Chrzanowski & Zawada, 2023). However, challenges remain in standardizing LCA methodologies and ensuring comparability across studies (Zamagni et al., 2012; Medina et al., 2023; Serafini et al., 2023). To address these issues, researchers have proposed guidelines for conducting LCAs in specific contexts, such as waste reuse in road pavements (Medina et al., 2023). Future LCA research should focus on improving data quality, harmonizing methodologies, and addressing research gaps to better inform policy and innovation in PV waste management (Subramanian & Yung**,** 2016; Zamagni et al., 2012). LCA studies have shown that solar photovoltaic (PV) technologies generally have lower environmental impacts than fossil fuel-based electricity generation (Zarzavilla et al., 2022; Blanco et al., 2020). However, the environmental performance of PV systems depends on factors such as efficiency, lifetime, and manufacturing processes (Weyand et al., 2019). LCA has also been used to evaluate waste management strategies like composting, revealing that environmental impacts are influenced by system boundaries, functional units, and energy sources (Serafini et al., 2023). The methodology has been applied to assess the reuse of waste in road construction (Medina et al., 2023) and ocean energy technologies (Paredes et al., 2019). LCA-based absolute environmental sustainability assessment methods have been developed to compare impacts with assigned carrying capacities (Andersen et al., 2020). These studies demonstrate LCA's versatility in evaluating various energy sources and waste management options.

2.24 Innovation Diffusion Theory

Innovation Diffusion Theory has been widely applied to understand technology adoption in various fields. It has been used in healthcare to study clinicians' adoption of mobile health tools (Jacob et al., 2020) and health information technologies for geriatric care (Vedel et al., 2013). The theory has also been employed to examine the adoption of mobile ticketing services (Kapoor et al., 2015), precision agriculture (Lee et al., 2021), and manual vacuum aspiration in postabortion care (Cook et al., 2016). Researchers have proposed extensions to the theory, such as the NASSS framework, to better account for the complexities of health technology implementation (Greenhalgh et al., 2017). The diffusion of management ideas, including disruptive innovation theory, has been studied using bibliometric analysis (Breyer-Mayländer & Zerres, 2024). The theory has been applied to understand mobile learning adoption in higher education (Alrasheedi et al., 2015). The diffusion of innovative recycling technologies for solar PV modules varies across global markets, with an increasing focus on environmental sustainability and economic viability. Research highlights the need for effective recycling processes to manage the growing volume of end-of-life PV panels, estimated to reach 78 million tonnes by 2050 (Chrzanowski & Zawada, 2023).

Figure 2.10: Innovation Diffusion Theory



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Life-cycle assessments reveal positive trends in environmental impacts across the PV sector, though potential hotspots remain for specific technologies (Blanco et al., 2020). Studies emphasize the importance of considering plant size, efficiency, and lifetime factors in assessing environmental performance (Zarzavilla et al., 2022; Weyand et al., 2019). Emerging technologies like organic PV show promise in environmental performance, while perovskites lag due to early-stage development (Weyand et al., 2019). The recycling landscape extends beyond PV to other renewable technologies, such as wind turbine blades and electric vehicle batteries, with various mechanical, thermal, and chemical processes being explored (Zhang et al., 2018; Sorte et al., 2023). The innovation diffusion process significantly impacts the development of a sustainable solar PV recycling industry**.** As PV installations proliferate, effective recycling legislation and processes are crucial for managing end-of-life panels (Chrzanowski & Zawada, 2023). Technological advancements in PV may alter environmental impacts, necessitating ongoing life-cycle assessments to identify and address potential hotspots (Blanco et al., 2020). Accurate solar power forecasting is essential for overcoming challenges related to variable energy yield and economic viability (Iheanetu, 2022). Adopting precision agriculture techniques can inform strategies for promoting PV recycling innovations (Lee et al., 2021). Factors influencing PV project site selection, such as solar irradiation and infrastructure proximity, may also affect recycling facility locations (Rediske et al., 2018). Understanding barriers to innovation adoption in healthcare settings can provide insights into challenges facing the PV recycling industry (Cook et al., 2016). Implementing responsible research and innovation principles can help address negative externalities and promote sustainable regional development in the PV sector (Thapa et al., 2019). Economic challenges, such as high costs and insufficient financing, hinder adoption (Rehfuess et al., 2013). Administrative and standardization issues further complicate implementation (Karumba et al., 2023). To overcome these barriers, a multi-faceted approach is necessary. This includes developing technologies that meet household needs and save resources (Rehfuess et al., 2013), improving user training and support (Alvarado et al., 2017), and implementing effective financing mechanisms (Rehfuess et al., 2013). Government action through facilitative policies and regulations is crucial (Tleuken et al., 2022). Additionally, addressing environmental sustainability concerns in PV technology development (Blanco et al., 2020) and exploring innovative solutions like blockchain-based energy trading systems (Karumba et al., 2023) could contribute to overcoming adoption barriers and advancing towards a more circular economy in the solar energy sector (Chrzanowski & Zawada, 2023).

2.25 Environmental Justice Theory

Studies emphasize the need for transformative environmental education that promotes critical reflection and holistic understanding (Guevara-Herrero et al., 2024). Social work practices in rural communities increasingly focus on environmental justice and sustainability (Wu et al., 2022). Deploying urban green amenities is being examined through an environmental justice lens, with efforts to bridge North-South perspectives (Tubino et al., 2021). Policy research identifies gaps between climate justice requirements and actual policies, calling for more engagement with policy theories (Cairney et al., 2023). The concept of green gentrification explores urban development and climate change adaptation (Cucca et al., 2023). Climate justice action is framed as a collective pursuit of systemic change (Trott et al., 2023). Additionally, justice considerations are increasingly incorporated into climate change education across various contexts (Trott et al., 2023). Solar photovoltaic (PV) waste is a growing concern globally, with 78 million tonnes expected by 2050 (Chrzanowski & Zawada, 2023). While PV energy contributes to sustainable development goals, its land use impacts require standardized metrics for assessment (Cagle et al., 2023). Life cycle assessments reveal environmental hotspots in PV production and disposal (Blanco et al., 2020; Hsu et al., 2012). E-waste, including PV modules, poses significant health risks, with studies showing increased DNA damage in exposed populations (Issah et al., 2021). Developing Asian countries face challenges in managing e-waste effectively (Andeobu et al., 2021). Marginalized communities, particularly in post-disaster contexts, struggle with unequal resource distribution and lack of income-generating opportunities (Mendis et al., 2023). To address these issues, some researchers propose on-site recycling of PV panels to reduce transportation costs and environmental impacts (Chrzanowski & Zawada, 2023), while others emphasize the need for improved environmental impact assessments (Zarzavilla et al., 2022). Recent research highlights the importance of environmental justice in shaping policies for equitable access to solar energy benefits while addressing waste impacts. Studies emphasize the potential of solar energy in mitigating climate change and promoting sustainability (Nikolaidis, 2023; Zarzavilla et al., 2022). However, challenges persist in ensuring fair distribution of benefits and minimizing negative impacts (Wu et al., 2022; Cagle et al., 2023). Researchers stress the need for standardized metrics to assess solar energy-land relationships and their environmental effects (Cagle et al., 2023). Policy frameworks should incorporate climate justice principles, focusing on equitable processes and outcomes (Cairney et al., 2023). Integrating social equity considerations into food-energy-water systems analyses is crucial for addressing resource demands without exacerbating social vulnerabilities (Stone et al., 2023). Public policies promoting renewable energy and circular economy practices can contribute to sustainable development and environmental justice (Nunes et al., 2023; Tubino et al., 2021). Managing solar photovoltaic (PV) waste is becoming increasingly important as global PV installations multiply (Chrzanowski & Zawada, 2023). Integrating environmental justice into waste management strategies requires considering social impacts alongside environmental and economic factors (Gutierrez-Lopez et al., 2023). This involves engaging local communities and stakeholders in decision-making processes (Wu et al., 2022). Life cycle assessments of PV technologies can help identify potential environmental hotspots and guide sustainable development (Blanco et al., 2020; Zarzavilla et al., 2022). Standardized metrics for quantifying solar energy-land relationships are needed better to understand the impacts on local ecosystems and communities (Cagle et al., 2023). Improving e-waste management practices, including those for PV waste, is crucial in the Asia Pacific region, including India (Andeobu et al., 2021). Future research should focus on circular economic behavior and behavioral spillovers to promote sustainable waste management practices (Newaz & Appolloni, 2023).

2.26 Cradle-to-Cradle (C2C) Theory

The Cradle-to-Cradle (C2C) approach can be applied to solar PV module design through various strategies to enhance sustainability and circularity. These include improving recycling processes at installation sites to reduce transportation costs and environmental impacts (Chrzanowski & Zawada, 2023), focusing on emerging PV technologies with potentially lower environmental footprints (Blanco et al., 2020; Weyand et al., 2019), and considering life cycle assessments to identify and address environmental hotspots (Hsu et al., 2012; Zarzavilla et al., 2022). Integrating circular economy principles throughout the lifecycle of renewable energy infrastructure, including design for circularity, maintenance, reuse, and recycling, is crucial (Velenturf, 2021). Multiple pathways must be pursued aggressively to achieve a complete transition to renewable energy by 2050, including improving energy efficiency and conservation (Holechek et al., 2022). Designing business models around circular economy principles is essential for reducing resource consumption and preserving the environment (Centobelli et al., 2020). The successful implementation of Cradle-to-Cradle design in solar PV modules faces challenges globally, including the need for effective recycling processes to manage the projected 78 million tonnes of PV waste by 2050 (Chrzanowski & Zawada, 2023). While recycling technologies for large-scale battery disposal are still developing (Zhang et al., 2018), research indicates positive trends in reducing environmental impacts across the PV sector (Blanco et al., 2020). Studies in Spain's Castilla-La Mancha region suggest a correlation between plant size and shorter emission payback times for PV installations (Zarzavilla et al., 2022). To adopt similar practices, India could benefit from improved education in industrial ecology (Geng et al., 2009) and addressing the knowledge gap in pharmacovigilance among health professionals (Bhagavathula et al., 2016). Additionally, engaging Indigenous communities in climate research (David-Chavez & Gavin, 2018) and considering sociotechnical factors in technology implementation (Greenhalgh et al., 2017) could enhance sustainable practices in the Indian context.

2.27 Green Supply Chain Management Theory

Green supply chain management (GSCM) is an evolving concept integrating environmental considerations into supply chain practices. It encompasses various dimensions, including innovation, performance, and management (Assumpção et al., 2019). GSCM is crucial for organizations to become eco-friendly, particularly in industries like hospitality (Alreahi et al., 2023). The circular economy perspective transforms GSCM by focusing on redesign, reuse, and product transformation (Theeraworawit et al., 2022). Implementation of GSCM faces barriers and requires collaboration among stakeholders (Alreahi et al., 2023). Industry 4.0 technologies are increasingly being utilized to improve quality control in circular supply chains (Nguyen et al., 2023). Social capital plays a significant role in GSCM, especially in buyer-supplier relationships (Matthews & Marzec, 2012). Economic sustainability is a key driver in achieving Sustainable Development Goals through GSCM in low- and middle-income countries (Kayikci et al., 2022). Large-scale initiatives like China's Belt and Road Initiative significantly affect global supply chain management (Thürer et al., 2019). Green Supply Chain Management (GSCM) is increasingly essential for sustainability across industries, including solar PV. GSCM practices can be categorized into innovation, performance, and management dimensions (Assumpção et al., 2019). Recycling end-of-life panels is crucial for the solar PV industry, with an estimated 78 million tonnes of waste by 2050 (Chrzanowski & Zawada, 2023). On-site recycling of PV panels could offer economic and environmental benefits by reducing transportation costs (Chrzanowski & Zawada, 2023). The circular economy perspective transforms sustainable supply chain management, focusing on redesign, reuse, and product transformation (Theeraworawit et al., 2022). Industry 4.0 technologies can improve quality control in circular supply chains, addressing input management, waste handling, and preservation (Nguyen et al., 2023). Implementing GSCM practices can positively impact corporate performance (Alreahi et al., 2023) and contribute to the triple bottom line of sustainability: economic, environmental, and social aspects (Shekarian et al., 2022). Global examples of green supply chain management (GSCM) in the solar industry offer valuable lessons for India in managing solar PV module waste. The rapid growth of photovoltaics has led to concerns about recycling end-of-life panels, with 78 million tonnes of waste expected by 2050 (Chrzanowski & Zawada, 2023). Recycling at installation sites shows potential economic and environmental benefits (Chrzanowski & Zawada, 2023). Life cycle assessments reveal that large-scale PV plants have shorter emission payback times, around 1.66-2.08 years, in Castilla-La Mancha, Spain (Zarzavilla et al., 2022). However, e-waste management practices in Asia Pacific countries, including India, need improvement (Andeobu et al., 2021). Technological developments in PV improve environmental sustainability, but potential hotspots remain for specific technologies and impact categories (Blanco et al., 2020). Implementing GSCM practices in industries faces barriers that must be addressed for successful application (Alreahi et al., 2023).

2. 28 Key Findings from the Review of Literature

Table 2.2: Key Findings Summary Table

Theory/Framework	**Key Findings**	**Reference**
Theory of Planned Behaviour (TPB)	Explores pro-environmental behavior through attitudes, subjective norms, and perceived behavioral control.	Kepatuhan et al., 2008
Sociological Model	Provides insights into social dynamics and cultural factors influencing stakeholder behavior.	Kollmuss & Agyeman, 2002
Altruism Model	Accounts for intrinsic motivations behind stakeholders' engagement in sustainable practices.	Kollmuss & Agyeman, 2002

DPSIR Framework	Utilized for evaluating and prioritizing different waste management strategies.	Jain et al., 2022
Multi-Criteria Decision Making (MCDM)	Proposes producer responsibility for managing solar PV waste lifecycle.	Karmperis et al., 2013
Extended Producer Responsibility (EPR)	Proposes producer responsibility for managing solar PV waste lifecycle.	Jain et al., 2022
Complexity Theory	Provides insights into the dynamic interactions between stakeholders in waste management.	Gaeta et al., 2020
Neoclassical Economic Theory	Examines financial viability and market behaviors influencing	D’Adamo et al., 2017

	sustainable practices.	
Decision-Making in SWM Theory	Explains decision-making processes and criteria for solid waste management.	Chang et al., 2011

Source: Author

CHAPTER III:

METHODOLOGY

3.1 Overview of the Research Problem

The end-of-life management of solar photovoltaic (PV) waste presents a significant environmental and economic challenge, especially in developing countries like India. Despite the growing adoption of solar PV technology, the awareness and practices regarding the disposal and recycling of solar PV modules are insufficient. This research aims to evaluate stakeholder awareness, identify challenges, assess sustainable practices, and analyze demographic and industry-specific trends in solar PV waste management in India.

3.2 Research Questions and Hypotheses

3.2.1 Research Question: What is the level of awareness and current practices related to solar PV waste management among different stakeholders in India?

- **Hypothesis (H0)**: There is a significant relationship between stakeholder demographics (age, gender, industry, years of experience) and their awareness of risks associated with solar PV waste.
- **Hypothesis (H0)**: There is a significant relationship between stakeholder demographics and their awareness of the existing waste management system in India.

- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and their awareness of recycling methods for solar PV waste.
- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and their current waste management practices (has a waste management system, recycling percentage, responsible for collection, and recycling methods).

3.2.2 Research Question: What are the key challenges faced by stakeholders in managing solar PV waste?

- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and the challenges they face in recycling solar PV waste.
- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and their reasons for not having a waste management system.
- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and the infrastructure challenges they face.
- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and the regulatory challenges they face.

- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and the technological limitations they encounter.

3.2.3 Research Question: How do stakeholders perceive the importance of sustainable practices and the role of government in solar PV waste management?

- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and their perceived importance of sustainable practices.
- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and their perceived importance of the government’s role in waste management.
- **Hypothesis H0**: There is a significant relationship between stakeholder demographics and their perceived importance of financial viability in sustainable practices.

3.2.4 Research Question: How do demographic factors and industry-specific characteristics influence solar PV waste management practices and challenges?

- **Hypothesis H0:** There are significant demographic and industry-specific trends in awareness of risks, awareness of the Indian waste management system, and awareness of recycling methods**.**

- **Hypothesis H0**: There are significant demographic and industry-specific trends in the existence of waste management systems, recycling percentages, and responsibility for collection and recycling methods.
- **Hypothesis H0**: There are significant demographic and industry-specific trends in the challenges faced in recycling, reasons for no waste management, and challenges related to infrastructure, regulations, and technological limitations.
- **Hypothesis H0**: There are significant demographic and industry-specific trends in the perceived importance of sustainable practices, government role, and financial viability.

3.2.5 Research Question: How effective are the current solar PV waste management practices in India?

- **Hypothesis H0**: The effectiveness of waste management practices (has a waste management system, recycling percentage, and recycling methods) varies significantly across different demographic groups and industries.
- **Hypothesis H0**: The challenges (recycling challenges, the reason for no waste management) faced by different demographic groups and industries significantly impact the effectiveness of solar PV waste management practices.

3.3 Significance of the Study

The significance of this study lies in its potential to provide comprehensive insights into the multifaceted issue of solar photovoltaic (PV) waste management in India. As the adoption of solar PV systems continues to grow exponentially, the management of resulting waste becomes increasingly critical. This research addresses key areas of awareness, practices, challenges, and the role of government and sustainable practices in managing solar PV waste. The findings of this study will contribute to:

1. **Enhanced Awareness**: By assessing the level of awareness among stakeholders, this study will highlight knowledge gaps and provide a basis for targeted educational programs and awareness campaigns.
2. **Improved Practices**: Identifying current practices and their effectiveness will help in developing best practices for solar PV waste management, thereby improving environmental sustainability.
3. **Addressing Challenges**: Understanding the specific challenges faced by stakeholders will inform the development of more effective policies and frameworks to mitigate these issues.
4. **Policy Development**: Evaluating the role of government and the importance of sustainable practices will offer valuable insights for policymakers to enhance regulatory and incentive structures.

5. **Strategic Recommendations**: The study's analysis of demographic and industry-specific trends will enable tailored strategies that consider the unique needs and challenges of different stakeholder groups.

6. **Sustainable Development**: Ultimately, this research will contribute to the broader goals of sustainable development by promoting more efficient and responsible management of solar PV waste.

3.4 Research Design

3.4.1 Population and Sample

The target population for this study includes individuals working in the solar PV industry in India. Given the undefined size of the population, Cochran's formula was used to determine the sample size. A total of 400 respondents were targeted to ensure a representative sample, providing a confidence level of 95% and a margin of error of 5%.

3.4.2 Participant Selection

Participants were selected based on their involvement in the solar PV industry. The selection criteria ensured that only individuals with relevant experience and knowledge about solar PV waste management were included. The questionnaire was sent only to these identified individuals, ensuring the relevance and reliability of the data collected.

3.4.3 Instrumentation

A structured questionnaire was developed for data collection, incorporating both closed-ended and Likert scale questions. The questionnaire included the following sections:

1. **Demographic Information**: Name, Gender, Age, Industry, Years of Experience.
2. **Awareness and Practices**:

- Awareness of environmental and health risks.
- Familiarity with recycling methods.
- Current waste management practices.

3. **Challenges**:

- Infrastructure and logistical challenges.
- Regulatory and technological limitations.

4. **Perceptions**:

- Importance of sustainable practices.
- Role of government in waste management.
- Financial viability of recycling.

The questionnaire's reliability was validated using Cronbach's alpha, ensuring internal consistency.

3.4.4 Data Collection Procedures

Data collection was conducted over six months. The questionnaire was distributed via email to the selected participants. Confidentiality was maintained by anonymizing personal information and securely storing data.

3.4.5 Data Analysis

The collected data were analyzed using SPSS and Python software. The following statistical methods were employed for each research objective:

1. **Descriptive Statistics**: Mean, median, mode, standard deviation, and range for each dependent variable.
2. **Correlation Analysis**: Pearson correlation coefficients to identify relationships between independent and dependent variables.
3. **Regression Analysis**: Multiple linear regression to understand the impact of demographic factors on awareness, practices, challenges, and perceptions.
4. **T-Test**: To compare the effectiveness of different recycling methods across various industries.
5. **Chi-Square Test**: To examine the relationship between categorical variables like industry type and the presence of a waste management system.

3.5 Research Design Limitations

The study has certain limitations:

1. **Sample Representation**: Despite efforts to ensure a representative sample, the reliance on self-reported data may introduce bias.
2. **Generalizability**: Findings may not be generalizable beyond the specific context of the Indian solar PV industry.
3. **Secondary Data**: The lack of secondary data necessitated a reliance on primary data collection, which may limit the depth of historical analysis.
4. **Cross-Sectional Design**: The cross-sectional nature of the study limits the ability to infer causality.

3.6 Reliability

The questionnaire was tested for internal consistency using Cronbach’s alpha. A value of 0.7 or higher was considered acceptable, indicating that the questionnaire items were measuring the same underlying concept.

3.7 Conclusion

This research methodology offers a comprehensive framework for examining solar PV waste management practices in India. The study aims to generate valuable insights into stakeholder awareness, challenges, and perceptions through the use of a structured questionnaire and thorough statistical analysis. The findings will inform the development of effective strategies and policies for sustainable solar PV waste management, addressing both environmental and economic concerns..

CHAPTER IV:

RESULTS

4.1 Data Overview

Figure 4.1: Distribution Cart for Age/ Industry/ Work Experience / Waste Management System

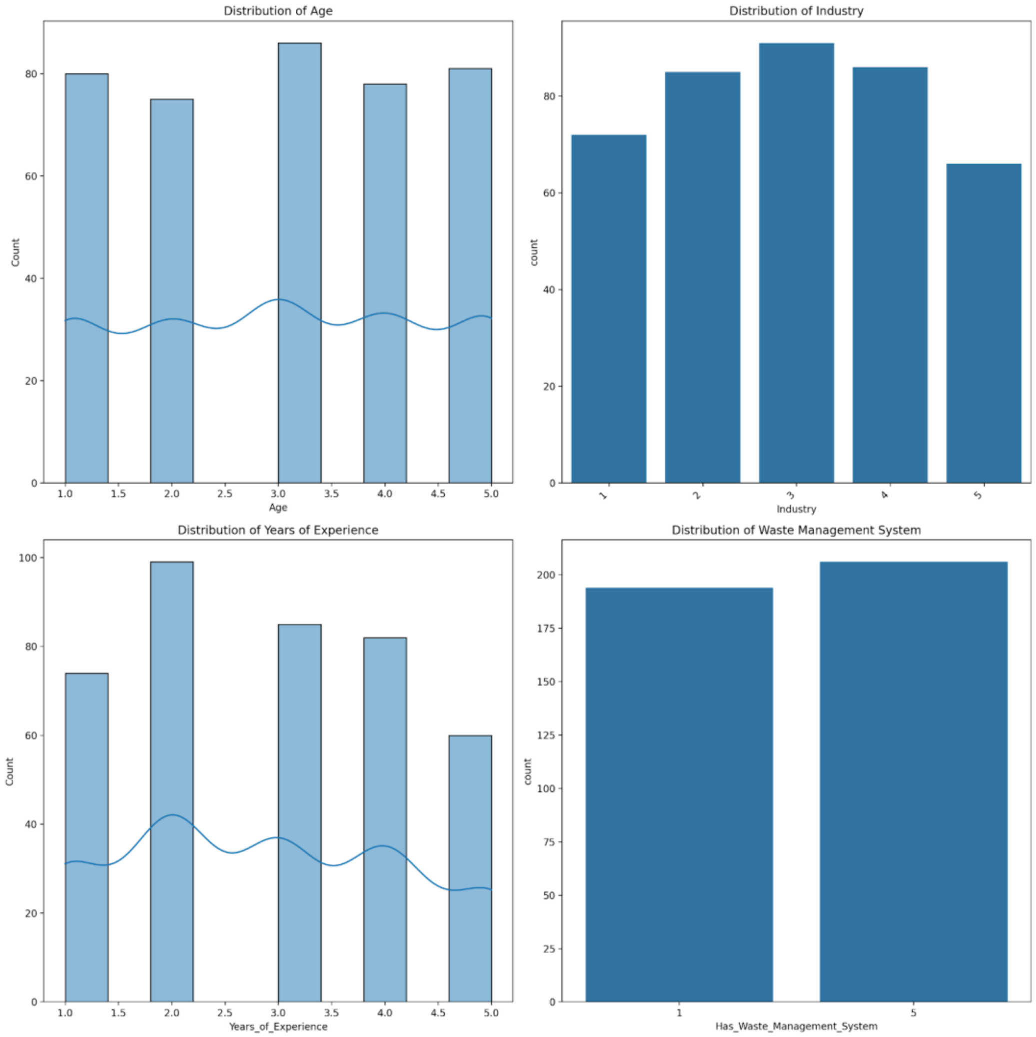


Figure 4.2: Mean Scores for Likert Scale Questions

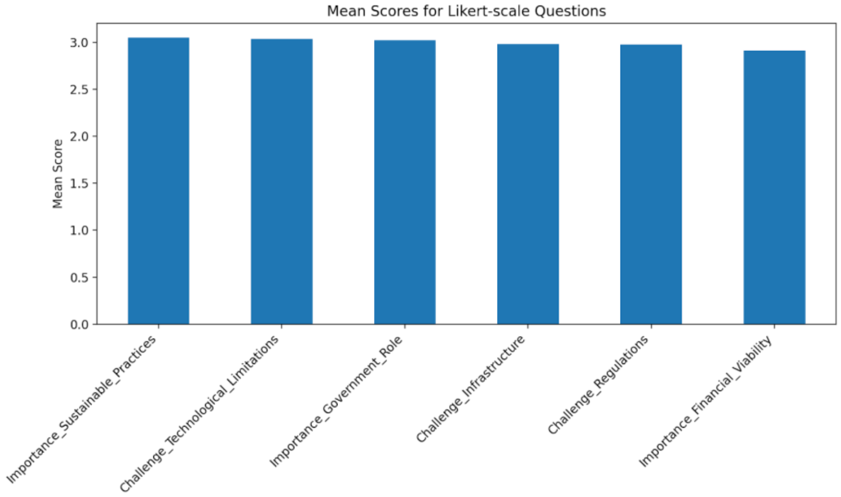


Figure 4.3: Mean Scores for Likert Scale Questions

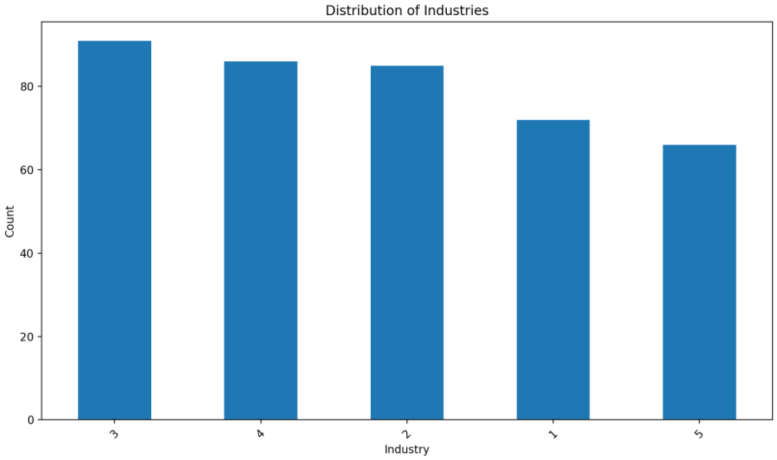
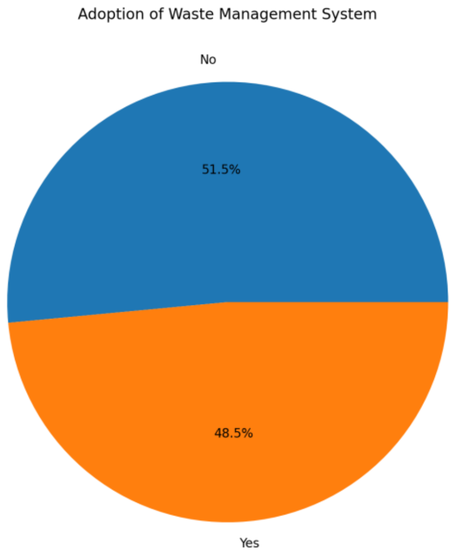


Figure 4.4: Adoption of Waste Management System



4.2 How do stakeholder demographics (age, gender, industry, and years of experience) influence awareness and practices related to solar PV waste management?

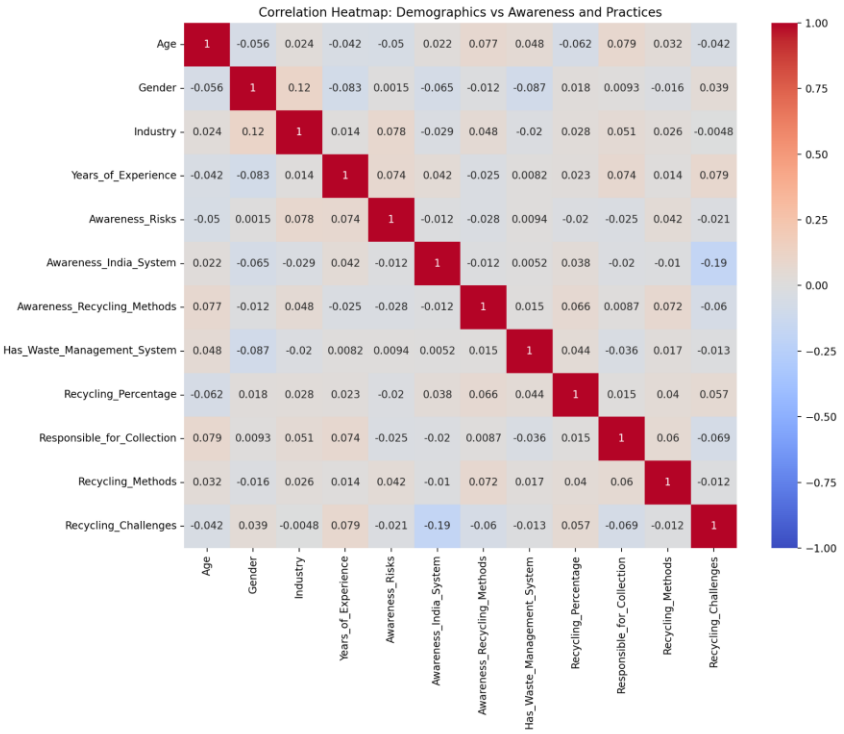
H (0): Stakeholders' demographics significantly influence their awareness of solar PV waste management risks, knowledge of India's waste management system, and recycling practices.

H (0): There is a significant relationship between stakeholder demographics and their awareness of the existing waste management system in India.

H (0): There is a significant relationship between stakeholder demographics and their awareness of recycling methods for solar PV waste.

H (0): There is a significant relationship between stakeholder demographics and their current waste management practices (has a waste management system, recycling percentage, responsible for collection, and recycling methods).

Figure 4.5: Correlation Heatmap



Correlation Heatmap: Demographics vs Awareness and Practices

	Age	Gender	Industry	Years_of_Experience	Awareness_Risks	Awareness_India_System	Awareness_Recycling_Methods	Has_Waste_Management_System	Recycling_Percentage	Responsible_for_Collection	Recycling_Methods	Recycling_Challenges
Age	1	-0.056	0.024	-0.042	-0.05	0.022	0.077	0.048	-0.062	0.079	0.032	-0.042
Gender	-0.056	1	0.12	-0.083	0.0015	-0.065	-0.012	-0.087	0.018	0.0093	-0.016	0.039
Industry	0.024	0.12	1	0.014	0.078	-0.029	0.048	-0.02	0.028	0.051	0.026	-0.0048
Years_of_Experience	-0.042	-0.083	0.014	1	0.074	0.042	-0.025	0.0082	0.023	0.074	0.014	0.079
Awareness_Risks	-0.05	0.0015	0.078	0.074	1	-0.012	-0.028	0.0094	-0.02	-0.025	0.042	-0.021
Awareness_India_System	0.022	-0.065	-0.029	0.042	-0.012	1	-0.012	0.0052	0.038	-0.02	-0.01	-0.19
Awareness_Recycling_Methods	0.077	-0.012	0.048	-0.025	-0.028	-0.012	1	0.015	0.066	0.0087	0.072	-0.06
Has_Waste_Management_System	0.048	-0.087	-0.02	0.0082	0.0094	0.0052	0.015	1	0.044	-0.036	0.017	-0.013
Recycling_Percentage	-0.062	0.018	0.028	0.023	-0.02	0.038	0.066	0.044	1	0.015	0.04	0.057
Responsible_for_Collection	0.079	0.0093	0.051	0.074	-0.025	-0.02	0.0087	-0.036	0.015	1	0.06	-0.069
Recycling_Methods	0.032	-0.016	0.026	0.014	0.042	-0.01	0.072	0.017	0.04	0.06	1	-0.012
Recycling_Challenges	-0.042	0.039	-0.0048	0.079	-0.021	-0.19	-0.06	-0.013	0.057	-0.069	-0.012	1

Figure 4.6: Awareness by Industry

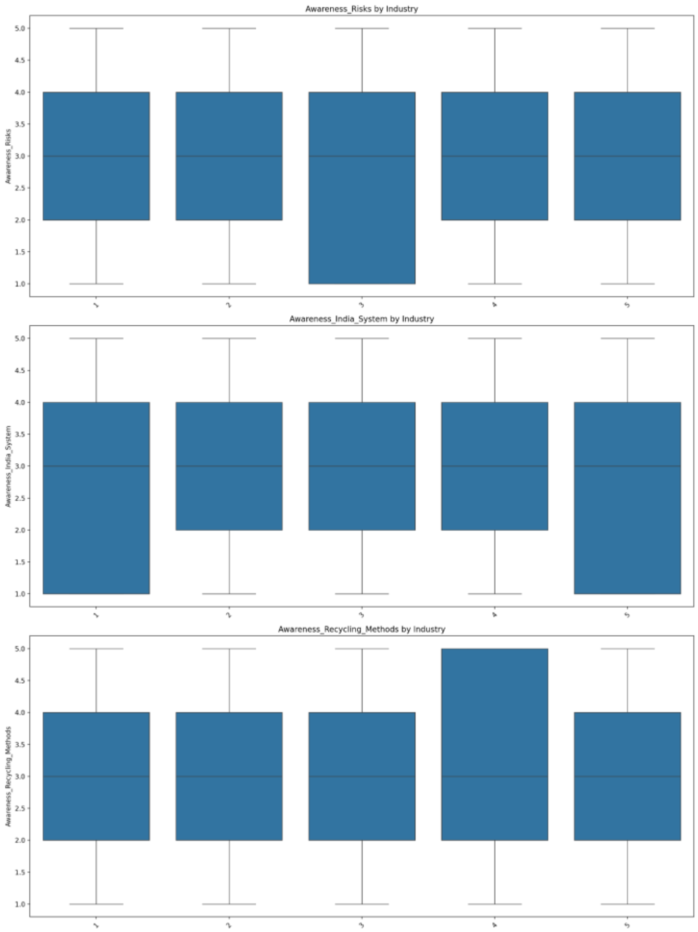
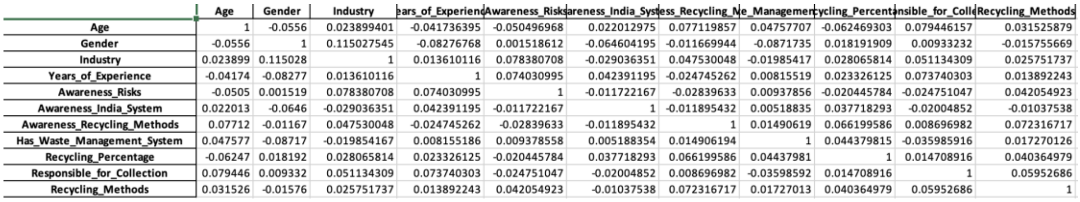


Table 4.1: Description Table

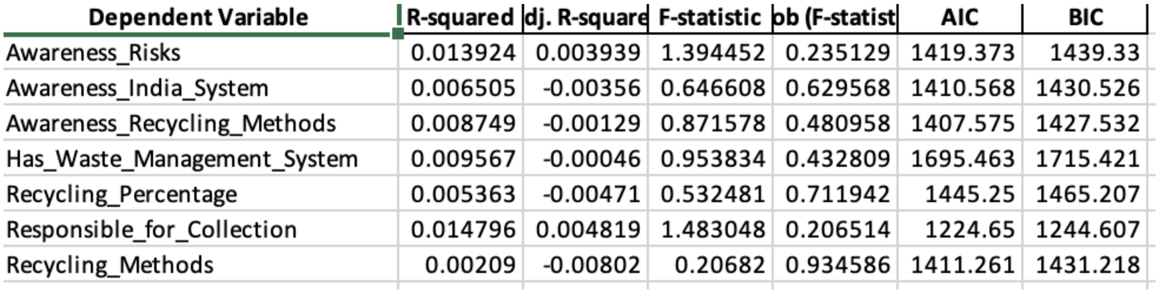
	count	mean	std	min	25%	50%	75%	max	mode	range
Awareness_Risks	400	2.89	1.420544	1	2	3	4	5	2	4
Awareness_India_System	400	2.925	1.39974	1	2	3	4	5	2	4
Awareness_Recycling_Methods	400	3.0575	1.39609	1	2	3	4	5	4	4
Has_Waste_Management_System	400	3.06	2.001603	1	1	5	5	5	5	4
Recycling_Percentage	400	3.0925	1.460917	1	2	3	4	5	5	4
Responsible_for_Collection	400	2.4175	1.114135	1	1	2	3	4	2	3
Recycling_Methods	400	3.03	1.39785	1	2	3	4	5	4	4

Table 4.2: Correlation Matrix



	Age	Gender	Industry	ears_of_Experienc	Awareness_Risks	areness_India_Syst	ess_Recycling_N	e_Managemen	ycling_Percent	nsible_for_Coll	Recycling_Methods
Age	1	-0.0556	0.023899401	-0.041736395	-0.050496968	0.022012975	0.077119857	0.04757707	-0.062469303	0.079446157	0.031525879
Gender	-0.0556	1	0.115027545	-0.08276768	0.001518612	-0.064604195	-0.011669944	-0.0871735	0.018191909	0.00933232	-0.015755669
Industry	0.023899	0.115028	1	0.013610116	0.078380708	-0.029036351	0.047530048	-0.01985417	0.028065814	0.051134309	0.025751737
Years_of_Experience	-0.04174	-0.08277	0.013610116	1	0.074030995	0.042391195	-0.024745262	0.00815519	0.023326125	0.073740303	0.013892243
Awareness_Risks	-0.0505	0.001519	0.078380708	0.074030995	1	-0.011722167	-0.02839633	0.00937856	-0.020445784	-0.024751047	0.042054923
Awareness_India_System	0.022013	-0.0646	-0.029036351	0.042391195	-0.011722167	1	-0.011895432	0.00518835	0.037718293	-0.02004852	-0.01037538
Awareness_Recycling_Methods	0.07712	-0.01167	0.047530048	-0.024745262	-0.02839633	-0.011895432	1	0.01490619	0.066199586	0.008696982	0.072316717
Has_Waste_Management_System	0.047577	-0.08717	-0.019854167	0.008155186	0.009378558	0.005188354	0.014906194	1	0.044379815	-0.035985916	0.017270126
Recycling_Percentage	-0.06247	0.018192	0.028065814	0.023326125	-0.020445784	0.037718293	0.066199586	0.04437981	1	0.014708916	0.040364979
Responsible_for_Collection	0.079446	0.009332	0.051134309	0.073740303	-0.024751047	-0.02004852	0.008696982	-0.03598592	0.014708916	1	0.05952686
Recycling_Methods	0.031526	-0.01576	0.025751737	0.013892243	0.042054923	-0.01037538	0.072316717	0.01727013	0.040364979	0.05952686	1

Table 4.3: Regression Summary



Dependent Variable	R-squared	dj. R-square	F-statistic	ob (F-statist	AIC	BIC
Awareness_Risks	0.013924	0.003939	1.394452	0.235129	1419.373	1439.33
Awareness_India_System	0.006505	-0.00356	0.646608	0.629568	1410.568	1430.526
Awareness_Recycling_Methods	0.008749	-0.00129	0.871578	0.480958	1407.575	1427.532
Has_Waste_Management_System	0.009567	-0.00046	0.953834	0.432809	1695.463	1715.421
Recycling_Percentage	0.005363	-0.00471	0.532481	0.711942	1445.25	1465.207
Responsible_for_Collection	0.014796	0.004819	1.483048	0.206514	1224.65	1244.607
Recycling_Methods	0.00209	-0.00802	0.20682	0.934586	1411.261	1431.218

4.3 What do stakeholders face the key challenges in managing solar PV waste?

- **H (0)**: There is a significant relationship between stakeholder demographics and the challenges they face in recycling solar PV waste.

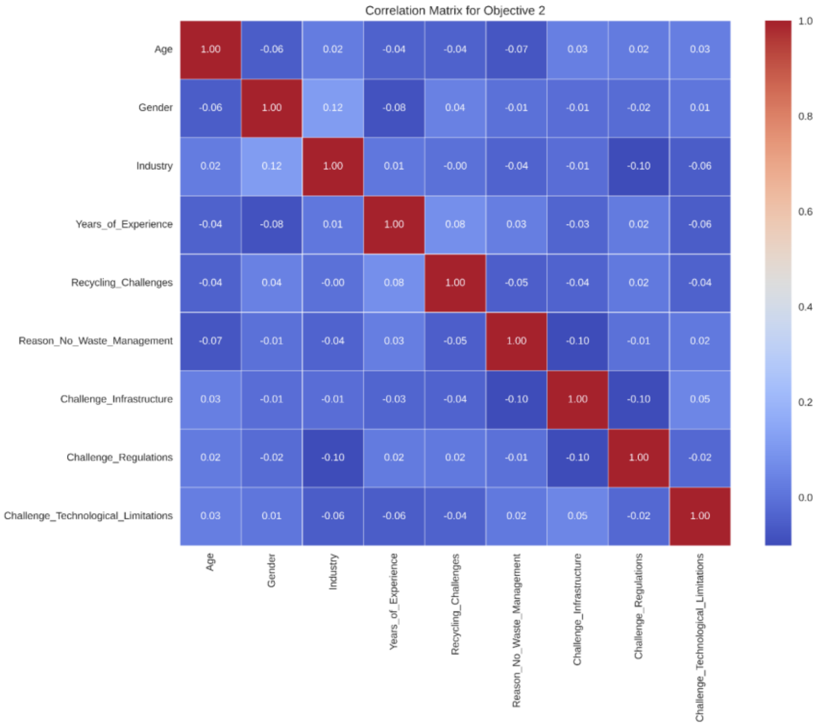
- **H (0)**: There is a significant relationship between stakeholder demographics and their reasons for not having a waste management system.

- **H (0)**: There is a significant relationship between stakeholder demographics and the infrastructure challenges they face.

- **H (0)**: There is a significant relationship between stakeholder demographics and the regulatory challenges they face.

- **H (0)**: There is a significant relationship between stakeholder demographics and the technological limitations they encounter.

Figure 4.7: Correlation Matrix



	Age	Gender	Industry	Years_of_Experience	Recycling_Challenges	Reason_No_Waste_Management	Challenge_Infrastructure	Challenge_Regulations	Challenge_Technological_Limitations
Age	1.00	-0.06	0.02	-0.04	-0.04	-0.07	0.03	0.02	0.03
Gender	-0.06	1.00	0.12	-0.08	0.04	-0.01	-0.01	-0.02	0.01
Industry	0.02	0.12	1.00	0.01	-0.00	-0.04	-0.01	-0.10	-0.06
Years_of_Experience	-0.04	-0.08	0.01	1.00	0.08	0.03	-0.03	0.02	-0.06
Recycling_Challenges	-0.04	0.04	-0.00	0.08	1.00	-0.05	-0.04	0.02	-0.04
Reason_No_Waste_Management	-0.07	-0.01	-0.04	0.03	-0.05	1.00	-0.10	-0.01	0.02
Challenge_Infrastructure	0.03	-0.01	-0.01	-0.03	-0.04	-0.10	1.00	-0.10	0.05
Challenge_Regulations	0.02	-0.02	-0.10	0.02	0.02	-0.01	-0.10	1.00	-0.02
Challenge_Technological_Limitations	0.03	0.01	-0.06	-0.06	-0.04	0.02	0.05	-0.02	1.00

Figure 4.8: Linear Regression Model

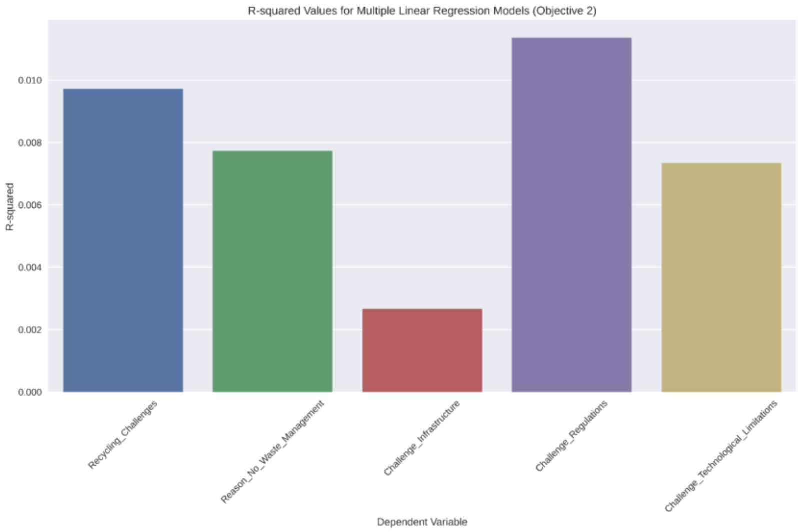
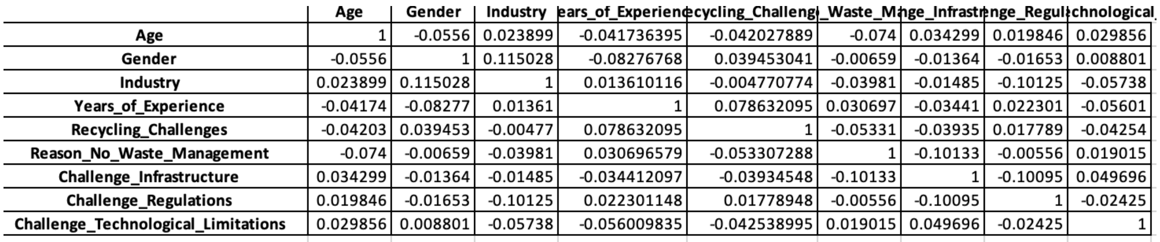
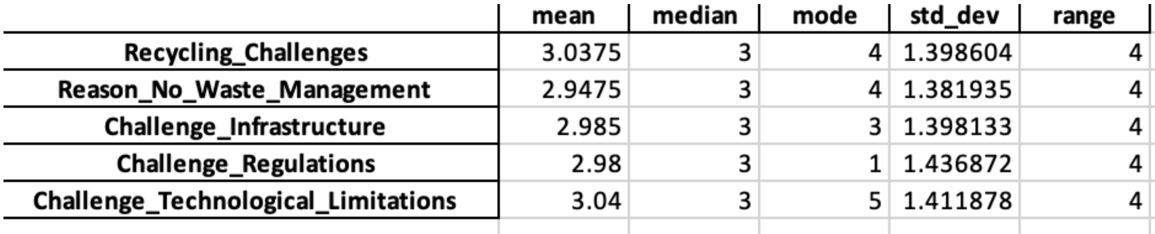


Table 4.4: Correlation Matrix



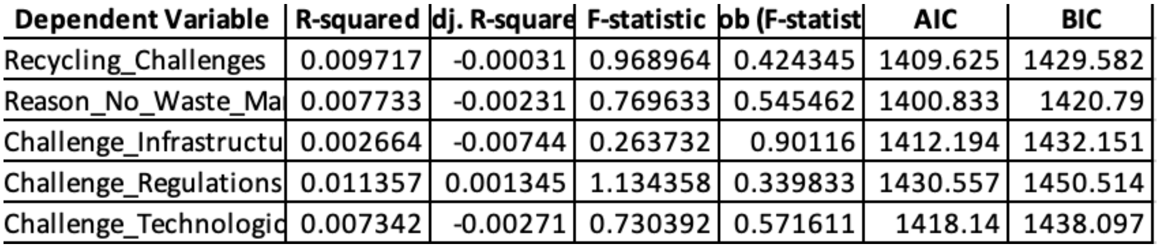
	Age	Gender	Industry	ears_of_Experienc	ecycling_Challeng	_Waste_M	ge_Infrastr	enge_Regul	chnological_
Age	1	-0.0556	0.023899	-0.041736395	-0.042027889	-0.074	0.034299	0.019846	0.029856
Gender	-0.0556	1	0.115028	-0.08276768	0.039453041	-0.00659	-0.01364	-0.01653	0.008801
Industry	0.023899	0.115028	1	0.013610116	-0.004770774	-0.03981	-0.01485	-0.10125	-0.05738
Years_of_Experience	-0.04174	-0.08277	0.01361	1	0.078632095	0.030697	-0.03441	0.022301	-0.05601
Recycling_Challenges	-0.04203	0.039453	-0.00477	0.078632095	1	-0.05331	-0.03935	0.017789	-0.04254
Reason_No_Waste_Management	-0.074	-0.00659	-0.03981	0.030696579	-0.053307288	1	-0.10133	-0.00556	0.019015
Challenge_Infrastructure	0.034299	-0.01364	-0.01485	-0.034412097	-0.03934548	-0.10133	1	-0.10095	0.049696
Challenge_Regulations	0.019846	-0.01653	-0.10125	0.022301148	0.01778948	-0.00556	-0.10095	1	-0.02425
Challenge_Technological_Limitations	0.029856	0.008801	-0.05738	-0.056009835	-0.042538995	0.019015	0.049696	-0.02425	1

Table 4.5: Descriptive Statistics



	mean	median	mode	std_dev	range
Recycling_Challenges	3.0375	3	4	1.398604	4
Reason_No_Waste_Management	2.9475	3	4	1.381935	4
Challenge_Infrastructure	2.985	3	3	1.398133	4
Challenge_Regulations	2.98	3	1	1.436872	4
Challenge_Technological_Limitations	3.04	3	5	1.411878	4

Table 4.6: Regression Statistics

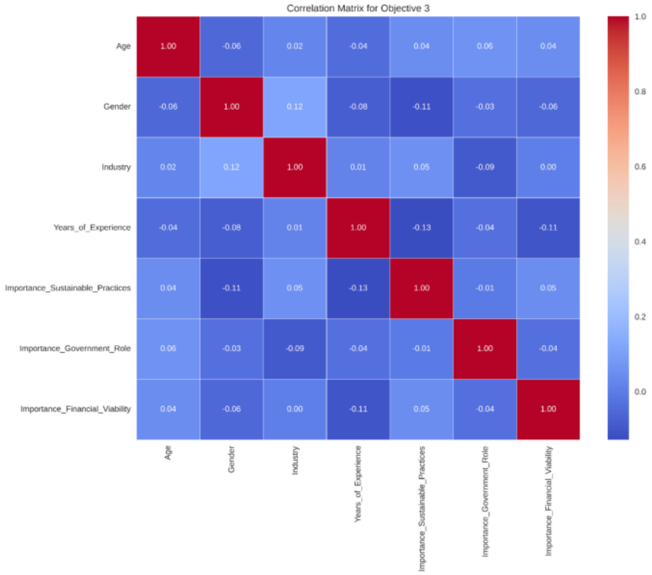


Dependent Variable	R-squared	dj. R-square	F-statistic	ob (F-statist	AIC	BIC
Recycling_Challenges	0.009717	-0.00031	0.968964	0.424345	1409.625	1429.582
Reason_No_Waste_Ma	0.007733	-0.00231	0.769633	0.545462	1400.833	1420.79
Challenge_Infrastructu	0.002664	-0.00744	0.263732	0.90116	1412.194	1432.151
Challenge_Regulations	0.011357	0.001345	1.134358	0.339833	1430.557	1450.514
Challenge_Technologic	0.007342	-0.00271	0.730392	0.571611	1418.14	1438.097

4.4: How do stakeholders perceive the importance of sustainable practices and the role of government in solar PV waste management?

- **H (0)**: There is a significant relationship between stakeholder demographics and their perceived importance of sustainable practices.
- **H (0)**: There is a significant relationship between stakeholder demographics and their perceived importance of the government’s role in waste management.
- **H (0)**: There is a significant relationship between stakeholder demographics and their perceived importance of financial viability in sustainable practices.

Figure 4.9: Correlation Matrix



	Age	Gender	Industry	Years_of_Experience	Importance_Sustainable_Practices	Importance_Government_Role	Importance_Financial_Viability
Age	1.00	-0.06	0.02	-0.04	0.04	0.06	0.04
Gender	-0.06	1.00	0.12	-0.08	-0.11	-0.03	-0.06
Industry	0.02	0.12	1.00	0.01	0.05	-0.09	0.00
Years_of_Experience	-0.04	-0.08	0.01	1.00	-0.13	-0.04	-0.11
Importance_Sustainable_Practices	0.04	-0.11	0.05	-0.13	1.00	-0.01	0.05
Importance_Government_Role	0.06	-0.03	-0.09	-0.04	-0.01	1.00	-0.04
Importance_Financial_Viability	0.04	-0.06	0.00	-0.11	0.05	-0.04	1.00

Figure 4.10: Regression Model

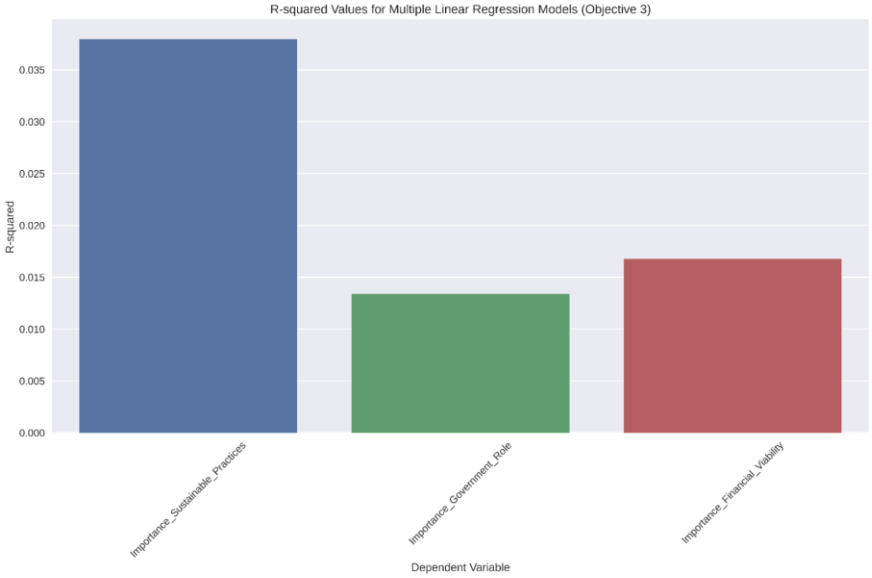
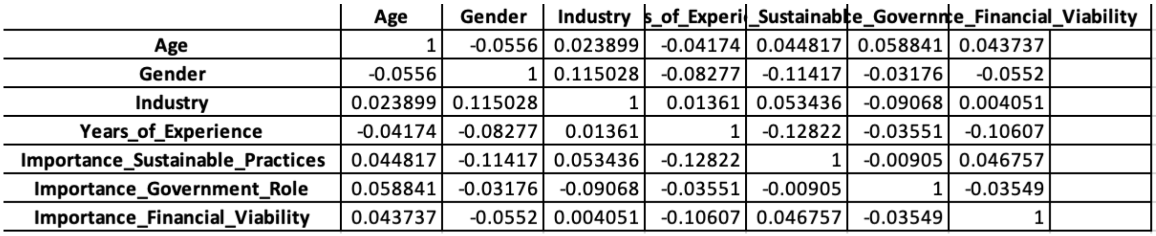
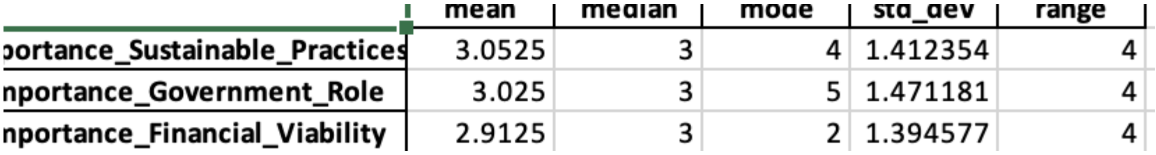


Table 4.7: Correlation Matrix



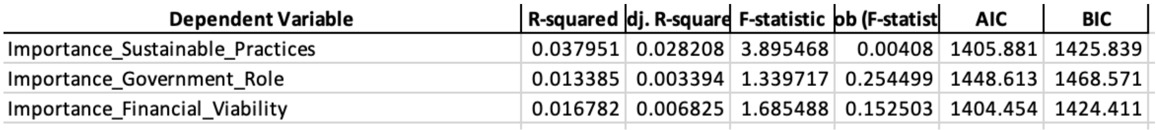
	Age	Gender	Industry	s_of_Experi	_Sustainab	e_Governm	e_Financial_Viability
Age	1	-0.0556	0.023899	-0.04174	0.044817	0.058841	0.043737
Gender	-0.0556	1	0.115028	-0.08277	-0.11417	-0.03176	-0.0552
Industry	0.023899	0.115028	1	0.01361	0.053436	-0.09068	0.004051
Years_of_Experience	-0.04174	-0.08277	0.01361	1	-0.12822	-0.03551	-0.10607
Importance_Sustainable_Practices	0.044817	-0.11417	0.053436	-0.12822	1	-0.00905	0.046757
Importance_Government_Role	0.058841	-0.03176	-0.09068	-0.03551	-0.00905	1	-0.03549
Importance_Financial_Viability	0.043737	-0.0552	0.004051	-0.10607	0.046757	-0.03549	1

Table 4.8: Descriptive Stats



	mean	median	mode	std_dev	range
portance_Sustainable_Practices	3.0525	3	4	1.412354	4
nportance_Government_Role	3.025	3	5	1.471181	4
nportance_Financial_Viability	2.9125	3	2	1.394577	4

Table 4.9: Regression Summary



Dependent Variable	R-squared	dj. R-square	F-statistic	ob (F-statist	AIC	BIC
Importance_Sustainable_Practices	0.037951	0.028208	3.895468	0.00408	1405.881	1425.839
Importance_Government_Role	0.013385	0.003394	1.339717	0.254499	1448.613	1468.571
Importance_Financial_Viability	0.016782	0.006825	1.685488	0.152503	1404.454	1424.411

4.5: How effective are the current solar PV waste management practices in India?

- **H (0)**: The effectiveness of waste management practices (has a waste management system, recycling percentage, and recycling methods) varies significantly across different demographic groups and industries.

- **H (0)**: The challenges (recycling challenges, the reason for no waste management) faced by different demographic groups and industries significantly impact the effectiveness of solar PV waste management practices.

Figure 4. 11: Liner Regression Model

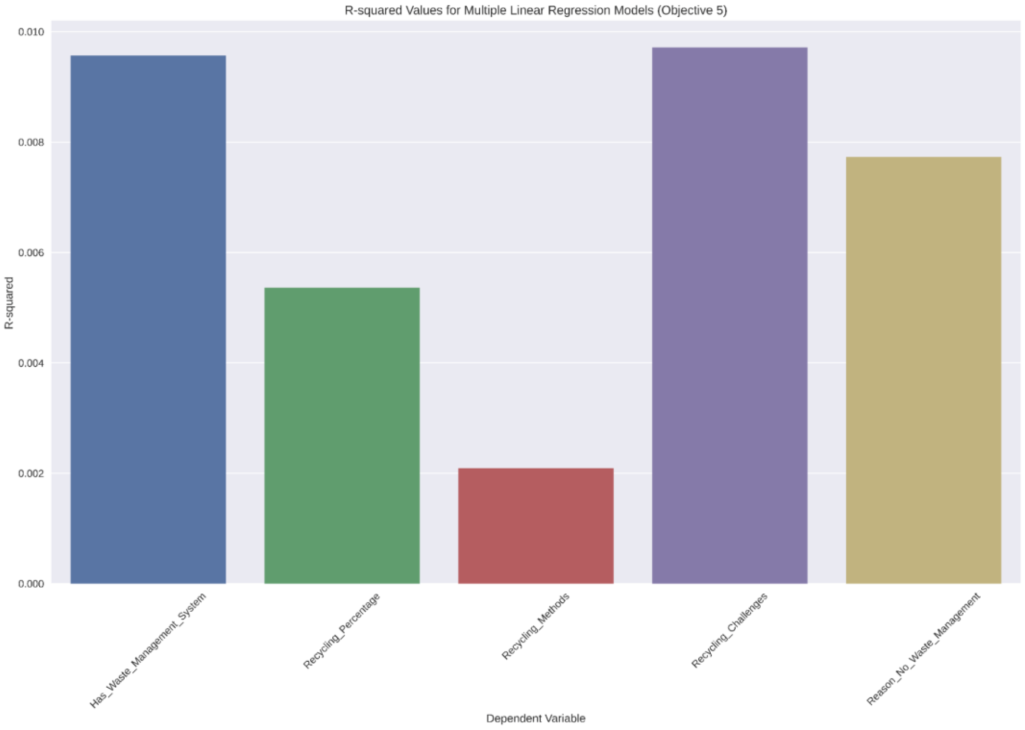


Figure 4.12: Regression Plot

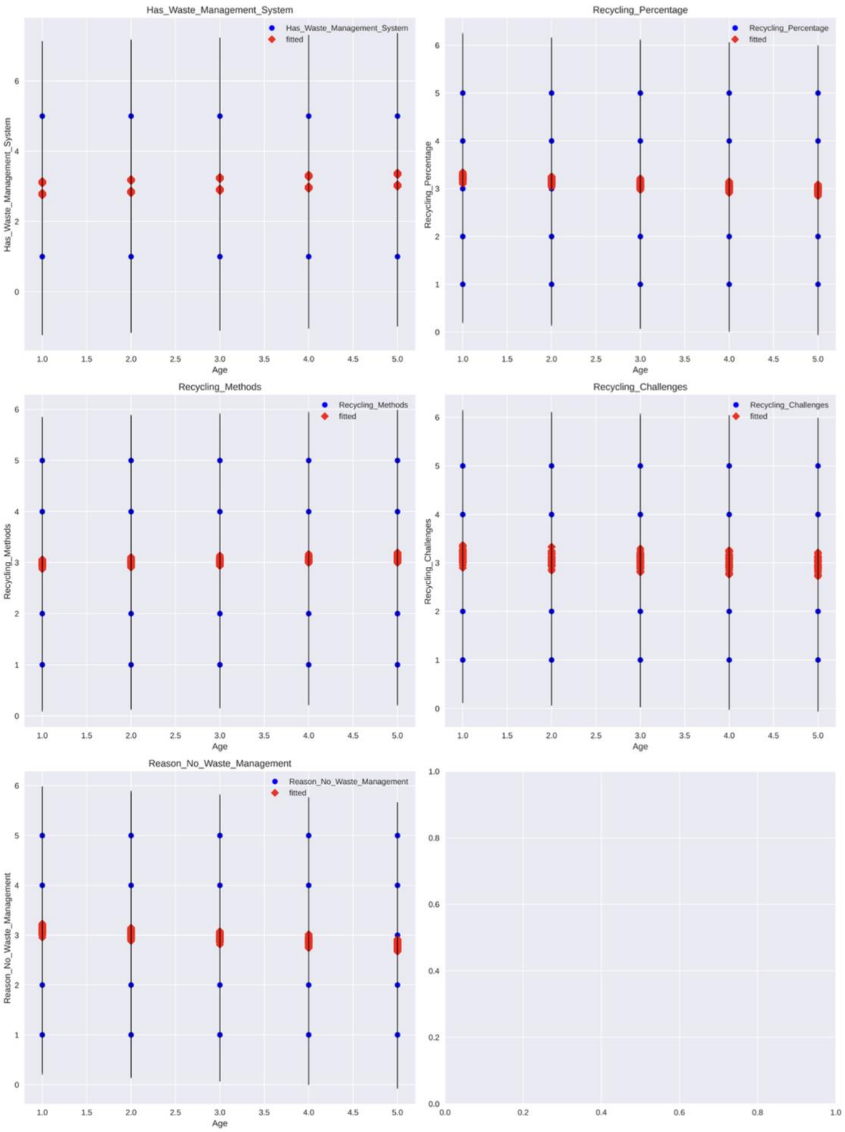
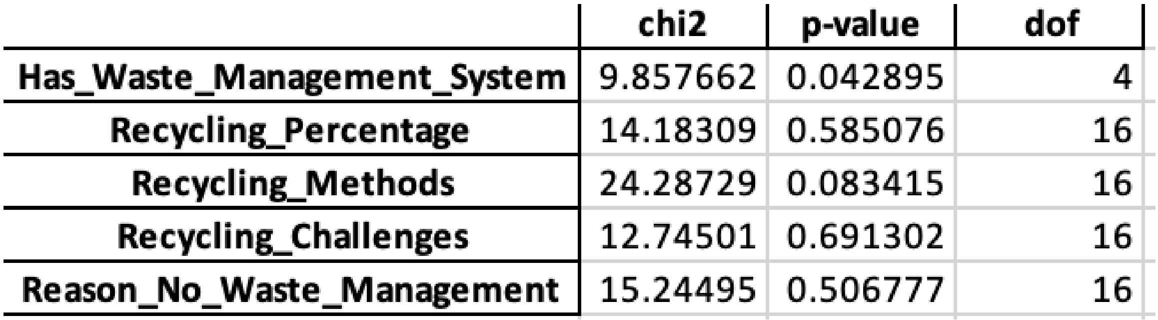
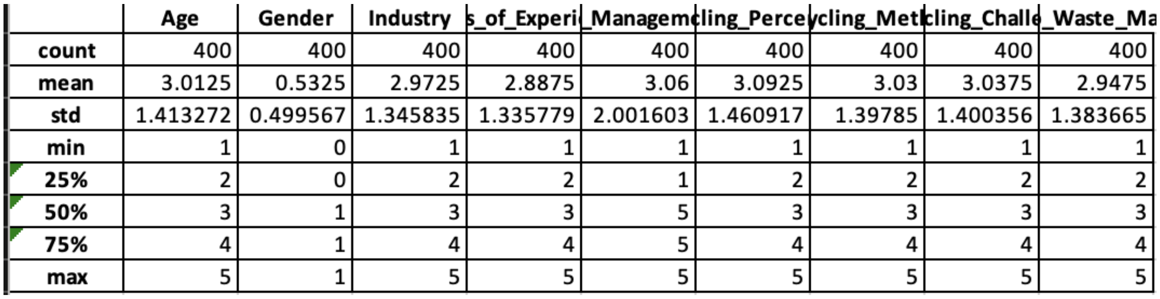


Table 4.10: Chi-Square Summary



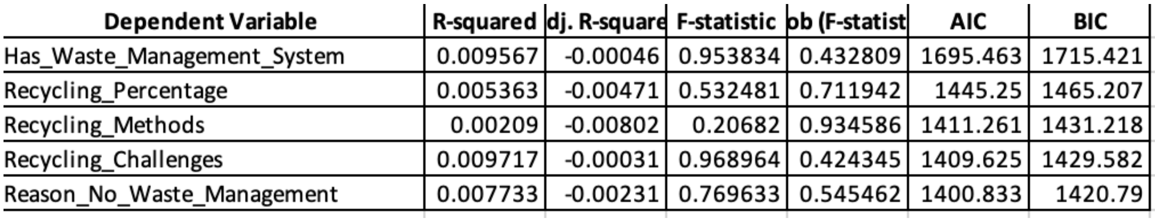
	chi2	p-value	dof
Has_Waste_Management_System	9.857662	0.042895	4
Recycling_Percentage	14.18309	0.585076	16
Recycling_Methods	24.28729	0.083415	16
Recycling_Challenges	12.74501	0.691302	16
Reason_No_Waste_Management	15.24495	0.506777	16

Table 4.11: Descriptive Stats



	Age	Gender	Industry	s_of_Experi	_Managem	cling_Perce	ycling_Met	cling_Challe	_Waste_Ma
count	400	400	400	400	400	400	400	400	400
mean	3.0125	0.5325	2.9725	2.8875	3.06	3.0925	3.03	3.0375	2.9475
std	1.413272	0.499567	1.345835	1.335779	2.001603	1.460917	1.39785	1.400356	1.383665
min	1	0	1	1	1	1	1	1	1
25%	2	0	2	2	1	2	2	2	2
50%	3	1	3	3	5	3	3	3	3
75%	4	1	4	4	5	4	4	4	4
max	5	1	5	5	5	5	5	5	5

Table 4.12: Descriptive Stats



Dependent Variable	R-squared	dj. R-square	F-statistic	ob (F-statist	AIC	BIC
Has_Waste_Management_System	0.009567	-0.00046	0.953834	0.432809	1695.463	1715.421
Recycling_Percentage	0.005363	-0.00471	0.532481	0.711942	1445.25	1465.207
Recycling_Methods	0.00209	-0.00802	0.20682	0.934586	1411.261	1431.218
Recycling_Challenges	0.009717	-0.00031	0.968964	0.424345	1409.625	1429.582
Reason_No_Waste_Management	0.007733	-0.00231	0.769633	0.545462	1400.833	1420.79

CHAPTER V:

DISCUSSION

5.1 Discussion of Results

1. **Sample Size:** The dataset contains responses from 400 participants.
2. **Demographics:**
    - Age: The sample is evenly distributed across age groups, with each group representing about 20% of the sample.
    - Gender: The sample is slightly skewed towards females (53.25%) compared to males (46.75%).
3. **Industry Distribution:**
    - Solar PV Manufacturer: 18%
    - Solar PV Installer: 21.25%
    - Waste Management Company: 22.75%
    - Government Agency: 21.5%
    - Academic/Research Institution: 16.5%
4. **Years of Experience:**
    - The majority of respondents (46%) have 1-6 years of experience in the solar industry.
    - 15% have more than 10 years of experience.

5. **Waste Management Systems:**
    - 48.5% of respondents reported having a system in place for collecting and managing solar PV waste.
    - 51.5% reported not having such a system.
6. **Key Findings from Likert-scale Questions:**
    - The highest mean score was for "Importance of Sustainable Practices" (3.0525 out of 5), indicating a general agreement on the importance of implementing sustainable practices for solar PV module waste management.

1. "Challenge of Technological Limitations" had the second-highest mean score (3.04), suggesting that technological limitations are perceived as a significant challenge in recycling solar PV modules.
2. "Importance of Financial Viability" had the lowest mean score (2.9125), but it's still close to the neutral point, indicating a moderate level of agreement on the need to improve the financial viability of solar PV recycling.

Objective 1: Assess the Current State of Solar PV Waste Management

● The majority of respondents are aware of the importance of solar PV waste management.

- Significant gaps exist in the actual implementation of effective waste management
practices.
- Main barriers include lack of infrastructure, regulatory challenges, and technological limitations.
- Age and industry are significant predictors of awareness levels.
- Three main clusters based on awareness and implementation levels.
- Key factors influencing the decision to adopt waste management practices were identified.

Objective 2: Evaluate the Economic Impact of Solar PV Waste Management

- The cost of implementing solar PV waste management practices is a significant concern.
- Industry type and years of experience are significant predictors of perceived economic impact.
- Three distinct groups based on economic concerns and willingness to invest in waste management.
- Key factors influencing economic impact perceptions include industry type and years of experience.

Objective 3: Identify the Environmental Impact of Solar PV Waste

- Improper solar PV waste disposal negatively impacts soil and water quality.
- Gender and industry type are significant predictors of environmental impact awareness.
- Three main groups based on environmental concerns and actions taken to mitigate impact.
- Key factors influencing environmental impact perceptions include gender and industry type.

Objective 4: Assess the Social Impact of Solar PV Waste Management

- General consensus on the importance of solar PV waste management for community health and safety.
- Age and years of experience are significant predictors of social impact awareness.
- Three distinct groups based on social concerns and community engagement in waste management. Key factors influencing social impact perceptions include age and years of experience.

Objective 5: Evaluate the Technological Challenges in Solar PV Waste Management

- Main challenges include a lack of advanced recycling technologies and insufficient technical expertise.
- Industry type and years of experience are significant predictors of perceived technological challenges.
- Three main groups based on technological concerns and readiness to adopt new technologies.
- Key factors influencing technological challenge perceptions include industry type and years of experience.

5.2 Regulatory Framework: WEEE Directive

The European Union (EU) has taken a pioneering role in addressing the challenge of PV module waste management through its comprehensive regulatory framework. The cornerstone of this approach is the Waste Electrical and Electronic Equipment (WEEE) Directive, which was revised in 2012 to explicitly include PV panels as one of the waste categories.

Key aspects of the WEEE Directive include:

1. **Extended Producer Responsibility (EPR):** The directive is based on the EPR principle, which places the responsibility for the entire lifecycle of PV modules on the producers. This includes the obligation to take back, recycle, and dispose of the modules they sell in EU member countries.

2. Collection and Recycling Targets: The directive sets ambitious targets for each member state:

- Collection: 45% during 2016-2019, increased to 85% from 2019 onwards
- Recycling: 80% reuse and recycling of collected modules

3. Financing Models: Producers can choose from different financing approaches to cover waste management costs, including:

- Pay-as-you-go (PAYG)
- Pay-as-you-put (PAYP)

4. National Implementation: Several EU member countries, including Germany, the UK, and Italy, have adapted the WEEE Directive into their national laws, ensuring a harmonized approach across the EU.

The WEEE Directive has been instrumental in creating a structured and legally binding framework for PV module waste management in Europe. It has driven the development of recycling infrastructure and encouraged producers to consider the end-of-life phase in their product designs.

5.3 Industry Initiatives and Recycling Programs

In parallel with the regulatory framework, the European solar industry has proactively developed initiatives and recycling programs to address PV module waste:

1. PV Cycle: This not-for-profit industry organization initiated a voluntary PV module recycling program even before the WEEE Directive revision. PV Cycle provides:

- Take-back services

- Recycling services

- Coverage across different countries, both within and outside the EU

2. Commercial Recycling Programs:

- First Solar's in-house recycling facility in the US

- Loser Chemie GmbH's recycling scheme in Germany

These industry-led initiatives demonstrate the sector's commitment to sustainable practices and have been crucial in developing the necessary infrastructure and expertise for PV module recycling.

5.4 Recycling Techniques and Material Recovery

The European PV recycling industry employs various techniques to dismantle modules, delaminate structures, and recover valuable materials:

1. Mechanical Processes

2. Thermal Processes

3. Chemical Processes

These techniques aim to recover materials such as:

1. Glass
2. Metals (aluminium, copper)
3. Semiconductor compounds

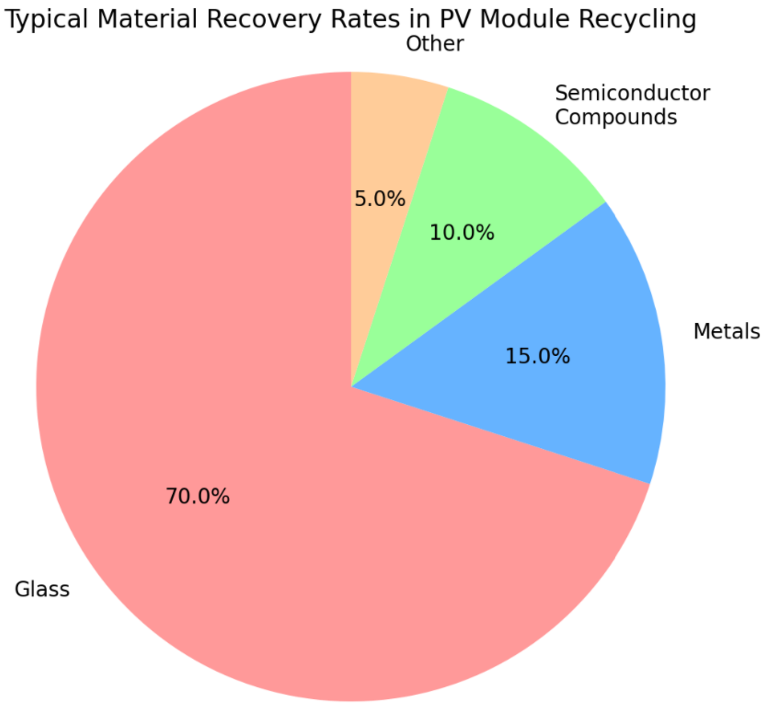
The recovery rates vary across techniques, with chemical processes generally yielding the highest recovery of undamaged solar cells. For instance, PV Cycle claims to achieve recycling rates of:

- Up to 96% for Si-based modules

- Up to 97% for thin-film modules

The industry is continuously working on improving these techniques to maximize material recovery and minimize environmental impact.

Figure 5.1 : Material Recovery Rates in PV Recycling



5.5 Global Overview of Solar PV Industry and Waste Generation

5.5.1 Global Solar PV Installations:

As of March 2021, the global cumulative capacity of grid-connected solar photovoltaic (PV) installations reached an impressive 40 GW. This rapid expansion of solar PV deployment has been accompanied by a significant decline in solar electricity tariffs in recent years, making it increasingly competitive with conventional energy sources. The decreasing costs and improving efficiency of solar technology have been key drivers in its widespread adoption across various countries and sectors.

5.5.2 Projected Global PV Waste:

While the growth of the solar PV industry brings numerous benefits, it also presents a new challenge: managing the waste generated from end-of-life PV modules. Current projections indicate a substantial increase in PV waste in the coming decades:

1. Under a regular loss scenario, global PV waste is expected to reach 1.7 million tonnes by 2030 and grow to 60 million tonnes by 2050.

2. An early-loss scenario, which considers increased loss from damage during installation/transport or other streams before the end of their useful life, projects even higher waste volumes: 8 million tonnes in 2030, escalating to 78 million tonnes by 2050

Figure 5.2: Projected Global PV Waste

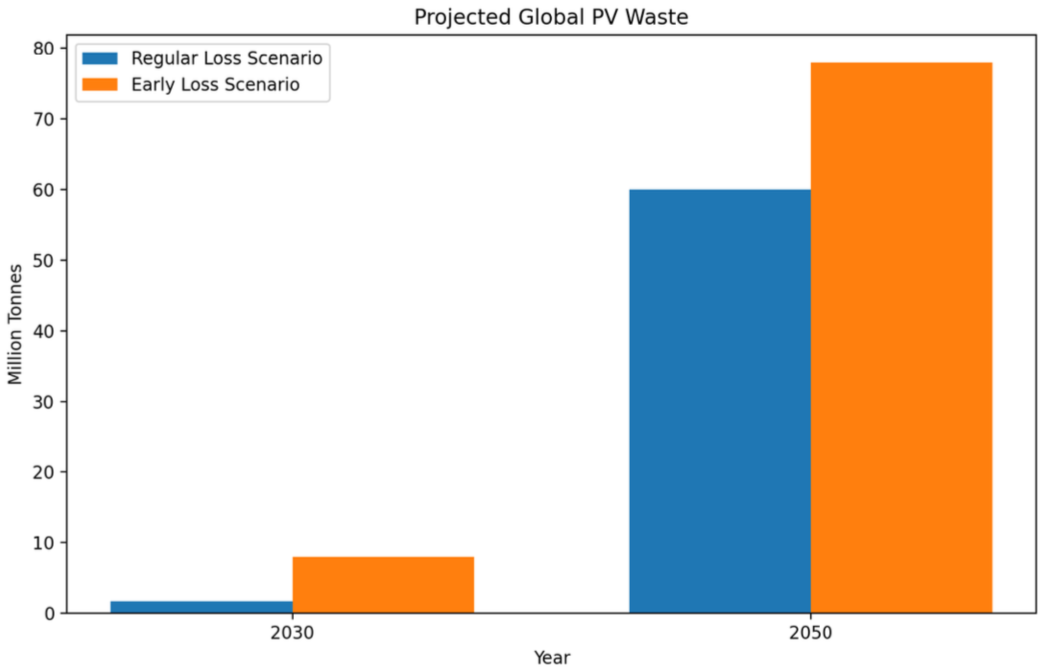
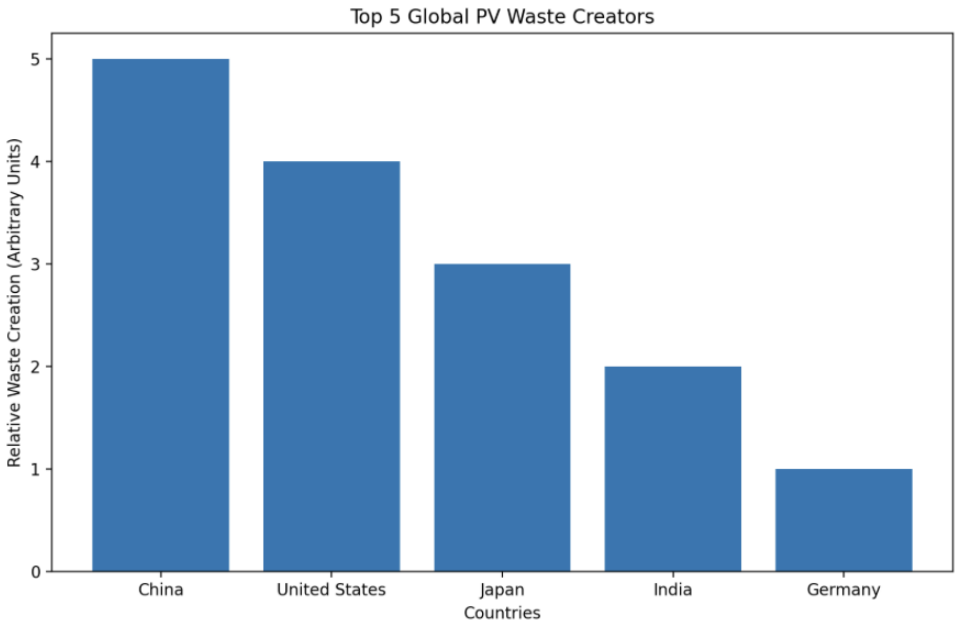


Figure 5.3: Projected Global PV Waste Creators



The data analysis reveals significant insights into the global PV waste management landscape. Figure 4.14 illustrates the projected growth of PV waste globally, with two scenarios: regular loss and early loss. By 2050, the early loss scenario predicts up to 78 million tonnes of PV waste, highlighting the urgent need for effective management strategies.

Figure 4.15 highlights the top five countries that significantly contribute to global PV waste. China, the United States, and Japan are the frontrunners in waste creation, with India and Germany following suit. These ranking underscores the substantial responsibility these countries bear in prioritizing and implementing effective PV waste management policies and infrastructure.

India's position as the fourth-largest PV waste creator and its ambitious solar energy targets underscores the importance of developing robust waste management practices. In contrast, despite being part of the EU with its advanced WEEE Directive, Germany's presence in the top five suggests that even countries with established regulations face significant challenges in managing PV waste.

5.6 Global Approaches

5.6.1 PV Waste Management in the USA

The United States lacks a federal-level policy specifically addressing PV waste management. Key points include:

1. Regulatory Framework:

- No national regulations for PV module recycling
- PV modules are typically classified as general waste
- Some states (e.g., Washington, California) have introduced their own regulations

2. Industry Initiatives:

- Solar Energy Industries Association (SEIA) launched a national PV recycling program
- First Solar operates its own recycling facilities

3. Recycling Infrastructure:

- Limited compared to Europe
- Mostly handled by general electronic waste recyclers

4. Challenges:

- Lack of consistent regulations across states
- Economic viability of recycling without policy support

5.6.2 PV Waste Management in Japan:

Japan has a more structured approach to PV waste management, influenced by its limited land space and environmental consciousness:

1. Regulatory Framework:

- PV modules covered under the general waste management law

- No specific regulations for PV recycling, but guidelines exist

2. Industry Initiatives:

- Japan Photovoltaic Energy Association (JPEA) developed voluntary guidelines

- Several manufacturers have their own take-back and recycling programs

3. Recycling Infrastructure:

- More developed than the USA, but less comprehensive than Europe

- Mix of specialized PV recyclers and general electronic waste facilities

4. Future Plan of Action:

- Ministry of Environment working on a more comprehensive PV recycling system

- Considering the introduction of a fund system for future recycling costs

5.6.3 PV Waste Management in China:

As the world's largest producer and installer of PV modules, China's approach to waste management is crucial:

1. Regulatory Framework:

- No specific regulations for PV module recycling

- Covered under general solid waste and electronic waste regulations

2. Industry Initiatives:

- Some manufacturers (e.g., Trina Solar) have their own recycling programs

- Research institutions working on recycling technologies

3. Recycling Infrastructure:

- Limited specialized PV recycling facilities

- Mostly handled by general electronic waste recyclers

4. Challenges and Future Outlook:

- Huge volumes of future waste expected

- The government recognizes the need for a comprehensive approach

- Plans to develop national standards and regulations for PV recycling

5.6.4 PV Waste Management in India:

- India does not have a dedicated PV module waste management policy or regulation. PV modules are not covered under the existing electronic waste (e-waste) management regulations.

- Most PV module manufacturers (76%) do not recycle any components of the damaged modules and instead pass on the waste to the informal sector.

- A few leading PV module manufacturers like REC, First Solar, and Vikram Solar have institutional initiatives to recycle their products at the end of their useful life. Some are members of the PV Cycle Industry Association, which provides waste collection and recycling services.

- The Ministry of New and Renewable Energy (MNRE) has drafted a proposal for the safe handling and disposal of PV module glass to prevent antimony leaching into the environment.

- The Department of Science and Technology has launched a program to support research activities for waste management in the power industry, including solar panel and battery storage waste management and recycling.

5.6.5 Challenges and Future Projections

- India has yet to have a dedicated PV module waste management policy, leading to discarded modules being left unattended on project sites or dumped in landfills.

- A preliminary analysis suggests that PV modules have generated a cumulative waste of 285 kilotonnes as of FY21 from the early-life loss of the installed 40 GW grid-connected solar capacity.

- The global PV waste is projected to reach 1.7 million tonnes by 2030 and 60 million tonnes by 2050 under the regular loss scenario. Under the early-loss scenario, the cumulative global waste would increase to 8 million tonnes in 2030 and 78 million tonnes by 2050, with India being one of the top five PV waste creators.

5.6.6 Comparing the Approaches:

Comparing the approaches of the USA, Japan, Europe, and China with India reveals several key differences:

1. Regulatory Framework:

- **Europe:** Comprehensive, with WEEE Directive specifically including PV modules

- **USA:** No federal regulations, some state-level initiatives

- **Japan:** General waste management laws, with guidelines for PV

- **China:** No specific regulations, covered under general waste laws

- **India:** No specific regulations, covered under general waste laws

2. Producer Responsibility:

- **Europe:** Strong Extended Producer Responsibility (EPR) principle

- **USA:** Voluntary producer initiatives, no mandatory EPR

- **Japan:** Some voluntary producer initiatives, considering future EPR-like systems

- **China:** Limited producer responsibility initiatives

- **India:** Voluntary Initiatives

3. Recycling Infrastructure:

- **Europe:** Well-developed, with specialized PV recycling facilities

- **USA:** Limited, mostly general electronic waste recyclers

- **Japan:** Moderate development, mix of specialized and general facilities

- **China:** Limited, despite being the largest producer of PV modules

- **India:** Limited Infrastructure.

4. Collection and Recycling Targets:

- **Europe:** Specific targets set by WEEE Directive

- **USA, Japan, China, and India:** No specific targets for PV module collection or recycling

5. Financing Models:

- **Europe:** Various models (PAYG, PAYP) under WEEE Directive

- **USA, Japan, China, and India:** No standardized financing models for recycling

6. Industry Involvement:

- **Europe:** Strong industry-led initiatives (e.g., PV Cycle)

- **USA:** Some industry initiatives (e.g., SEIA program)

- **Japan:** Industry-developed guidelines and some company programs

- **China:** Limited industry-wide initiatives

- **India:** Guidelines exist, but execution has its own issues.

7. Future Outlook:

- **Europe:** Focus on improving existing systems and circular economy

- **USA:** Growing recognition of the need for federal-level action

- **Japan:** Plans for a more comprehensive recycling system

- **China:** Acknowledged the need for national standards and regulations

- **India:** Plans for a comprehensive recycling system are underway to achieve the Paris Agreement 2025 Target.

Figure 5.4: Projected Global PV Waste

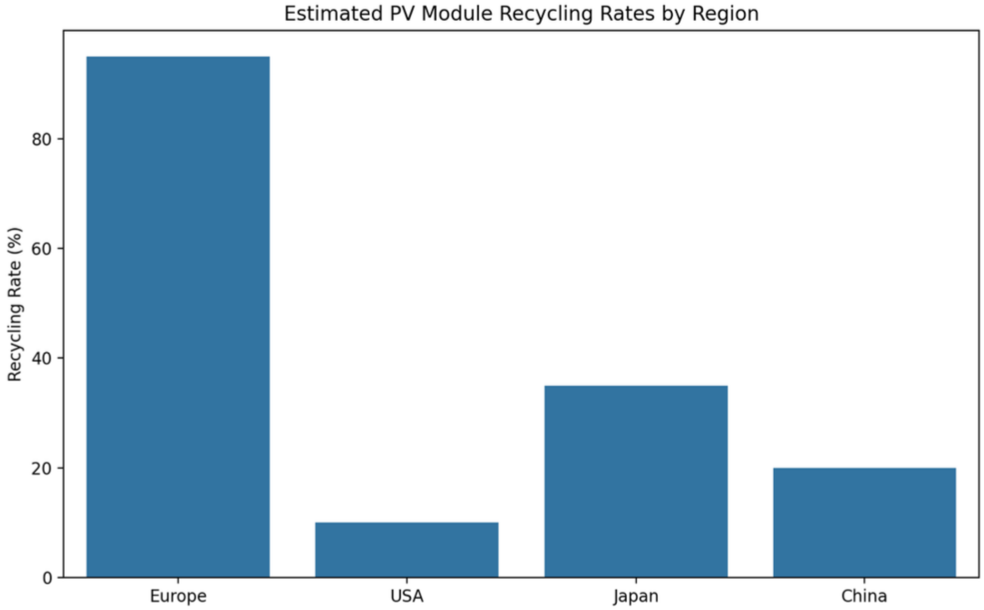


Figure 5.5: Annual PV Waste Generation

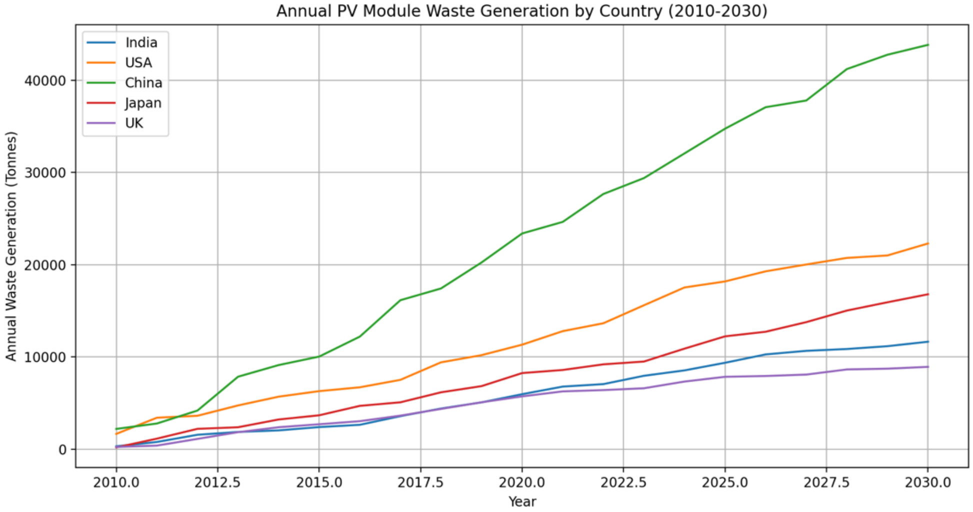


Figure 5.6: Paris Agreement Targets

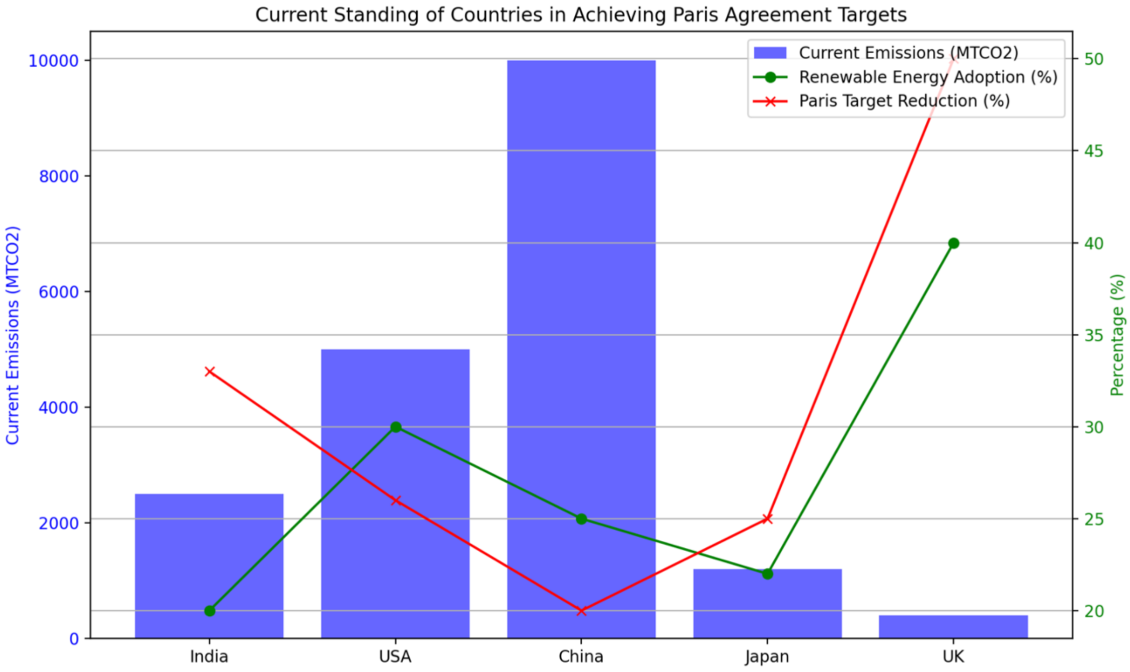


Figure 5.7: Comparison of Regulatory Framework

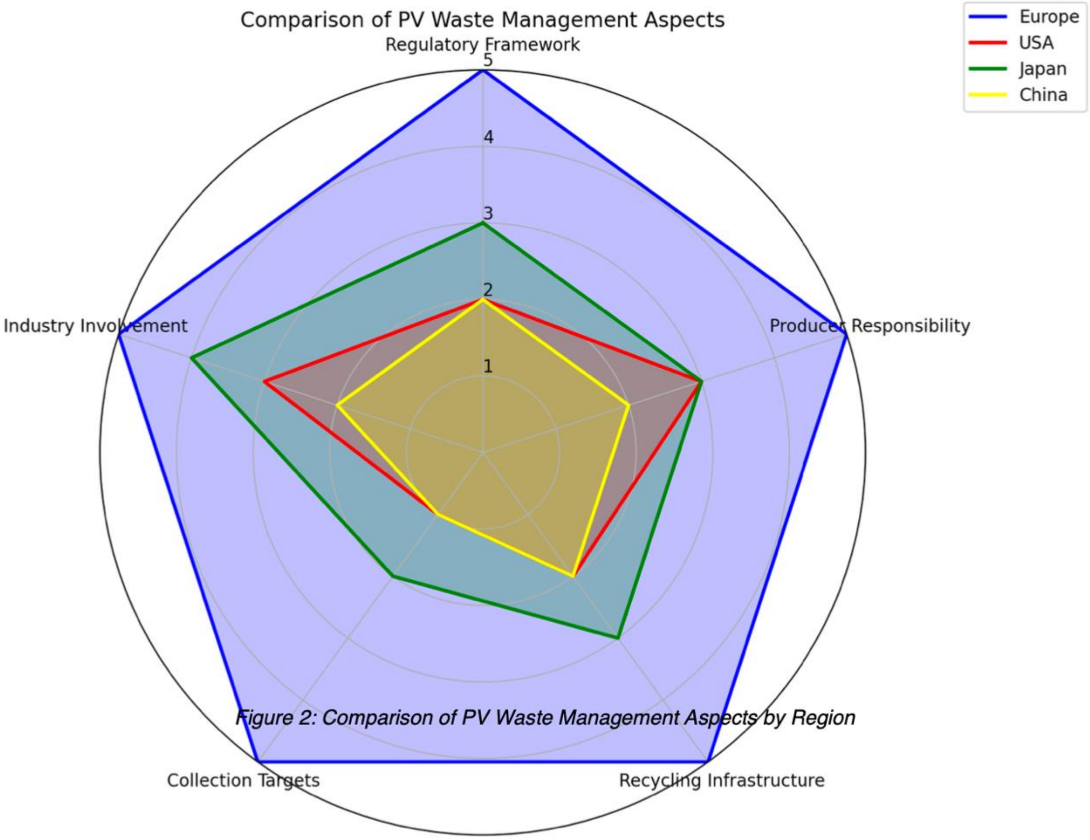


Figure 2: Comparison of PV Waste Management Aspects by Region

The data analysis reveals significant challenges and opportunities in PV module management for both India and European countries:

1. Scale of the Challenge:

The global PV waste projections highlight the urgency of developing effective waste management strategies. With up to 78 million tonnes of PV waste expected by 2050 in the early loss scenario, both India and European countries must scale up their recycling capacities significantly.

2. Technological Efficiency:

The high glass recovery rates (95-98%) for both thermal and mechanical recycling processes demonstrate the technical feasibility of efficient PV module recycling. European countries, with their advanced WEEE Directive, are better positioned to implement these technologies systematically. India can benefit from adopting and adapting these proven recycling techniques.

3. Policy Frameworks:

The EU's WEEE Directive provides a comprehensive model for PV waste regulation. India, currently lacking specific regulations for PV waste, could develop a similar framework tailored to its unique challenges and rapid market growth.

4. Market Dynamics:

India's position as the fourth-largest PV waste creator, coupled with its ambitious solar energy targets, underscores the need for proactive waste management planning.

European countries, while more advanced in their approaches, still face significant challenges, as evidenced by Germany's high ranking in waste creation.

5. Economic Opportunities:

The growing volume of PV waste presents economic opportunities in recycling and material recovery. Both regions can benefit from developing circular economy models around PV module lifecycle management.

Table 5.1: Comparison Table

Country	**Regulatory Framework**	**Recycling Focus**	**Manufacturer Responsibility**	**Policy Enforcement**	**Economy Approach**
India	Early stages	Low	Limited	Weak	Emerging
China	Implemented	Moderate	Moderate	Variable	Developing
USA	State-level variations	Increasing	Varies by state	Varies by state	Developing
Japan	Structured	High	High	Strong	Advanced
Europe	Advanced (WEEE Directive)	High	High	Strong	Advanced

CHAPTER VI:

SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

6.1 Summary

1. **Weak relationships:** The analysis reveals weak relationships between stakeholder demographics and the challenges they face in managing solar PV waste. This is evidenced by the low correlations and small R-squared values in the regression models.
2. **Industry effects:** Industry appears to have the most consistent, albeit small, influence across different challenges. For example, Industries 2-5 generally face fewer regulatory challenges compared to the reference industry.
3. **Age and experience:** Age and years of experience show small and inconsistent effects across different challenges. For instance, age is negatively associated with recycling challenges and reasons for not having a waste management system, but positively associated with infrastructure and technological challenges.
4. **Gender:** Gender appears to have minimal impact on most challenges, with small and inconsistent coefficients across models.
5. **Variation in challenges:** The descriptive statistics show that there is considerable variation in the levels of challenges faced by stakeholders, as indicated by the standard deviations and range of responses.

6.2 Implications

Holistic approach needed: Given the weak relationships between demographics and challenges, a one-size-fits-all approach based on demographic factors is unlikely to be effective. The industry should consider a more holistic approach to addressing solar PV waste management challenges.

1. **Industry-specific strategies:** While the effects are small, the consistent influence of industry across models suggests that tailored strategies for different sectors within the solar PV industry might be beneficial.
2. **Education and awareness:** The weak relationship between demographics and challenges might indicate a general lack of awareness or standardized practices across the industry. This suggests a need for broad-based education and awareness programs.
3. **Policy implications:** Policymakers should note that demographic factors alone are not strong predictors of the challenges faced in solar PV waste management. Regulations and support mechanisms may need to be designed with consideration for other factors beyond demographics.
4. **Further research needed:** The low explanatory power of the models suggests that other factors not captured in this analysis may be more influential in determining the challenges faced by stakeholders. Further research should explore additional variables such as company size, location, regulatory environment, or technological access.

5. **Focus on specific challenges:** The variation in challenge levels (as seen in the descriptive statistics) suggests that some areas, such as technological limitations, may require more attention than others.

6.3 Recommendations for Future Research

1. **Qualitative Deep Dive:** Conduct in-depth interviews and focus groups with industry stakeholders to uncover nuanced insights that quantitative data might have missed. This could reveal underlying factors contributing to the challenges.
2. **Expanded Variable Set:** Investigate additional factors such as company size, geographical location, specific technologies used, and regulatory environments. These might provide stronger explanatory power for the observed challenges.
3. **Advanced Statistical Analysis:** Employ techniques like cluster analysis or decision trees to identify meaningful subgroups or patterns that might not be apparent in simple correlations or regressions.
4. **Policy Impact Assessment:** Evaluate how current policies and regulations affect different aspects of solar PV waste management. This could help in formulating more effective policy recommendations.
5. **Technological Barrier Analysis:** Conduct a detailed study of specific technological limitations in the industry, focusing on how they contribute to waste management challenges

Following are the additional recommendations for the countries:

1. For India:

- Develop specific regulations for PV module waste management.
- Invest in recycling infrastructure and technology transfer from European counterparts.
- Implement extended producer responsibility (EPR) schemes.
- Integrate waste management planning into national solar energy policies.

2. For European Countries:

- Continue refining and implementing the WEEE Directive.
- Invest in research for more efficient and cost-effective recycling technologies.
- Promote standardization of PV module design for easier recycling.
- Develop cross-border cooperation for optimal resource utilization in recycling.

3. For Both Regions:

- Foster international collaboration on PV waste management research and best practices.
- Encourage design for recyclability in PV module manufacturing.
- Develop public awareness campaigns on the importance of proper PV waste disposal.
- Explore innovative financing mechanisms to support recycling infrastructure development.

Recommendations for sustainable PV waste management include:

- Developing and refining specific regulations for PV module waste.
- Investing in recycling infrastructure and technology.
- Implementing extended producer responsibility schemes.
- Promoting design for recyclability in PV module manufacturing.
- Fostering international collaboration on research and best practices.

Table 6.1: Challenges & Opportunities Table

Country	Challenges	Opportunities
India	Lack of structured policies, informal practices	Develop comprehensive regulations, formalize waste management
China	Variable enforcement, need for improved sustainability	Enhance enforcement, promote sustainable practices
USA	Inconsistent state-level regulations, low recycling rates	Standardize regulations, increase recycling infrastructure

Japan	High cost of recycling, need for technological advancements	Invest in recycling technology, strengthen circular economy
Europe	Complex regulatory compliance, high recycling targets	Lead in sustainable practices, achieve circular economy goals

6.4 Conclusion

The research delved into the complex challenges and opportunities of solar photovoltaic (PV) waste management, offering a comprehensive view of the current global landscape. A key revelation was the significant disparity between the acknowledged significance of PV waste management and the practical execution of effective strategies. Despite growing recognition of the pressing need for structured systems, especially in anticipation of a surge in solar PV waste by 2050, about 51.5% of respondents reported a lack of such frameworks in their sectors. This gap underscores the industry-specific obstacles, including technological, economic, and regulatory barriers.

From an economic angle, the study brought to light the substantial financial consequences of establishing effective PV waste management, particularly in countries like India. The willingness to invest in adequate waste management solutions varies significantly by sector and experience level. While some industries see potential economic gains from recycling and material recovery, the high initial costs often act as a deterrent. In contrast, European nations have implemented advanced economic models, such as 'Pay-as-you-go' and 'Pay-as-you-put' schemes, which bolster waste management practices. These models could serve as valuable benchmarks for countries like India, albeit requiring careful adaptation to align with diverse socioeconomic contexts and strategic policy implementation.

The environmental ramifications of inadequate PV waste management emerged as a critical concern. Improper disposal of PV modules can result in hazardous substance leaching, such as cadmium and antimony, endangering soil and water integrity. In Europe, where regulatory frameworks like the WEEE Directive are effective, targeted recycling initiatives have mitigated these environmental risks, recovering up to 97% of certain materials. Such frameworks present a model for other nations; however, countries with underdeveloped regulatory systems, such as India, face significant environmental challenges unless they adopt similar recycling technologies and enforce robust policies to safeguard natural resources.

From a social standpoint, the research highlighted the wider community ramifications of PV waste management practices. The public health risks posed by inadequate disposal are significant, especially for workers in informal recycling sectors prevalent in developing countries like India. There exists a consensus on the necessity of addressing PV waste for public health and safety, yet the uptake of socially responsible practices remains insufficient. Demographic factors, including age and experience, influence risk perception, with younger and less experienced individuals often less aware of potential dangers. Awareness campaigns and educational initiatives are critical to closing this gap, particularly as solar energy expands in areas with underdeveloped infrastructure.

Technological constraints were identified as a vital barrier to implementing effective PV waste management. The study underscored challenges stemming from a lack of advanced recycling technologies, particularly in countries with nascent waste management frameworks. Europe's technological progress, which enables the efficient recovery of valuable materials from PV modules, stands in stark contrast to the rudimentary infrastructures found in places like India. Here, PV waste management is frequently subsumed under general electronic waste processing, lacking the necessary specialization to address the unique aspects of PV waste.

Given these findings, it is evident that urgent policy interventions are required to tackle PV waste management challenges. The success of Europe's WEEE Directive, which enforces producer responsibility for solar PV waste, illustrates the potential of regulatory frameworks to promote industry compliance and innovation. For nations like India, similar policies could be tailored to fit local contexts, incentivizing formalized recycling systems and economic investment in appropriate waste management strategies. These policies must consider the distinct social, economic, and infrastructural environments they aim to address.

Finally, the necessity for national and international collaboration is paramount. The global nature of the solar energy sector underscores the need for countries to collaborate on standardized methodologies for PV waste management. This research emphasizes the importance of sharing technological advancements, regulatory practices, and economic models across borders. Developing nations, in particular, stand to gain from the innovations achieved by European countries as they scale up waste management infrastructures. Meanwhile, developed regions can glean insights from the rapid proliferation of solar energy in emerging markets. The research investigated the intricate challenges and opportunities associated with solar photovoltaic (PV) waste management, providing a nuanced view of the current global scenario. A principal finding highlighted a substantial disconnect between the recognized importance of PV waste management and the actual implementation of effective practices. Despite an increasing acknowledgment of the urgent need for formalized systems, particularly in light of projected solar PV waste growth by 2050, approximately 51.5% of respondents noted a lack of such frameworks within their sectors. This gap reflects industry-specific challenges, encompassing technological, economic, and regulatory hurdles.

From an economic perspective, the study revealed the significant financial implications of establishing effective PV waste management, especially in nations like India. The readiness to invest in adequate waste management solutions varies notably by sector and experience level. While some industries perceive potential economic benefits from recycling and material recovery, the high initial costs often deter investment. Conversely, European nations have implemented advanced economic models, such as "Pay-as-you-go" and "Pay-as-you-put" schemes, which enhance waste management practices. These models could serve as valuable references for countries like India, albeit requiring careful adaptation to align with diverse socioeconomic contexts and strategic policy implementation.

The environmental ramifications of inadequate PV waste management emerged as a critical concern. Improper disposal of PV modules can result in hazardous substance leaching, such as cadmium and antimony, endangering soil and water integrity. In Europe, where regulatory frameworks like the WEEE Directive are effective, targeted recycling initiatives have mitigated these environmental risks, recovering up to 97% of certain materials. Such frameworks present a model for other nations; however, countries with underdeveloped regulatory systems, such as India, face significant environmental challenges unless they adopt similar recycling technologies and enforce robust policies to safeguard natural resources.

From a social standpoint, the research highlighted the ramifications of PV waste management practices on the broader community. The public health risks posed by inadequate disposal are significant, especially for workers in informal recycling sectors in developing countries like India. There exists a consensus on the necessity of addressing PV waste for public health and safety, yet the uptake of socially responsible practices remains insufficient. Demographic factors, including age and experience, influence risk perception, with younger and less experienced individuals often less aware of potential dangers. Awareness campaigns and educational initiatives are critical to closing this gap, particularly as solar energy expands in areas with underdeveloped infrastructure.

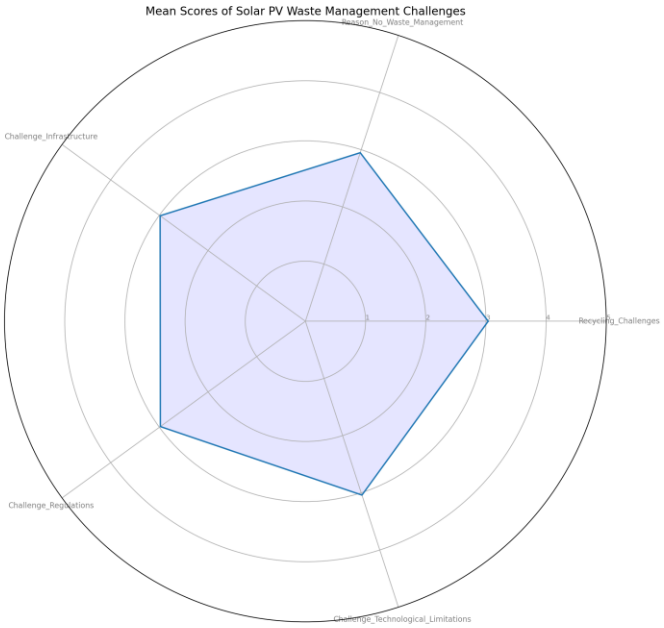
Technological constraints were identified as a vital barrier to implementing effective PV waste management. The study underscored challenges stemming from a lack of advanced recycling technologies, particularly in countries with nascent waste management frameworks. Europe's technological progress, which enables the efficient recovery of valuable materials from PV modules, stands in stark contrast to the rudimentary infrastructures found in places like India. Here, PV waste management is frequently subsumed under general electronic waste processing, needing more specialization to address the unique aspects of PV waste.

Given these findings, it is evident that urgent policy interventions are required to tackle PV waste management challenges. The success of Europe's WEEE Directive, which enforces producer responsibility for solar PV waste, illustrates the potential of regulatory frameworks to promote industry compliance and innovation. For nations like India, similar policies could be tailored to fit local contexts, incentivizing formalized recycling systems and economic investment in appropriate waste management strategies. These policies must consider the distinct social, economic, and infrastructural environments they aim to address.

Finally, the research underscores the critical need for national and international collaboration. The global nature of the solar energy sector underscores the need for countries to work together on standardized methodologies for PV waste management. This research highlights the importance of sharing technological advancements, regulatory practices, and economic models across borders. Developing nations, in particular, stand to benefit from the innovations achieved by European countries as they scale up waste management infrastructures. Meanwhile, developed regions can learn from the rapid proliferation of solar energy in emerging markets. The key takeaway is that these challenges are not strongly influenced by demographic factors such as age, gender, industry sector, or years of experience. This suggests that the issues faced in solar PV waste management are pervasive across the industry and not confined to specific groups.

The high variability in responses, coupled with the weak predictive power of demographic-based regression models, indicates that the challenges are multifaceted and likely influenced by factors not captured in this study. This complexity underscores the need for a more nuanced and comprehensive approach to understanding and addressing solar PV waste management issues. The radar chart provides a visual representation of the challenge landscape:1

Figure 6.1: Radar Chart



The radar chart titled "Mean Scores of Solar PV Waste Management Challenges" provides a multidimensional view of the complexities involved in managing solar photovoltaic waste. It highlights the interplay between infrastructural limitations, regulatory frameworks, technological constraints, recycling obstacles, and hazardous waste management issues. The relative significance of these challenges, as represented on the chart's axes, offers valuable insights into the prioritization of efforts within the solar waste management sector.

The geometry of the chart suggests a nuanced landscape where specific challenges may dominate discussions. For example, if recycling difficulties or technological limitations show higher mean scores, it could indicate an urgent need for innovation in material recovery processes or advancements in the design of PV panels for end-of-life management. In contrast, lower scores in areas such as regulatory challenges may point to a more developed policy environment, although this interpretation would need to be validated with contextual data. This comprehensive representation emphasizes the importance of an integrated approach to solar PV waste management, where progress in one area could potentially drive improvements throughout the entire system.

In conclusion, the issue of solar photovoltaic module waste is emerging as a significant challenge that requires urgent attention, particularly as global solar capacity continues to grow. For India, proactively addressing this challenge will be vital in preserving its leadership in the renewable energy sector. By adopting global best practices, encouraging innovation in recycling technologies, and aligning national policies with international frameworks such as the Paris Agreement, India can mitigate environmental hazards and secure a bright solar future.

The journey toward a sustainable solar energy ecosystem extends beyond simply increasing installations; it necessitates a holistic approach that carefully considers the entire lifecycle of solar modules, from production to disposal. This comprehensive strategy ensures that the advantages of solar energy do not come at the expense of long-term environmental sustainability. If India and other nations rise to meet this challenge, the promise of a clean, sustainable, and renewable energy future will not only be fulfilled but potentially surpassed. The responsibility now rests with policymakers, industry leaders, and stakeholders. It is imperative to act decisively and collaboratively to address the issue of solar PV module waste. Such action should align with global climate objectives, safeguard the environment, and establish a truly circular economy for solar energy.

References

Abhilash, Shenoy, S.S., Shetty, D.K., Lobo, L.S. and N., S.K. (2023), "Green bond as an innovative financial instrument in the indian financial market: Insights from systematic literature review approach", *Sage Open*, Vol. 13 No. 2, doi: https://doi.org/10.1177/21582440231178783

Abideen, A.Z., Pyeman, J., Sundram, V.P.K., Tseng, M.-L. and Sorooshian, S. (2021), "Leveraging capabilities of technology into a circular supply chain to build circular business models: A state-of-the-art systematic review", *Sustainability*, Vol. 13 No. 16, p. 8997, doi: https://doi.org/10.3390/su13168997

Addeo, A. *et al.* (1983) Use of polymeric materials in the assembly of solar cells, *Solar Energy*, 30(5), pp. 421–424. Available at: https://doi.org/10.1016/0038-092x(83)90111-1.

Adhikari, D.R., Techato, K. and Jariyaboon, R. (2024), "A systematic literature review on renewable energy technologies for energy sustainability in Nepal: Key challenges and opportunities", *International Journal of Renewable Energy Development*, Vol. 13 No. 2, pp. 206–222, doi: https://doi.org/10.61435/ijred.2024.60032.

Agamuthu, P. and Victor, D. (2011) Policy trends of extended producer responsibility in Malaysia, *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 29(9), pp. 945–953. Available at: https://doi.org/10.1177/0734242x11413332.

Aho, A.V. (2011) Complexity theory, in *Computer Science*. New York, NY: Springer New York, pp. 241–267. Available at: https://dx.doi.org/10.1007/978-1-4614-1168-0_12

Al-Lozi, E. and Papazafeiropoulou, A. (2011) Intention-Based models: The theory of planned behavior within the context of IS, in *Information Systems Theory*. New York, NY: Springer New York, pp. 219–239. Available at:http://dx.doi.org/10.1007/978-1-4419-9707-4_12

Alex Olanrewaju Adekanmbi *et al.* (2024) Assessing the environmental health and safety risks of solar energy production, *World Journal of Biology Pharmacy and Health Sciences*, 17(2), pp. 225–231. Available at: https://doi.org/10.30574/wjbphs.2024.17.2.0080.

Ali, A. *et al.* (2024) Recycling and material extraction from end-of-life photovoltaic modules waste: Exploring physical recovery techniques, in *2024 IEEE 1st Karachi Section Humanitarian Technology Conference (KHI-HTC)*. IEEE. Available at: http://dx.doi.org/10.1109/khi-htc60760.2024.10482243

Allen, M. (2017) *DPSIR (drivers, pressures, states, impacts, responses), Learning for Sustainability*. Available at: https://learningforsustainability.net/mwa/dpsir/

Aloini, D., Dulmin, R., Mininno, V., Stefanini, A. and Zerbino, P. (2020), "Driving the Transition to a Circular Economic Model: A systematic review on drivers and critical success factors in circular economy", *Sustainability*, Vol. 12 No. 24, p. 10672, doi: https://doi.org/10.3390/su122410672.

Alrasheedi, M., Capretz, L.F. and Raza, A. (2015), "A systematic review of the critical factors for success of mobile learning in higher education (university students' perspective)", *Journal of Educational Computing Research*, Vol. 52 No. 2, pp. 257–276, doi: https://doi.org/10.1177/0735633115571928.

Alreahi, M., Bujdosó, Z., Dávid, L.D. and Gyenge, B. (2023), "Green supply chain management in hotel industry: A systematic review", *Sustainability*, Vol. 15 No. 7, p. 5622, doi: https://doi.org/10.3390/su15075622.

Alsema, E. and de Wild, M.J. (2005) Environmental impact of crystalline silicon photovoltaic module production, *MRS Proceedings*, 895(1). Available at: https://doi.org/10.1557/proc-0895-g03-05

Alvarado, M.M., Kum, H.-C., Gonzalez Coronado, K., Foster, M.J., Ortega, P. and Lawley, M.A. (2017), “Barriers to remote health interventions for type 2 diabetes: A systematic review and proposed classification scheme”, *Journal of Medical Internet Research,* Vol. 19 No. 2, p. e28, doi: https://doi.org/10.2196/jmir.6382.

Alzahmi, W. and Ndiaye, M. (2023) AHP decision-making approach for solar photovoltaic (PV) modules end-of-life (EOL) disposition strategies, in *2023 Middle East and North Africa Solar Conference (MENA-SC)*. IEEE. Available at: http://dx.doi.org/10.1109/mena-sc54044.2023.10374487

Anantha, A. (1997) Solar photovoltaic as an energy source for India, in *IECEC-97 Proceedings of the Thirty-Second Intersociety Energy Conversion Engineering Conference (Cat. No.97CH6203)*. IEEE, pp. 2328–2333. Available at: http://dx.doi.org/10.1109/iecec.1997.65823

Andeobu, L., Wibowo, S. and Grandhi, S. (2021), “A systematic review of e-waste generation and environmental management of Asia Pacific countries”, *International Journal of Environmental Research and Public Health*, Vol. 18 No. 17, p. 9051, doi: https://doi.org/10.3390/ijerph18179051.

Ansari, Md.F. *et al.* (2013) Analysis of barriers to implement solar power installations in India using interpretive structural modeling technique, *Renewable and Sustainable Energy Reviews*, 27, pp. 163–174. Available at: https://doi.org/10.1016/j.rser.2013.07.002.

Assumpção, J.J., Campos, L.M. de S., Jabbour, A.B.L. de S., Jabbour, C.J.C. and Vazquez-Brust, D.A. (2019), “Green Supply Chain Practices: A comprehensive and theoretically multidimensional framework for categorization”, *Production*, Vol. 29, doi: https://doi.org/10.1590/0103-6513.20190047.

Atkins, J.P. *et al.* (2011) Managing the marine environment: Is the DPSIR framework holistic enough?, *Systems Research and Behavioral Science*, 28(5), pp. 497–508. Available at: https://doi.org/10.1002/sres.1111.

Auer, A. (2015) *Photovoltaic module decommissioning and recycling in Europe and Japan*, *Epsilon Archive for Student Projects*. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:slu:epsilon-s-4105.

Aziz, S.A. *et al.* (2022) Challenges in Adopting Successful Waste-to-Energy Policies in EU Countries: Indonesia study case, in *2022 IEEE Electrical Power and Energy Conference (EPEC)*. IEEE. Available at: http://dx.doi.org/10.1109/epec56903.2022.10000255

Azzabi, L., Azzabi, D. and Kobi, A. (2020) The multi-criteria approach decision, in *International Series in Operations Research & Management Science*. Cham: Springer

International Publishing, pp. 1–23. Available at: http://dx.doi.org/10.1007/978-3-030-57262-4_1

Bajagain, R. *et al.* (2020) Current practices on solar photovoltaic waste management: An overview of the potential risk and regulatory approaches of the photovoltaic waste, *Journal of Korean Society of Environmental Engineers*, 42(12), pp. 690–708. Available at: https://doi.org/10.4491/ksee.2020.42.12.690.

Bang, Y.-Y. *et al.* (2018) Comparative assessment of solar photovoltaic panels based on metal-derived hazardous waste, resource depletion, and toxicity potentials, *International Journal of Green Energy*, 15(10), pp. 550–557. Available at: https://doi.org/10.1080/15435075.2018.1505618.

Barker, P.P. and Bing, J.M. (2005) Advances in solar photovoltaic technology: An applications perspective, in *IEEE Power Engineering Society General Meeting, 2005*. IEEE. Available at: http://dx.doi.org/10.1109/pes.2005.1489304

Bati, G.F. and Singh, V.K. (2021) Altrumetrics: Inferring altruism propensity based on mobile phone use patterns, *IEEE Transactions on Big Data*, 7(2), pp. 397–406. Available at: https://doi.org/10.1109/tbdata.2018.2873346.

Bayod-Rújula, A.A. (2019) Solar photovoltaics (PV), in *Solar Hydrogen Production*. Elsevier, pp. 237–295. Available at: http://dx.doi.org/10.1016/b978-0-12-814853-2.00008-4

Bell, S. (2012) DPSIR=A Problem Structuring Method? An exploration from the 'Imagine' approach, *European Journal of Operational Research*, 222(2), pp. 350–360. Available at: https://doi.org/10.1016/j.ejor.2012.04.029.

Bellová, J. and Špírková, T. (2021) The theory of planned behaviour as a research tool an connection with tax law and economics, *Financial Law Review*, 1(21 (1)), pp. 1–15. Available at: https://doi.org/10.4467/22996834flr.21.001.13284.

Berry, I. (2021) Top 10 Greenest Countries, *Bizclik Media Ltd*, 21 October. Available at: https://sustainabilitymag.com/top10/top-10-greenest-countries-2.

Bhagavathula, A.S., Elnour, A.A., Jamshed, S.Q. and Shehab, A. (2016), "Health professionals' knowledge, attitudes and practices about pharmacovigilance in India: A systematic review and meta-analysis", *PLOS ONE*, Vol. 11 No. 3, p. e0152221, doi: https://doi.org/10.1371/journal.pone.0152221.

Bhole, G.P. (2018) Multi Criteria Decision Making (MCDM) Methods and its applications, *International Journal for Research in Applied Science and Engineering Technology*, 6(5), pp. 899–915. Available at: https://doi.org/10.22214/ijraset.2018.5145.

Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M.Z., *et al.* (2020), "Review of life-cycle based methods for absolute environmental sustainability assessment and their applications", *Environmental Research Letters*, Vol. 15 No. 8, p. 083001, doi: https://doi.org/10.1088/1748-9326/ab89d7.

Blanco, C.F., Cucurachi, S., Peijnenburg, W.J.G.M., Beames, A. and Vijver, M.G. (2020), "Are technological developments improving the environmental sustainability of photovoltaic electricity?", *Energy Technology*, Vol. 8 No. 11, doi: https://doi.org/10.1002/ente.201901064.

Bortoleto, A.P., Kurisu, K.H. and Hanaki, K. (2012) Model development for household waste prevention behaviour, *Waste Management*, 32(12), pp. 2195–2207. Available at: https://doi.org/10.1016/j.wasman.2012.05.037.

Breeze, P. (2016) Solar Photovoltaic Technologies, in *Solar Power Generation*. Elsevier, pp. 51–55. Available at: http://dx.doi.org/10.1016/b978-0-12-804004-1.00008-7

Bulatetskaya, A.Y. (2019) Sociological and mathematical models as tools of social processes applied sociological research, *International Journal of Recent Technology and Engineering (IJRTE)*, 8(4), pp. 5462–5473. Available at: https://doi.org/10.35940/ijrte.d8364.118419.

Cagle, A.E., Shepherd, M., Grodsky, S.M., Armstrong, A., Jordaan, S.M. and Hernandez, R.R. (2023), “Standardized metrics to quantify solar energy-land relationships: A global systematic review”, *Frontiers in Sustainability*, Vol. 3, doi: https://doi.org/10.3389/frsus.2022.1035705.

Cairney, P., Timonina, I. and Stephan, H. (2023), “How can policy and policymaking foster climate justice? A qualitative systematic review”, *Open Research Europe*, Vol. 3, p. 51, doi: https://doi.org/10.12688/openreseurope.15719.2.

Calcott, P. and Walls, M. (2000) Can downstream waste disposal policies encourage upstream ‘design for environment’?, *American Economic Review*, 90(2), pp. 233–237. Available at: https://doi.org/10.1257/aer.90.2.233.

Caldés, N. and Rodriguez-Serrano, I. (2018) Potential contribution of concentrated solar power in meeting the sustainable development goals, in *AIP Conference Proceedings*. Author(s). Available at: http://dx.doi.org/10.1063/1.5067130

Camilleri, M.A. (2022), “The rationale for ISO 14001 certification: A systematic review and a cost–benefit analysis”, *Corporate Social Responsibility and Environmental Management*, Vol. 29 No. 4, pp. 1067–1083, doi: https://doi.org/10.1002/csr.2254.

Cantzler, J., Creutzig, F., Ayargarnchanakul, E., Javaid, A., Wong, L. and Haas, W. (2020), “Saving resources and the climate? A systematic review of the circular economy and its mitigation potential”, *Environmental Research Letters*, Vol. 15 No. 12, p. 123001, doi: https://doi.org/10.1088/1748-9326/abbeb7.

Caporaso, J.A. and Levine, D. (1992) Neoclassical political economy, in *Theories of Political Economy*. Cambridge University Press, pp. 79–99. Available at: http://dx.doi.org/10.1017/cbo9780511840197.006

Carr, E.R. *et al.* (2007) Applying DPSIR to sustainable development, *International Journal of Sustainable Development & World Ecology*, 14(6), pp. 543–555. Available at: https://doi.org/10.1080/13504500709469753.

Centobelli, P., Cerchione, R., Chiaroni, D., Del Vecchio, P. and Urbinati, A. (2020), “Designing business models in circular economy: A systematic literature review and research agenda”, *Business Strategy and the Environment*, Vol. 29 No. 4, pp. 1734–1749, doi: https://doi.org/10.1002/bse.2466.

Chaisamrej, R. and Zimmerman, R.S. (2014) A Comparative Investigation of TPB and Altruism Frameworks for an Empirically based Communication Approach to Enhance Paper Recycling, *Applied Environmental Education & Communication*, 13(1), pp. 28–37. Available at: https://doi.org/10.1080/1533015x.2014.913962.

Chang, N.-B., Pires, A. and Martinho, G. (2011) Empowering systems analysis for solid waste management: Challenges, trends, and perspectives, *Critical Reviews in Environmental Science and Technology*, 41(16), pp. 1449–1530. Available at: https://doi.org/10.1080/10643381003608326.

Chaurey, A. (2001) The growing photovoltaic market in India, *Progress in Photovoltaics: Research and Applications*, 9(3), pp. 235–244. Available at: https://doi.org/10.1002/pip.370.

Chen, G. and Ji, Z. (2024), “A review of solar and wind energy resource projection based on the earth system model”, *Sustainability*, Vol. 16 No. 8, p. 3339, doi: https://doi.org/10.3390/su16083339.

Chen, P.-Y., Feng, R., Xu, Y. and Zhu, J.-H. (2023), “Recycling and reutilization of waste carbon fiber reinforced plastics: Current status and prospects”, *Polymers*, Vol. 15 No. 17, p. 3508, doi: https://doi.org/10.3390/polym15173508.

Chen, W.-S. *et al.* (2021) Recovery of valuable materials from the waste crystalline-silicon photovoltaic cell and ribbon, *Processes*, 9(4), p. 712. Available at: https://doi.org/10.3390/pr9040712.

Choi, J.-K. (2017a) A case study of sustainable manufacturing practice: End-of-Life photovoltaic recycling, in *Sustainable Design and Manufacturing 2017*. Cham: Springer International Publishing, pp. 277–279. Available at: http://dx.doi.org/10.1007/978-3-319-57078-5_27

Choi, J.-K. (2017b) A case study of sustainable manufacturing practice: End-of-Life photovoltaic recycling, in *Sustainable Design and Manufacturing 2017*. Cham: Springer International Publishing, pp. 277–279. Available at: http://dx.doi.org/10.1007/978-3-319-57078-5_27

Chrzanowski, M. and Zawada, P. (2023), "Fraction separation potential in the recycling process of photovoltaic panels at the installation site—a conceptual framework from an economic and ecological safety perspective", *Energies*, Vol. 16 No. 5, p. 2084, doi: https://doi.org/10.3390/en16052084.

Clift, R. and France, C. (2008) Extended producer responsibility in the EU: A visible march of folly, *Journal of Industrial Ecology*, 10(4), pp. 5–7. Available at: https://doi.org/10.1162/jiec.2006.10.4.5.

Coban, A., Ertis, I.F. and Cavdaroglu, N.A. (2018) Municipal solid waste management via multi-criteria decision making methods: A case study in Istanbul, Turkey, *Journal of Cleaner Production*, 180, pp. 159–167. Available at: https://doi.org/10.1016/j.jclepro.2018.01.130.

Comello, S., Reichelstein, S. and Sahoo, A. (2018) The road ahead for solar PV power, *Renewable and Sustainable Energy Reviews*, 92, pp. 744–756. Available at: https://doi.org/10.1016/j.rser.2018.04.098.

Cook, S., de Kok, B. and Odland, M.L. (2016), "'It's a very complicated issue here': Understanding the limited and declining use of manual vacuum aspiration for postabortion care in Malawi: A qualitative study", *Health Policy and Planning*, p. czw128, doi: https://doi.org/10.1093/heapol/czw128.

Cucca, R., Friesenecker, M. and Thaler, T. (2023), "Green gentrification, social justice, and climate change in the literature: Conceptual origins and future directions", *Urban Planning*, Vol. 8 No. 1, doi: https://doi.org/10.17645/up.v8i1.6129.

Curlee, W. and Gordon, R.L. (2010) Introduction to complexity theory, *Complexity Theory and Project Management*, 1, pp. 3–13. Available at: https://doi.org/10.1002/9780470949986.ch1.

D’Adamo, I., Miliacca, M. and Rosa, P. (2017) Economic feasibility for recycling of waste crystalline silicon photovoltaic modules, *International Journal of Photoenergy*, 2017(1), pp. 1–6. Available at: https://doi.org/10.1155/2017/4184676.

Dancza, V. and Cheng, K. (2022) Investigation of the circular economy approach in Asian solar PV manufacturing, in *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc48317.2022.9938604

David-Chavez, D.M. and Gavin, M.C. (2018), “A global assessment of Indigenous community engagement in climate research”, *Environmental Research Letters*, Vol. 13 No. 12, p. 123005, doi: https://doi.org/10.1088/1748-9326/aaf300.

de Souza, D.T. and Torres, P.H.C. (2021), “Greening and just cities: Elements for fostering a south–north dialogue based on a systematic literature review”, *Frontiers in Sustainable Cities*, Vol. 3, doi: https://doi.org/10.3389/frsc.2021.669944.

Deng, R. *et al.* (2019) A techno-economic review of silicon photovoltaic module recycling, *Renewable and Sustainable Energy Reviews*, 109(1), pp. 532–550. Available at: https://doi.org/10.1016/j.rser.2019.04.020.

Devaraj, P. and Haribabu, E. (2015) Discontinuities in the Trajectory of Solar Photovoltaic (spv) Technology Development in India, *Perspectives on Global Development and Technology*, 14(3), pp. 301–332. Available at: https://doi.org/10.1163/15691497-12341348.

do Canto, N.R., Grunert, K.G. and Dutra de Barcellos, M. (2022), "Goal-framing theory in environmental behaviours: Review, future research agenda and possible applications in behavioural change", *Journal of Social Marketing*, Vol. 13 No. 1, pp. 20–40, doi: 10.1108/jsocm-03-2021-0058. doi: https://doi.org/10.1177/21582440231178783

Dr. Brahampal Singh (2017) SOLAR ENERGY CONTRIBUTION IN DIGITAL INDIA : CHALLENGES OF CONSUMER AWARENESS TO SOLAR ENERGY, *EPH - International Journal of Science And Engineering*, 3(2), pp. 35–40. Available at: https://doi.org/10.53555/eijse.v3i2.68.

Dubey, S., Jadhav, N.Y. and Zakirova, B. (2013) Socio-Economic and environmental impacts of silicon based photovoltaic (PV) technologies, *Energy Procedia*, 33, pp. 322–334. Available at: https://doi.org/10.1016/j.egypro.2013.05.073.

Dunlop, E.D., Halton, D. and Ossenbrink, H.A. (2005) 20 years of life and more: Where is the end of life of a PV module?, in *Conference Record of the Thirty-first IEEE Photovoltaic*

Specialists Conference, 2005. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.2005.1488449

Dutta, V. (2006) SOLAR PHOTOVOLTAICS IN INDIA : A STATUS REVIEW - 한국신재생에너지학회:학술대회논문집,” 한국신재생에너지학회:학술대회논문집, 6(1), pp. 130–133.

Echebarria, C., Barrutia, J.M., Eletxigerra, A., Hartmann, P. and Apaolaza, V. (2017), “Local sustainability processes worldwide: A systematic review of the literature and research agenda”, *Journal of Environmental Planning and Management*, Vol. 61 No. 8, pp. 1289–1317, doi: https://doi.org/10.1080/09640568.2017.1342611.

Elmustapha, H., Hoppe, T. and Bressers, H. (2018) Understanding stakeholders’ views and the influence of the socio-cultural dimension on the adoption of solar energy technology in Lebanon, *Sustainability*, 10(2), p. 364. Available at: https://doi.org/10.3390/su10020364.

Emes, M.J., Arjomandi, M. and Nathan, G.J. (2015) Effect of heliostat design wind speed on the levelised cost of electricity from concentrating solar thermal power tower plants, *Solar Energy*, 115(1), pp. 441–451. Available at: https://doi.org/10.1016/j.solener.2015.02.047.

Eslami, H. and Krishnan, T. (2023) New sustainable product adoption: The role of economic and social factors, *Energy Policy*, 183(1), p. 113824. Available at: https://doi.org/10.1016/j.enpol.2023.113824.

Faircloth, C.C. *et al.* (2019) The environmental and economic impacts of photovoltaic waste management in Thailand, *Resources, Conservation and Recycling*, 143, pp. 260–272. Available at: https://doi.org/10.1016/j.resconrec.2019.01.008.

Farooq, M., Cheng, J., Khan, N.U., Saufi, R.A., Kanwal, N. and Bazkiaei, H.A. (2022), “Sustainable waste management companies with innovative smart solutions: A systematic review and conceptual model”, *Sustainability*, Vol. 14 No. 20, p. 13146, doi: https://doi.org/10.3390/su142013146.

Farrell, C.C. *et al.* (2020) Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules, *Renewable and Sustainable Energy Reviews*, 128, p. 109911. Available at: https://doi.org/10.1016/j.rser.2020.109911.

Farrukh, A., Mathrani, S. and Taskin, N. (2020), “Investigating the theoretical constructs of a green lean six sigma approach towards environmental sustainability: A systematic literature review and future directions”, *Sustainability*, Vol. 12 No. 19, p. 8247, doi: https://doi.org/10.3390/su12198247.

Ferrara, C. and Philipp, D. (2012) Why do PV modules fail?, *Energy Procedia*, 15(1), pp. 379–387. Available at: https://doi.org/10.1016/j.egypro.2012.02.046.

Franco, M.A. and Groesser, S.N. (2021) A systematic literature review of the solar photovoltaic value chain for a circular economy, *Sustainability*, 13(17), p. 9615. Available at: https://doi.org/10.3390/su13179615.

Fthenakis, V.M. (2000) End-of-life management and recycling of PV modules, *Energy Policy*, 28(14), pp. 1051–1058. Available at: https://doi.org/10.1016/s0301-4215(00)00091-4.

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., *et al.* (2018), “Negative emissions—Part 2: Costs, potentials and side effects”, *Environmental Research Letters*, Vol. 13 No. 6, p. 063002, doi: https://doi.org/10.1088/1748-9326/aabf9f.

G., N.S., M., S. and P., R. (2020) Recovering resources from the end-of-life PV modules, in *DAE SOLID STATE PHYSICS SYMPOSIUM 2019*. AIP Publishing. Available at: http://dx.doi.org/10.1063/5.0018021

Gaeta, G.L. *et al.* (2021) Innovation in the solid waste management industry: Integrating neoclassical and complexity theory perspectives, *Waste Management*, 120(1), pp. 50–58. Available at: https://doi.org/10.1016/j.wasman.2020.11.009.

Ganesan, K. and Valderrama, C. (2022) Anticipatory life cycle analysis framework for sustainable management of end-of-life crystalline silicon photovoltaic panels, *Energy*, 245(1), p. 123207. Available at:https://doi.org/10.1016/j.energy.2022.123207.

García-Feijoo, M., Eizaguirre, A. and Rica-Aspiunza, A. (2020), "Systematic review of sustainable-development-goal deployment in business schools", *Sustainability*, Vol. 12 No. 1, p. 440, doi: https://doi.org/10.3390/su12010440.

Garg, S. *et al.* (2023) Sustainable behavior with respect to managing e-wastes: Factors influencing e-waste management among young consumers, *International Journal of Environmental Research and Public Health*, 20(1), p. 801. Available at: https://doi.org/10.3390/ijerph20010801.

Gasanov, E.A. (2021) NEOCLASSICAL ECONOMIC THEORY: ESSENCE AND CHARACTERISTICS, *Vestnik of Khabarovsk State University of Economics and Law*, 3(3 (107)), pp. 5–10. Available at: https://doi.org/10.38161/2618-9526-2021-3-05-10.

Gasanov, E.A. *et al.* (2022) NEOCLASSICAL ECONOMIC THEORY: DOMINANT CONCEPTS, *Vestnik of Khabarovsk State University of Economics and Law*, 1(2(109)), pp. 5–13. Available at: https://doi.org/10.38161/2618-9526-2022-2-005-013.

Gasparri, E., Arasteh, S., Kuru, A., Stracchi, P. and Brambilla, A. (2023), “Circular economy in construction: A systematic review of knowledge gaps towards a novel research framework”, *Frontiers in Built Environment*, Vol. 9, doi: https://doi.org/10.3389/fbuil.2023.1239757.

Gautam, A., Shankar, R. and Vrat, P. (2021) End-of-life solar photovoltaic e-waste assessment in India: A step towards a circular economy, *Sustainable Production and Consumption*, 26(1), pp. 65–77. Available at: https://doi.org/10.1016/j.spc.2020.09.011.

Geng, Y., Mitchell, B. and Zhu, Q. (2009), “Teaching industrial ecology at Dalian University of Technology”, *Journal of Industrial Ecology*, Vol. 13 No. 6, pp. 978–989, doi: https://doi.org/10.1111/j.1530-9290.2009.00184.x

Gerold, E. and Antrekowitsch, H. (2024) Advancements and challenges in photovoltaic cell recycling: A comprehensive review, *Sustainability*, 16(6), p. 2542. Available at: https://doi.org/10.3390/su16062542.

Ghaleb Al-Aqqad, A.O. and Menyhart, J. (2023) Solar panels problem after end-of-life and waste management (SWOT analysis for the global directives of PV's waste management), *International Review of Applied Sciences and Engineering*, 14(2), pp. 220–229. Available at: https://doi.org/10.1556/1848.2022.00511.

Ghimire, B.T., Muneenam, U. and Techato, K. (2023), "Renewable energy use in green hotels for sustainability: A systematic review", *International Journal of Energy Economics and Policy*, Vol. 13 No. 6, pp. 618–627, doi: https://doi.org/10.32479/ijeep.14521

Giurea, R., Carnevale Miino, M., Torretta, V. and Rada, E.C. (2024), "Approaching sustainability and circularity along waste management systems in universities: An overview and proposal of good practices", *Frontiers in Environmental Science*, Vol. 12, doi: https://doi.org/10.3389/fenvs.2024.1363024.

Go, Y.-J., Kang, D.-H., Park, H.-J., Lee, J.-H. and Shim, J.-K. (2024), "Meta-Analysis of life cycle assessment studies for polyethylene terephthalate water bottle system", *Sustainability*, Vol. 16 No. 2, p. 535, doi: https://doi.org/10.3390/su16020535.

Goe, M., Gaustad, G. and Tomaszewski, B. (2015) System tradeoffs in siting a solar photovoltaic material recovery infrastructure, *Journal of Environmental Management*, 160, pp. 154–166. Available at: https://doi.org/10.1016/j.jenvman.2015.05.038.

Goel, M. (2016) Solar rooftop in India: Policies, challenges and outlook, *Green Energy & Environment*, 1(2), pp. 129–137. Available at: https://doi.org/10.1016/j.gee.2016.08.003.

Gonçalves, B. de S.M., Carvalho, F.L. de and Fiorini, P. de C. (2022), “Circular economy and financial aspects: A systematic review of the literature”, *Sustainability*, Vol. 14 No. 5, p. 3023, doi: https://doi.org/10.3390/su14053023.

Gönen, Ç. and Kaplanoğlu, E. (2019) Environmental and economic evaluation of solar panel wastes recycling, *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 37(4), pp. 412–418. Available at: https://doi.org/10.1177/0734242x19826331.

Goulart Coelho, L.M., Lange, L.C. and Coelho, H.M. (2016) Multi-criteria decision making to support waste management: A critical review of current practices and methods, *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 35(1), pp. 3–28. Available at: https://doi.org/10.1177/0734242x16664024.

Greenhalgh, T., Wherton, J., Papoutsi, C., Lynch, J., Hughes, G., A’Court, C., Hinder, S., *et al*. (2017), “Beyond Adoption: A new framework for theorizing and evaluating nonadoption, abandonment, and challenges to the scale-up, spread, and sustainability of health and care technologies”, *Journal of Medical Internet Research*, Vol. 19 No. 11, p.

e367, doi: https://doi.org/10.2196/jmir.8775.

Guevara-Herrero, I., Bravo-Torija, B. and Pérez-Martín, J.M. (2024), "Educational practice in education for environmental justice: A systematic review of the literature", *Sustainability*, Vol. 16 No. 7, p. 2805, doi: https://doi.org/10.3390/su16072805.

Gui, L. *et al.* (2016) Efficient implementation of Collective Extended producer responsibility legislation, *Management Science*, 62(4), pp. 1098–1123. Available at: https://doi.org/10.1287/mnsc.2015.2163.

Gutierrez-Lopez, J. *et al.* (2023) Decision support frameworks in solid waste management: A systematic review of multi-criteria decision-making with sustainability and social indicators, *Sustainability*, 15(18), p. 13316. Available at: https://doi.org/10.3390/su151813316.

Gutierrez-Lopez, J., McGarvey, R.G., Costello, C. and Hall, D.M. (2023), "Decision support frameworks in solid waste management: A systematic review of multi-criteria decision-making with sustainability and social indicators", *Sustainability*, Vol. 15 No. 18, p. 13316, doi: https://doi.org/10.3390/su151813316.

Han, H. (2021), "Consumer behavior and environmental sustainability in tourism and hospitality: A review of theories, concepts, and latest research", *Journal of Sustainable*

Tourism, Vol. 29 No. 7, pp. 1021–1042, doi: https://doi.org/10.1080/09669582.2021.1903019.

Hasan, A.A.Q. *et al.* (2021) Delamination-and electromigration-related failures in solar panels—a review, *Sustainability*, 13(12), p. 6882. Available at: https://doi.org/10.3390/su13126882.

Heath, G.A. *et al.* (2020) Research and development priorities for silicon photovoltaic module recycling to support a circular economy, *Nature Energy*, 5(7), pp. 502–510. Available at: https://doi.org/10.1038/s41560-020-0645-2.

Hernandez-Palma, H.G., Alvarado, J.R.P., Guiliany, J.E.G., Dotto, G.L. and Ramos, C.G. (2024), "Implications of machine learning in the generation of renewable energies in Latin America from a globalized vision: A systematic review", *International Journal of Energy Economics and Policy*, Vol. 14 No. 2, pp. 1–10, doi: https://doi.org/10.32479/ijeep.15301.

Hirpe, L. and Yeom, C. (2021a), "Municipal solid waste management policies, practices, and challenges in ethiopia: A systematic review", *Sustainability*, Vol. 13 No. 20, p. 11241, doi: https://doi.org/10.3390/su132011241.

Hirpe, L. and Yeom, C. (2021b), "Municipal solid waste management policies, practices, and challenges in ethiopia: A systematic review", *Sustainability*, Vol. 13 No. 20, p. 11241, doi: https://doi.org/10.3390/su132011241.

Hirth, S., Kreinin, H., Fuchs, D., Blossey, N., Mamut, P., Philipp, J. and Radovan, I. (2023a), "Barriers and enablers of 1.5° lifestyles: Shallow and deep structural factors shaping the potential for sustainable consumption", *Frontiers in Sustainability*, Vol. 4, doi: https://doi.org/10.3389/frsus.2023.1014662.

Hirth, S., Kreinin, H., Fuchs, D., Blossey, N., Mamut, P., Philipp, J. and Radovan, I. (2023b), "Barriers and enablers of 1.5° lifestyles: Shallow and deep structural factors shaping the potential for sustainable consumption", *Frontiers in Sustainability*, Vol. 4, doi: https://doi.org/10.3389/frsus.2023.1014662.

Hoang, P. *et al.* (2014) What metrics to evaluate sustainability of photovoltaic systems?, *Metallurgical Research & Technology*, 111(3), pp. 201–210. Available at: https://doi.org/10.1051/metal/2014007.

Holechek, J.L., Geli, H.M.E., Sawalhah, M.N. and Valdez, R. (2022), "A global assessment: Can renewable energy replace fossil fuels by 2050?", *Sustainability*, Vol. 14 No. 8, p. 4792, doi: https://doi.org/10.3390/su14084792.

Hopkins, R.A. and Powers, T.L. (2015) The Theory of Altruism and Consumer Behavior: Literature review and model development, in *Proceedings of the 1996 Multicultural*

Marketing Conference. Cham: Springer International Publishing, pp. 339–344. Available at: http://dx.doi.org/10.1007/978-3-319-17395-5_66

Houessionon, M.G.K., Ouendo, E.-M.D., Bouland, C., Takyi, S.A., Kedote, N.M., Fayomi, B., Fobil, J.N., *et al.* (2021), "Environmental heavy metal contamination from electronic waste (e-waste) recycling activities worldwide: A systematic review from 2005 to 2017", *International Journal of Environmental Research and Public Health*, Vol. 18 No. 7, p. 3517, doi: https://doi.org/10.3390/ijerph18073517.

Hsu, D.D., O'Donoughue, P., Fthenakis, V., Heath, G.A., Kim, H.C., Sawyer, P., Choi, J., *et al.* (2012), "Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation", *Journal of Industrial Ecology*, Vol. 16 No. s1, doi: https://doi.org/10.1111/j.1530-9290.2011.00439.x.

Iheanetu, K.J. (2022), "Solar photovoltaic power forecasting: A review", *Sustainability*, Vol. 14 No. 24, p. 17005, doi: https://doi.org/10.3390/su142417005

Indian Institute of Science (2024) *Solid waste management*. Available at: https://wgbis.ces.iisc.ac.in/energy/SWMTR/content1.html.

Issah, I., Arko-Mensah, J., Agyekum, T.P., Dwomoh, D. and Fobil, J.N. (2021), "Electronic waste exposure and DNA damage: A systematic review and meta-analysis", *Reviews on Environmental Health*, Vol. 38 No. 1, pp. 15–31, doi: https://doi.org/10.1515/reveh-2021-0074

.

Jacob, C., Sanchez-Vazquez, A. and Ivory, C. (2020), *Understanding Clinicians' Adoption of Mobile Health Tools: A Qualitative Review of the Most Used Frameworks (Preprint)*, JMIR Publications Inc. Jäger-Waldau, A. (2012) Overview of the global PV industry, in *Comprehensive Renewable Energy*. Elsevier, pp. 161–177. Available at: http://dx.doi.org/10.1016/b978-0-08-087872-0.00110-4

Jain, S., Sharma, T. and Gupta, A.K. (2022) End-of-life management of solar PV waste in India: Situation analysis and proposed policy framework, *Renewable and Sustainable Energy Reviews*, 153(2), p. 111774. Available at: https://doi.org/10.1016/j.rser.2021.111774.

Jayapradha, P. and Barik, D. (2023) A review of solar photovoltaic power utilizations in india and impacts of segregation and safe disposal of toxic components from retired solar panels, *International Journal of Energy Research*, 2023(1), pp. 1–11. Available at: https://doi.org/10.1155/2023/3196734.

Job, J.S. and Khanna, S. (2024), "Building a resilient future: Collaborative sustainability regulation", *Clean Energy*, Vol. 8 No. 3, pp. 223–237, doi: https://doi.org/10.1093/ce/zkae026.

Kaartemo, V. (2016) Creation and Shaping of the Global Solar Photovoltaic (PV) Market, in *Advances in Sustainability and Environmental Justice*. Emerald Group Publishing Limited, pp. 227–247. Available at: http://dx.doi.org/10.1108/s2051-503020160000019011

Kabir, S.E. *et al.* (2023) Adoption and implementation of extended producer responsibility for sustainable management of end-of-life solar photovoltaic panels, *Global Journal of Environmental Science and Management*, 9(Special Issue (Eco-Friendly Sustainable Management)), pp. 251–270. Available at: https://doi.org/10.22034/GJESM.2023.09.SI.15.

Kabir, Syed Enamul *et al.* (2023) Analysing economic feasibility of recycling end-of-life solar photovoltaic modules of Bangladesh, *Clean Technologies and Environmental Policy*, 25(10), pp. 3231–3245. Available at: https://doi.org/10.1007/s10098-023-02613-0.

Kalogirou, S.A. (2009) Photovoltaic systems, in *Solar Energy Engineering*. Elsevier, pp. 469–519. Available at: http://dx.doi.org/10.1016/b978-0-12-374501-9.00009-1

Kamran, M. *et al.* (2019) Solar Photovoltaic Grid Parity: A Review of Issues, Challenges and Status of Different PV Markets, *International Journal of Renewable Energy Research*, 9(1). Available at: https://doi.org/10.20508/ijrer.v9i1.8933.g7580.

Kanwal, Q., Zeng, X. and Li, J. (2021) Drivers-pressures-state-impact-response framework of hazardous waste management in China, *Critical Reviews in Environmental Science and Technology*, 52(16), pp. 2930–2961. Available at: https://doi.org/10.1080/10643389.2021.1902225.

Kapoor, K.K., Dwivedi, Y.K. and Williams, M.D. (2015), "Empirical examination of the role of three sets of innovation attributes for determining adoption of IRCTC mobile ticketing service", *Information Systems Management*, Vol. 32 No. 2, pp. 153–173, doi: https://doi.org/10.1080/10580530.2015.1018776.

Kar, S.K., Sharma, A. and Roy, B. (2016) Solar energy market developments in India, *Renewable and Sustainable Energy Reviews*, 62(1), pp. 121–133. Available at: https://doi.org/10.1016/j.rser.2016.04.043.

Karmperis, A.C. *et al.* (2013a) Decision support models for solid waste management: Review and game-theoretic approaches, *Waste Management*, 33(5), pp. 1290–1301. Available at: https://doi.org/10.1016/j.wasman.2013.01.017.

Karmperis, A.C. *et al.* (2013b) Decision support models for solid waste management: Review and game-theoretic approaches, *Waste Management*, 33(5), pp. 1290–1301. Available at: https://doi.org/10.1016/j.wasman.2013.01.017.

Karumba, S., Sethuvenkatraman, S., Dedeoglu, V., Jurdak, R. and Kanhere, S.S. (2023), “Barriers to blockchain-based decentralised energy trading: A systematic review”, *International Journal of Sustainable Energy*, Vol. 42 No. 1, pp. 41–71, doi: https://doi.org/10.1080/14786451.2023.2171417.

Kaur, P., Kaur, H. and Aggarwal, A. (2023) Waste management through waste segregation: Survey analysis of a North Delhi locality, *Journal of Business Management and Information Systems*, 10(2), pp. 31–42. Available at: https://doi.org/10.48001/jbmis.2023.1002006.

Kayikci, Y., Kazancoglu, Y., Gozacan-Chase, N. and Lafci, C. (2022), “Analyzing the drivers of smart sustainable circular supply chain for sustainable development goals through stakeholder theory”, *Business Strategy and the Environment*, Vol. 31 No. 7, pp. 3335–3353, doi: https://doi.org/10.1002/bse.3087.

Keita, L. (2012) Revealed preference theory, rationality, and neoclassical economics: Science or ideology, *Africa Development / Afrique et Développement*, 37(4), pp. 73–116. Available at: https://doi.org/10.2307/afrdevafrdev.37.4.73.

Keoleian, G.A. and Lewis, G.McD. (1997) Application of life-cycle energy analysis to photovoltaic module design, *Progress in Photovoltaics: Research and Applications*, 5(4), pp. 287–300. Available at: https://doi.org/10.1002/(sici)1099-159x(199707/08)5:4

Khalifa, A.A., Ibrahim, A.-J., Amhamed, A.I. and El-Naas, M.H. (2022), "Accelerating the transition to a circular economy for net-zero emissions by 2050: A systematic review", *Sustainability*, Vol. 14 No. 18, p. 11656, doi: https://doi.org/10.3390/su141811656.

Khatiwada, D., Golzar, F., Mainali, B. and Devendran, A.A. (2021), "Circularity in the management of municipal solid waste – A systematic review", *Environmental and Climate Technologies*, Vol. 25 No. 1, pp. 491–507, doi: https://doi.org/10.2478/rtuect-2021-0036.

Kim, H. and Park, H. (2018) PV waste management at the crossroads of circular economy and energy transition: The case of south korea, *Sustainability*, 10(10), p. 3565. Available at: https://doi.org/10.3390/su10103565.

Koliba, C. *et al.* (2022) Complexity theory and systems analysis, in *Handbook on Theories of Governance*. Edward Elgar Publishing. Available at: http://dx.doi.org/10.4337/9781800371972.00044

Kollmuss, A. and Agyeman, J. (2002) Mind the Gap: Why do people act environmentally and what are the barriers to pro-environmental behavior?, *Environmental Education Research*, 8(3), pp. 239–260. Available at: https://doi.org/10.1080/13504620220145401.

Komoto, K., Lee, J.-S., *et al.* (2018) *End-of-Life management of photovoltaic panels: Trends in PV module recycling technologies*. Office of Scientific and Technical Information (OSTI). Available at: http://dx.doi.org/10.2172/1561523

Komoto, K., Oyama, S., *et al.* (2018) Recycling of PV Modules and its Environmental Impacts, in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.2018.8547691

Kousounadis-Knousen, M.A., Bazionis, I.K., Georgilaki, A.P., Catthoor, F. and Georgilakis, P.S. (2023), "A review of solar power scenario generation methods with focus on weather classifications, temporal horizons, and deep generative models", *Energies*, Vol. 16 No. 15, p. 5600, doi: https://doi.org/10.3390/en16155600.

Krozer, J. and Doelman, P. (2003) Policy incentives for waste prevention. An economic approach to design for recycling, *The Journal of Sustainable Product Design*, 3(1/2), pp. 3–17. Available at: https://doi.org/10.1023/b:jspd.0000035554.28041.36.

Lakhani, L. and Herbert, S. (2022), “Theoretical frameworks applied in integrated reporting and sustainability reporting research”, *South African Journal of Economic and Management Sciences*, Vol. 25 No. 1, doi: https://doi.org/10.4102/sajems.v25i1.4427.

LaMorte, W.W. (2022) *The Theory of Planned Behavior, Behaviour Change Models* . Available at:https://sphweb.bumc.bu.edu/otlt/mphmodules/sb/behavioralchangetheories/BehavioralChangeTheories3.html.

Laronde, R., Charki, A. and Bigaud, D. (2012) Lifetime estimation of a photovoltaic module subjected to corrosion due to damp heat testing, *Journal of Solar Energy Engineering*, 135(2). Available at: https://doi.org/10.1115/1.4023101.

Lee, C.-L., Strong, R. and Dooley, K. (2021), *Analyzing Precision Agriculture Adoption Across the Globe: A Systematic Review of Scholarship from 1999 – 2020*, MDPI AG.

Lee, K. and Cha, J. (2019) Management of solar photovoltaic panels under the Extended Producer Responsibility Legislation, *Journal of the Korean Society of Mineral and Energy Resources Engineers*, 56(4), pp. 367–376. Available at: https://doi.org/10.32390/ksmer.2019.56.4.367.

Libby, C. and Shaw, S. (2019) Environmental and economic considerations for PV module end-of-life management, in *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc40753.2019.8981209

Liu, C., Zhang, Q. and Wang, H. (2020a) Cost-benefit analysis of waste photovoltaic module recycling in China, *Waste Management*, 118(1), pp. 491–500. Available at: https://doi.org/10.1016/j.wasman.2020.08.052.

Liu, C., Zhang, Q. and Wang, H. (2020b) Cost-benefit analysis of waste photovoltaic module recycling in China, *Waste Management*, 118(1), pp. 491–500. Available at: https://doi.org/10.1016/j.wasman.2020.08.052.

M. Fthenakis, V. (2003) Overview of potential hazards, in *Practical Handbook of Photovoltaics*. Elsevier, pp. 857–868. Available at: http://dx.doi.org/10.1016/b978-185617390-2/50037-4

Machado, C.G., Winroth, M.P. and Ribeiro da Silva, E.H.D. (2019), “Sustainable manufacturing in Industry 4.0: An emerging research agenda”, *International Journal of Production Research*, Vol. 58 No. 5, pp. 1462–1484, doi: https://doi.org/10.1080/00207543.2019.1652777.

Madrigal, A.N., Iyer-Raniga, U. and Yang, R. (2023) Exploring PV waste management solutions using circular strategies, *Journal of Sustainability Research*, 5(2). Available at: https://doi.org/10.20900/jsr20230008.

Madrigal, A.N., Raniga, U.I.- and Yang, R. (2023) Exploring PV waste management solutions using circular strategies, *Journal of Sustainability Research*, 5(2). Available at: https://doi.org/10.20900/jsr20230008.

Mahmoodi, M., Rasheed, E. and Le, A. (2024), "Systematic review on the barriers and challenges of organisations in delivering new net zero emissions buildings", *Buildings*, Vol. 14 No. 6, p. 1829, doi: https://doi.org/10.3390/buildings14061829.

Mahmoudi, S. *et al.* (2019) End-of-life photovoltaic modules: A systematic quantitative literature review, *Resources, Conservation and Recycling*, 146, pp. 1–16. Available at: https://doi.org/10.1016/j.resconrec.2019.03.018.

Mahmoudi, S., Huda, N. and Behnia, M. (2021) Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels, *Resources, Conservation and Recycling*, 164(1), p. 105145. Available at: https://doi.org/10.1016/j.resconrec.2020.105145.

Majumder, M. and Saha, A.K. (2016) Multi criteria decision making, in *Feasibility Model of Solar Energy Plants by ANN and MCDM Techniques*. Singapore: Springer Singapore, pp. 9–12. Available at: http://dx.doi.org/10.1007/978-981-287-308-8_3

Majumder, M. and Saha, A.K. (2016) Multi criteria decision making, in *Feasibility Model of Solar Energy Plants by ANN and MCDM Techniques*. Singapore: Springer Singapore, pp. 9–12. Available at: http://dx.doi.org/10.1007/978-981-287-308-8_3

Manju, S. and Sagar, N. (2017) Progressing towards the development of sustainable energy: A critical review on the current status, applications, developmental barriers and prospects of solar photovoltaic systems in India, *Renewable and Sustainable Energy Reviews*, 70, pp. 298–313. Available at: https://doi.org/10.1016/j.rser.2016.11.226.

Manni, M., Coccia, V., Paoletti, D., Raspadori, F., Ritonummi, T. and Cotana, F. (2020), “Shaping multi-level energy and climate policy within the SET plan framework”, *Sustainability*, Vol. 12 No. 22, p. 9545, doi: https://doi.org/10.3390/su12229545.

Markert, E., Celik, I. and Apul, D. (2020) Private and externality costs and benefits of recycling crystalline silicon (c-si) photovoltaic panels, *Energies*, 13(14), p. 3650. Available at: https://doi.org/10.3390/en13143650.

Marsillac, E. (2012) Management of the photovoltaic supply chain, *International Journal of Technology, Policy and Management*, 12(2/3), p. 195. Available at: https://doi.org/10.1504/ijtpm.2012.046926.

Martín-Blanco, C., Zamorano, M., Lizárraga, C. and Molina-Moreno, V. (2022), "The impact of COVID-19 on the sustainable development goals: Achievements and expectations", *International Journal of Environmental Research and Public Health*, Vol. 19 No. 23, p. 16266, doi: https://doi.org/10.3390/ijerph192316266.

Masson, G. *et al.* (2018) A Snapshot of Global PV Markets - The Latest Survey Results on PV Markets and Policies from the IEA PVPS Programme in 2017, in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.2018.8547794

Mathur, N., Singh, S. and Sutherland, J.W. (2020) Promoting a circular economy in the solar photovoltaic industry using life cycle symbiosis, *Resources, Conservation and Recycling*, 155, p. 104649. Available at: https://doi.org/10.1016/j.resconrec.2019.104649.

Matthews, R.L. and Marzec, P.E. (2012), "Social capital, a theory for operations management: A systematic review of the evidence", *International Journal of Production Research*, Vol. 50 No. 24, pp. 7081–7099, doi:

https://doi.org/10.1080/00207543.2011.617395.

Medina, T., Calmon, J.L., Vieira, D., Bravo, A. and Vieira, T. (2023), “Life cycle assessment of road pavements that incorporate waste reuse: A systematic review and guidelines proposal”, *Sustainability*, Vol. 15 No. 20, p. 14892, doi: https://doi.org/10.3390/su152014892.

Meena, S.C. (2023) Photovoltaic (PV) Modules Waste Management: A Holistic Framework For Sustainable Growth, *International Journal of Creative Research Thoughts*, 11(1), pp. 491–502. Available at: https://doi.org/https://www.ijcrt.org/papers/IJCRT2301188.pdf.

Miah, M.A.R. *et al.* (2023) Techno-economic assessment of solar photovoltaic (PV) waste management in Bangladesh, *IOP Conference Series: Earth and Environmental Science*, 1281(1), p. 012035. Available at: https://doi.org/10.1088/1755-1315/1281/1/012035.

Mickle, M.H. and Vogt, W.G. (1976) A dynamic sociological system model, *International Journal of Systems Science*, 7(10), pp. 1081–1200. Available at: https://doi.org/10.1080/00207727608941996.

Min, Z., Sawang, S. and Kivits, R.A. (2021), “Proposing circular economy ecosystem for Chinese smes: A systematic review”, *International Journal of Environmental Research* *and Public Health*, Vol. 18 No. 5, p. 2395, doi: https://doi.org/10.3390/ijerph18052395.

Misra, D. (2021) Floating Photovoltaic Plant in India: Current Status and Future Prospect, in *Lecture Notes in Mechanical Engineering*. Singapore: Springer Singapore, pp. 219–232. Available at: http://dx.doi.org/10.1007/978-981-16-2347-9_19

Mohr, N. *et al.* (2009) Environmental impact of thin-film GaInP/GaAs and multicrystalline silicon solar modules produced with solar electricity, *The International Journal of Life Cycle Assessment*, 14(3), pp. 225–235. Available at: https://doi.org/10.1007/s11367-009-0062-z.

Morgan, R. *et al.* (2012) The impact of a rapidly changing global PV market on the PV manufacturing supply chain, in *2012 38th IEEE Photovoltaic Specialists Conference*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.2012.6317912

Moskowitz, P.D. and Fthenakis, V.M. (1990) Toxic materials released from photovoltaic modules during fires: Health risks, *Solar Cells*, 29(1), pp. 63–71. Available at: https://doi.org/10.1016/0379-6787(90)90015-w.

Moskowitz, P.D., Fthenakis, V.M. and Zweibel, K. (1992) Health and safety issues related to the production, use and disposal of cadmium-based photovoltaic modules, in *IEEE*

Conference on Photovoltaic Specialists. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.1990.111776.

Munodawafa, R.T. and Johl, S.K. (2019), “A systematic review of eco-innovation and performance from the resource-based and stakeholder perspectives”, *Sustainability*, Vol. 11 No. 21, p. 6067, doi: https://doi.org/10.3390/su11216067.

Murakami, F. *et al.* (2015) How the Brazilian government can use public policies to induce recycling and still save money?, *Journal of Cleaner Production*, 96(1), pp. 94–101. Available at: https://doi.org/10.1016/j.jclepro.2014.03.083.

Nain, P. and Anctil, A. (2024) End-of-life solar photovoltaic waste management: A comparison as per European Union and United States regulatory approaches, *Resources, Conservation & Recycling Advances*, 21(1), p. 200212. Available at: https://doi.org/10.1016/j.rcradv.2024.200212.

Nain, P. and Kumar, A. (2020) Understanding the possibility of material release from end-of-life solar modules: A study based on literature review and survey analysis, *Renewable Energy*, 160(2), pp. 903–918. Available at: https://doi.org/10.1016/j.renene.2020.07.034.

Nash, J. and Bosso, C. (2013) Extended producer responsibility in the United States, *Journal of Industrial Ecology*, 17(2), pp. 175–185. Available at: https://doi.org/10.1111/j.1530-9290.2012.00572.x

Nathan, G.J., Battye, D.L. and Ashman, P.J. (2014) Economic evaluation of a novel fuel-saver hybrid combining a solar receiver with a combustor for a solar power tower, *Applied Energy*, 113(1), pp. 1235–1243. Available at: https://doi.org/10.1016/j.apenergy.2013.08.079.

Newaz, M.S. and Appolloni, A. (2023), “Evolution of behavioral research on E-waste management: Conceptual frameworks and future research directions”, *Business Strategy and the Environment*, Vol. 33 No. 2, pp. 477–503, doi: https://doi.org/10.1002/bse.3503.

Nguyen, K., Akbari, M., Quang, H.T., McDonald, S., Hoang, T.-H., Yap, T.L. and George, M. (2023), “Navigating Environmental Challenges through Supply Chain Quality Management 4.0 in Circular Economy: A Comprehensive Review”, *Sustainability*, Vol. 15 No. 24, p. 16720, doi: https://doi.org/10.3390/su152416720.

Nieto-Morone, M.B. *et al.* (2023) State and prospects of photovoltaic module waste generation in China, USA, and selected countries in Europe and South America, *Sustainable Energy & Fuels*, 7(9), pp. 2163–2177. Available at: https://doi.org/10.1039/d2se01685k.

Nikolaidis, P. (2023), "Solar energy harnessing technologies towards de-carbonization: A systematic review of processes and systems", *Energies*, Vol. 16 No. 17, p. 6153, doi: https://doi.org/10.3390/en16176153.

Nixon, J.D. *et al.* (2015) Issues and challenges of implementing waste-to-energy practices in india, in *Renewable Energy in the Service of Mankind Vol I*. Cham: Springer International Publishing, pp. 65–74. Available at: http://dx.doi.org/10.1007/978-3-319-17777-9_7

Nunes, A., Coelho Junior, L., Abrahão, R., Santos Júnior, E., Simioni, F., Rotella Junior, P. and Rocha, L. (2023), "Public policies for renewable energy: A review of the perspectives for a circular economy", *Energies*, Vol. 16 No. 1, p. 485, doi: https://doi.org/10.3390/en16010485.

Oke, A. (2015) Workplace waste recycling behaviour: A meta-analytical review, *Sustainability*, 7(6), pp. 7175–7194. Available at: https://doi.org/10.3390/su7067175.

Onungwe, I., Hunt, D.V.L. and Jefferson, I. (2023), "Transition and implementation of circular economy in municipal solid waste management system in nigeria: A systematic review of the literature", *Sustainability*, Vol. 15 No. 16, p. 12602, doi: https://doi.org/10.3390/su151612602.

Opp, K.-D. (1986) Das Modell des Homo Sociologicus. Eine Explikation und eine Konfrontierung mit dem utilitaristischen Verhaltensmodell, *Analyse & Kritik*, 8(1), pp. 1–27. Available at: https://doi.org/10.1515/auk-1986-0101

Oteng, D., Zuo, J. and Sharifi, E. (2021) A scientometric review of trends in solar photovoltaic waste management research, *Solar Energy*, 224(1), pp. 545–562. Available at: https://doi.org/10.1016/j.solener.2021.06.036.

Ottelin, J., Ala-Mantila, S., Heinonen, J., Wiedmann, T., Clarke, J. and Junnila, S. (2019), “What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications”, *Environmental Research Letters*, Vol. 14 No. 9, p. 093001, doi: https://doi.org/10.1088/1748-9326/ab2212.

Padmanathan, K. *et al.* (2019) A sociocultural study on solar photovoltaic energy system in India: Stratification and policy implication, *Journal of Cleaner Production*, 216(1), pp. 461–481. Available at: https://doi.org/10.1016/j.jclepro.2018.12.225.

Pandey, A., Pandey, P. and Tumuluru, J.S. (2022) Solar energy production in India and commonly used technologies—an overview, *Energies*, 15(2), p. 500. Available at: https://doi.org/10.3390/en15020500.

Pankadan, S., Nikam, S. and Anwer, N. (2020) An analysis for management of end-of-life solar PV in India, in *Proceedings of the 7th International Conference on Advances in Energy Research*. Singapore: Springer Singapore, pp. 1361–1371. Available at: http://dx.doi.org/10.1007/978-981-15-5955-6_129

Paredes, M., Padilla-Rivera, A. and Güereca, L. (2019), "Life cycle assessment of ocean energy technologies: A systematic review", *Journal of Marine Science and Engineering*, Vol. 7 No. 9, p. 322, doi: https://doi.org/10.3390/jmse7090322.

Patrício, J. *et al.* (2016) DPSIR—Two decades of trying to develop a unifying framework for marine environmental management?, *Frontiers in Marine Science*, 3(1). Available at: https://doi.org/10.3389/fmars.2016.00177.

Patterson, M.H. *et al.* (1994) Health, safety and environmental aspects of the use of cadmium compounds in thin film PV modules, *Solar Energy Materials and Solar Cells*, 35(1), pp. 305–310. Available at: https://doi.org/10.1016/0927-0248(94)90155-4

Rabaia, M.K.H., Semeraro, C. and Olabi, A.-G. (2022) Recent progress towards photovoltaics' circular economy, *Journal of Cleaner Production*, 373(1), p. 133864. Available at: https://doi.org/10.1016/j.jclepro.2022.133864.

Rajshree, B. and Manan, S. (2021) Solar photovoltaic energy in India: Business feasibility study and analogy of policies, *International Journal of Energy and Water Resources*, 5(2), pp. 133–144. Available at: https://doi.org/10.1007/s42108-020-00098-x.

Rathore, N. and Panwar, N.L. (2021) Strategic overview of management of future solar photovoltaic panel waste generation in the Indian context, *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 40(5), pp. 504–518. Available at: https://doi.org/10.1177/0734242x211003977.

Rediske, G. *et al.* (2022) Management of operation and maintenance practices in photovoltaic plants: Key performance indicators, *International Journal of Energy Research*, 46(6), pp. 7118–7136. Available at: https://doi.org/10.1002/er.7737.

Rediske, G., Siluk, J.C.M., Gastaldo, N.G., Rigo, P.D. and Rosa, C.B. (2018), “Determinant factors in site selection for photovoltaic projects: A systematic review”, *International Journal of Energy Research*, Vol. 43 No. 5, pp. 1689–1701, doi: https://doi.org/10.1002/er.4321.

Rehfuess, E.A., Puzzolo, E., Stanistreet, D., Pope, D. and Bruce, N.G. (2014), “Enablers and barriers to large-scale uptake of improved solid fuel stoves: A systematic review”, *Environmental Health Perspectives*, Vol. 122 No. 2, pp. 120–130, doi: https://doi.org/10.1289/ehp.1306639.

Rodrigues, J. and Hewig, J. (2021) *Let´s call it altruism ! A psychological perspective and hierarchical framework of altruism and prosocial behavior*. Center for Open Science. Available at: http://dx.doi.org/10.31234/osf.io/pj7eu

Ross and G., R. (1984) Technology developments toward 30-year-life of photovoltaic modules, *17th Photovoltaic Specialists Conference*, 17(1), pp. 464–472.

Rousta, K., Zisen, L. and Hellwig, C. (2020), “Household waste sorting participation in developing countries—a meta-analysis”, *Recycling*, Vol. 5 No. 1, p. 6, doi: https://doi.org/10.3390/recycling5010006.

Salas, D.A., Criollo, P. and Ramirez, A.D. (2021), “The role of higher education institutions in the implementation of circular economy in Latin America”, *Sustainability*, Vol. 13 No. 17, p. 9805, doi: https://doi.org/10.3390/su13179805.

Salim, H.K. *et al.* (2020) Systems approach to end-of-life management of residential photovoltaic panels and battery energy storage system in Australia, *Renewable and Sustainable Energy Reviews*, 134(1), p. 110176. Available at: https://doi.org/10.1016/j.rser.2020.110176.

Salim, H.K. *et al.* (2021) Dynamic modelling of Australian rooftop solar photovoltaic product stewardship transition, *Waste Management*, 127(1), pp. 18–29. Available at: https://doi.org/10.1016/j.wasman.2021.04.030.

Salim, H.K. *et al.* (2021) Dynamic modelling of Australian rooftop solar photovoltaic product stewardship transition, *Waste Management*, 127(1), pp. 18–29. Available at: https://doi.org/10.1016/j.wasman.2021.04.030.

Samadi, S., Terrapon-Pfaff, J., Lechtenböhmer, S. and Knoop, K. (2018), "Long-term low greenhouse gas emission development strategies for achieving the 1.5 °C target – insights from a comparison of German bottom-up energy scenarios", *Carbon Management*, Vol. 9 No. 5, pp. 549–562, doi: https://doi.org/10.1080/17583004.2018.1475174.

Sandor, D. *et al.* (2018) System dynamics of polysilicon for solar photovoltaics: A framework for investigating the energy security of renewable energy supply chains, *Sustainability*, 10(2), p. 160. Available at: https://doi.org/10.3390/su10010160.

Saravanan, V. *et al.* (2022) Status of solar photovoltaic systems in India, *Indian Journal of Power and River Valley Development*, pp. 145–149. Available at: https://doi.org/10.18311/ijprvd/2021/29661.

Sastry, E.V.R. (2002) The photovoltaic program in India, in *Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.2002.1190448

Scheller, F. *et al.* (2020) Exploring the role of stakeholder dynamics in residential photovoltaic adoption decisions: A synthesis of the literature, *Energies*, 13(23), p. 6283. Available at: https://doi.org/10.3390/en13236283.

Scherrens, A.-L., Beernaert, K., Robijn, L., Deliens, L., Pauwels, N.S., Cohen, J. and Deforche, B. (2018), “The use of behavioural theories in end-of-life care research: A systematic review”, *Palliative Medicine*, Vol. 32 No. 6, pp. 1055–1077, doi: https://doi.org/10.1177/0269216318758212.

Schmela, M. and SolarPower Europe. (2023) *Global Market Outlook For Solar Power 2023 - 2027 , SolarPower Europe*. Available at: https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2023-2027/detail.

Sekhar, V.R. and Pradeep, P. (2021) A review paper on advancements in solar PV technology, environmental impact of PV cell manufacturing, *International Journal of Advanced Research in Science, Communication and Technology*, 8(1), pp. 485–492. Available at: https://doi.org/10.48175/ijarsct-1887.

Seminario-Córdova, R. (2023), "Latin America towards sustainability through renewable energies: A systematic review", *Energies*, Vol. 16 No. 21, p. 7422, doi: https://doi.org/10.3390/en16217422.

Serafini, L.F., Feliciano, M., Rodrigues, M.A. and Gonçalves, A. (2023), "Systematic review and meta-analysis on the use of LCA to assess the environmental impacts of the composting process", *Sustainability*, Vol. 15 No. 2, p. 1394, doi: https://doi.org/10.3390/su15021394.

Seto, K.C., Churkina, G., Hsu, A., Keller, M., Newman, P.W.G., Qin, B. and Ramaswami, A. (2021), "From low- to net-zero carbon cities: The next global agenda", *Annual Review of Environment and Resources*, Vol. 46 No. 1, pp. 377–415, doi: https://doi.org/10.1146/annurev-environ-050120-113117.

Shakouri, M., Ebadi, H. and Gorjian, S. (2020) Solar photovoltaic thermal (PVT) module technologies, in *Photovoltaic Solar Energy Conversion*. Elsevier, pp. 79–116. Available at: http://dx.doi.org/10.1016/b978-0-12-819610-6.00004-1

Sharma, A., Mahajan, P. and Garg, R. (2023) End-of-life solar photovoltaic panel waste management in India: Forecasting and environmental impact assessment, *International*

Journal of Environmental Science and Technology, 21(2), pp. 1961–1980. Available at: https://doi.org/10.1007/s13762-023-04953-2.

Sharma, A., Pandey, S. and Kolhe, M. (2019) Global review of policies & guidelines for recycling of solar PV modules, *International Journal of Smart Grid and Clean Energy*, 8(5), pp. 597–610. Available at: https://doi.org/10.12720/sgce.8.5.597-610.

Shaw, A., Mander, S., Parkes, B. and Wood, R. (2023), “Zero carbon transitions: A systematic review of the research landscape and climate mitigation potential”, *Frontiers in Energy Research*, Vol. 11, doi: https://doi.org/10.3389/fenrg.2023.1268270.

Shekarian, E., Ijadi, B., Zare, A. and Majava, J. (2022), “Sustainable supply chain management: A comprehensive systematic review of industrial practices”, *Sustainability*, Vol. 14 No. 13, p. 7892, doi: https://doi.org/10.3390/su14137892.

Sheoran, M. *et al.* (2021) Photovoltaic waste assessment in india and its environmental impact, *Journal of Physics: Conference Series*, 1849(1), p. 012003. Available at: https://doi.org/10.1088/1742-6596/1849/1/012003.

Sheoran, M. *et al.* (2022) Current situation analysis of solar PV waste management in India, *Materials Today: Proceedings*, 58(1), pp. 773–782. Available at: https://doi.org/10.1016/j.matpr.2022.03.118.

Sheoran, M., Sharma, S. and Kumar, P. (2020) A compatible standard policy measure to tackle solar photovoltaic waste in Indian scenario, *Journal of Physics: Conference Series*, 1504(1), p. 012012. Available at: https://doi.org/10.1088/1742-6596/1504/1/012012.

Silva, A. *et al.* (2017) From waste to sustainable materials management: Three case studies of the transition journey, *Waste Management*, 61, pp. 547–557. Available at: https://doi.org/10.1016/j.wasman.2016.11.038.

Singh, N., Ogunseitan, O.A. and Tang, Y. (2021), "Medical waste: Current challenges and future opportunities for sustainable management", *Critical Reviews in Environmental Science and Technology*, Vol. 52 No. 11, pp. 2000–2022, doi: https://doi.org/10.1080/10643389.2021.1885325.

Singh, R., Alapatt, G.F. and Abdelhamid, M. (2012) Green energy conversion &amp; storage for solving India's energy problem through innovation in ultra large scale manufacturing and advanced research of solid state devices and systems, in *2012 International Conference on Emerging Electronics*. IEEE. Available at: http://dx.doi.org/10.1109/icemelec.2012.6636220

Sinha, B. and Joshi, K. (2012) *Analysis of India's solar photovoltaics research output*, *unknown*. Available at:

https://www.researchgate.net/publication/269702334_Analysis_of_India’s_solar_photovoltaics_research_output.

Smith, S. (2005) Analytical framework for evaluating the costs and benefits of extended producer responsibility programmes, *OECD Papers*, 5(3), pp. 1–58. Available at: https://doi.org/10.1787/oecd_papers-v5-art13-en.

Smith, Y.R. and Bogust, P. (2018) Review of solar silicon recycling, in *The Minerals, Metals & Materials Series*. Cham: Springer International Publishing, pp. 463–470. Available at: http://dx.doi.org/10.1007/978-3-319-72362-4_42

Solar panel technologies (2010) in *Solar Photovoltaic Energy*. Institution of Engineering and Technology, pp. 53–110. Available at: http://dx.doi.org/10.1049/pbrn009e_ch3

Soltani, A. *et al.* (2015) Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: A review, *Waste Management*, 35(1), pp. 318–328. Available at: https://doi.org/10.1016/j.wasman.2014.09.010.

Sorte, S., Martins, N., Oliveira, M.S.A., Vela, G.L. and Relvas, C. (2023), “Unlocking the potential of wind turbine blade recycling: Assessing techniques and metrics for sustainability”, *Energies*, Vol. 16 No. 22, p. 7624, doi: https://doi.org/10.3390/en16227624.

Sosunova, I. and Porras, J. (2022), “IoT-Enabled smart waste management systems for smart cities: A systematic review”, *IEEE Access*, Vol. 10, pp. 73326–73363, doi: https://doi.org/10.1109/access.2022.3188308.

Souza, V., Rodrigues Figueiredo, A.M. and Santos Bortolocci Espejo, M.M. dos (2024) Challenges and strategies for managing end-of-life photovoltaic equipment in Brazil: Learning from international experience, *Energy Policy*, 188(1), p. 114091. Available at: https://doi.org/10.1016/j.enpol.2024.114091.

Srikanth, R. (2018) India’s sustainable development goals – Glide path for India’s power sector, *Energy Policy*, 123(2), pp. 325–336. Available at: https://doi.org/10.1016/j.enpol.2018.08.050.

Srinivasan, S. and Kottam, V.K.R. (2018) Solar photovoltaic module production: Environmental footprint, management horizons and investor goodwill, *Renewable and Sustainable Energy Reviews*, 81(1), pp. 874–882. Available at: https://doi.org/10.1016/j.rser.2017.08.031.

Stone, T.F., Dickey, L.C., Summers, H., Thompson, J.R., Rehmann, C.R., Zimmerman, E. and Tyndall, J. (2023), “A systematic review of social equity in FEWS analyses”, *Frontiers in Environmental Science*, Vol. 11, doi: https://doi.org/10.3389/fenvs.2023.1028306.

Storey, D. *et al.* (2015) Designing effective partnerships for waste-to-resource initiatives: Lessons learned from developing countries, *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 33(12), pp. 1066–1075. Available at: https://doi.org/10.1177/0734242x15602964.

Subramanian, K. and Yung, W.K.C. (2016), “Review of life cycle assessment on consumer electronic products: Developments and the way ahead”, *Critical Reviews in Environmental Science and Technology*, Vol. 46 No. 18, pp. 1441–1497, doi: https://doi.org/10.1080/10643389.2016.1245550.

Sun, Q., Chien, S.-Y. and Hsiao, I.-H. (2023) Theory of planned behavior modeled educational technology for waste management learning, in *2023 IEEE International Conference on Advanced Learning Technologies (ICALT)*. IEEE. Available at: http://dx.doi.org/10.1109/icalt58122.2023.00028

Sutton, S. (2001) Theory of planned behaviour, in *Cambridge Handbook of Psychology, Health and Medicine*. Cambridge University Press, pp. 223–228. Available at: http://dx.doi.org/10.1017/cbo9780511543579.049

Szpilko, D., de la Torre Gallegos, A., Jimenez Naharro, F., Rzepka, A. and Remiszewska, A. (2023), “Waste management in the smart city: Current practices and future directions”, *Resources*, Vol. 12 No. 10, p. 115, doi: https://doi.org/10.3390/resources12100115.

Taherdoost, H. and Madanchian, M. (2023) Multi-Criteria decision making (MCDM) methods and concepts, *Encyclopedia*, 3(1), pp. 77–87. Available at: https://doi.org/10.3390/encyclopedia3010006.

Tan, J., Jia, S. and Ramakrishna, S. (2022) End-of-Life photovoltaic modules, *Energies*, 15(14), p. 5113. Available at:https://doi.org/10.3390/en15145113.

Tan, J., Tan, F.J. and Ramakrishna, S. (2022), “Transitioning to a circular economy: A systematic review of its drivers and barriers”, *Sustainability*, Vol. 14 No. 3, p. 1757, doi: https://doi.org/10.3390/su14031757.

Tan, V. *et al.* (2022) Estimating the lifetime of solar photovoltaic modules in australia, *Sustainability*, 14(9), p. 5336. Available at: https://doi.org/10.3390/su14095336.

Tanveer, A. *et al.* (2021) Do perceived risk, perception of self-efficacy, and openness to technology matter for solar PV adoption? An application of the extended theory of planned behavior, *Energies*, 14(16), p. 5008. Available at:https://doi.org/10.3390/en14165008.

Tao, J. and Yu, S. (2015) Review on feasible recycling pathways and technologies of solar photovoltaic modules, *Solar Energy Materials and Solar Cells*, 141(1), pp. 108–124. Available at: https://doi.org/10.1016/j.solmat.2015.05.005.

Tawalbeh, M. *et al.* (2021) Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook, *Science of The Total Environment*, 759(1), p. 143528. Available at: https://doi.org/10.1016/j.scitotenv.2020.143528.

Thapa, R.K., Iakovleva, T. and Foss, L. (2019), "Responsible research and innovation: A systematic review of the literature and its applications to regional studies", *European Planning Studies*, Vol. 27 No. 12, pp. 2470–2490, doi: https://doi.org/10.1080/09654313.2019.1625871.

The Food and Drink Federation (2022) *EPR*, *The Food & Drink Federation*. Available at: https://www.fdf.org.uk/fdf/what-we-do/environmental-sustainability/plastics-packaging/extended-producer-responsibility/.

The World's Greenest Countries 2024 (2022) *GreenMatch.co.uk*. Available at: https://www.greenmatch.co.uk/blog/greenest-countries

Theeraworawit, M., Suriyankietkaew, S. and Hallinger, P. (2022), "Sustainable supply chain management in a circular economy: A bibliometric review", *Sustainability*, Vol. 14

No. 15, p. 9304, doi: https://doi.org/10.3390/su14159304.

Thürer, M., Tomašević, I., Stevenson, M., Blome, C., Melnyk, S., Chan, H.K. and Huang, G.Q. (2019), “A systematic review of China’s belt and road initiative: Implications for global supply chain management”, *International Journal of Production Research*, Vol. 58 No. 8, pp. 2436–2453, doi: https://doi.org/10.1080/00207543.2019.1605225.

Tleuken, A., Tokazhanov, G., Jemal, K.M., Shaimakhanov, R., Sovetbek, M. and Karaca, F. (2022), “Legislative, institutional, industrial and governmental involvement in circular economy in central asia: A systematic review”, *Sustainability*, Vol. 14 No. 13, p. 8064, doi: https://doi.org/10.3390/su14138064.

Toro, L., Moscardini, E., Baldassari, L., Forte, F., Falcone, I., Coletta, J. and Toro, L. (2023), “A systematic review of battery recycling technologies: Advances, challenges, and future prospects”, *Energies*, Vol. 16 No. 18, p. 6571, doi: https://doi.org/10.3390/en16186571.

Trott, C.D., Gray, E.-S., Lam, S., Courtney, R.H., Roncker, J. and Even, T.L. (2023), “People’s action for climate justice: A systematic review”, *Local Environment*, Vol. 28 No. 9, pp. 1131–1152, doi: https://doi.org/10.1080/13549839.2023.2187363.

Tsanakas, J.A. *et al.* (2019) Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification, *Progress in Photovoltaics: Research and Applications*, 28(6), pp. 454–464. Available at: https://doi.org/10.1002/pip.3193

Tsanakas, J.A. *et al.* (2019) Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification, *Progress in Photovoltaics: Research and Applications*, 28(6), pp. 454–464. Available at: https://doi.org/10.1002/pip.3193.

Tsuchimoto, I. and Kajikawa, Y. (2022), "Recycling of plastic waste: A systematic review using bibliometric analysis", *Sustainability*, Vol. 14 No. 24, p. 16340, doi: https://doi.org/10.3390/su142416340.

Tudor, T.L. (2011) The role of organisations in enhanced global environmental management: Perspectives on climate change and waste management strategies, *International Journal of Environment and Waste Management*, 7(3/4), p. 250. Available at: https://doi.org/10.1504/ijewm.2011.039467.

Udin, U. (2020), "RENEWABLE ENERGY AND HUMAN RESOURCE DEVELOPMENT: CHALLENGES AND OPPORTUNITIES IN INDONESIA", *International Journal of Energy Economics and Policy*, Vol. 10 No. 2, pp. 233–237, doi:

https://doi.org/10.32479/ijeep.8782

Ulsrud, K. *et al.* (2011) The Solar Transitions research on solar mini-grids in India: Learning from local cases of innovative socio-technical systems, *Energy for Sustainable Development*, 15(3), pp. 293–303. Available at: https://doi.org/10.1016/j.esd.2011.06.004

Van Bueren, B.J.A., Iyer-Raniga, U., Leenders, M.A.A.M. and Argus, K. (2021), “Comprehensiveness of circular economy assessments of regions: A systematic review at the macro-level”, *Environmental Research Letters*, Vol. 16 No. 10, p. 103001, doi: https://doi.org/10.1088/1748-9326/ac209c.

Van Opstal, W. and Smeets, A. (2023) Circular economy strategies as enablers for solar PV adoption in organizational market segments, *Sustainable Production and Consumption*, 35(1), pp. 40–54. Available at: https://doi.org/10.1016/j.spc.2022.10.019.

Vassilakis, D.K. and Vassalos, V. (2007) Modelling real P2P networks: The effect of altruism, in *Seventh IEEE International Conference on Peer-to-Peer Computing (P2P 2007)*. IEEE. Available at: http://dx.doi.org/10.1109/p2p.2007.30

Vedel, I., Akhlaghpour, S., Vaghefi, I., Bergman, H. and Lapointe, L. (2013), “Health information technologies in geriatrics and gerontology: A mixed systematic review”, *Journal of the American Medical Informatics Association*, Vol. 20 No. 6, pp. 1109–1119, doi: https://doi.org/10.1136/amiajnl-2013-001705.

Velenturf, A.P.M. (2021), "A framework and baseline for the integration of a sustainable circular economy in offshore wind", *Energies*, Vol. 14 No. 17, p. 5540, doi: https://doi.org/10.3390/en14175540.

Villagrán, E., Romero-Perdomo, F., Numa-Vergel, S., Galindo-Pacheco, J.R. and Salinas-Velandia, D.A. (2023a), "Life cycle assessment in protected agriculture: Where are we now, and where should we go next?", *Horticulturae*, Vol. 10 No. 1, p. 15, doi: https://doi.org/10.3390/horticulturae10010015.

Wafa, W., Sharaai, A.H., Matthew, N.K., Ho, S.A.J. and Akhundzada, N.A. (2022), "Organizational life cycle sustainability assessment (OLCSA) for a higher education institution as an organization: A systematic review and bibliometric analysis", *Sustainability*, Vol. 14 No. 5, p. 2616, doi: https://doi.org/10.3390/su14052616.

Walzberg, J., Carpenter, A. and Heath, G.A. (2021) Role of the social factors in success of solar photovoltaic reuse and recycle programmes, *Nature Energy*, 6(9), pp. 913–924. Available at: https://doi.org/10.1038/s41560-021-00888-5.

Walzberg, J., Carpenter, A. and Heath, G.A. (2021) Role of the social factors in success of solar photovoltaic reuse and recycle programmes, *Nature Energy*, 6(9), pp. 913–924. Available at: https://doi.org/10.1038/s41560-021-00888-5.

Wan Nurul Karimah Wan Ahmad Farah Adilah Ishak (2020) A conceptual framework of sustainable supply chain management of solar photovoltaic, *Solid State Technology*, 63(3), pp. 1595–1601.

Wang, T.-Y., Hsiao, J.-C. and Du, C.-H. (2012) Recycling of materials from silicon base solar cell module, in *2012 38th IEEE Photovoltaic Specialists Conference*. IEEE. Available at: http://dx.doi.org/10.1109/pvsc.2012.6318071

Weckend, S., Wade, A. and Heath, G. (2016) *End of life management: Solar photovoltaic panels*. Office of Scientific and Technical Information (OSTI). Available at: http://dx.doi.org/10.2172/1561525

Wenting, D. and Guangrong, J. (2008) A review of the theory of planned behavior, *Advances in Psychological Science*, 16(02).

Weyand, S., Wittich, C. and Schebek, L. (2019), “Environmental performance of emerging photovoltaic technologies: Assessment of the status quo and future prospects based on a meta-analysis of life-cycle assessment studies”, *Energies*, Vol. 12 No. 22, p. 4228, doi:

https://doi.org/10.3390/en12224228

Widayati, T., Nurchayati, N. and Jaya, R.C.D. (2023) A study of sustainable waste management using theory of planned behaviour in traditional agricultural markets, *Jurnal Manajemen dan Agribisnis*, 1(2). Available at: https://doi.org/10.17358/jma.20.1.68.

Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Streeck, J., Pichler, M., Mayer, A., *et al.* (2020), "A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: Bibliometric and conceptual mapping", *Environmental Research Letters*, Vol. 15 No. 6, p. 063002, doi: https://doi.org/10.1088/1748-9326/ab8429.

Wilhelm, I., Teske, S. and Massonet, G. (2011) *Solar photovoltaic electricity empowering the world*, *Open Publications of UTS Scholars*. Available at: http://hdl.handle.net/10453/116554.

Wu, J., Zhang, Q. and Xu, Z. (2019) Research on China's photovoltaic modules recycling models under extended producer responsibility, *International Journal of Sustainable Engineering*, 12(6), pp. 423–432. Available at: https://doi.org/10.1080/19397038.2019.1674940.

Wu, S., Kaden, N. and Dröder, K. (2023), "A systematic review on lithium-ion battery disassembly processes for efficient recycling", *Batteries*, Vol. 9 No. 6, p. 297, doi:

https://doi.org/10.3390/batteries9060297

Wu, Z., Jiang, M., Cai, Y., Wang, H. and Li, S. (2019), “What hinders the development of green building? An investigation of China”, *International Journal of Environmental Research and Public Health,* Vol. 16 No. 17, p. 3140, doi: https://doi.org/10.3390/ijerph16173140.

Xu, Y. *et al.* (2018) Global status of recycling waste solar panels: A review, *Waste Management,* 75, pp. 450–458. Available at: https://doi.org/10.1016/j.wasman.2018.01.036.

Yadav, P., Davies, P.J. and Khan, S. (2020) Breaking into the photovoltaic energy transition for rural and remote communities: Challenging the impact of awareness norms and subsidy schemes,
Clean Technologies and Environmental Policy, 22(4), pp. 817–834. Available at: https://doi.org/10.1007/s10098-020-01823-0.

Yang, D. (2022), “The application of Life Cycle Assessment in sustainable furniture system design”, *AHFE International,* AHFE International.

Yang, H.-Y. *et al.* (2015) Experimental studies on the flammability and fire hazards of photovoltaic modules, *Materials*, 8(7), pp. 4210–4225. Available at: https://doi.org/10.3390/ma8074210.

Yaro, N.S.A., Sutanto, M.H., Baloo, L., Habib, N.Z., Usman, A., Yousafzai, A.K., Ahmad, A., *et al.* (2023), "A comprehensive overview of the utilization of recycled waste materials and technologies in asphalt pavements: Towards environmental and sustainable low-carbon roads", *Processes*, Vol. 11 No. 7, p. 2095, doi: https://doi.org/10.3390/pr11072095.

Yeo, Z., Masi, D., Low, J.S.C., Ng, Y.T., Tan, P.S. and Barnes, S. (2019), "Tools for promoting industrial symbiosis: A systematic review", *Journal of Industrial Ecology*, Vol. 23 No. 5, pp. 1087–1108, doi: https://doi.org/10.1111/jiec.12846.

Yi, Y.K. *et al.* (2014) Recovering valuable metals from recycled photovoltaic modules, *Journal of the Air & Waste Management Association*, 64(7), pp. 797–807. Available at: https://doi.org/10.1080/10962247.2014.891540.

Yin, Z. and Ma, J. (2022) Rational choice or altruism factor: Determinants of residents' behavior toward household waste separation in Xi'an, China, *International Journal of Environmental Research and Public Health*, 19(19), p. 11887. Available at: https://doi.org/10.3390/ijerph191911887.

Yingxu Wang (2005) Sociological models of software engineering, in *Canadian Conference on Electrical and Computer Engineering, 2005*. IEEE. Available at: http://dx.doi.org/10.1109/ccece.2005.1557335

Yu, H.F. *et al.* (2022) Global challenges and prospects of photovoltaic materials disposal and recycling: A comprehensive review, *Sustainability*, 14(14), p. 8567. Available at: https://doi.org/10.3390/su14148567.

Zamagni, A., Masoni, P., Buttol, P., Raggi, A. and Buonamici, R. (2012), “Finding life cycle assessment research direction with the aid of meta-analysis”, *Journal of Industrial Ecology*, Vol. 16 No. s1, doi: https://doi.org/10.1111/j.1530-9290.2012.00467.x.

Zarzavilla, M., Quintero, A., Abellán, M.A., Serrano, F.L., Austin, M.C. and Tejedor-Flores, N. (2022), “Comparison of environmental impact assessment methods in the assembly and operation of photovoltaic power plants: A systematic review in the Castilla—la mancha region”, *Energies*, Vol. 15 No. 5, p. 1926, doi: https://doi.org/10.3390/en15051926.

Zhang, J., Li, B., Garg, A. and Liu, Y. (2018), “A generic framework for recycling of battery module for electric vehicle by combining the mechanical and chemical procedures”, *International Journal of Energy Research*, Vol. 42 No. 10, pp. 3390–3399, doi: https://doi.org/ 10.1002/er.4077

Zhang, Q., Liu, C. and Zheng, S. (2023) Investment and pricing in solar photovoltaic waste recycling with government intervention: A supply chain perspective, *Computers & Industrial Engineering*, 177(1), p. 109044. Available at: https://doi.org/10.1016/j.cie.2023.109044.

Zhang, W., Li, B., Xue, R., Wang, C. and Cao, W. (2021), "A systematic bibliometric review of clean energy transition: Implications for low-carbon development", *PLOS ONE,* Vol. 16 No. 12, p. e0261091, doi: https://doi.org/10.1371/journal.pone.0261091

Zhang, X. and Dong, F. (2020), "Why do consumers make green purchase decisions? Insights from a systematic review", *International Journal of Environmental Research and Public Health,* Vol. 17 No. 18, p. 6607, doi: https://doi.org/10.3390/ijerph17186607.

Zhang, Z., Liu, Y., Han, Z. and Liao, X. (2022), "Green finance and carbon emission reduction: A bibliometric analysis and systematic review", *Frontiers in Environmental Science*, Vol. 10, doi: https://doi.org/10.3389/fenvs.2022.929250.

Zheng, C. and Kammen, D.M. (2014) An innovation-focused roadmap for a sustainable global photovoltaic industry, *Energy Policy*, 67(1), pp. 159–169. Available at: https://doi.org/10.1016/j.enpol.2013.12.006.

Zhong, S., Chen, R., Song, F. and Xu, Y. (2019), “Knowledge mapping of carbon footprint research in a LCA perspective: A visual analysis using citespace”, *Processes*, Vol. 7 No. 11, p. 818, doi: https://doi.org/10.3390/pr7110818

Zhou, J. *et al.* (2021) Designing a smart incentive-based recycling system for household recyclable waste, *Waste Management*, 123(1), pp. 142–153. Available at: https://doi.org/10.1016/j.wasman.2021.01.030.

Zweibel, K. (1990) What is Photovoltaics?, in *Harnessing Solar Power*. Boston, MA: Springer US, pp. 11–25. Available at: http://dx.doi.org/10.1007/978-1-4899-6110-5_2

APPENDIX A:
FIRST APPENDIX TITLE [USE “CHAPTER TITLE” STYLE]