

Swatilekha Ghosh

Chap 1-7

 Research Paper

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CHAPTER 1

INTRODUCTION

1.1 Preamble

Photovoltaic (PV) energy has great potential for sustainably decarbonizing the energy sector. Apart from being a clean energy source, it has several other advantages over other energy sources. Firstly, the availability of primary energy resource, such as sunlight, is abundant. Approximately 885 TWh of solar energy is received at the terrestrial surface each year, which is 3,500 times higher than the estimated primary energy requirement for 2050 (IEA, 2014). Secondly, the availability of the raw material required to manufacture crystalline silicon PV cells, *i.e.*, sand in abundance and within easy reach. As a result, the Levelized Cost of Energy (LCOE) from PV plants is among the lowest of all energy technologies. And finally, due to its modular nature, PV installations can be seamlessly integrated with building architecture and city planning, considering space availability, and no rehabilitation is required, unlike large-scale hydropower projects and conventional power plants. Due to its numerous advantages, photovoltaic energy has garnered the attention of investors, researchers, manufacturers, and policymakers worldwide. The collective effort of all the stakeholders has created an ecosystem for innovation in the fields of technology, project financing, and project execution. Recently, technological innovations have transcended the PV cell efficiency beyond the psychological limit of 30% (EPFL, 2022). The innovations in policymaking, project financing, sourcing, and execution have resulted in exponential growth in PV installed capacity since the beginning of the 21st century, and it has now surpassed 1420 GW

(IRENA, 2024) as shown in Fig. 1.1. Therefore, there is a widespread euphoric rush to adopt PV energy technology at all levels worldwide.

However, solar PV technology also has several areas of concern, especially from the perspective of both energy and environmental sustainability, that demand the attention of manufacturers and policymakers. Firstly, the energy produced by solar PV systems is intermittent; therefore, large-scale battery-based energy storage systems are required to balance daily fluctuations in generation and load, thereby providing consistent power. Although PV technology is safe for the environment during operation, most of the materials used in these batteries are hazardous to the environment and pose a risk of fire hazards during operation. However, an adequate policy framework is not yet in place on a global scale for the safe mining of its raw materials (e.g., lithium and cobalt) and

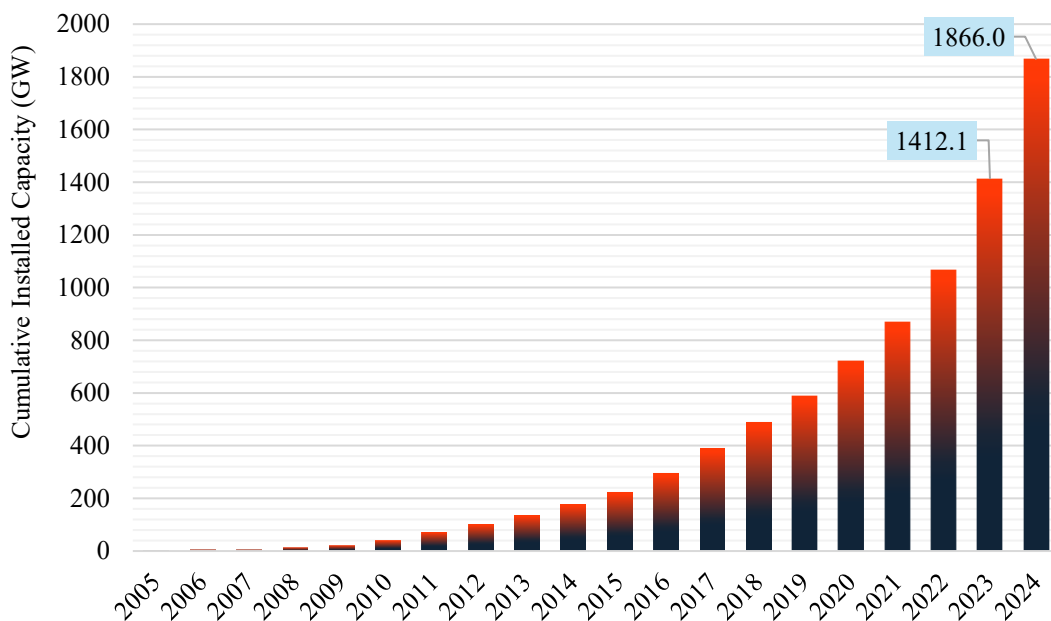


Fig. 1.1. Global trend of PV installed capacity rise (IRENA, 2025).

the safe disposal or recycling of these materials at the end of their useful life. Secondly, the solar PV systems are susceptible to environmental conditions, and past research shows that the output fluctuates widely with the wind speed, wind direction, chemical composition of the dust available in the environment, dust particle size, and relative

humidity as well (Alves dos Santos et al., 2021), apart from the intensity of the irradiation. To maintain the output of PV installations at the intended or design levels, they require frequent cleaning with fresh water, a scarce resource in many parts of the world (Sharma & Singh, 2022; Singh & Noori, 2022).

Apart from the power output, some environmental factors also affect PV reliability, and partial shading conditions (PSC) are one of these. PSC may be created by non-uniform dust deposition over the module, inconsistent cleaning of the module glass, bird droppings, leaves, and shading from nearby trees, electric towers, and modules of adjacent rows at a low sun altitude. Under PSC, the shaded cells become non-productive or under-productive, depending on the intensity of the shade. In such situations, the affected cells become a load on the productive or generating PV cells. This implies that the cell under PSC starts consuming or dissipating energy rather than generating it, and the temperature of the affected cells begins to rise. The literature reveals that the temperature of the cells may reach as high as 400°C under PSC (Amerasekera et al., 1993). Apart from reducing the efficiency and power output of the PV system at elevated temperatures (Mahamudul et al., 2016), this also affects its reliability. The high-temperature gradient created within the module causes the top glass to crack in extreme cases. Under such scenarios, atmospheric oxygen enters the module through cracks. It causes the Ethylene/Vinyl Acetate (EVA), which is used as a sealant in the modules, to catch fire (Fertig et al., 2011; Guerriero et al., 2019).

The phenomenon discussed in the above paragraph is one of the dominant early failure modes of PV modules, which, together with the end-of-life (EoL) waste volume, contributes to the cumulative volume of PV waste. The EoL PV waste management has not caught enough attention from the researchers yet, as the EoL PV waste generation has a temporal offset of 25-30 years (*i.e.*, the expected life of the PV modules) (Munoz et al., 2011; Mahmoudi et al., 2019). Although the history of PV application for power generation dates back about seven decades, the installed capacity began to grow exponentially only at the beginning of the 21st century. And hence, presently, the EoL PV waste generation and its management are still a crisis in the making;

however, probably the world has reached a stage where it is imperative to recognize the issue the world is heading to face in the near future (Ndzibah et al., 2022; Mathur et al., 2020). For example, California (CA) was one of the early adopters of solar PV installations, achieving 1.3 million rooftop PV installations by heavily incentivizing the scheme since 2006. Consequently, CA has become the leading producer of solar energy in the USA (U.S. Energy Information Administration (EIA), 2025). Due to the remarkable growth in PV installed capacity in CA, she became a role model not only for other states in the USA but also for other countries. However, although CA spent over USD 3.3 billion on incentivizing rooftop solar PV installations, no budget was allocated, and no policy was established for PV waste management (Kisela, 2022). It is no surprise, then, that the other governments did not take any steps in these directions either. But as the early installations have started approaching their EoL, waste management has begun raising concerns amongst the policymakers of CA (Kisela, 2022), and so is the case around the world.

The PV waste volume was 1000 times less than the electronic waste generated globally in 2014; however, the total PV waste may reach 8 million tons by 2030 and 78 million tons by 2050, in an early failure scenario (see Fig. 1.2). However, an IRENA report

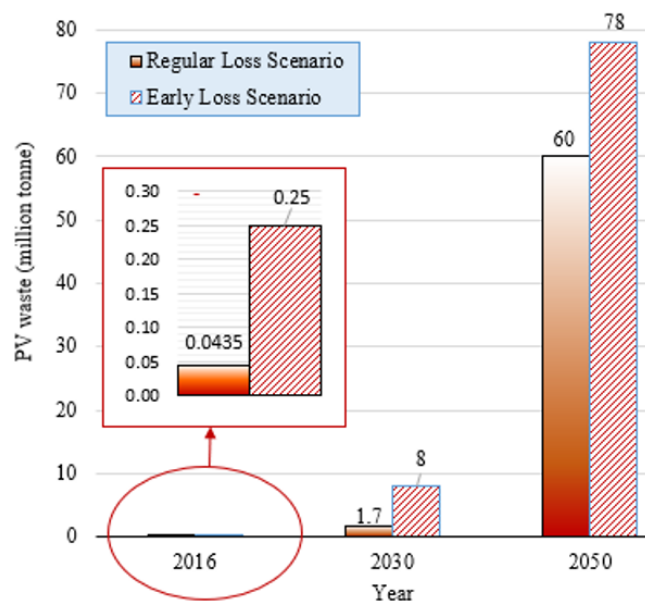


Fig. 1.2. Estimated quantity of end-of-life PV waste (IRENA, 2016).

reveals (IRENA, 2016) that, interestingly, these figures may drop by 78% in 2030 and 30% in 2050 if early failures are averted or mitigated. Hence, it is the need of the hour to innovate in increasing PV reliability and reducing early failure, as PV recycling technologies have yet to achieve commercial viability and scale. The infrastructure required to deal with even the existing E-waste volume is insufficient in developing countries, and 90% of this volume is treated in non-scientific ways (Vats & Singh, 2014). The additional volume of PV waste will overburden the infrastructure, which is even inadequate to handle the existing e-waste volume, if the rate of PV waste generation is not restricted.

From the discussion in the preceding paragraph, it is evident that the prevention and mitigation of early failures have the potential to substantially reduce PV waste generation in the near future, thereby mitigating the possibility of environmental pollution. Since PV recycling technology has yet to reach commercial viability, a large volume of this waste may end up in landfills, polluting the environment by leaching heavy metals into the soil and groundwater (Mathur et al., 2020) as well as the oceanic environment (Yuan et al., 2010). Hence, it is imperative to investigate the effect of different environmental factors on PV reliability and devise methods to mitigate the early failures. The research objectives derived from the above motivation are summarized below.

1.2 Research Objective

- (a) To characterize the effect of different environmental factors, such as partial shading conditions and aerosol deposition, on different array configurations.
- (b) To experimentally study the failure modes of PV modules and the effectiveness of the protection mechanisms provided to prevent failure from unfavorable environmental conditions.
- (c) Comparative analysis of different PV technologies based on technical efficiency and eco-toxicity.
- (d) To identify methods to mitigate PV module failure and thereby reduce PV waste generation.

1.3 Research Contributions

The main contributions of the present research work are as follows.

- (a) Critically analyzes the renewable energy growth trend over the last two decades and identifies various technical and environmental challenges that arose because of the policy biases in the related policy, and proposes recommendations for policy changes.
- (b) The ecological footprint of the two most widely used technologies, i.e., crystalline silicon and CdTe, is analyzed holistically over the complete life cycle, and the environmental impact of c-Si is found to be greater than that of the CdTe technology, which is contrary to the common perception. Hence, a policy change is recommended to incentivize the production and use of CdTe PV modules.
- (c) Crystalline Silicon PV modules are further evaluated for the effectiveness of the hotspot prevention mechanism under partial shading conditions and identify the lacunae in the existing commercial design of PV modules.
- (d) Proposes a new maximum power point tracking algorithm for making the bypass circuit of the extant commercial PV modules effective.

1.4 Outline of The Thesis

The thesis is organized into seven chapters that examine the sustainability challenges associated with the rapid deployment of photovoltaic (PV) technologies, with particular emphasis on environmental impacts, waste management, policy frameworks, and module reliability. Chapter 1 introduces the research problem by discussing the growing role of solar photovoltaic systems in the global energy transition and the emerging concerns related to PV waste generation, environmental sustainability, and end-of-life management. The chapter presents the research objectives, key contributions, and overall structure of the thesis. Chapter 2 provides a comprehensive review of the literature covering the evolution of PV technologies, their environmental impacts,

ecotoxicity concerns, end-of-life management pathways, recycling technologies, sustainability strategies, regulatory frameworks, socio-economic aspects, and future prospects for PV waste management. The review establishes the foundation for the subsequent analyses and identifies key research gaps.

Chapter 3 presents a critical analysis of global renewable energy capacity augmentation strategies, with particular focus on the rapid expansion of solar PV installations. The chapter examines the implications of this growth, including grid stability challenges such as the duck curve, environmental emissions, increasing end-of-life PV waste, inadequate recycling infrastructure, and deficiencies in waste management policies. **Chapter 4** undertakes a comparative analysis of the ecotoxicity associated with crystalline silicon (c-Si) and thin-film PV technologies. By examining their manufacturing processes and material compositions, the chapter evaluates their environmental footprints and associated ecotoxicological impacts. **Chapter 5** critically evaluates the global PV waste management policy paradigm by reviewing existing regulatory frameworks, assessing implementation challenges, and identifying shortcomings in current approaches. The chapter also discusses best practices and policy directions for improving sustainable PV waste management.

Chapter 6 focuses on the experimental investigation of early failure modes in PV modules that can contribute to premature module replacement and increased waste generation. The chapter reviews common failure mechanisms, presents observations from real-world installations, and describes experimental studies conducted under partial shading conditions using String, Total Cross-Tied (TCT), and Series-Parallel (SP) array configurations. The results are analyzed to assess their impact on module performance and reliability. Finally, **Chapter 7** summarizes the major findings of the research, highlights its contributions to PV sustainability and waste management, identifies future research opportunities, and discusses the broader environmental and societal implications of promoting a sustainable and circular approach to photovoltaic technology deployment.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Preamble

Photovoltaic (PV) technologies have made significant progress, with crystalline silicon (c-Si) and thin-film variants like cadmium telluride (CdTe) leading market adoption. This chapter reviews the recent literature to explore the historical development, material compositions, and environmental profiles of various PV technologies, emphasizing differences in resource consumption and ecotoxicity. End-of-life (EoL) management strategies, including reuse, refurbishment, and recycling, are examined with regard to technological processes, economic viability, and regulatory frameworks across different regions globally. Recycling techniques for c-Si and thin-film modules are analyzed, focusing on mechanical, thermal, and chemical treatments aimed at recovering valuable materials such as high-purity silicon, silver, cadmium, and tellurium. The adoption of circular economy principles is discussed as a way to reduce dependence on virgin resources and lessen environmental impacts, despite remaining economic and infrastructural hurdles. Policy frameworks, like extended producer responsibility schemes and international regulations, are considered for their impact on effective waste management systems. Socioeconomic factors, stakeholder engagement, and public perception are seen as key influences on adoption and compliance. Future outlooks emphasize design innovations for improved recyclability, standardization of international guidelines, predictive waste modeling, and aligning PV waste management with renewable energy policies to support sustainable solar growth without harming the environment.

2.2 Introduction

Photovoltaic (PV) technologies have seen continuous development over the past thirty years, leading to exponential growth in installed capacity, now exceeding 1420 GW globally (IRENA, 2024). However, as PV deployment increases worldwide to meet decarbonization targets, larger amounts of decommissioned PV modules are expected to enter waste streams soon, given that PV modules typically have a lifespan of 25-30 years. Studies warn that improper handling of PV waste, whether through uncontrolled landfill disposal or inadequate recycling, can lead to contamination and hinder the adoption of PV technology. Negative public perceptions could also shift political priorities away from large-scale renewables if environmental mismanagement becomes apparent (Vinayagamoorthia et al., 2024). Therefore, adopting a circular economy approach that includes reuse, repair, refurbishment, and advanced recycling in PV lifecycle planning is crucial (Basnet et al., 2025). Such strategies aim to recover valuable materials, such as high-purity silicon, silver, and aluminum, while reducing dependence on new resources and extending the life of already processed materials, thereby lowering the overall ecological footprint associated with resource extraction.

However, the main challenge is aligning technical capabilities with effective policy frameworks across different jurisdictional contexts. Legislative diversity adds complexity to PV waste management outcomes. For example, under the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive, PV modules are specifically classified for regulated collection and recovery rates of key recyclable materials (J. Wang et al., 2024b). In contrast, in the United States, categorization falls under the Resource Conservation and Recovery Act framework, where hazardous designation depends on results from toxicity characteristic leaching procedure (TCLP) tests; heavy metal-rich modules that fail TCLP are then treated more restrictively (J. Wang et al., 2024b). Different regulatory structures make it challenging to adopt standardized technological strategies on a global scale. Research indicates that predictive modeling of future waste streams could support coherent policy development. Anticipating both the

timing and volume can help governments establish targeted collection systems before market surges make current systems inadequate. This foresight is especially important for countries with growing manufacturing industries but still developing PV recycling capabilities. The gap between production growth and waste management readiness is widely seen as a significant weakness in the renewable energy transition. Despite its apparent benefits for material recovery and emission reductions, PV module recycling faces practical challenges: complex lamination structures hinder easy separation; chemical treatments pose secondary pollution risks; and current logistics often fail to collect enough End-of-Life (EoL) panels for economically viable plant operation (Ndaloka et al., 2024). Additionally, geographic differences mean that while some nations have operational industrial-scale facilities for advanced module recycling—capable of recovering glass sheets without shattering or reclaiming semiconductor layers intact—others mainly rely on basic dismantling or disposal. Without structured management strategies, the increase in EoL materials could undermine public trust in the environmental benefits of solar energy (Basnet et al., 2025).

The current research on recycling methods emphasizes refining mechanical delamination combined with thermal or chemical treatments to maximize recovery yields without creating additional hazards (Das & Sarmah, 2025). However, circular economic thinking extends beyond recovery; recovered materials must meet stringent performance standards to ensure their seamless reintegration into new PV products, thereby completing the cycle efficiently and securely. Technological innovations here may help address current quality gaps, but they often face challenges related to scaling up, particularly in terms of cost structures and variable feedstock quality. Economic viability remains another constant obstacle. While policy mandates can require collection and recycling efforts, without appropriate incentives or subsidies, these systems can quickly become financially burdensome for manufacturers or third-party operators (Singh et al., 2023). However, literature shows that well-designed economic tools could turn PV waste into a profitable sector that supports resource efficiency goals. This directly links to broader sustainability metrics: policies introducing extended producer responsibility schemes not

only fund but also promote design choices that enhance recyclability. A common theme across various studies is the need to combine stronger regulations with technology-driven advancements as a dual strategy (Das & Sarmah, 2025). Countries at early stages can benefit from embedding these guidelines into emerging market structures, rather than trying to retrofit them later, especially when faced with increasing waste stockpiles. By integrating unified global frameworks with region-specific implementation plans that consider local industry maturity, it is possible to align environmental protection goals with the expansion of clean energy.

Based on current knowledge, crystalline silicon is regarded as the benchmark for lower ecotoxic potential compared to specific thin-film alternatives, such as CdTe (Yu et al., 2024). However, isolated studies reveal that in the case of CdTe modules, closed-loop recycling can recover up to 90% of the semiconductor content, which can potentially reduce the cadmium leakage risk and thereby help conserve tellurium (Priya & Stonier, 2025). Similarly, processes for CIGS can incorporate selective leaching to recover indium, thereby minimizing secondary waste efficiently. Hence, it is necessary to critically evaluate the hypothesis on the lower ecological footprint of c-Si and compare the ecotoxicity of various technologies by considering their entire life cycle, not just the final product. Furthermore, a future-oriented and sustainable approach should be adopted on PV technology and material selection, encompassing systemic preparation through predictive analytics, legislative alignment, infrastructure development, and ongoing technological innovation. The present chapter examines each of these aspects in the following sections.

2.3. Evolution of Different PV Technologies and Their Competitive Landscape

The development path of photovoltaic systems spans several distinct technological generations, each marked by advances in materials science, manufacturing techniques, and application-specific needs. PV technologies can be broadly grouped based on the materials used for their active layers and the architectures through which sunlight is converted into electricity. The main types include crystalline silicon (c-Si), thin-film

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semiconductors like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), as well as emerging third-generation designs that explore new physical concepts and hybrid structures. Each type has unique trade-offs in terms of efficiency, cost, resource utilization, and environmental impact, which influence their suitability for specific applications and their potential for long-term market growth. Early PV research focused on crystalline silicon (c-Si). This technology now dominates global installations due to its optimal balance of efficiency, cost-effectiveness, and durability in real-world conditions (Nain & Anctil, 2024). The first generation, based on mono- and multi-crystalline silicon wafers, offers the highest efficiency (see Fig. 2.1); therefore, it is utilized in a wide range of applications, from niche satellites to large land-based power plants (Celep et al., 2025).

Simultaneously, the search for alternative semiconductors led to the development of thin-film technologies. The mechanical rigidity of c-Si makes it suitable for fixed installations on rooftops or ground-mounted arrays, but it is less adaptable to curved or flexible surfaces; for such applications, thin-film is the best alternative. The thin-film PV mainly belongs to the second generation of PV cells, which includes cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous

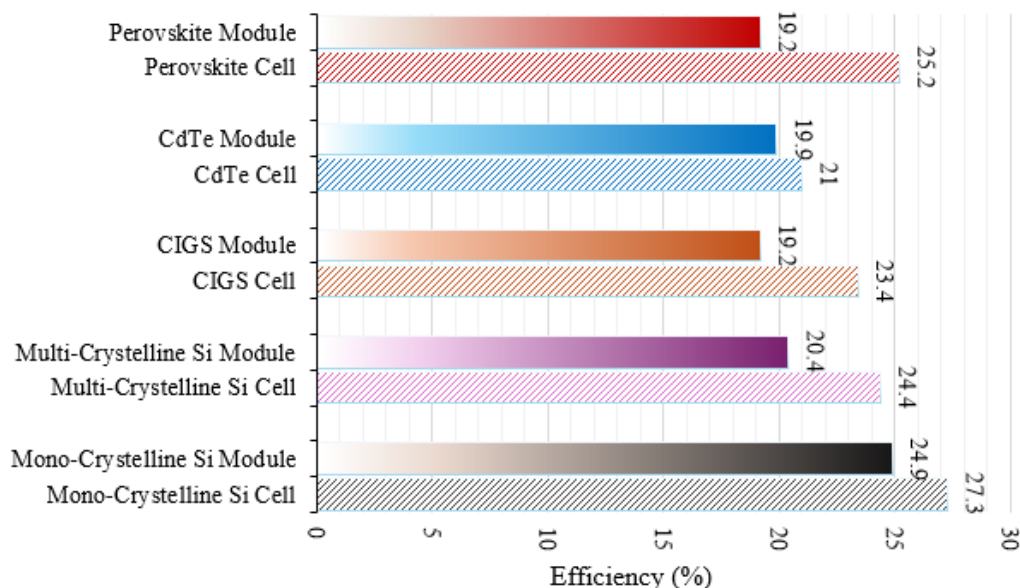


Fig. 2.1. Highest efficiency achieved so far for different PV technologies at the laboratory scale (Green et al., 2024).

silicon (a-Si) (Celep et al., 2025b). Thin-film cells offered compelling advantages over c-Si in specific contexts, including reduced raw material requirements, lighter module weight, potential for flexible substrates, and lower manufacturing costs—partly due to simpler deposition processes (Priya & Stonier, 2025). Copper indium gallium diselenide (CIGS) cells combine high absorption coefficients with tunable bandgap properties by adjusting the gallium content, enabling the efficient capture of sunlight across a broad spectral range (Nagaraja et al., 2025). Laboratory-scale devices have demonstrated conversion efficiencies exceeding what places them among the top-performing thin films (J. Wang et al., 2024a) (also see Fig. 2.1). One advantage is their ability to be fabricated on lightweight, flexible substrates such as polyimide films (Celep et al., 2025), opening applications from building-integrated photovoltaics to transportation sectors where conformability matters. At the same time, large-scale deployment is limited by supply considerations for indium and gallium, as well as by the process complexity compared to other thin-film technologies, such as CdTe.

CdTe has a lower temperature coefficient of power ($-0.21\ \%/^{\circ}\text{C}$) compared to c-Si ($-0.48\ \%/^{\circ}\text{C}$), indicating better performance in warmer climates (Virtuani et al., 2010). CdTe also shows a higher irradiance absorption coefficient, using a broader light spectrum (400-850 nm), more efficiently (Islam et al., 2021). Additionally, CdTe offers greater installation flexibility, such as in building-integrated photovoltaics (BIPV) (Intal & Abasifreke, 2024), where c-Si is less suitable. Furthermore, the life cycle analysis shows that CdTe modules require significantly less water during production (0.73 liters/kWh) compared to c-Si (7.2 liters/kWh) (Bosnjakovic et al., 2023). While greenhouse gas emissions of c-Si emissions are 48% higher than those of CdTe (Bosnjakovic et al., 2023). Moreover, CdTe has a shorter energy payback time and a lower cost per watt (0.4 USD/Watt) compared to c-Si (0.7-1.5 USD/Watt) (Bhandari et al., 2015; Scarpulla et al., 2023). Due to the advantages (summarized in Table 2.1), CdTe has found a role in utility-scale projects and managed to grab a small market share (see Fig. 2.2), especially where high-temperature performance and lower cost per area outweigh the marginally lower efficiency

Table 2.1

Comparison of Technical, Economic, and Qualitative Parameters

<i>Parameters</i>	<i>CdTe</i>	<i>c-Si</i>
Temperature coefficient of power (%/°C)	-0.21	-0.48
Irradiance absorption coefficient	Higher	Lower
Flexibility	Higher	Nil
Water usage (liter/kWh)	0.73	7.2
Greenhouse gas emission (g CO ₂ /kWh)	27	40
Energy payback time	Shorter	Longer
Cost (USD/Watt)	0.4	0.7-1.5

At the same time, advances in c-Si cell engineering drove sustained competitiveness.

Innovations such as passivated emitter rear contact (PERC) structures, enhanced light-trapping schemes, and refined back surface field layers have significantly boosted c-Si efficiency without incurring substantial cost penalties. Research into thin-film crystalline silicon variants combined attributes of both generations, offering material savings while retaining higher efficiency potential (Priya & Stonier, 2025). Some laboratory-scale polycrystalline thin-film silicon cells achieved a conversion efficiency exceeding 19% through targeted thickness optimization and texturing for optical enhancement. Yet market share remained modest; even in recent years, thin film collectively represents only about 2.6% of global PV deployment (see Fig. 2.2), while C-Si technologies still command the majority of deployed systems. Countries now install gigawatts of new c-Si-based PV capacity annually. Thin films did not replace c-Si; instead, they carved out specialized niches while c-Si continued its dominant trend through steady refinement and economies of scale (Al-Ali et al., 2025; Maghraby et al., 2025). CdTe's installed capacity growth is suppressed by tellurium availability and competing material needs, which introduce uncertainty into its long-term scalability (Ravikumara & Malghan, 2013). Market analysts frequently observe that resource constraints for certain thin-film constituents are directly correlated with system cost volatility, which can potentially

hinder market penetration if supply chains are disrupted. Other thin-film variants, such as amorphous silicon (a-Si) and copper indium gallium selenide (CIGS), have seen more limited uptake (see Fig. 2.2). The former is already experiencing a gradual decline in projected waste shares, starting around 2024, due to an earlier loss of competitive positioning (Yu et al., 2024). CIGS retains potential for niche applications due to its adaptability to flexible substrates and favorable temperature coefficients; however, it has yet to capture a substantial global market share compared to CdTe or c-Si (See Fig. 2.2).

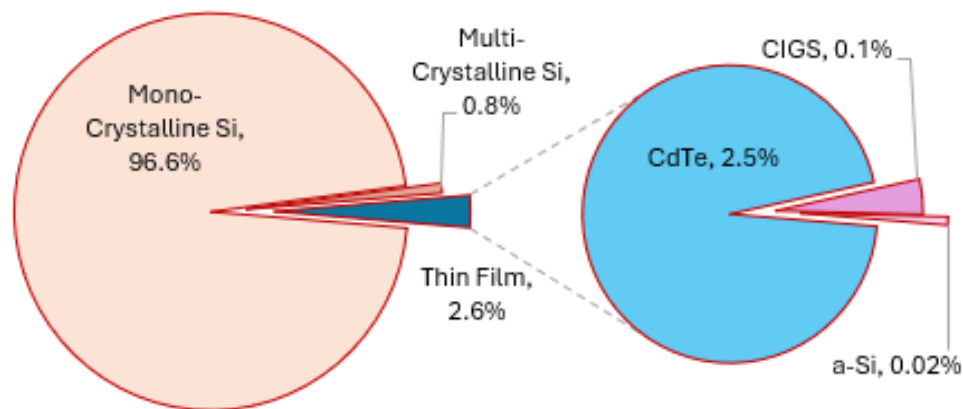


Fig. 2.2. Market share of various PV technologies (FISE, 2024).

The third generation of PV concepts introduced fundamentally new device architectures aimed at surpassing the limits of single-junction devices. Perovskite solar cells (PSCs), quantum dot solar cells (QDSCs), dye-sensitized solar cells (DSSCs), and organic photovoltaics (OPV) exemplify this category (Celep et al., 2025). These designs explore novel light absorption mechanisms or utilize multijunction stacks to extend spectral utilization beyond what traditional semiconductors can efficiently capture. Tandem solar cells (TSCs), which combine perovskites with silicon, demonstrate how hybrid structures can harness high-energy photons in the top cell layer while allowing lower-energy photons to be absorbed by an underlying c-Si cell (Priya & Stonier, 2025). Such approaches already show substantial theoretical efficiency gains over single-material devices. Policy incentives, including feed-in tariffs and net metering schemes, have significantly influenced these technological milestones by shaping market preferences

toward specific technologies at various times (Nain & Anctil, 2024). For instance, changes in subsidy structures influenced whether manufacturers favored a rapid ramp-up of established c-Si production lines or invested in scaling emerging thin-film and third-generation PV production. These non-technical factors sometimes accelerated the adoption of less mature technologies when economic conditions were favorable. Hence, apart from the ecological footprint and technical performance parameters, the policy framework also plays a crucial role in defining the competitive landscape of PV technologies.

2.4 Environmental Impact of PV Technologies

2.4.1 Global trends in PV waste generation and associated challenges and Opportunities

The expansion of photovoltaic capacity worldwide inevitably leads to an increase in end-of-life modules. This trend reflects not only cumulative deployment but also changes in technology lifespans, manufacturing practices, and degradation rates. Current projections suggest that crystalline silicon (c-Si) installations will comprise the largest share of decommissioned panels over the next few decades, primarily because they are prevalent in past and present markets (Das & Sarmah, 2025). However, rapid growth in thin-film variants means that waste streams will become more diverse, requiring flexible treatment systems that can efficiently process different architectures. The rate at which PV module waste builds up is closely tied to product lifespan assumptions. While typical service lives are often listed at 25–30 years, early retirements due to technological obsolescence, mechanical damage, or performance decline can speed up waste generation. Policy-driven repowering, such as in feed-in tariff regimes where replacing older modules with higher-efficiency ones maximizes revenue, can increase disposal rates even when modules are still operational. This leads to spikes in local waste volumes that can challenge existing collection capacity if not forecasted through demand–supply models. Modern forecasting tools are increasingly incorporating region-specific factors, such as degradation rates, climate stressors, and market policy changes, resulting in more detailed projections than those based on earlier global averages (Zaabi & Ghosh, 2024). The

forecasting models estimate concentrated surges in decommissioning within major markets such as China, the U.S., Japan, India, and Germany starting in the mid-2030s. Different countries are already showing varying readiness for these expected volumes. In China, government-supported pilot recycling programs focus on crystalline silicon waste, handling tens of megawatts annually as initial steps (Preet & Smith, 2024). Although modest compared to estimated future flows, these efforts are part of broader policies under the National High-tech R&D Program that aim to establish specialized PV recycling regulations. Conversely, South Korea lacks dedicated PV disposal rules; instead, it relies on broader renewable energy laws to promote recycling without specific collection mandates (Preet & Smith, 2024). Waste distribution maps reveal significant differences across regions, tied to their respective installation histories. Countries that adopted utility-scale solar later, often with newer modules, will likely see waste peaks lag behind those of early adopters but may face greater per-capita volumes once initial lifespans expire (Das & Sarmah, 2025). This pattern complicates international manufacturing strategies: regions with aging fleets will need recycling facilities sooner, while emerging markets might plan infrastructure buildouts aligned with global supply chains. Economically, the viability of recycling depends on the value of the recovered material versus the processing costs. Studies suggest that improving the purity of recovered materials—such as high-quality glass and semiconductor fractions—can open higher-value markets and boost profits (J. Wang et al., 2024b). Without such improvements, facilities risk operating at a loss if commodity prices fall or transportation costs from dispersed collection points outweigh sale revenues. These logistical challenges are substantial; poor collection networks increase per-unit freight costs and contribute to environmental impacts by increasing fuel consumption. Developing countries face additional hurdles due to limited formal infrastructure for hazardous waste management, often shipping hazardous waste modules abroad for processing, which poses environmental and economic risks (Celep et al., 2025).

Harmonized standards for cross-border PV waste transfer could help mitigate disparities. Still, they require a political consensus, which is often difficult to achieve

outside tightly integrated regions, such as the European Union. In mature regulatory environments, such as Japan's FIT scheme, upfront funding for recycling smooths out future disposal costs as mass decommissioning occurs. Similarly, Victoria's ban on landfilling PV modules pushes diverting waste into recovery channels, regardless of short-term raw material market conditions. By contrast, California classifies retired PV modules as general waste rather than hazardous waste, which lowers immediate handling costs but potentially reduces investment in advanced recycling technologies capable of recovering rare elements at scale (G. Wang et al., 2024). Forecasts indicate that key secondary resources, including tellurium from CdTe modules and indium from CIGS, will increasingly be sourced from waste streams rather than primary mining as the deployment of these technologies expands. Without scalable recovery methods tailored to specific chemistries, these elements risk being lost permanently in diffuse repositories where retrieval is unfeasible. Thus, global trends signal a dual challenge: managing rising waste volumes mainly composed of glass and aluminum, while protecting bottleneck materials crucial for PV production.

Socio-economic impacts are also significant. Efficient recycling sectors could generate jobs in dismantling, logistics, process engineering, and downstream material markets. However, inadequate infrastructure planning might leave recyclers unprepared for demand, resulting in overwhelmed facilities, stockpiling, or illegal disposal practices that undermine environmental goals. Literature suggests that adaptable policies responsive to market shifts, rather than rigid regulations, improve resilience (Singh et al., 2023). Over \$500 billion in PV investments are expected annually, entrenching long-term waste streams whose management must be integrated into planning now rather than later (Das & Sarmah, 2025). Achieving this requires combining advances in design for recyclability and geographic planning of recycling facilities to match regional retirements. Without this integration, environmental management gaps will grow with solar capacity, threatening the sustainability goals that initially drove renewable energy expansion (Zaabi & Ghosh, 2024).

2.4.2 Hazards associated with different PV technologies

As discussed in [Section 2](#), photovoltaic modules of various technologies are built from different materials, each chosen for specific functions. However, many of these components can pose environmental and health risks if released into ecosystems during manufacturing, operation, or disposal. For crystalline silicon (c-Si) modules, the main active layer is high-purity silicon derived from quartz through energy-intensive processes. While elemental silicon itself is non-toxic, risks come from other substances in the module assembly. Lead-based solders are still commonly used in older designs for electrical connections, and backsheet layers or encapsulants may contain fluoropolymers, which complicate recycling and can release hazardous substances upon thermal decomposition ([J. Wang et al., 2024b](#)). Trace amounts of tin and silver are also found in contact materials; although less hazardous than lead or cadmium, they can contribute to ecological toxicity when leached into groundwater and soil at larger scales ([Maghraby et al., 2025](#)).

Thin-film technologies, such as cadmium telluride (CdTe), fundamentally differ in their active material, which embeds significant amounts of cadmium within a stable crystalline matrix along with tellurium. Cadmium's acute and chronic toxicity is well known; it bioaccumulates in organisms, persists in the environment, and can harm kidneys, disrupt bone metabolism, and cause cancers ([Zhang et al., 2023](#)). Regular operation typically prevents exposure through encapsulation, but mechanical breakage, improper disposal, or insufficient recycling can lead to leaching into soil and water. Tellurium is less toxic but is scarce, making its recovery a concern for both environmental and supply issues. Semiconductor layers are generally applied using close-spaced sublimation (CSS) or sputtering techniques, which reduce waste but pose safety risks due to airborne cadmium particles if safety measures fail ([Priya & Stonier, 2025](#)). Even with controls, process residues must be handled carefully to prevent emissions. Copper indium gallium diselenide (CIGS) modules contain elements with unique hazards and scarcity issues. Copper is generally safe at low levels but becomes toxic to aquatic life above certain thresholds. Indium and gallium are rare elements that require considerable

chemical use during mining and refining, which can lead to localized pollution (Nagaraja et al., 2025). Selenium's toxicity, especially in aquatic systems, is concerning as it bioaccumulates and can harm fish populations. Improper disposal, such as uncontrolled landfilling, can mobilize these metals under acidic conditions caused by waste degradation, similar to concerns for cadmium-bearing modules (Ali et al., 2023). Long-term risks grow as waste accumulates without safeguards to prevent leachate migration. Most PV modules feature a front glass sheet bonded to the active layer with an encapsulant, such as ethylene-vinyl acetate (EVA). Although EVA has low toxicity, its resistance to degradation makes recycling challenging. Thermal breakdown can release acetic acid vapors and other volatile organic compounds, which may irritate or harm workers if not correctly managed during processing (J. Wang et al., 2024b). Back sheet materials often combine polyethylene terephthalate (PET) with polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF), thereby increasing persistence and the potential for the release of fluorinated compounds during incineration. Both c-Si and thin-film modules use aluminum alloy frames; aluminum has relatively low toxicity but adds significantly to the embedded energy of the product. Risks are not solely linked to material toxicity but also depend on how end-of-life management is handled. Modules classified as hazardous waste based on tests such as the Toxicity Characteristic Leaching Procedure (TCLP) require stricter handling under regulations like the United States Resource Conservation and Recovery Act (RCRA) (Li et al., 2024). Failures in TCLP testing are more likely to occur in CdTe or CIGS devices if protective laminates degrade or if manufacturing defects result in unbound metal residues. For c-Si units with lead solder joints exceeding regulated thresholds without mitigation measures, such as lead-free alloys, TCLP violations can occur, although less frequently than with cadmium-rich modules (J. Wang et al., 2024b).

Module processing also generates solid waste, hazardous residues, liquid effluents, and greenhouse gases, especially when dismantling involves mechanical shredding followed by acid leaching (Zhang et al., 2022). Without proper controls to capture fine particles and neutralize acidic effluents, these processes can shift

environmental burdens rather than eliminate them. Potential release pathways include air emissions during manufacturing or recycling, stormwater contamination at storage sites holding damaged panels, soil infiltration from landfills, and bioaccumulation in aquatic food webs affected by leachate. Occupational exposure to silica dust during the mining of metallurgical-grade feedstock poses known risks of respiratory diseases, such as silicosis (Zhang et al., 2023). The energy used in purification significantly impacts the carbon footprint of module production; reliance on coal-fired grids increases greenhouse gas emissions per unit (Mao et al., 2024). These emissions do not directly cause toxicity, but they contribute to climate-driven ecological stresses, which are part of broader hazard assessments (Maghraby et al., 2025). Hence, aligning technological development, deployment, and end-of-life waste management with the environmental norms is crucial through their life cycle assessment (LCA), as many installations from 20 to 30 years ago are approaching the end of their life.

2.4.3 Review of Comparative ecotoxicity

Comparisons of ecotoxicity profiles between different photovoltaic technologies often reflect the interplay of intrinsic material toxicity, emission potential across life cycle stages, and the effectiveness of containment or recovery processes at the end of life. Evaluations that focus on thin-film technologies such as CdTe modules generally highlight the presence of cadmium as the primary source of heightened ecotoxic risk compared to c-Si systems (Zhang et al., 2023). Cadmium can enter terrestrial and aquatic ecosystems during uncontrolled disposal or if encapsulation layers are compromised, leading to bioaccumulation and chronic ecological impacts. Laboratory hazard characterizations confirm that cadmium compounds exert toxicity even at trace environmental concentrations, impairing various biological functions in plants and animals. While advocates for CdTe technology emphasize that encapsulated forms present reduced solubility and leachability under field conditions, risk scenarios modelled under damaged-module or landfill-leachate simulations consistently produce higher endpoint toxicity scores for cadmium-containing designs compared to c-Si modules (Skarkos et al.,

2025). LCA models incorporating midpoint categories, such as terrestrial ecotoxicity and aquatic ecotoxicity, extend this comparison beyond chemical composition to include upstream processes, including mining, refining, and cell fabrication. In these frameworks, production stages account for the majority of the ecotoxic burden across all PV types, but reach maxima for thin-film designs incorporating heavy metals (Long et al., 2025). For CdTe, the extraction and refining of tellurium, often as a byproduct of copper smelting, contribute additional toxicological loadings through sulfur dioxide emissions and trace metal residues in waste streams. C-Si technologies, while largely avoiding the use of high-toxicity elements in cell layers, nevertheless carry non-negligible ecotoxic scores due to ancillary materials, such as lead in solders, and emissions linked to high-temperature quartz reduction furnaces (Fthenakis et al., 2020). Even so, aggregated LCA results consistently indicate that c-Si modules score lower in chronic eco-hazard potential across multiple methods, such as ReCiPe Endpoint and TRACI, when normalized per kilowatt-hour generated (Skarkos et al., 2025).

Mechanical shredding without hazardous-material separation can aerosolize or mobilize embedded substances. For CdTe devices, this means cadmium-bearing particulates may enter leachates; for c-Si modules, the most common concern is lead liberation from interconnects, which occurs less readily and at smaller mass fractions (Li et al., 2024). Toxicity Characteristic Leaching Procedure (TCLP) assessments reveal higher failure rates for thin films, such as CdTe, when barrier layers degrade, or encapsulation is thermally damaged in fires or incinerators (Maghraby et al., 2025a). CIGS technology also demonstrates elevated copper and selenium releases under acidic leach conditions (Ali et al., 2023). Novel LCA modelling approaches have deepened this comparative picture by revealing that 76–99% of total ecotoxic impact for c-Si stems from manufacturing energy use and associated raw-material processing emissions rather than direct toxic releases from module materials themselves (Long et al., 2025). In contrast, thin films containing cadmium exhibit a more balanced distribution of burdens between production-stage emissions and potential releases during disposal, indicating that improvements require both cleaner manufacturing inputs and adequate end-of-life

safeguards. One nuance is that modern industrial-scale CdTe production has implemented closed-loop recycling capable of recovering over 90% of semiconductor content before environmental release (Das & Sarmah, 2025). However, their penetration remains uneven geographically; facilities with mature take-back schemes exist primarily in regions with strong regulatory push, such as under EU WEEE obligations, while large parts of global deployment lack access to equivalent infrastructure (Maghraby et al., 2025).

Comparative assessments must also account for advances in material efficiency. Since 2004, the industry has halved semiconductor intensity in CdTe layers without sacrificing electrical performance (Fthenakis et al., 2020), thereby reducing absolute quantities of hazardous elements per watt manufactured. This trend suggests potential narrowing of relative ecotoxicity differences per unit energy output if collection rates at end-of-life improve markedly. C-Si does not escape scrutiny entirely; older installations employing lead-tin solders can exceed hazardous-waste thresholds under TCLP depending on alloy composition, storage conditions before testing, and physical state of interconnects (Li et al., 2024). In specific scenarios involving aggressive thermal cycling damage, microcracking can accelerate exposure pathways similar in principle to lamination failures observed in thin films. Nevertheless, key lifecycle impact assessment methods continue to assign higher ecosystem-quality impacts, particularly to the acidification and ecotoxicity categories, to CdTe modules compared with c-Si, due to residual elemental toxicity risk, regardless of reduced quantities (Skarkos et al., 2025).

Emerging third-generation PV types introduce uncertainties: perovskites may contain lead on par with or exceeding the solder content in older c-Si units; organic semiconductors often use halogenated solvents during processing, which have differing downstream environmental behaviors; and quantum-dot absorbers may involve cadmium or other chalcogenide compounds, analogous to those already discussed. Without comprehensive LCAs integrating both chronic-ecotoxic endpoints and acute-release likelihood across complete life cycles, including manufacture, operation under varied climates, accidental breakage events, and decommissioning logistics, direct comparisons

remain provisional. Ultimately, comparative ecotoxicity assessments across PV technology types are most informative when paired with policy mechanisms that guide safe handling throughout their value chain. Extended producer responsibility schemes create economic drivers for manufacturers to adopt inherently safer chemistries or ensure closed-loop recovery operations are viable at scale (Preet & Smith, 2024).

Regulatory variance aligns closely with observed outcome disparities: EU-aligned markets report lower unmanaged-release incidence due to mandatory collection quotas for PV e-waste; jurisdictions without such frameworks exhibit recycling bottlenecks that heighten aggregate release probabilities despite potential technological superiority in some product classes. Thus while quantified LCIA metrics currently place crystalline silicon ahead of cadmium telluride thin films in terms of reduced baseline ecotoxic potential per functional unit delivered (Zhang et al., 2023), real-world performance will hinge on concurrent progress in clean energy sourcing for production phases, targeted redesigns eliminating or stabilizing harmful constituents, regionally comprehensive end-of-life infrastructure build-out, and harmonized regulations enforcing safe material recovery wherever PV capacity is deployed.

2.5 EoL management pathways for PV modules

End-of-life (EoL) management pathways for photovoltaic modules encompass a spectrum of strategies ranging from re-use and refurbishment to recycling and final disposal. The choice among these depends not only on module conditions at retirement but also on prevailing regulatory environments, economic incentives, and available technological capabilities. Given the increasing volumes of PV systems approaching the end of their service lifetimes, the mechanisms by which these modules are processed after decommissioning will significantly impact their environmental and economic footprint (Celep et al., 2025). In practice, EoL routes often begin with collection systems that vary in sophistication. In regions with robust extended producer responsibility policies, such as those influenced by the EU Waste Electrical and Electronic Equipment (WEEE) Directive, manufacturers or importers are responsible for facilitating

structured collection and transport to licensed treatment facilities (Ali et al., 2023). Here, formal infrastructure ensures modules are documented, sorted, and either sent for disassembly or evaluated for potential re-use. By contrast, in jurisdictions lacking such frameworks, unregulated disposal or informal sector recovery is more likely; these scenarios can result in uncontrolled handling that increases environmental risk, particularly for thin-film types containing cadmium or selenium (G. Wang et al., 2024).

Re-use pathways typically require functional modules. Units retired due to system repowering or partial failure may still produce adequate power if cosmetic defects or slight efficiency drops are acceptable in secondary markets. However, ensuring electrical safety standards and reliability in different climatic conditions makes widespread second-hand deployment heavily dependent on testing protocols and recertification processes (J. Wang et al., 2024b). Although technically less resource-intensive than recycling new material streams, the economic viability of re-use is fragile; freight costs relative to residual energy yield often undermine it unless recipients face high local electricity prices or lack affordable alternatives. When direct re-use is not feasible, recycling becomes central. For crystalline silicon (c-Si) modules, the most prevalent globally, mechanical dismantling combined with delamination is commonly used to recover aluminum frames and glass sheets before targeting the silicon cells themselves. Advanced techniques that achieve high-purity silicon recovery through thermal treatment followed by chemical etching can yield wafers comparable in quality to virgin material (Das & Sarmah, 2025). These approaches can exceed 90% recovery rates for certain material streams; however, they involve capital-intensive equipment and careful process control to avoid secondary emissions during chemical usage. While operationally mature for c-Si in some countries, scaling such systems globally faces barriers from low-throughput plants in emerging markets (J. Wang et al., 2024b).

Thin-film modules, such as cadmium telluride (CdTe), require more specialized approaches. Chemical leaching under controlled conditions dissolves semiconductor layers, allowing cadmium and tellurium to be precipitated or

electrolytically recovered (Ali et al., 2023). This processing must be enclosed with effluent treatment stages to prevent toxic releases. Industrial closed-loop systems have demonstrated recovery efficiencies above 90% for semiconductor content while retaining glass sheet integrity; nonetheless, these systems are not universally deployed due to both cost considerations and insufficient collection volumes in many regions (Das & Sarmah, 2025). Copper indium gallium selenide (CIGS) modules follow similar principles, though selective leaching chemistry differs; indium recovery rates are critical given its scarcity, placing emphasis on minimizing impurity levels in recovered fractions so they can re-enter high-value manufacturing chains (Ali et al., 2023). Mechanical processing often serves as an initial step across various technologies, as it reduces volume quickly and simplifies subsequent treatments. However, without follow-on separation of hazardous materials, this route may merely shift risk from solid waste streams into fine particulates susceptible to dispersion (Celep et al., 2025).

Pyrolysis offers another method: applying elevated temperatures under inert atmospheres degrades polymer encapsulants without oxidizing recovered metals or semiconductors; yet here too, fume capture is essential as decomposition products may include volatile organic compounds along with acid gases if fluorinated backsheets are present (J. Wang et al., 2024b). From a circular economy viewpoint, integrating multiple techniques sequentially yields the most comprehensive recovery profile, mechanical removal of bulk components followed by thermal loosening of encapsulants and targeted chemical extraction for semiconductor layers. Such hybrid processes strike a balance between high material retrieval and reduced reagent consumption compared to entirely chemical routes that start from intact panels (Das & Sarmah, 2025). They also facilitate the recovery of auxiliary materials, such as silver, from conductive pastes in c-Si cells, whose value helps offset processing costs. Nonetheless, capital amortization for small waste volumes remains a stumbling block; recurrent proposals suggest establishing regional demonstration facilities capable of processing diverse PV waste streams as both capacity-building exercises and economic proofs of concept (G. Wang et al., 2024). Disposal still occupies a share of current EoL outcomes where recycling infrastructure is

absent or economically non-viable. Landfilling poses distinct hazards depending on the module chemistry: leachate from CdTe or CIGS modules under acidic landfill conditions may transport dissolved heavy metals into groundwater, unless engineered liners perform flawlessly over decades (Ali et al., 2023). Even c-Si panels pose contamination risks if lead-containing solders degrade over time. Incineration for volume reduction without prior segregation is generally discouraged because it can volatilize toxic elements into fly ash, requiring separate hazardous waste containment (J. Wang et al., 2024b). Regulatory classifications, such as results from Toxicity Characteristic Leaching Procedure (TCLP) tests, determine whether PV waste qualifies as hazardous; failures trigger stringent disposal routes, which are costlier but safer environmentally (Li et al., 2024). Given these varied pathways, policy frameworks play an outsized role in steering outcomes toward safe material loops rather than contaminative endpoints. Extended producer responsibility schemes have demonstrated effectiveness in underwriting collection logistics while driving design changes that facilitate the dismantling or reduction of harmful constituents at the source (Ali et al., 2023). Incentive alignment remains a recurring theme: without financial signals, either subsidies favoring recycled over virgin input streams or penalties on landfilling recyclable components, market forces often default toward lower-cost but environmentally inferior options. The projected escalation of PV waste generation over the coming decades means that today's patchwork of treatment methods must evolve into coherent networks integrated with both national legislation and international material flows if full life-cycle sustainability goals outlined earlier are to be met at scale (J. Wang et al., 2024b).

2.5.1 Recycling Technologies for PV Modules

2.5.1.1 Recycling of crystalline silicon PV modules

Recycling of crystalline silicon (c-Si) photovoltaic modules has gained considerable technological and regulatory momentum as these devices dominate global installations and consequently constitute the largest fraction of end-of-life PV waste. The recycling process generally begins with mechanical dismantling to separate easily recoverable components such as aluminum frames and junction boxes, which are both

valuable and readily marketable secondary materials (See [Fig. 2.1](#)). Glass sheets, which represent the bulk mass of a module, can also be mechanically removed at relatively low cost. However, their reuse in high-value applications requires maintaining surface integrity to meet optical and strength specifications. Simple comminution approaches often generate cullet unsuitable for remelting into PV-grade glass, so preservation of larger panes through controlled separation has been prioritized in advanced facilities ([J. Wang et al., 2024b](#)). After the removal of structural components, recovery focuses on the cell layer stack. Delamination —the separation of the encapsulant from the cells —is essential here, since c-Si cells are laminated with ethylene-vinyl acetate (EVA), which forms a stable crosslinked matrix that impedes direct material access. Thermal treatment is a common industrial approach: panels are exposed to elevated temperatures that degrade EVA without oxidizing the silicon, facilitating its release ([J. Wang et al., 2024b](#)). Operating atmospheres are sometimes inert to prevent discoloration or microstructural damage to glass and semiconductor layers. Alternatives include solvent-based swelling or dissolution of encapsulants, but these present secondary pollution challenges due to chemical handling requirements ([Das & Sarmah, 2025](#)). Once freed from encapsulation, silicon wafers undergo downstream treatments tailored to target purity levels (see [Fig. 2.2](#)). For metallurgical-grade recovery, simple physical separations combined with mild acidic cleaning suffice; however, reclaiming electronic-grade feedstock capable of re-entering PV manufacturing demands much more stringent purification ([Fiandra et al., 2023](#)). Techniques may include acid leaching using mixtures such as HNO_3 and HF to dissolve metal contacts and remove anti-reflective coatings. Subsequent etching steps strip away doped surface layers like phosphorus-diffused emitters, restoring near-bulk composition before recrystallization or melting. This high-value recycling route yields silicon with impurity levels low enough for solar cell production, but comes at substantially higher operational costs compared to downcycling into metallurgy or alloy

MECHANICAL	•Simpler and comparatively most economic process. •Difficult to sperate out high value items.
ETCHING	•Possible to recover high value material at high purity. •Energy intensive and poosibility of chemical emission to environment.
VACUUM BLASTING	•Possibility of recovering the semiconductor layer. •Longer processing time and probability of metal particle emmissions to environment.
EROSION	•Chemical-free process, the glass material can be salvaged • Additional prepurification stage is necessary.
LEACHING	•Chemical intesive process. •Complete removal of metals is possible but precise control is required over the chemicals for effectiveness.
FLOATATION	•The process not chemical intensive. •Higher number of stages involved, including pre-purification stage.
TENSIDE CHEMISTRY	•Reusable chemical (tenside) is used. • Allows complete disintegration of metals from glass.

Fig 2.3. Delamination and material separation processes of PV modules.

markets. Silver recovery is also an important economic driver in c-Si module recycling. Silver is used in front-side metallization pastes and can be extracted during contact removal steps; depending on market conditions, recovered silver can offset part of the processing costs (Das & Sarmah, 2025). Other metals present at trace levels, such as tin or lead from solder joints, are typically recovered during smelting stages or filtered from process effluents when chemical leaching is used (J. Wang et al., 2024b).

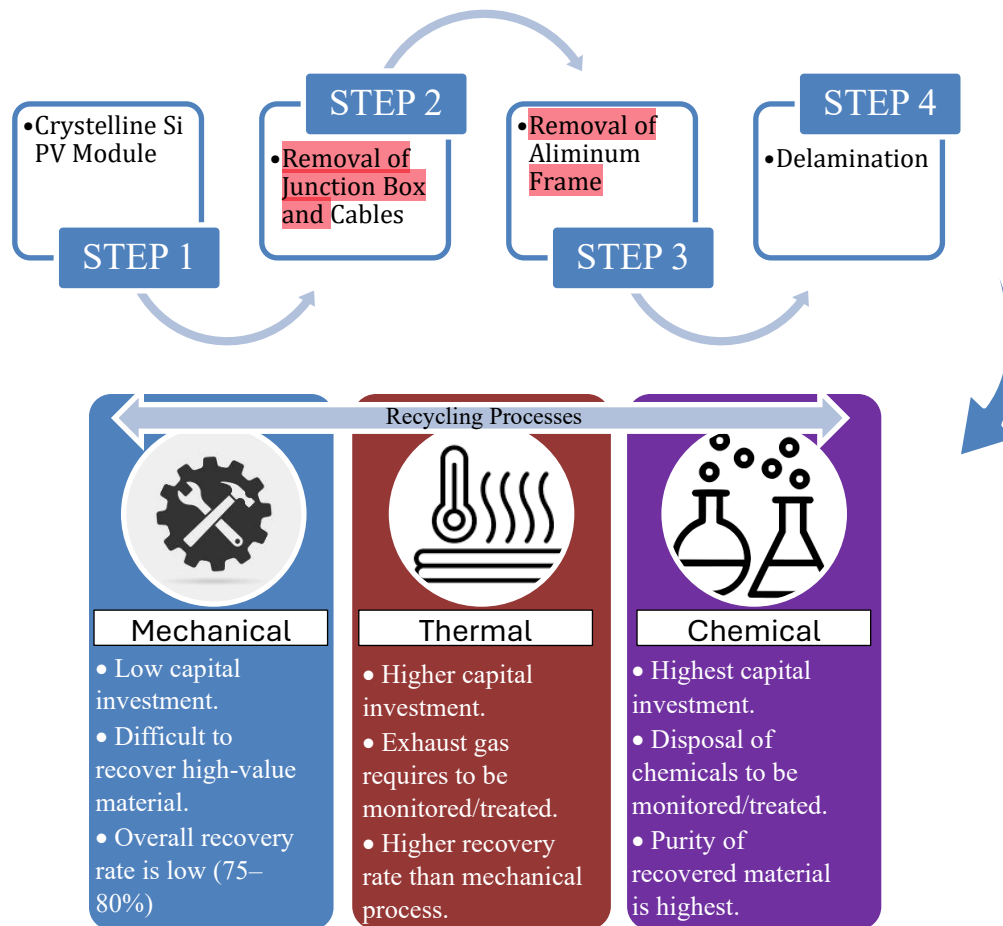


Fig 2.4. Recycling process of PV modules.

safeguards become critical: lead-containing residues must be immobilized or substituted upstream to comply with hazardous waste regulations (J. Wang et al., 2024b). Mechanical processing alone can simplify logistics by reducing waste volume before targeted treatments, but without integrated hazard control, it risks generating fine particulate matter containing toxic substances (Celep et al., 2025). Consequently, hybrid processes have emerged that combine mechanical pre-treatment with either thermal or chemical stages in sequence. Mechanical removal lowers subsequent reagent usage in chemical baths and enhances thermal homogeneity during pyrolytic delamination. The balance between yield maximization and minimizing secondary burdens drives process design decisions. For example, facilities in Europe under extended producer responsibility schemes opt for

closed-loop water treatment systems to capture acid fumes and recycle rinse water (Das & Sarmah, 2025). From an energy and environmental perspective, reusing recovered silicon reduces embodied energy requirements by up to 40% compared with producing virgin material via quartz reduction and Siemens-process purification (J. Wang et al., 2024b). Such savings directly reduce life-cycle greenhouse gas emissions associated with new PV manufacturing (J. Wang et al., 2024). However, maintaining wafer thickness tolerances after recovery remains a technical bottleneck; breakage during handling increases the share of silicon destined for remelting rather than direct reuse as wafers. Optimizing module design for disassembly could mitigate this issue by incorporating encapsulants with controlled debonding properties or frame designs that facilitate non-destructive opening. Transport logistics also influence recycling system performance. Consolidating EoL modules at regional aggregation points before processing reduces per-unit freight impacts but requires coordinated collection networks supported by policy instruments (Celep et al., 2025a). In jurisdictions like the EU where WEEE directives impose collection targets and recycling quotas on producers, this has incentivized investments in specialized c-Si recovery plants that integrate these logistical considerations into overall system efficiency (Das & Sarmah, 2025). In contrast, areas lacking binding mandates often experience lower recovery rates, not only because of absent infrastructure but also because of fluctuating commodity prices that disincentivize sustained operation of high-cost purification lines.

Different national contexts have therefore yielded varying adoption rates of advanced c-Si recycling technologies. Japan's model uses a combination of mechanical dismantling plants feeding into central chemical refining units operated semi-continuously under strict emission controls; China's initiatives often start with pilot programs linked to research institutions developing automation for wafer liberation before scaling facility capacity (Preet & Smith, 2024). These diverse approaches illustrate that while technological maturity exists for high-yield c-Si module recycling, widespread deployment hinges on aligning economic feasibility with environmental safeguards within specific regulatory regimes. There is ongoing innovation aimed at reducing both costs and

the energy intensity of recovery operations. Emerging selective delamination techniques use infrared heating tuned to EVA absorption spectra for rapid encapsulant breakdown without bulk panel heating, potentially enabling throughput gains while preserving glass sheet quality. Similarly, bioleaching concepts using metal-targeting microbes have been proposed for selective contact removal without the use of concentrated acid; such methods may find niche applications where chemical procurement or disposal is logistically challenging. Given the anticipated growth in EoL volumes, scaling these processes will demand modular plant designs capable of flexible operation across varying feed quantities. Integration with other waste-electronics recovery streams could spread fixed costs across a higher aggregate throughput while respecting the cross-contamination limits necessary to produce PV-grade outputs. The challenge will lie in ensuring that, as capacity expands globally, recovery systems maintain yields high enough for both critical-material conservation and climate-impact mitigation goals underpinning the original deployment of crystalline silicon photovoltaics.

2.5.1.2 Recycling of thin-film PV modules

Recycling thin-film photovoltaic (PV) modules requires processing routes tailored to their distinct layered structures and material compositions, which differ substantially from crystalline silicon devices. Thin-film technologies deposit semiconductor layers such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or amorphous silicon (a-Si) directly onto substrates, such as glass, with transparent conductive oxide (TCO) coatings serving as the front contact. The intimate adhesion between these layers and the substrate, often reinforced by encapsulants and protective backsheets, makes selective separation a critical technical challenge (Sanathia et al., 2024). Unlike c-Si, where wafer liberation is central, thin-film recycling focuses on detaching or dissolving minuscule yet valuable semiconductor films while preserving or recovering the underlying glass. For CdTe PV modules, established industrial practice begins with mechanical removal of frames and junction boxes, followed by size reduction to expose internal surfaces. However, retaining large glass intact, where possible, can

increase the reuse potential of high-quality sheet glass (Celep et al., 2025). The semiconductor removal stage typically employs chemical leaching under controlled conditions. Acidic solutions dissolve both cadmium telluride and cadmium sulfide emitter layers applied during manufacturing (Celep et al., 2025). Downstream treatment precipitates cadmium and tellurium as pure compounds or recovers them via electro-winning, enabling reintegration into manufacturing supply chains. Process control here is paramount: improper pH management or inadequate effluent treatment risks dispersing toxic cadmium into waste streams, contravening environmental safety goals (Das & Sarmah, 2025). Closed-loop industrial systems have demonstrated recovery efficiencies exceeding 90% for semiconductor content while generating minimal secondary waste; nonetheless, their deployment remains concentrated in regions with strong regulatory frameworks mandating producer responsibility (Sanathia et al., 2024). CIGS module recycling poses analogous but more chemically diverse challenges. Copper, indium, gallium, and selenium exist within the absorber layer in varying proportions depending on bandgap engineering during fabrication (J. Wang et al., 2024a). Mechanical comminution exposes the film-coated glass for subsequent targeted leaching steps. Selectivity is often key, common approaches use sequences of acids or deep eutectic solvents to solubilize indium preferentially before tackling copper and gallium (Das & Sarmah, 2025). This staged recovery minimizes cross-contamination among recovered fractions and reduces refining costs downstream. Selenium volatility during thermal treatments warrants careful atmospheric control; unmitigated emissions could carry ecological hazards comparable in severity to those posed by cadmium discharges.

Amorphous silicon panels offer somewhat lower inherent toxicity but still require encapsulant removal before semiconductor retrieval (Celep et al., 2025). A typical route involves thermal decomposition of EVA in inert atmospheres, followed by acidic stripping of silicon-based films from the glass substrate. Hydrofluoric acid and other fluoride-containing solutions are effective at dissolving residual silicon sub-oxides but demand rigorous handling safeguards for workers and environments alike (Celep et al., 2025). Metal contacts embedded within TCO or back-contact structures are recovered via

hydrometallurgical purification steps similar to those used for other thin-film chemistries. Hybrid processes combining mechanical, thermal, and chemical stages are gaining traction across thin-film types because they balance recovery effectiveness against reagent consumption (Das & Sarmah, 2025). For example, the SENSE project integrated waterjet cutting for CIGS substrates with pyrolysis to remove polymers before chemical leaching recovered metals from both CIGS and CdTe modules (Celep et al., 2025). Pneumatic separation was employed for polymer backings in a-Si panels, followed by grinding, ensuring downstream process compatibility.

Such integration not only increases yields across multiple material categories — glass, metals, and semiconductors — but also reduces total energy demand compared to standalone full-chemical approaches. Nonetheless, constraints limit the widespread adoption of sophisticated recycling lines. Facilities must be designed to accommodate heterogeneous feedstocks; collection volumes for any single thin-film technology may be insufficient locally to justify the construction of dedicated plants (Sanathia et al., 2024). This drives interest in adaptable platforms capable of switching chemistries between processing batches without extensive retrofitting. Economic viability also hinges on commodity prices for recovered elements such as tellurium and indium; price downturns can quickly erode margins, given the higher operational complexity compared with bulk-material recovery from c-Si systems (Das & Sarmah, 2025).

Safety considerations cut across all technological pathways. Thermal decomposition stages must incorporate gas-capture systems capable of scrubbing acid gases, such as hydrogen fluoride, when fluoropolymer back sheets are processed alongside thin-film devices (Maghraby et al., 2025). Fine particulates generated during mechanical erosion of coated substrates can contain concentrated amounts of target metals; adequate filtration and containment protocols are therefore essential to prevent occupational exposure or environmental release. These requirements add capital and operating costs but are necessary to meet environmental compliance standards in regulated markets. Demonstration-scale projects highlight both progress and persistent hurdles. In Europe,

industrial lines coupling mechanical crushing with tailored leaching have operated since at least 2016 at scales up to hundreds of megawatts per year throughput for CIGS glass and associated metal recovery (J. Wang et al., 2024a). Japan has explored scraping methods to directly separate CIS layers from the substrate glass without destroying the entire panel. This approach can yield cleaner glass outputs suitable for re-melting into high-grade applications while simplifying semiconductor isolation later in the process. Other Japanese initiatives employ thermal cutting to remove encapsulation from various module types before acid leaching recovers specific contact metals, such as molybdenum.

From a circular-economy standpoint, integrating these specialized recovery processes into broader PV waste strategies offers dual benefits: conserving scarce critical elements needed for ongoing PV manufacturing and reducing hazardous waste burdens associated with the disposal of toxicity-bearing materials such as cadmium or selenium (Das & Sarmah, 2025). Regulatory backing is often decisive; benign neglect can result in landfilling without pre-treatment when economics disfavor recycling investment. Conversely, jurisdictions enforcing landfill bans on PV modules compel diversion toward material recovery even if market values slump temporarily. Looking ahead, incorporating design changes upstream can improve recyclability without sacrificing performance: adopting encapsulants that debond under mild heating enables non-destructive substrate separation; optimizing semiconductor deposition thicknesses lowers total mass of hazardous constituents per module while maintaining output ratings; exploring non-toxic replacements for high-risk elements could eventually reduce dependency on complex chemical removal steps altogether. These advances would materially ease the processing burdens now associated with recycling thin-film PV modules while aligning with policy trends that place greater emphasis on producer-led stewardship throughout product lifecycles.

2.6 Sustainability Strategies for PV Waste Management

2.6.1 Circular economy approaches

A circular economy framework applied to photovoltaic (PV) technologies represents a shift from the conventional linear model of “make, use, dispose” toward maintaining material value within the system for as long as possible. This transition emphasizes closing resource loops through reuse, remanufacturing, and high-quality recycling, supported by the systemic integration of life-cycle thinking. In practice, it means designing PV modules with eventual recovery in mind, deploying efficient collection and logistics systems for end-of-life (EoL) products, and reinjecting recovered materials, metals, glass, and semiconductor compounds into manufacturing chains at equal or higher functional quality. One key principle that emerges in this context is reducing reliance on virgin resource extraction by reclaiming components from retired modules. Material recovery from EoL PV panels captures scarce resources such as tellurium and indium, alongside abundant but energy-intensive inputs such as aluminum and high-purity silicon (Skarkos et al., 2025). Designing processes to achieve high recovery yields not only mitigate environmental damage from mining but also address looming bottlenecks in the supply of critical materials as global PV deployment scales. For thin-film types such as cadmium telluride (CdTe), this implies recovering cadmium under controlled conditions that eliminate toxicity risks while securing tellurium for reuse (Das & Sarmah, 2025).

Operationalizing a circular approach faces economic and infrastructural constraints. Studies indicate that, at present, the cost of recycling a single PV module can be an order of magnitude greater than landfill disposal fees (Sanathia et al., 2024). This cost imbalance discourages voluntary participation in recycling unless policies create binding obligations or offer economic support mechanisms such as subsidies, tax credits, or recycled content requirements. Some proposals advocate implementing deposit–refund schemes or up-front recycling fees embedded within module sale prices to finance future processing (G. Wang et al., 2024). Under extended producer responsibility legislation, as

seen in several European markets, this financial liability motivates manufacturers to develop easier-to-disassemble designs or adopt materials that retain higher secondary-market value after initial use. The role of regional policy alignment is essential here. Life cycle impact assessment methodologies differ across geographies; TRACI captures indicators tailored to U.S. conditions, while Eco-indicator 99 focuses on European ecosystems (Skarkos et al., 2025). These methodological differences can influence how environmental priorities are weighed in decision-making, potentially impacting industry investment in circularity measures. Regions where regulatory frameworks explicitly classify PV modules under dedicated waste electrical and electronic equipment (WEEE) categories tend to achieve more consistent collection rates and secondary material reintegration (G. Wang et al., 2024). By contrast, jurisdictions without PV-specific waste codes risk inconsistent handling practices and missed recovery opportunities. Integration into existing industrial symbioses offers another strategic pathway. For example, certain metallurgical residues generated during battery recycling have been repurposed into automotive-grade magnetorheological fluids (Sanathia et al., 2024), demonstrating how cross-sectoral valorization can extend circularity beyond a single product category. Similar principles could apply to PV, a facility designed for electronic waste treatment could adapt leaching stages or sorting lines to handle both PV components and other electronics with overlapping material profiles.

A mature circular system would take cues from existing best-practice examples in which manufacturers operate vertically integrated, closed-loop recycling plants capable of returning over 90% of semiconductor mass into new modules while reusing intact glass sheets (Das & Sarmah, 2025). Such systems minimize downcycling losses that otherwise diminish material utility over successive loops. However, these successes are often constrained by geographic scope; global scalability hinges on harmonizing international standards for acceptable contaminant levels in secondary materials so they can move freely across borders without violating hazardous waste controls. There is also a systemic dimension: maximizing utility from existing material stocks implies prolonging the operational lifespan of deployed modules before recycling becomes necessary. Strategies

include preventative maintenance programs, repair networks for subcomponent replacement (such as junction boxes), and re-certification protocols enabling continued second-life usage in less demanding environments (Tan et al., 2024). Although keeping modules in use delays feedstock arrival at recycling plants, it reduces near-term environmental burdens by deferring energy inputs needed for remanufacturing replacements.

Circular economy implementation is likely to be uneven globally without platforms that link research institutions, manufacturers, recyclers, policymakers, and end-users. The absence of cohesive global management regimes opens space for leakage of recyclable PV waste into regions lacking safe processing capacity (Zaabi & Ghosh, 2024). International collaboration, potentially via standardized reporting formats for recovered quantities, achieved purity grades, and energy intensity metrics, could accelerate technology transfer and benchmark setting. There is room too for innovation upstream at the design phase: replacing toxic constituents like lead-based solders with benign alloys makes later handling less hazardous; adopting encapsulants engineered for clean release under defined stimuli simplifies delamination; opting for modular frame systems facilitates non-destructive opening without bulk shredding (Skarkos et al., 2025). Ultimately embedding PV technology within a circular economy framework appears less about inventing singular breakthrough processes than about synchronizing multiple complementary changes: cleaner production energy inputs lowering upstream impacts (Kwok et al., 2024), product designs easing dismantling, incentivized collection infrastructures ensuring steady throughput to advanced processing lines, high-yield recovery routes preserving material value at former-function quality levels, and market channels willing to absorb secondary outputs competitively against virgin alternatives. Without this interplay sustained over decades, the same timescales over which current generation installations will retire, the ambition of matching renewable electricity's low-carbon generation profile with an equally regenerative material footprint will remain aspirational rather than realized.

2.6.2 Integration with renewable energy policies

Linking PV waste management strategies with broader renewable energy policy frameworks creates opportunities to align environmental objectives **across the entire life cycle of** solar technologies. Policies originally designed to accelerate deployment, **such as feed-in tariffs,** net-metering provisions, **and renewable portfolio standards,** can be restructured or expanded to account for end-of-life (EoL) responsibilities. This integration ensures that growth in installed capacity does not outpace the development of adequate collection and recycling infrastructure, a concern underscored by forecasts showing large surges in module retirements within constrained timeframes (Zaabi & Ghosh, 2024). Without embedding EoL considerations into renewable energy policy instruments, there is a risk of inadvertently incentivizing rapid capacity additions while externalizing long-term waste liabilities. Extended producer responsibility (EPR) systems offer a clear point of connection between these domains. By obligating manufacturers and importers to finance or operate recycling programs proportionate to their market share, EPR transforms module producers from passive recipients of deployment incentives into active stakeholders in waste minimization (Ndalloka et al., 2024).

Policy models such as the EU's WEEE directive already demonstrate this principle in action within the PV sector; adapting such schemes for other geographies would require calibrating recovery targets, contaminant thresholds, and reporting protocols to domestic industry capabilities (Celep et al., 2025). Critically, embedding EPR into national renewable energy legislation rather than treating it as stand-alone environmental regulation can tie compliance directly to eligibility for installation subsidies or participation in government auctions. Some jurisdictions incorporate pre-funded recycling mechanisms into their solar incentive programs. For example, levying an upfront recycling fee at the point of sale ensures that future processing costs are covered regardless of commodity market volatility (G. Wang et al., 2024). Structuring such fees within existing renewable incentive payments minimizes administrative overhead while building predictable capital reserves for treatment facility investments. Conversely, where landfill

disposal remains cheaper than recycling, as still occurs in many markets, the absence of aligned policy levers can stall development of advanced recovery technologies despite their environmental benefits. Integrating PV waste objectives with renewable policy also allows cross-linkages with industrial support programs. Subsidies or tax breaks offered for local PV manufacturing could be conditioned on demonstrable design changes that improve recyclability or reduce hazardous material content (Ali et al., 2023). This not only aligns upstream production practices with downstream environmental goals but also fosters domestic expertise in eco-design principles applicable across clean tech sectors. Relatedly, R&D funding earmarked under national renewable energy roadmaps could explicitly target innovations in low-impact recycling processes or modular product designs that allow straightforward disassembly at EoL (Ali et al., 2023; Ndalloka et al., 2024).

Coordination at the international level is another dimension where linking waste management with renewable policy could yield benefits. Harmonized regulations on transboundary movement of PV waste would prevent “leakage” to jurisdictions lacking adequate safeguards, a common problem when retired modules are exported under generic scrap classifications (Celep et al., 2025). Multilateral climate agreements and renewable energy alliances could serve as platforms for integrating minimum recycling standards or take-back obligations into broader decarbonization commitments. There is also scope for aligning PV waste strategies with grid integration and capacity planning policies. Incentive structures promoting repowering —replacing older modules with higher-efficiency units before technical EoL —should be evaluated against the resulting waste volumes. Linking repowering approvals to verified recycling pathways could temper unnecessary early retirements while ensuring that when replacements do occur, material recovery is maximized. Similarly, auction designs for utility-scale projects might require bidders to submit decommissioning and recycling plans alongside construction proposals; compliance could be tracked throughout project lifecycles via monitoring systems already used for performance reporting. Linkages can extend further into green public procurement policies. Governments procuring solar power systems for public assets could

mandate certified recyclability criteria or require suppliers to participate in accredited take-back schemes. Such requirements ripple through supply chains, influencing material choices and design approaches, even among manufacturers whose primary markets are private-sector buyers (Zaabi & Ghosh, 2024). When coupled with life cycle assessment-based scoring weighted within tender evaluations, these measures embed circularity metrics directly into competitive dynamics.

The interplay between financial incentives and regulatory obligations must also take into account the operational realities faced by recyclers. For instance, preferential tariff rates granted to facilities using recycled PV materials in new module production would create pull factors that stabilize demand for secondary outputs during commodity troughs (Das & Sarmah, 2025). Conversely, penalties such as landfill taxes calibrated to higher levels for recyclable PV components can push material flows toward formal recovery channels rather than uncontrolled disposal (Ndalloka et al., 2024). Public awareness components within renewable energy promotion campaigns can likewise integrate messaging about proper EoL handling (Zaabi & Ghosh, 2024). Educating system owners about available collection points or legal obligations regarding hazardous components increases participation in official recovery programs. This aligns social license narratives underpinning renewable expansion, positioning solar power not only as low-carbon during operation but also as responsible throughout its whole lifespan.

Policy integration should remain adaptive over time. Evolving technology profiles will alter EoL processing needs; e.g., perovskite tandem cells may introduce new chemical risks, requiring different infrastructure than either c-Si or CdTe lines (Das & Sarmah, 2025). Embedding regular review cycles into renewable energy legislation allows adjustment of waste management provisions alongside shifts in market composition or advancements in recycling efficiency. The most effective integrations tend toward multi-instrument approaches: pairing regulatory compulsion (e.g., binding recovery quotas) with economic stimuli (e.g., recycled-content subsidies), technical standards (e.g., eco-design rules), and informational tools (e.g., labeling recovered-material percentages).

When embedded holistically within clean energy policy frameworks rather than treated as separate environmental concerns, these instruments can ensure that scaling up PV deployment contributes positively to both climate mitigation and resource sustainability, without leaving behind a legacy of unmanaged solar waste.

2.7. Regulatory and Policy Frameworks

2.7.1 International policy landscape

The global policy architecture governing photovoltaic waste management is marked by wide variation in scope, enforcement mechanisms, and the degree of technology-specific regulation. While some jurisdictions have enacted explicit rules addressing end-of-life (EoL) management of PV modules, others subsume them under general waste or electronic waste categories, leading to inconsistencies in collection, treatment, and material recovery outcomes (Zaabi & Ghosh, 2024). These disparities complicate efforts to establish standardized recycling practices that could facilitate cross-border cooperation and economies of scale in processing infrastructure. Within the European Union, PV modules are explicitly covered under the Waste Electrical and Electronic Equipment (WEEE) Directive. This inclusion imposes extended producer responsibility (EPR), binding collection quotas, and recovery targets for specific material fractions. The regulatory structure mandates that producers finance take-back and recycling systems while meeting defined contaminant thresholds for recovered materials to re-enter the market (Kwok et al., 2024). Such specificity has driven higher formal collection rates compared to regions without dedicated PV provisions. Member states like Germany, Italy, and the UK operationalize these requirements through national registry systems that monitor compliance. At the same time, Scandinavian countries couple these frameworks with community-based collection models and subsidies for treatment costs. This policy alignment enables manufacturers to anticipate obligations at the design stage, adopting eco-design modifications to facilitate dismantling or reduce hazardous constituents such as lead solders.

The United States applies a less centralized approach. At the federal level, PV panels fall under the Resource Conservation and Recovery Act (RCRA), which categorizes waste based on toxicity testing protocols like the Toxicity Characteristic Leaching Procedure (TCLP). Modules that fail TCLP are managed as hazardous waste, imposing stricter handling and disposal standards. However, absent a nationwide PV-specific mandate, regulatory detail resides at the state level. Washington State stands out for enacting legislation that requires manufacturer-funded stewardship programs for PV module take-back and recycling. Other states rely on general e-waste laws without explicit PV references, which may weaken participation incentives for producers whose products do not consistently trigger hazardous classification. In Asia, regulatory maturity is heterogeneous. Japan is moving toward formalizing PV-dedicated legislation via its Ministry of Economy, Trade and Industry (METI) and Ministry of the Environment (MOE) (Zaabi & Ghosh, 2024). Proposed frameworks emphasize both safe material recovery, especially for potentially toxic semiconductors, and strategic conservation of scarce elements like tellurium or indium. Pilot-scale recycling facilities are already operational under government–industry partnerships that serve as validation platforms for future regulatory codification. China illustrates a different trajectory: despite being the largest producer and installer of PV capacity globally, it currently lacks standalone regulations explicitly tailored to PV waste management. Policies applicable to EoL panels are derived from broader instruments such as the Solid Waste Law and Waste Electrical and Electronic Product Recycling Management Regulation (Das & Sarmah, 2025). Additionally, there have been attempts to standardize thin-film recycling processes through technical guidance documents rather than binding legal codes (Zaabi & Ghosh, 2024). These voluntary norms coexist with emerging institutional structures like the China PV Recycling Centre alliance formed in 2022 (Das & Sarmah, 2025), suggesting a gradual move towards more formalized governance. India provides another example of an economy with substantial solar expansion, but where policy frameworks lag behind deployment pace. As of now, discarded PV modules are managed under general solid waste or hazardous waste rules administered by the Ministry of Environment, Forest and

Climate Change; there is no dedicated statute addressing their specific composition or EoL routes (Preet & Smith, 2024). This absence leaves uncertainty around responsibilities for safe treatment, potentially impeding investment in specialized recycling infrastructure. Similar conditions exist in South Korea, where PV waste is addressed within more general renewable energy amendments without clear operational standards (Preet & Smith, 2024). In contrast to many Asian contexts, certain Middle Eastern states have begun integrating PV waste considerations into renewable energy strategies at early stages of deployment planning. While legislative details remain sparse publicly, policy documents signal intent to avoid retrofitting EoL governance after large-scale buildout, a lesson drawn from markets now confronting steep decommissioning curves without adequate infrastructure. Internationally harmonized approaches remain elusive despite commonalities in environmental objectives. For instance, transboundary movements of decommissioned modules often fall under Basel Convention provisions governing hazardous waste shipments; however, classification disputes persist over whether non-hazardous c-Si panels require equivalent controls when moving between jurisdictions with divergent TCLP interpretation thresholds (Zaabi & Ghosh, 2024). A lack of uniform reporting metrics on recovery yields or contaminant levels further hampers mutual recognition across borders, limiting opportunities for regionalized processing hubs. Policy gaps also manifest in economic instruments linked to compliance.

In places with landfill bans on PV modules, such as enacted in certain Australian states, diversion into formal treatment streams is immediate (G. Wang et al., 2024), yet without accompanying subsidies, technology operators may opt for low-recovery mechanical shredding rather than advanced hydrometallurgical lines necessary for reclaiming high-value metals from thin-film devices. Conversely, areas with minimal disposal restrictions risk creating perverse incentives that make landfill cheaper than regulated recovery. Canadian provinces mirror the fragmented nature seen elsewhere: British Columbia classifies PV panels within its broader extended producer responsibility program for electronics, but without differentiated targets keyed to semiconductor type or hazard potential. This generalist stance provides flexibility yet offers limited steering

toward process innovation specific to photovoltaics. Efforts by multilateral bodies to address these mismatches have so far centered on information sharing more than binding commitments. Agencies like IRENA have issued technical guidelines highlighting best practices drawn from established markets (Kwok et al., 2024), aiming to inform emerging economies before mass-retirement phases commence. Still, guidance uptake depends heavily on domestic political will and perceived economic trade-offs. One recurring challenge across jurisdictions is synchronizing rapid capacity addition targets embedded in climate policies with realistic timelines for building parallel EoL systems (Zaabi & Ghosh, 2024). Markets emphasizing accelerated deployment without embedding recovery obligations tend to postpone difficult policy debates until post-peak installation periods, by which time accumulating waste inflows can overwhelm nascent recycling chains. Aligning renewable energy incentives with binding EoL provisions could pre-empt this imbalance. Overall, the international landscape reveals a patchwork evolution: highly prescriptive regimes like the EU's WEEE directive sit at one end; soft-law guidance coupled with voluntary industry initiatives mark the other; between them lie hybrid approaches combining existing e-waste laws with pilot recycling projects intended as prototypes for fuller mandates. Without convergence on key elements, classification criteria for hazardousness, minimum recycled content thresholds in new modules, standardized metrics for process yield, the ability to develop cost-effective multinational material recovery networks remains constrained even as global EoL volumes rise steeply over the coming decades.

2.7.2 Policy frameworks in leading countries in PV deployment

Examining national-level policy frameworks in countries with high photovoltaic (PV) deployment reveals striking contrasts in scope, enforcement, and integration with broader energy and environmental strategies. Germany, as one of the earliest and most influential adopters of large-scale solar, embeds PV waste governance within its transposition of the European Union's WEEE Directive. This framework assigns producers direct responsibility for collection, disassembly, and either recycling or disposal

of decommissioned modules, channeling them through a National Register for Waste Electrical Equipment to track compliance (Vinayagamoorthia et al., 2024). Such mechanisms ensure not merely end-of-pipe management but also influence upstream design choices. Manufacturers operating in this regulatory landscape often prioritize ease of disassembly and reduction of hazardous constituents to meet recovery quotas while avoiding costly hazardous waste classification. Recovery targets aligned with EU standards encourage technological investments in processes that can reintegrate glass, metals, and semiconductor materials into production cycles at quality levels comparable to virgin resources (Yu et al., 2024). The United States presents a decentralized picture. At the federal level, PV modules are subject to RCRA rules when they fail TCLP tests for hazardous leachate potential (Sanathia et al., 2024). This pass/fail criterion produces variability across product types: some c-Si units meet non-hazardous thresholds while certain CdTe configurations do not due to cadmium content. In the absence of a comprehensive national PV-specific statute, states have taken divergent paths. Washington State's legislation is notable; it mandates manufacturer-funded stewardship plans for collection and recycling, effectively creating an EPR scheme similar in intent to EU rules but without an overarching recovery quota imposed from above (Preet & Smith, 2024b). California has opted for classifying most retired PV panels as universal waste instead of hazardous material, thereby lowering immediate handling costs but arguably diminishing regulatory impetus to develop advanced recovery lines for valuable or toxic elements (Sanathia et al., 2024). Other states rely on general e-waste legislation without adapting requirements to the specific material profiles of PV modules. This patchwork limits opportunities for harmonized processing infrastructure across state borders. In East Asia, Japan operates under the Law for Promotion of Effective Utilization of Resources but currently excludes thin-film PV from explicit coverage (Curtin et al., 2020). Nevertheless, both the Ministry of Economy, Trade and Industry (METI) and the Ministry of the Environment (MOE) are advancing toward codifying PV-dedicated regulations, which are expected to merge safe treatment obligations with strategic raw material conservation objectives (Zaabi & Ghosh, 2024). Pilot projects integrating industrial

98

12

partners test chemical recovery routes for cadmium- and indium-bearing devices under strict effluent controls; outcomes from these initiatives are informing final legislative designs.

South Korea's Act for Recycling of Electrical/Electronic Products and Automobiles similarly mirrors EU principles in broad structure yet omits thin-film PV from its current scope (Curtin et al., 2020). Without explicit inclusion or defined collection mandates, treatment depends on extended e-waste streams that may not differentiate appropriately between module chemistries or hazard potentials. China's situation reflects its status as both the largest global installer and manufacturer of PV systems. Despite this scale, no standalone legal framework governs EoL module management (Kwok et al., 2024). Instead, general laws such as the Solid Waste Law are applied alongside technical guidance documents promoting best practice recycling methods for crystalline silicon and thin-film types (Zaabi & Ghosh, 2024). Early-stage pilot operations process limited volumes, tens of megawatts annually, but signal government intention toward formalized standards over time. Industry alliances like the China PV Recycling Centre have emerged to coordinate stakeholders; however, without binding regulation, these efforts remain voluntary and regionally uneven. The lack of centralized data reporting on recovered quantities constrains planning for nationwide infrastructure build-out proportionate to the projected waste surges.

India exemplifies another high-growth solar market yet without PV-specific waste mandates; end-of-life panels fall under general hazardous or solid waste categories depending on TCLP outcomes (Preet & Smith, 2024). Regulatory ambiguity creates uncertainty over who bears financial responsibility for safe treatment, deterring private investment in dedicated recycling facilities despite forecasts showing large volumes retiring post-2035. Similar gaps exist in legislative drafting around permissible landfill disposal versus mandatory recovery routes; without clear prohibitions or incentives, the default pathway risks being unmanaged dumping or low-yield mechanical shredding lacking proper containment measures. Australia exhibits a more proactive element at

subnational levels: Victoria has enacted a ban on landfilling PV waste outright, compelling diversion into recovery channels regardless of market pricing trends for secondary materials (Sanathia et al., 2024). This intervention increases throughput certainty for recyclers but also exposes shortcomings where capacity is insufficient, stockpiling becomes a near-term risk unless paired with parallel investment in compliant processing plants and logistics networks capable of transporting bulky modules economically from dispersed rural arrays to centralized facilities.

Across these leading markets, policy efficiency correlates with the degree to which obligations are tied to producers' operational decision-making. Jurisdictions mandating EPR with enforceable recovery rates, like Germany, achieve higher formal collection percentages and show greater industry uptake of eco-design features aimed at dismantling productivity (Vinayagamoorthia et al., 2024). Where frameworks remain generic or voluntary, as seen in China's current stage, the pace of infrastructure maturation lags behind deployment curves even when overall political commitment to renewable scaling is high. The U.S., straddling both models via state differentiation, illustrates how partial adoption leads to fragmented recycling ecosystems lacking cross-jurisdictional economies of scale (Preet & Smith, 2024). There is evidence that embedding recycling responsibilities within broader renewable energy incentive programs can streamline administrative oversight and bolster compliance by linking subsidy eligibility to demonstrable end-of-life planning (G. Wang et al., 2024). Conversely, missing such linkages may perpetuate a linear flow from installation incentives through unregulated disposal phases, a trajectory incompatible with stated climate and resource conservation goals even in technologically advanced markets.

2.8. Socio-Economic Aspects of PV Waste Management

2.8.1 Economic feasibility of recycling

Evaluating the economic feasibility of photovoltaic (PV) module recycling requires balancing multiple interdependent variables, many of which fluctuate over time and differ by technology type. Cost structures are heavily influenced by factors such as

material composition, recovery yields, processing technology maturity, throughput volume, and prevailing commodity prices for recovered outputs (Zaabi & Ghosh, 2024). A recurring observation is that in the current market environment, landfill or low-yield mechanical treatments often remain cheaper than advanced recycling routes, especially in jurisdictions lacking supportive policy instruments (Souza et al., 2024). This economic gap is exacerbated in regions where landfill tipping fees are minimal and where regulatory frameworks do not internalize environmental costs associated with hazardous element dispersion. Capital investment requirements present a substantial barrier to entry for high-purity recovery facilities. For crystalline silicon (c-Si) modules, achieving solar-grade silicon reclamation capable of re-entering manufacturing chains demands thermal, chemical, and mechanical processes in combination; these carry both high operational energy use and chemical waste management costs (Celep et al., 2025). While secondary market prices for silver recovered from c-Si metallization can help offset costs, given its relatively high unit value, the proportionate mass within a module is small, limiting the overall impact on profitability without robust silver price stability (Liu et al., 2024).

Similarly, in thin-film cadmium telluride (CdTe) modules, cadmium and tellurium recovery depend on market demand for tellurium, a rare but industrially strategic element. Yet, volatility in global supply-demand balance can quickly erode projected returns from recycling investments (Celep et al., 2025). Labour costs often dominate operational expense profiles at both laboratory and industrial scales. These labour costs can exceed those attributable to energy consumption or consumable reagents, particularly in early-stage or small-batch processing lines where automation is limited (Tembo & Subramanian, 2023). Scaling up can reduce per-unit labour inputs but introduces new complexities such as feedstock heterogeneity and long-distance transportation from collection nodes to centralized plants. Transport adds a further cost burden; modules are large and heavy relative to their recoverable material value, which can diminish the attractiveness of centralized treatment unless regional aggregation hubs are efficiently located (Celep et al., 2025).

Process selection also affects feasibility calculations. Hybrid approaches combining mechanical dismantling with targeted chemical or thermal treatments reduce reagent usage and allow selective material concentration but require integrated plant designs that increase initial capital outlay (Das & Sarmah, 2025). Purely mechanical downcycling to glass cullet and mixed-metal scrap carries a lower upfront cost yet reduces long-term system value by forfeiting high-purity semiconductor recovery potential. Economic trade-off analysis between these pathways needs to account for avoided costs of virgin resource extraction; however, such externalities are rarely priced into financial models without policy intervention. Material market dynamics play a decisive role. Scenario modelling for different PV technologies has indicated that cumulative recycled output could reach values in the tens of billions of dollars by 2050 under optimistic recovery rate assumptions. For instance, forecasts suggest c-Si panel recycling could generate around \$12.4 billion in recovered value at mid-century, 31.5% of which may derive from silver alone, if both collection rates and technological efficiencies improve steadily (Liu et al., 2024). CdTe module recycling benefits mainly from copper and tellurium valorization; CIGS panels yield aluminium-dominated resale streams alongside indium recovery. Yet these projections rest on uncertain long-term trajectories for metal demand across industries like electronics and electric vehicles; substitution trends or novel mining operations could depress prices during critical revenue windows for recyclers. Cash flow structures reveal additional sensitivities: analyses that integrate net present value (NPV) calculations with projected silver price variations show significant swings between profitable and loss-making scenarios for otherwise technically viable processes (Granata et al., 2022). In other words, even modest commodity fluctuations can determine whether an advanced process sees a return on investment over a 15-year horizon.

This volatility underlines why some operators hesitate to commit capital without stable policy supports like minimum price guarantees for secondary materials or subsidies offsetting fixed costs during market downturns. Governmental incentives remain one pathway to improving economic feasibility. Direct financial support during initial implementation phases can bridge gaps until economies of scale are realized. Suggestions

include refundable deposits applied at module sale, which form post-consumer recycling funds, or tax incentives tied to meeting specific recycled content thresholds in new modules (Souza et al., 2024). This type of intervention has been instrumental in other e-waste sectors when technological learning curves were still steep. Without such measures, many recyclers limit operations to recovering high-mass commodities like aluminum frames while disposing of or downcycling more complex components due to cost constraints. An emerging strategic consideration involves coupling PV recycling capacity planning with broader renewable sector targets so that rising decommissioning volumes match scaling treatment infrastructure (Mahmoudia et al., 2021). Misalignment creates inefficiencies: under-capacity drives up logistics costs through longer storage times or exports; over-capacity early on leads to poor asset utilization before waste flows peak. Predictive modelling tied into national deployment policies allows better phasing of plant expansions, supporting steadier amortization schedules that improve long-term viability. Innovations aimed at simplifying disassembly, such as encapsulants designed for clean release under mild heat or frame systems enabling non-destructive opening, could lower processing costs by reducing reliance on energy-intensive delamination stages (Celep et al., 2025).

However, adoption will require manufacturer buy-in supported by regulatory eco-design mandates or market differentiation premiums favoring recyclable products. Similarly, integrating recycling lines into multi-stream material recovery facilities handling other electronic wastes could spread overhead across higher aggregated input tonnage. Ultimately, the persistent challenge lies in transitioning from today's economically fragile niche operations toward mainstream industry segments resilient against short-term commodity swings. Achieving this shift likely demands a cocktail of measures: coordinated policy instruments ensuring steady feedstock flows; financial mechanisms buffering price risks; targeted R&D funding directed at process simplification; and international harmonization of contaminant thresholds permitting freer trade in recovered PV materials (Zaabi & Ghosh, 2024). Without such alignment, purely

market-driven uptake is unlikely given present-day disparities between environmental benefit valuations and direct profitability signals observable across the sector.

2.8.2 Stakeholder engagement and public perception

Perceptions and levels of engagement among diverse stakeholders, from manufacturers and policymakers to consumers and recycling operators, exert a considerable influence on the evolution of photovoltaic (PV) waste management systems. The previous focus on economic feasibility highlights that technical viability alone does not ensure successful large-scale adoption of advanced recycling or circular economy practices; these require social buy-in, industry cooperation, and policy alignment to function in reality. Engagement is shaped by differing priorities, incentive structures, and understandings of environmental risks associated with module end-of-life ([Souza et al., 2024](#)). One recurrent finding is the widespread lack of awareness among PV system owners about both the potential hazards embedded in certain module chemistries and the existence of formal recovery channels ([Ali et al., 2023](#)). Consumers often perceive solar panels as inherently “green” technologies, a perception reinforced during installation marketing, yet rarely updated to account for their eventual classification as complex e-waste containing toxic constituents. When expectations of sustainability collide with reports of improper disposal or landfill leakage from modules, particularly those with cadmium telluride (CdTe) active layers, the resulting dissonance can erode public trust in solar energy more broadly ([Mahmoudia et al., 2021](#)). Where such misperceptions persist, adoption of even the most sophisticated recycling technology faces an uphill battle against apathy or resistance from owners unwilling to bear extra transport or handling costs for decommissioned units.

The degree of stakeholder responsibility acceptance varies sharply across groups. Survey data indicate that while 60% of consumers support government-led recycling responsibility for PV waste, just over half of manufacturers prefer a shared model involving government, consumers, and producers ([G. Wang et al., 2024](#)). Only a minority, about 23%, of manufacturers express readiness to fully assume this role without additional

incentives. Disagreements over these roles delay consensus on funding mechanisms for collection systems or investments in centralized processing facilities. This diffusion of responsibility risks perpetuating informal disposal channels in jurisdictions with weak enforcement, particularly when module transportation is costly relative to residual material value. Manufacturers' perspectives are also influenced by legislative certainty. In places where extended producer responsibility (EPR) is mandated with clear quotas and penalties, industry actors adapt their designs toward recyclability; in voluntary or vague regimes, the same actors may prioritize short-term cost savings over modular design innovations that would facilitate future disassembly ([Maghraby et al., 2025b](#)).

Government agencies thus become not only regulators but also mediators between competing stakeholder visions, tasked with aligning private-sector cost concerns with public environmental protection goals. Public attitude is especially sensitive to visible environmental incidents. High-profile cases of heavy metal contamination from other sectors can prime communities to respond critically to any suggestion that PV modules, despite years of clean operation, might become hazardous if discarded carelessly ([Curtin et al., 2020](#)). In turn, negative sentiment can influence policy cycles: decision-makers wary of backlash might harden disposal regulations rapidly following isolated contamination events, even if broader datasets suggest low leaching likelihood under controlled conditions. This reactive policy pattern underscores why proactive information campaigns, targeting installers, property owners, and local waste handlers, are essential to stabilize perceptions before misinformation takes root. Engagement quality among recyclers themselves also affects downstream outcomes. Where recyclers are integrated early into policy development processes, they can signal pragmatic constraints such as batch-size requirements for economically viable runs or technical limitations when handling mixed-chemistry loads ([Das & Sarmah, 2025](#)). Ignoring this operational input risks designing schemes that look comprehensive on paper yet fail under real conditions due to bottlenecks in separation capability or prohibitive contamination controls. Behavioral tendencies documented in consumer studies add further complications: even in mature solar markets, participation rates in take-back schemes are hampered by factors

such as distant drop-off locations or opaque scheduling requirements (Souza et al., 2024). Low motivation pairs with limited knowledge about both regulatory obligations and ecological impacts. Without sustained engagement efforts, including digital reporting tools, visible collection bins tied into municipal waste interfaces, or rebate structures for returned panels, these participation gaps persist irrespective of policy provisions.

Stakeholder alignment becomes more challenging under fragmented regulatory arrangements where neighboring jurisdictions apply different classification standards for identical products. In such cases, regional recyclers may see cross-border flows dictated less by optimal logistics than by attempts to exploit weaker rules elsewhere, a phenomenon undermining both public trust and legitimate operator economics (Ali et al., 2023). Harmonizing hazard definitions and testing protocols can mitigate this effect while giving manufacturers a uniform compliance target rather than a patchwork. It also emerges that transparency in reporting recovery performance affects perception among environmentally conscious investors and end-users alike. Publicly available metrics on recovery yields, contamination control effectiveness, or greenhouse gas savings from recycled content help reinforce confidence that EoL management aligns with broader climate objectives (Kwok et al., 2024). Absence of such data leaves room for suspicion about greenwashing claims around PV sustainability narratives. Policymaker outreach strategies can play an enabling role here: hosting multi-stakeholder forums where recyclers present process improvements alongside independent auditors lends credibility that purely self-reported corporate sustainability statements may lack. Furthermore, linking community benefits, such as job creation at local dismantling centers, to recycling initiatives strengthens grassroots support beyond abstract ecological arguments.

Engagement approaches should also recognize regional cultural contexts influencing how responsibility is framed. In some political cultures, extended producer responsibility aligns smoothly with prevailing views on corporate environmental accountability; elsewhere, there may be stronger expectations for state provision of environmental services funded through general taxation rather than direct industry levies

(G. Wang et al., 2024). Crafting messaging that aligns with these norms while still nudging behavior toward shared stewardship tends to produce better uptake than one-size-fits-all advocacy models imported wholesale from other governance traditions. Finally, there is an interplay between stakeholder engagement levels and long-term infrastructural investment signals observed in Section 8.1. Demonstrated societal backing, through consistent consumer participation rates or industry–government partnerships, not only secures current recovery capacity but also encourages expansion plans calibrated to projected waste surges decades ahead. Conversely, tepid engagement feeds uncertainty that dampens willingness to commit capital toward advanced separation lines or closed-loop systems, which rely on predictable feedstock inflows over multi-year amortization periods. In summary, Public perception influences political momentum; political momentum then affects regulatory clarity; regulatory clarity shapes manufacturer behavior; and manufacturer behavior feeds back into both public perception and investor confidence. These dynamic feedback loops across all actors mean engagement strategies must be iterative: responsive not just to current attitudes but also adaptable as technology profiles evolve, preventing scenarios in which PV’s clean energy promise is overshadowed by preventable waste mismanagement narratives amplified through the eyes of disengaged stakeholders.

2.9. Future Perspectives for PV Waste Management

Looking ahead, the prospective trajectory of photovoltaic waste management appears poised to transition from fragmented, reactive measures toward more integrated, predictive systems embedded within policy and technology frameworks that prioritize material circularity. The anticipated surge in end-of-life (EoL) modules over the coming decades underscores a need for substantial scaling of both infrastructure and regulatory reach. This is particularly urgent in regions where deployment boomed over the last 10–15 years and where the first mass decommissions will coincide with still-maturing waste-handling capacities (Zaabi & Ghosh, 2024). Proactive planning will likely determine whether future PV waste flows become an environmental liability or a secondary resource

stream capable of offsetting raw material demand. A critical frontier involves upstream design innovation to ensure recyclability without compromising operational performance. Current research on encapsulants engineered for controlled debonding under specific stimuli, such as infrared heating tuned to polymer absorption peaks, offers promise in simplifying delamination while preserving glass sheets intact for high-value reuse ([J. Wang et al., 2024b](#)). Similarly, structural designs enabling non-destructive frame removal could cut processing time and reduce breakage rates that currently limit high-purity silicon wafer recovery. Embedding such features into mainstream manufacturing will probably require binding eco-design stipulations tied to market access or subsidy eligibility, as voluntary adoption has historically lagged where short-term production costs outweigh perceived long-term recovery benefits ([J. Wang et al., 2024b](#)).

Technological diversification in recycling methods may also be decisive. Hybrid approaches combining mechanical pretreatment with targeted thermal or chemical steps are emerging as efficient compromises between maximizing yield and minimizing reagent consumption ([Das & Sarmah, 2025](#)). Adapting these flexible platforms to handle mixed-chemistry loads —crystalline silicon, CdTe, and CIGS simultaneously —would allow facilities to serve heterogeneous waste inflows without idle capacity when any one technology's decommissioning cycle slows. However, this adaptability comes with higher initial capital requirements and demands skilled process control to avoid cross-contamination of recovered fractions, particularly for elements such as tellurium or indium, which require stringent purity for re-entry into PV manufacturing chains ([J. Wang et al., 2024a](#)). From a governance perspective, harmonization across borders is likely to grow in importance as PV supply chains and waste destinations are increasingly international. Contradictions between national hazardousness classifications, for example, differing outcomes of Toxicity Characteristic Leaching Procedure (TCLP) thresholds, currently complicate transboundary movement of spent modules and hinder regionalized processing strategies. Future policy development may gravitate toward baseline global criteria for PV waste handling under frameworks like the Basel Convention, supplemented by bilateral or multilateral agreements on contaminant standards that facilitate trade in

recovered materials without weakening environmental safeguards. Forecasting tools will continue to evolve from static lifespan assumptions toward dynamic models that incorporate early-retirement patterns driven by repowering incentives or damage-induced replacements (Zaabi & Ghosh, 2024). Integrating such modelling into national energy planning could synchronize recycling infrastructure rollouts with actual waste volume peaks, avoiding scenarios where premature infrastructure overcapacity drives economic underperformance or where insufficient capacity leads to environmentally harmful stockpiling. These models could also aid in siting decisions for regional aggregation hubs aimed at optimizing logistics efficiency, a nontrivial cost driver given the size-to-value ratio of retired modules (Celep et al., 2025a).

Economically viable scaling will depend heavily on stabilizing commodity revenue streams from recovered outputs. Future strategies might include contractual “offtake” agreements where downstream industries commit to purchasing recycled content at indexed prices over multi-year periods, insulating recyclers from volatile spot markets (Liu et al., 2024). Coupling this with policy tools such as recycled-content mandates in new PV products can create persistent pull factors sustaining demand even during raw material price troughs (G. Wang et al., 2024). Another dimension involves linking PV recycling with other electronic or clean energy technology recovery operations to spread fixed costs over larger aggregate throughput while maintaining material purity partitions; this could be achieved via co-located facilities processing both battery components and semiconductor e-waste. For thin-film chemistries, future perspectives hinge on sustaining high recovery rates for scarce elements alongside eliminating hazardous release risks during processing. Expansion of closed-loop industrial lines capable of returning >90% of CdTe semiconductor mass to production has shown that environmental hazard potential can be reduced markedly when modules never enter uncontrolled waste channels (Das & Sarmah, 2025).

Scaling similar systems worldwide may require knowledge transfer mechanisms and financial cooperation models, including public–private partnerships, to overcome cost

barriers in markets lacking immediate regulatory compulsion but facing imminent large-scale EoL volumes. Policy integration with renewable energy promotion measures remains an untapped lever for many jurisdictions. Conditioning incentive eligibility on submission and periodic updating of decommissioning plans could normalize life cycle thinking among developers while generating datasets useful for national forecasting repositories. Likewise, landfill bans paired with transitional subsidies to support the build-out of advanced recovery facilities can hardwire diversion behavior before high-volume waste phases commence (G. Wang et al., 2024). Such interventions benefit from being anticipatory rather than remedial. Public perception trends discussed earlier highlight another critical factor: transparent communication around material risks and resource opportunities inherent to PV module retirement will influence political bandwidth for implementing more ambitious regulatory schemes. Publishing independent audits of recovery yields and environmental performance at recycling facilities can reinforce social license and consumer participation in official take-back programs (Kwok et al., 2024). In turn, higher collection rates improve economies of scale, a feedback loop supportive of investment decisions in next-generation processing technologies.

In research domains, interdisciplinary collaborations combining materials science advances with process engineering optimization will likely accelerate progress. For example, exploring non-toxic absorber layers or substituting abundant elements without sacrificing efficiency could alleviate future recycling complexity while mitigating hazardous leachate risk profiles outright (Zaabi & Ghosh, 2024). Lifecycle assessment integration into early-stage technology development cycles would strengthen foresight capacity, flagging potential EoL bottlenecks before commercialization locks problematic designs into decades-long deployment horizons. Finally, aligning these future-oriented measures requires institutional coordination extending beyond the energy sector alone: trade ministries governing transboundary shipments; environment agencies overseeing hazardous substances; industry bodies setting technical standards; and academic consortia generating baseline data on degradation modes all have roles to play. The scale and asset lifetimes involved mean that fragmented action taken late will incur steeper economic

costs and heavier ecological debts than coherent preparation initiated well before mass retirements hit their stride. In essence, the trajectory toward sustainable PV waste management over the next decades will rest on how successfully technical potential, policy architecture, market mechanics, and societal engagement are woven into a united operational framework rather than treated as parallel but disconnected efforts (J. Wang et al., 2024b).

2.10. Chapter Summary

The ongoing expansion of photovoltaic technologies presents both remarkable opportunities and pressing challenges in managing the lifecycle of solar modules. As deployment scales up globally, the volume of end-of-life modules is set to increase substantially, demanding comprehensive strategies that integrate technical innovation, policy development, and economic considerations. Crystalline silicon modules, dominating current installations, will continue to represent the largest share of decommissioned panels, while thin-film variants such as cadmium telluride and copper indium gallium selenide contribute to a more heterogeneous waste stream requiring adaptable processing solutions.

Environmental assessments highlight that while crystalline silicon modules generally exhibit lower ecotoxic risks due to their material composition, thin-film technologies pose distinct challenges related to toxic element containment and recovery. Effective recycling processes must therefore balance high recovery yields with minimizing secondary pollution, employing hybrid mechanical, thermal, and chemical treatments optimized for each technology type. Advances in encapsulant design and module architecture aimed at facilitating disassembly promise to improve material recovery rates and reduce processing costs, yet widespread adoption depends on aligning manufacturing practices with regulatory incentives.

Policy frameworks play a decisive role in shaping end-of-life management outcomes. Extended producer responsibility schemes, as implemented in regions like the European Union, demonstrate how binding collection and recovery targets can drive

industry engagement and infrastructure development. Conversely, fragmented or voluntary approaches often result in lower recovery rates and increased environmental risks. Integrating waste management obligations within renewable energy incentive programs can ensure that capacity growth does not outpace the establishment of adequate recycling systems, thereby preventing the accumulation of unmanaged solar waste.

Economic feasibility remains a central concern, with current recycling costs exceeding landfill disposal fees in the absence of supportive policies. Market volatility for recovered materials, particularly scarce elements like tellurium and indium, adds uncertainty to investment decisions. Addressing these challenges requires coordinated policy instruments, financial mechanisms such as subsidies or deposit-refund schemes, and innovation in process simplification. Moreover, stakeholder engagement among manufacturers, consumers, recyclers, and regulators is essential to build awareness, foster shared responsibility, and maintain public confidence in solar energy's environmental benefits.

Looking ahead, the transition to a circular economy model for photovoltaic technologies depends on synchronizing advances in material science, process engineering, and regulatory harmonization. International cooperation to standardize hazardousness classifications and facilitate the transboundary movement of PV waste will support the development of regional processing hubs capable of efficiently handling diverse module chemistries.

Sustained progress will also hinge on transparent reporting of recovery performance and environmental outcomes, reinforcing social license and encouraging participation in formal take-back programs. Research into alternative absorber materials with lower toxicity profiles and improved recyclability could further ease future waste management burdens. Ultimately, embedding photovoltaic waste management within broader clean energy and environmental policies ensures that solar power remains a truly sustainable cornerstone of the global energy transition, avoiding the pitfalls of unmanaged downstream impacts and securing resource efficiency for decades to come.

CHAPTER 3

CRITICAL ANALYSIS OF GLOBAL RENEWABLE ENERGY CAPACITY AUGMENTATION STRATEGY

3.1 Preamble

This chapter critically analyses the trend of the global renewable energy sector's growth over the last two decades. It illustrates how both international and country-specific energy policies have tilted towards a single technology: solar photovoltaics. The analysis of time series data from 2011 to 2023 reveals that global photovoltaic installed capacity grew at an average annual rate of 28.1%, while the other technologies within the renewable energy basket were neglected entirely. The average growth rates of technologies that could be used to balance the intermittency of solar PV, viz., renewable hydro and pump storage, were only 2.4% and 2.6%, respectively. As a result, intermittent energy resources reached break-even with non-intermittent energy resources in the middle of 2019 and thereafter continued to overshadow them. Because of this euphoric rush over the last two decades toward a monocular vision for enhancing renewable energy capacity, the world has begun to face several technical and environmental challenges, which are presented in this paper. Based on the analysis, a course correction is strongly advocated in policy formulation to incentivize and promote energy technologies while ultimately aiming to decarbonize the energy sector.

3.2 Introduction

Renewable energy has great potential to help the world harness the continual rise in global average temperature by decarbonizing the energy sector. According to the Intergovernmental Panel on Climate Change (IPCC), the expedited adoption of renewable

energy sources could reduce up to 90% of carbon dioxide (CO₂) emissions from energy production by 2050. This approach can also help limit global temperature increase to a level significantly below 2 °C, closer to 1.5 °C, relative to pre-industrial levels (IPCC, 2020). Hence, policymakers across the globe have focused on augmenting renewable energy installed capacity since the beginning of the current century, resulting in a cumulative installed capacity of 4.14 TW globally as of date (IRENA, 2024). However, several parameters currently point to a lack of foresight and a balanced approach to policy formulation and technology incentivization. Some of these parameters include grid instability, scarcity of base-load serviceable power stations, a shortage of technologies to balance the intermittency of renewable energy, and environmental concerns due to the lack of feasible recycling technologies at a commercial scale. As evident from Fig. 1, the exponential rise in installed capacity in the global renewable energy sector is primarily driven by a single technology: solar energy, specifically solar photovoltaic. Presently, the cumulative installed capacity of solar energy has crossed 1420 GW, with solar photovoltaic energy accounting for a major share. There has been a global rush, since the beginning of the current century, to deploy photovoltaic (PV) devices in deserts, over water bodies, on residential rooftops, on vehicle roofs, in parking areas, and almost in all possible settings, and thereby the total installed PV capacity has presently surpassed 1185 GW worldwide (IRENA, 2024), which currently is the highest amongst all the renewable energy technologies. And with the current rate of PV deployment, the cumulative installed capacity of solar PV is projected to reach approximately 4,500 GW globally by 2050 (Ghosh & Yadav, 2021)

Undoubtedly, solar photovoltaic technology has numerous advantages, viz., modular design, ease of installation, short gestation period, and lowest levelized cost of energy (LCOE), which attracted sustained investments in research and development, as well as in projects involving PV technologies over the last two and a half decades. However, due to the perceived advantages of solar photovoltaic energy, as solar energy installed capacity increased exponentially, other energy sources were neglected and thus remained mostly stagnant (see Fig. 3.1) despite their immense potential. Wind energy had

an installed capacity three times that of solar energy in 2011; however, it lost the race due to a slower growth rate. On the other hand, renewable hydropower and pumped storage hydro energy remained almost flat over the last two decades (see Fig. 3.1), which could have offset the intermittency of solar and wind energy if they had received equal focus.

This lopsided growth in renewable installed capacity shows that the individual and cumulative efforts of the world to decarbonize the energy sector and thereby address global warming were unbalanced, the approach was not holistic, and the policies were probably more biased towards solar energy, particularly solar photovoltaics. The effects of this biased approach have begun to manifest globally, manifesting in technical and environmental issues, such as the deepening duck curve, **end-of-life waste management, and the leaching of water and soil pollutants** due to the lack of commercial-scale recycling facilities. This article critically analyses the effects of the unilateral growth in renewable energy installed capacity from 2011 to 2023, including the associated lost opportunities. It also discusses the technical and environmental issues that have already started

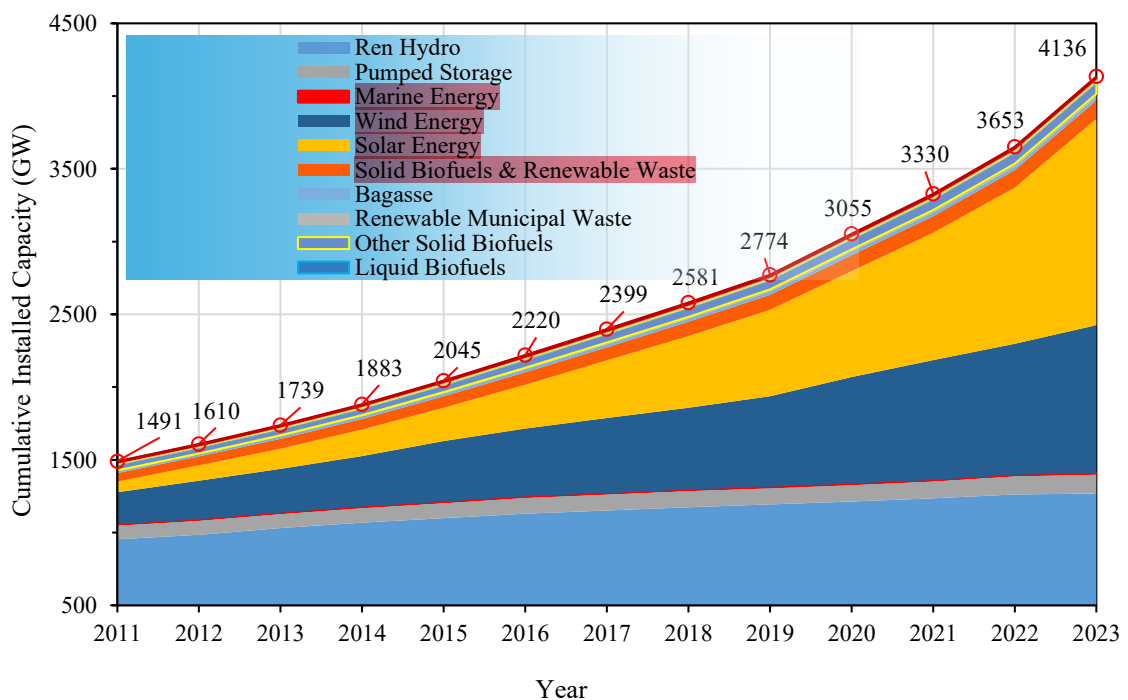


Fig. 3.1. Global trend of Technology-wise growth of renewable energy installed capacity (IRENA, 2024).

manifesting or are expected to inflict in the near future, due to the lopsided policies, in detail. It also highlights the immediate course correction needed in the policy framework to make the approach towards renewable energy more holistic and balanced.

3.3 Critical Analysis of the Ren Growth

As briefly discussed in Section 1.2, the main driver of the exponential growth in renewable energy installed capacity is solar energy. It recorded the highest growth rate of 41% in the year 2011-12 (see Fig. 3.2), which is not only the highest of its own growth rates to date, but also the highest amongst all the renewable energy technologies since the year 2011. During this period, the minimum growth attained by solar energy was 20% in the year 2020-21. When the whole world was crippled by the pandemic due to the COVID-19 virus, solar energy continued to grow at this astounding rate (i.e., 20%), which bounced back to 32.2% in the year 2022-23 and reached the cumulative installed capacity of 1419 GW globally. On the contrary, wind energy started from a larger base of 220 GW, which

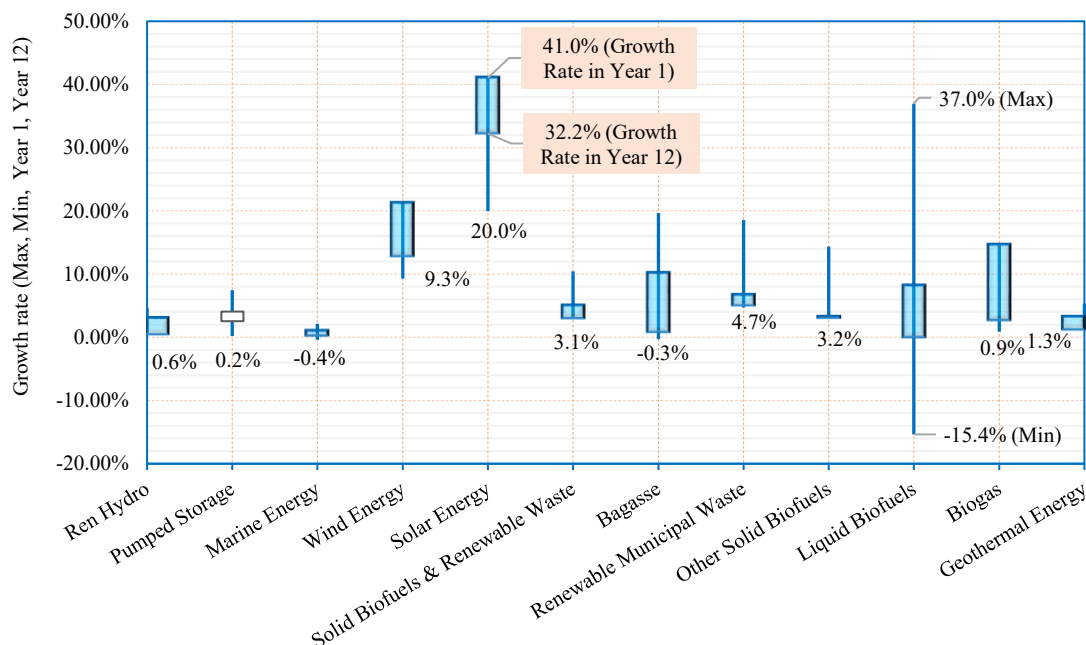


Fig. 3.2. Candlestick representation of the initial, final, minimum, and maximum growth rate of different renewable energy technologies over the period 2011–2023.

was close to three times the installed capacity of solar energy (74 GW), in 2011. However, this energy resource fell short of the growth rate (9.3% to 21.3%) from that of solar energy over the last decade and reached a cumulative installed capacity of 1017.2 GW only by the end of 2023, which is 28.3% lower than that of solar energy. The shortfall in the total installed capacity is due to its lower average growth rate over the period, despite having a good head start. The average growth rate recorded by solar energy was 28.1% during 2011-23, whereas that of wind energy was 13.1% only (see Fig. 3.3). Both the peak and average growth rates of all other energy technologies have been lower than solar and wind energy, with the only exception of liquid biofuels, which recorded the second-highest peak growth rate, after solar energy. It grew at an astounding rate of 37% in the year 2018-19. This shows sporadic effort and focus in augmenting the installed capacity of this sector. However, this growth rate could not be sustained during the COVID-19 pandemic and fell to a negative growth rate of -2.7% and -15.4% in 2019-20 and 2020-21, respectively. The growth rate of this technology has managed to recover from the negative zone and is presently hovering near 0.1%. Due to the lost focus and decisive policy intervention, the average growth rate in this sector settled at a mere 4% for the period 2011-23 (see Fig. 3.3). The third highest average growth rate after solar and wind energy is recorded in energy generation from municipal solid waste, which is 10.1% for the period of study, i.e., 2011-23 (see Fig. 3.3). However, since this energy resource started from a very low base of 7 GW in the year 2011, presently with a reasonable average growth rate of 10.1% managed to reach a global installed capacity of 21.436 GW only, which is merely about 0.52% of the total installed capacity. Hence, the average growth rate, though reasonably good, is not enough to offset the technical drawbacks of solar and wind energy, such as intermittency.

The statistics of the energy resources, which most contradict a balanced and holistic approach to the energy policy framework, are related to pumped hydro and renewable hydro energy. As these energy resources have the potential to support the base load and grid stability in the scenario of high penetration of other renewable resources,

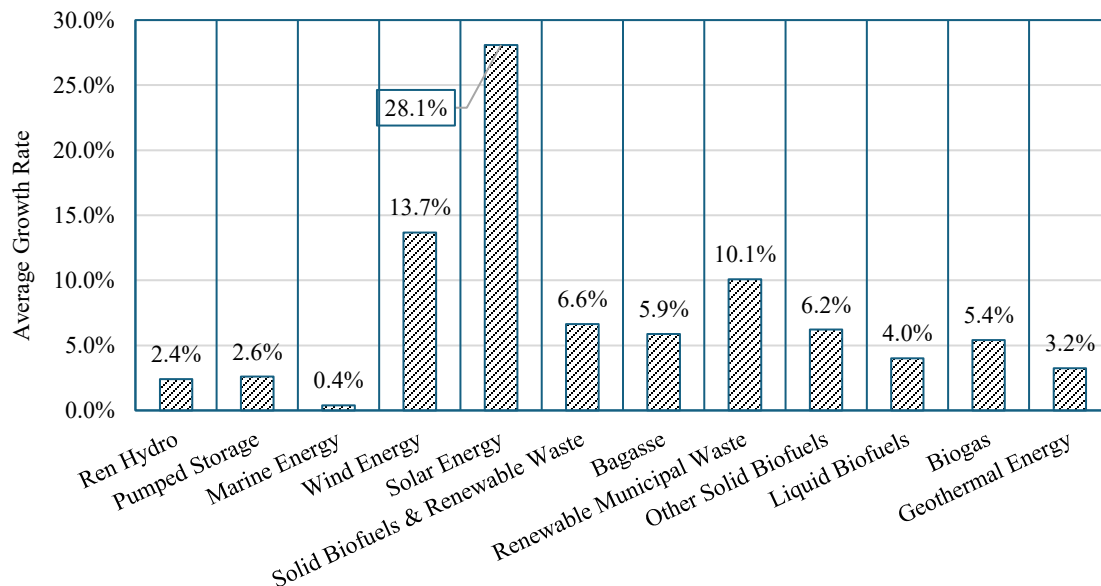


Fig. 3.3. Average growth rate of renewable energy technologies over the period 2011-23.

the growth of these two energy resources should have kept pace with the intermittent energy resources. The installed capacities of both of these two technologies were higher than that of solar energy, i.e., 103 GW and 954 GW, respectively, in 2011, however, the growth in the installed capacities of both of these two resources remained flat (below 2.6% (see Fig. 3.3)) over the last two decades and as a result the cumulative installed capacities of both the hydro energies fell behind the cumulative installed capacities of wind and solar energy. As illustrated in Fig. 4, the installed capacities of hydro power were 360% of the cumulative installed capacities of solar and wind energy in 2011, which reached a breakeven in the middle of 2019 and reduced to only 58% in 2023 due to a very marginal growth rate of around 2.5% over the last two decades. Extrapolating this trend, the gap between intermittent energy resources and non-intermittent energy resources is expected to widen exponentially (see Fig. 3.4), going forward with the present policy framework of renewable energy installed capacity augmentation, which will further intensify the technical issues posed by the intermittent energy resources.

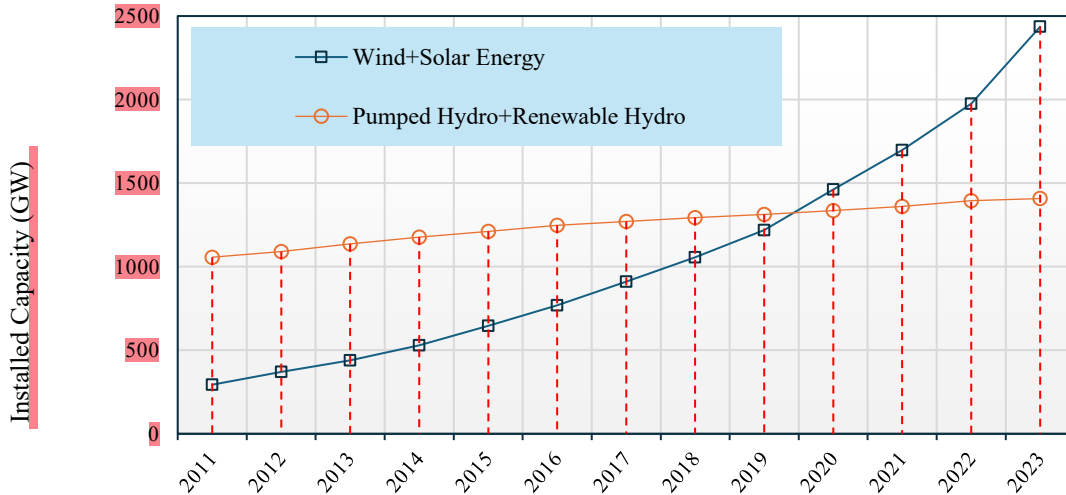


Fig. 3.4. Comparative trend of intermittent vs. non-intermittent energy resources' installed capacity.

3.4. Impacts of Unilateral Growth of Renewable Energy Capacity

As evident from the discussions from the previous Sections, all the efforts towards decarbonizing the energy sector over the last two and a half decades have been focused on a single technology, which is solar photovoltaic energy, and all other energy resources and technologies have been neglected. The trend of the exponential rise in the global installed capacity of photovoltaic energy since the beginning of the current century and its country-wise distribution are illustrated in Fig. 3.1. This section discusses the issues posed by this unilateral approach, which has started surfacing, rather, already started posing challenge before the power system operators, power producers, transmission, and distribution companies, and even environmental scientists.

3.4.1 Deepening “Duck Curve”

The energy demand is dynamic and varies not only with changing seasons but also with the time of day. It generally peaks in the late evening and slowly diminishes to its lowest value just before dawn. The demand again ramps up in the morning and drops a little during the day from the morning peak as the consumers go to work. The work of Gaur et al. (2016) may be referred to for a typical load curve. However, photovoltaic

energy generation peaks during noon and then diminishes post-noon, dropping to zero at sunset. Because the energy demand curve and the solar photovoltaic generation curve do not coincide, other resources are required to meet the demand not supplied by photovoltaics. If the power demand to be serviced by resources other than the photovoltaic generation is plotted against time, the curve takes the shape of a duck's belly, indicating high fluctuation. This implies that the reserve capacity is to be ramped up and down over a wide range throughout the day. This not only poses a technical challenge for the plant operators but also makes the reserve capacity resource technically nonviable because of the low plant load factor. As the increase in photovoltaic energy installed capacity is following an exponential trend line (see Fig. 3.1), dealing with the "duck curve" is expected to be more challenging in the future.

3.4.2 Environmental Emissions

Carbon dioxide equivalent (CO₂e) serves as the primary metric for assessing the global warming potential of the six greenhouse gases outlined in the Kyoto Protocol: carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), sulfur hexafluoride (SF₆), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). And the carbon emissions resulting from PV systems are reported to be in the range of only 14 to 73 grams of CO₂-equivalent per kilowatt-hour (g CO₂-eq/kWh). This is significantly lower (by an order of 10 to 53) compared to emissions generated from combusting oil, which stands at 742 g CO₂-eq/kWh (Tawalbeh et al., 2021). However, in-depth research shows that the potential environmental consequences associated with entire lifecycle technologies, from raw material sourcing to manufacturing and eventually to disposal, cannot be completely ignored (Heath et al., 2020). The production of various components within the PV system necessitates the use of diverse chemicals and hazardous materials, which may potentially release greenhouse gases (GHGs) and environmental hazards at various stages, from manufacturing to end-of-life disposal (Turney & Fthenakis, 2011; Fthenakis et al., 2008)

Literature reveals that the materials used in PV technologies may potentially impact not only land use patterns (Denholm & Margolis, 2008), but also the groundwater,

and soil quality (Tammam et al., 2016), water bodies and wildlife (Pimentel Da Silva and Branco, 2018), the climate (Alsema et al., 2012), and eventually the human health (Aman et al., 2015) as well. In a year-long study of the toxic leaching behavior of PV modules (Nain & Kumar, 2020), Solar panels in both intact and damaged states were subjected to three synthetic solutions and one actual leachate from a municipal solid waste landfill to explore post-end-of-life issues. The rainwater emulating solution was used as the primary medium to quantify the metal leaching from silicon-based photovoltaics over a period of one year, and Nain & Kumar (2020) reported that silver, lead, and chromium released at levels up to 683.26 mg/L (26.9%), 23.37 mg/L (17.6%), and 14.96 mg/L (13.05%), respectively.

3.4.3 End-of-Life Waste Generation

As illustrated in Fig. 3.1, PV installation started growing at an exponential rate since the beginning of the 21st century, and as the service life of the first-generation solar panels extends up to 25-30 years (Mahmoudi et al., 2019), presently, the world has reached the inflection point from where the generation of a large-scale end-of-life waste generation is imminent. According to projections by the International Renewable Energy Agency (IRENA), between 60 and 78 million tons of PV waste could be generated by 2050 (see Fig. 1.2). Solid waste handling infrastructure in most cities is already overloaded by the existing volume of municipal and other solid waste. Handling additional waste generated by end-of-life PV will be challenging, especially when recycling technology is still evolving and has not yet reached commercial scale. The status and challenges of PV waste recycling are discussed in the following paragraphs

3.4.4 Lack of PV waste recycling facilities on a commercial scale

Research on the recycling of photovoltaic solar modules began early (in the early 90s), even before the large-scale deployment of solar photovoltaic technology. This led to the registration of the first patent for recycling crystalline silicon (c-Si) PV panels in 1995. The continual research and innovation in this area have led to the registration of more than 128 patents worldwide to date (Komoto et al., 2018). However, the PV waste

recycling infrastructure is still in the very nascent stage, with regard to the availability of physical infrastructure on a commercial scale, policy framework, and technical standards (Corcelli et al., 2017). During the delamination of PV modules, separating silicon from metals such as silver, copper, lead, and tin without resorting to chemical treatments poses a significant challenge, as it is costly and time-intensive. Hence, high-value materials like silver and hazardous materials like lead are presently not reclaimed during the recycling of PV panels because of their relatively low proportions. Instead, they are disposed of together as a mixture in landfills after partially undergoing the recycling process (Nain & Anctil, 2024), especially in developing countries.

3.4.5 Lack of recycling policies

Though PV waste generation has already started posing challenges to environmentalists worldwide, there is still a lack of an adequate policy framework regarding its management and recycling (Xu et al., 2024), especially in non-European Union (EU) states. The EU took the first step in this direction by categorizing the End-of-life PV panels as Waste Electrical and Electronic Equipment (WEEE) and made it mandatory for the seller to collect them when they reached the end of their lifespan as early as 2012. Within the EU, Germany and the Netherlands impose a guaranteed fee of €180 and €40 per ton, respectively, from developers or manufacturers (Sica et al., 2018), (E.C. Directive, 2012). Recycling of PV panels will reduce production costs and benefit the countries supplying the raw materials and semi-finished products to EU, such as Turkey. However, the Turkish government has been slow to implement Europe's regulatory initiatives (Sica et al., 2018). As in Turkey, the policy initiatives have yet to be replicated in other countries, even though they are experiencing rapid growth in PV markets, such as China, India, the USA (except the state of Washington), Japan, and Australia. Despite being the largest consumers of PV modules, these countries have yet to establish specific and compulsory regulations for end-of-life (EoL) waste management of PV modules. This emerging risk will become increasingly apparent; therefore, it is essential to implement global regulations governing PV waste management.

3.5 Chapter summary

Renewable energy is a great hope and means for decarbonizing the energy sector. However, a critical analysis of the growth trends of a wide range of renewable energy technologies revealed that the global effort to increase the share of renewable energy focused solely on solar photovoltaic energy, while largely ignoring all other technologies despite their great potential. As a result, although the global installed capacity of renewable energy has increased at an exponential rate since the beginning of this century, it has been accompanied by several technical and environmental challenges, which are presented in this paper. The survey on readiness to address these challenges revealed that the world is underprepared, viz., managing grid instability, the intermittency of energy generation, and recycling and reusing the impending large volume of end-of-life PV waste.

CHAPTER 4

COMPARATIVE ANALYSIS OF ECOTOXICITY OF CRYSTALLINE AND THIN-FILM PV TECHNOLOGIES

4.1 Preamble

With the continual efforts of researchers and sustained investments worldwide over the last three decades, over 21 photovoltaic technologies have been developed with technical efficiencies high enough to achieve commercial viability. However, a significant chunk of the market share (97.4%) is held by crystalline silicon (c-Si) technology. Thin film technologies, despite being cheaper and less material guzzlers than c-Si technologies, constitute only about 2.5% of the market share as of date, and all other technologies mostly remain confined to research scale only. This paper critically analyses the veracity of the bias towards c-Si technology deployments through a holistic approach. For a holistic comparative analysis, various parameters are considered to have a socio-environmental impact, including water and energy consumption, the consumption and emission of ecotoxic and hazardous materials throughout the complete life cycle, and the greenhouse potential of directly consumed materials and byproducts of manufacturing processes. The findings of the analysis, particularly the critical analysis and comparison of the manufacturing process, reveal that the ecological footprint of PV technologies is significantly larger at the manufacturing stage than at the end-of-life waste management stage; however, this aspect has not been given due importance by researchers or policymakers in the past. Secondly, thin film technology, especially cadmium telluride (CdTe), is found to have several advantages over the c-Si technology with regard to

ecotoxicity and overall ecological footprint. Hence, a policy intervention is advocated to promote and incentivize technologies with a lesser environmental impact, such as CdTe.

4.2 Introduction

Solar photovoltaic energy is embraced by governments across the world as the most promising technology to support energy sector decarbonization initiatives, being modular, scalable, and having the lowest levelized cost of energy (LCOE). Hence, global PV installed capacity increased at a compounded annual growth rate of 34.67% from a modest value of approximately 1.5 GW in 2000 and reached over 1412 GW as of present (IRENA, 2024). This impressive growth rate is expected to accelerate further due to the continuous decline in module prices. Global solar PV module manufacturing capacity is estimated to have exceeded 1,100 GW, surpassing the yearly demand by more than double. This overcapacity has led to a decline of approximately 50% in module prices from their peak levels in early 2023. Following the current growth trend, the installed capacity is estimated to reach 4,209 GW (IEA, 2024), accounting for approximately 32% of the global electricity demand by 2030, surpassing the previous estimates for most countries (IEA, 2021).

However, the useful life of photovoltaic modules is approximately 25-30 years; hence, early installations are already nearing the end of their life (EoL). Consequently, the world has reached an inflection point, from which the volume of EoL waste modules is expected to grow at nearly the same exponential rate as PV installed capacity over the last two and a half decades. This massive volume of PV waste reaching its EoL shall be augmented by early failures, which are about 2%, according to the estimates of the International Energy Agency (IEA) (IEA, 2014a). Combining both the failure modes, the cumulative photovoltaic (PV) waste is projected to account for around 10% of cumulative Waste Electrical and Electronic Equipment (WEEE) generated worldwide by 2050 (Cucchiella et al., 2015). In 2016, the International Renewable Energy Agency (IRENA) (IRENA, 2016) estimated that 60-78 million metric tons of PV waste would be generated by 2050 (see Fig. 1.2). More recent studies indicate that this estimated

volume may exceed it by many times. Approximately 72–134 million metric tons of waste from photovoltaic panels are estimated to accumulate in China alone by 2050 (Song et al., 2023). Currently, the majority of PV waste ends up in landfills due to the unavailability of recycling facilities at commercial scales and inadequate capacities, especially in developing countries (Ghosh et al., 2023). Even in developed countries like Australia, approximately 84% of PV and battery waste is estimated to end up in landfills. At the same time, the rest is processed primarily in inefficient mechanical shredding facilities to recover the gross materials (Bontinck et al., 2021). The PV modules contain numerous potentially hazardous components that present significant environmental risks when improperly disposed of in landfills.

Sustained investment in the R&D of PV materials has led to the invention of a plethora of different PV technologies, which can be broadly classified into three categories. The 1st generation PV cells include PV technologies based on Crystalline Silicon (c-Si); the 2nd generation encompasses Thin Film technologies; and the 3rd generation includes emerging PV technologies such as organic, Quantum dot, and dye-sensitized PV cells. However, the first-generation PV technology, i.e., the mono and polycrystalline Silicon technology, still dominates the market and installed capacity worldwide. Crystalline silicon panels, which represent approximately 97.4% of the global market (FISE, 2024), typically contain lead in solder connections, antimony in glass, and various other metals (See Table 4.1) that can be environmentally harmful when released. Thin-film technologies, which hold about 2.5% market share (See Fig. 2.2), contain more concerning materials, including cadmium, selenium, and tellurium compounds, which are known toxins with potential carcinogenic properties. When PV modules enter landfill environments, they are subjected to crushing, fragmentation, and long-term environmental exposure that can accelerate the degradation of protective encapsulants, allowing toxic elements to leach into surrounding soil and groundwater systems.

Hence, past studies have mostly focused on the leaching of toxicity into the environment when waste is disposed of in landfills, and the possibility of releasing toxic

chemicals and metals at other stages of the life cycle has been largely ignored. The release of toxic and hazardous materials may lead to several negative environmental consequences if effective life cycle management is not in place, from mining raw material to end-of-life waste management. The release of heavy and toxic metals at any stage in the life cycle of PV modules can lead to soil and water contamination beyond safe limits, thereby diminishing the effectiveness of this green energy technology. To fill the research gap, the present work critically analyzes the manufacturing processes of the two most commonly used technologies, namely crystalline silicon and cadmium telluride, with a special focus on the potential release of toxic and hazardous materials into the environment. Other technical parameters, such as efficiency, temperature coefficient of output, irradiance absorption efficiency, and ecological parameters, including energy payback time, water consumption, and greenhouse gas emissions, are also briefly compared

4.3 The Manufacturing Process of c-Si Modules and Associated Ecotoxicity

As shown in Fig. 2.2, Crystalline silicon (Si) PV modules dominate global PV module production, accounting for 97.4% of the total, while thin-film and emerging technologies make up the remainder. The increase in the market for crystalline silicon technologies can be attributed, firstly, to a continuous reduction in material consumption while simultaneously increasing efficiency. Presently, the efficiency of monocrystalline cells is recorded at up to 27.3% under a laboratory environment, which is substantially higher than that of the thin film (See Fig. 2.2). On the other hand, material usage has reduced from 16 g/Wp to less than 2.5 g/Wp over the last two decades. The share of crystalline technology is expected to continue growing as module prices decline further. This may provide solace to researchers and policymakers, as crystalline silicon modules contain fewer toxic materials than thin-film modules (See Table 4.1). However, ecotoxicity is not solely associated with the EoL waste management stage; a diligent study of the environment and health hazards associated with crystalline technology over its complete life cycle, especially during manufacturing processes, reveals a contrasting perspective, which is discussed in the following paragraphs.

Table 4.1

Mass composition of metals in different Technologies (Gautam et al., 2021)

Category	Material/ Element	Composition (in Tones per GW)		
		<i>C-Si</i>	<i>CiGs</i>	<i>CdTe</i>
Precious Metals	Silver (Ag)	57.96	0	0
	Aluminum (Al)	16557.9	13590	166.16
	Chromium (Cr)	0	0	33.24
	Copper (Cu)	736.64	450	5538.47
	Tin (Sn)	0.06	90	0.01
	Nickel (Ni)	1.07	0	0
	Zinc (Zn)	0.01	90	0.01
	Titanium (Ti)	0.01	0	0.01
	Molybdenum (Mo)	0	90	0
Critical Metals	Magnesium (Mg)	522.8	423	0
	Gallium (Ga)	0	90	0
	Indium (In)	0	45	0
Toxic Metals	Lead (Pb)	4.7	0	7.76
	Selenium (Se)	0	90	0
	Cadmium (Cd)	0	270	221.54
	Tellurium (Te)	0	0	221.54
Other Materials	Silicon (Si)	795.31	0	553.85
	EVA	6518.86	8100	6646.16
	Glass	65840.5	135000	168369.2

Crystalline silicon PV modules are manufactured through a complex multi-stage process that combines various chemical and mechanical operations (See Fig. 4.1). Their manufacturing process begins with raw material (Silica sand) mining and proceeds through several distinct stages before reaching the final assembled product, as shown in Fig. 4.1, which has remained mostly consistent despite significant technological advancements in improving efficiency and reducing costs of the final product, i.e., the solar PV modules.

The manufacturing of crystalline silicon solar cells begins with the mining and processing of raw materials, primarily quartz or silica sand, which presents significant occupational and environmental hazards if proper care is not taken to isolate them from the human respiratory system. The initial stage involves mining quartz, which is later refined into elemental silicon. This process exposes miners to crystalline silica dust, posing a significant risk of developing silicosis — a fatal lung disease (OSHA, n.d.). This is identified as an important occupational hazard by the Occupational Safety and Health Administration (OSHA), and extensive safety measures, including exposure evaluations, adequate ventilation, proper housekeeping, and respiratory protection, are recommended.

The production of metallurgical-grade silicon from raw silica involves energy-intensive processes that have significant environmental impacts. The traditional method requires melting quartzite in electric arc furnaces at extremely high temperatures (over 1900 °C), followed by reactions with oxygen or oxygen-chloride mixtures to reduce impurities (Tsu et al., 1998). This process consumes substantial energy and resources; most of the metallurgical-grade silicon material (about 80%) produced initially is wasted. Heavy dependence on chlorinated compounds poses significant environmental concerns. The process typically involves reacting silicon with hydrogen chloride gas to form Trichlorosilane (SiHCl_3), which is then reduced using hydrogen at high temperatures (about 1100 °C). Trichlorosilane is purified through distillation to remove residual impurities, including chlorinated compounds of aluminum, iron, and carbon. Subsequently, it is either heated or treated with hydrogen to generate silane gas.

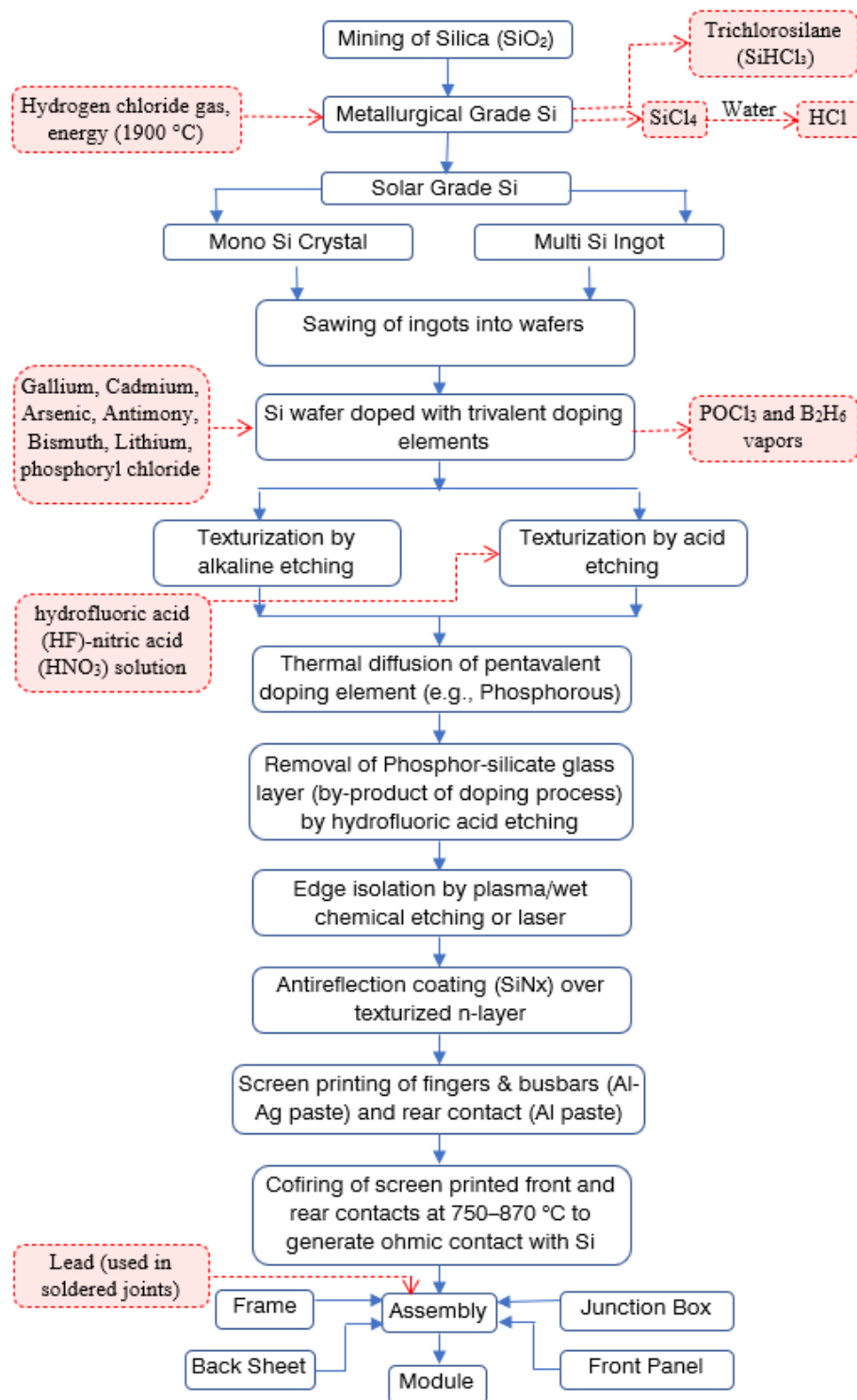


Fig. 4.1. Manufacturing process of crystalline PV modules and associated ecotoxicity (shown in light red).

This silane gas is then heated further to produce molten silicon. This acts as a precursor for the growth of monocrystalline silicon. Crystals or as a material for amorphous silicon production. These chlorinated compounds are environmentally damaging, and the process is not only energy-intensive but also wasteful. Additionally, it undergoes a reaction with hydrogen to form intermediate silicon compounds, specifically polysilicon and silicon tetrachloride (SiCl_4), in a 1:3 ratio. Notably, silicon tetrachloride (SiCl_4) is highly toxic (Kapias et al., 2001). With additional investment and infrastructure, SiCl_4 can be reprocessed to recover silicon; however, if disposed of in landfills, it will produce hydrochloric acid, reacting with water. Unfortunately, manufacturers often follow this practice to reduce production costs. Hence, stricter regulations are required to be framed and implemented to prevent the disposal of silicon tetrachloride (SiCl_4) in landfills.

During the crystal growth of monocrystalline silicon, controlled amounts of impurities or "dopants" are added to establish the desired electrical properties. Personnel may be exposed to these dopant gases and vapors (including POCl_3 and B_2H_6) if ventilation systems are inadequate, posing significant health risks (Fthenakis & Moskowitz, 2000). Multi-crystalline silicon is produced by pouring molten silicon into crucibles, where it gradually cools and solidifies into blocks or ingots. The above methods yield highly pure silicon crystals with purity levels over 99.99999%. The production of crystalline silicon requires extremely high temperatures, making it an energy-intensive and costly process that also generates significant waste. Up to 80% of the original metallurgical-grade silicon is lost during the manufacturing process.

The ingots are then sawed into wafers and prepared for cell manufacturing, introducing additional chemical exposures and waste streams. Wafer texturing and cleaning are essential step that involves the use of various acids and alkalis. Hydrofluoric acid (HF) and nitric acid (HNO_3) solutions are among the highly corrosive and toxic substances (Sreejith et al., 2022). It causes severe chemical burns upon contact with the skin and serious respiratory damage if inhaled. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) identifies sulfur hexafluoride (SF_6), a byproduct of the surface

etching process using HF and NH_4OH solutions, as the most potent greenhouse gas on a per-molecule basis. Its global warming potential is so high that just one ton of sulfur hexafluoride has the same environmental impact as 24.3 tons of carbon dioxide (Shi et al., 2023). Despite its high potency, the global atmospheric concentration of SF_6 increased by almost 3 times in 2020, from 3.67 parts per trillion (ppt) three decades ago, and continues to rise (Joshi, 2010), necessitating stricter regulatory controls on the release of these gases into the atmosphere.

4.4 The Manufacturing Process of Thin-Film Modules and Associated Ecotoxicity

Thin-film solar cells represent an advancement over traditional crystalline silicon cells in terms of cost reductions through lower material use and scalable manufacturing processes. Hence, although the current share of thin-film technology is only 2.6% (FISE, 2024), its installed capacity is growing at an exponential rate. The major commercial thin-film technologies include CIS, CIGS, CdTe, and a-Si. Amongst which, CdTe holds 95.3% market share (see Fig. 2.2) and continues to grow at a CAGR of 21.1% (see Fig. 4.2). Some researchers estimate that thin-film technologies will constitute as high as 44.2% of the market share. In comparison, the share of crystalline silicon is expected to fall to 44.8% by 2030 (IRENA, 2016). CIGS technology holds the second highest market share (3.8%) of the thin film market after CdTe; however, with respect to the overall PV market, the share of CIGS is still at a minuscule level of about 0.1% only and on a declining trend (See Fig. 4.2). The balance of 0.9% is held by a-silicon and other emerging technologies. These technologies use significantly less semiconductor material than traditional crystalline silicon cells but often incorporate potentially toxic elements in their structure (See Table 4.1). Since CdTe has a significant scale of installed capacity (12.5 GWp) and is on an increasing trend, this technology has been considered for analysis and comparison of ecotoxicity associated with the manufacturing processes (see Fig. 4.3), with that of the c-Si technology. The manufacturing of CdTe modules begins with the extraction of Cadmium as a byproduct of zinc, lead, and copper smelting and refining, often through hydrometallurgical or pyrometallurgical processes, and also recovered from spent nickel-cadmium batteries.

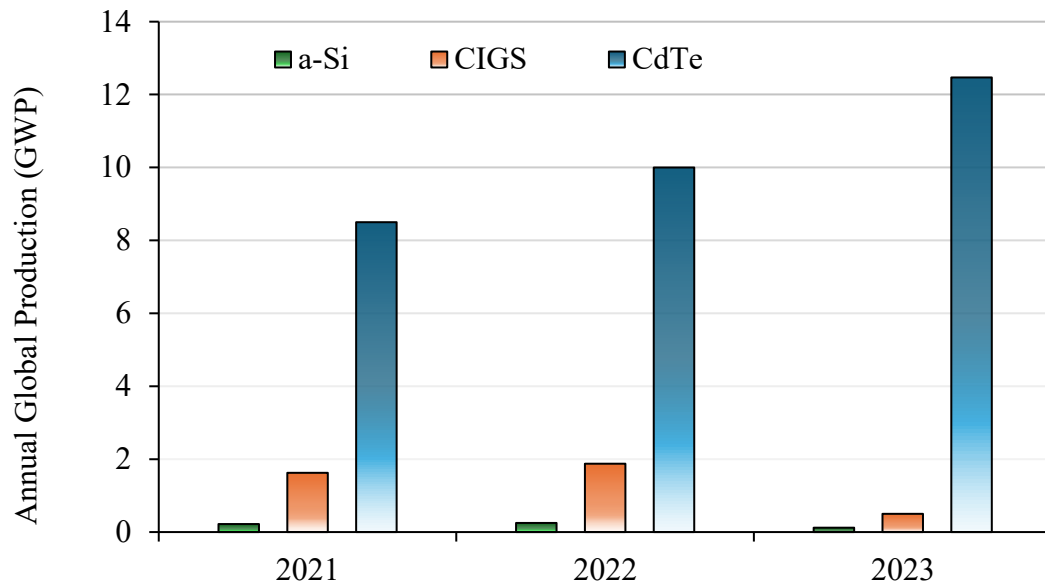


Fig. 4.2. Annual global production of thin-film PV modules (FISE, 2024).

This technology incorporates a thin absorber layer composed of p-type doped CdTe or a graded CdSeTe material. Typically, this layer is applied using physical vapor deposition techniques onto a multi-layered structure, which includes an n-type transparent conducting oxide (TCO) window layer and, in most cases, a buffer layer, as shown in Fig. 4.1. The buffer layers include magnesium zinc oxide (MZO) or undoped tin oxide (TO), positioned before the TCO layer. Some manufacturers use vapor-transport deposition (VTD) for absorber deposition, in which CdTe is sublimated and carried by an inert gas to the substrate (Scarpulla et al., 2023).

The composite film structure is subjected to laser tracing, which separates individual cells on the glass substrate, allowing for monolithic interconnection. After depositing the electrical contact layer, composed of multiple conductive metals, a layer of ethylene vinyl acetate (EVA) is added. EVA is a flexible polymer that serves as an encapsulant for the photovoltaic cell. The final step involves laminating the structure with an additional glass layer. The toxic materials that are directly consumed or emitted during the manufacturing process by different technologies are summarized in Table 4.2.

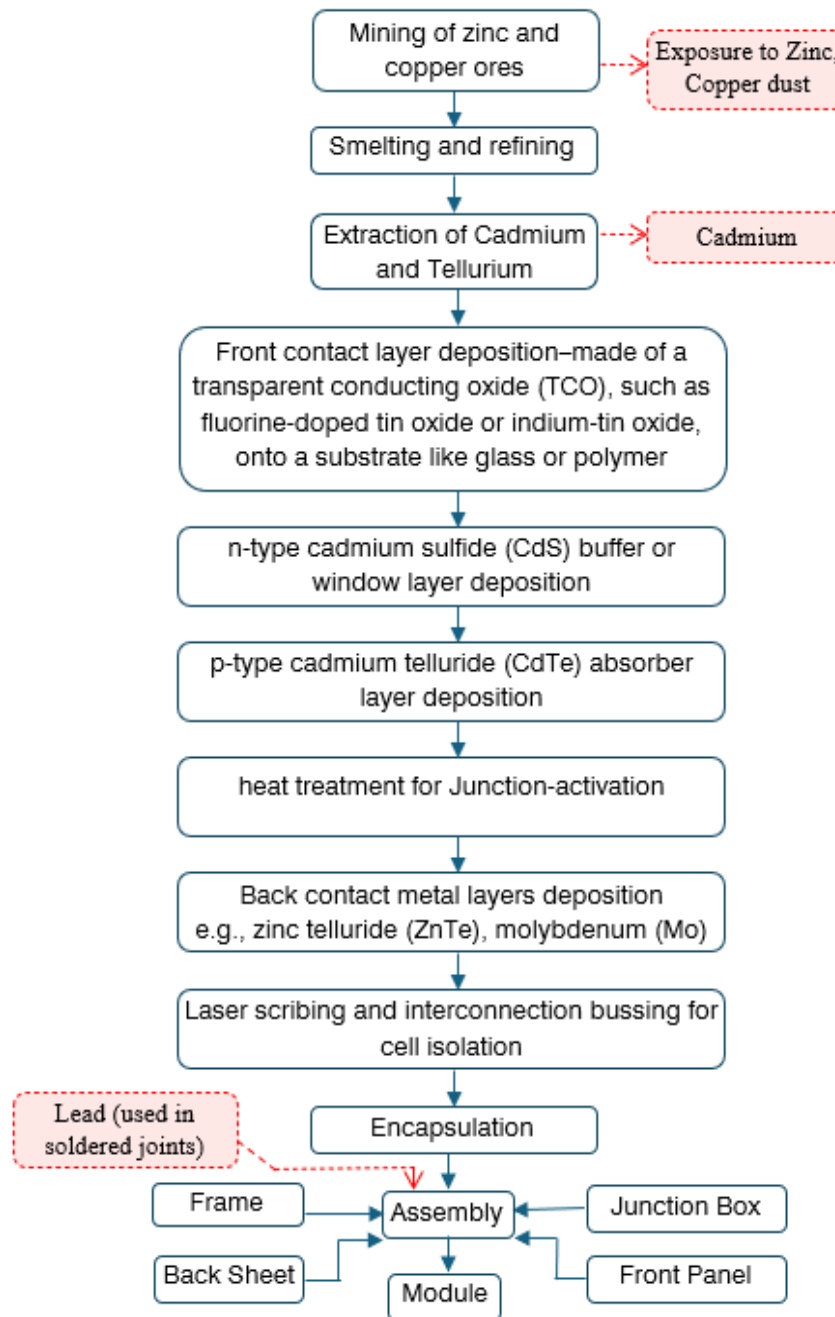


Fig. 4.3. Manufacturing process of CdTe module and associated ecotoxicity.

Table 4.2
Potential Hazardous Materials Used in Different PV Technologies at the Manufacturing Stage

Generation	Technology	Toxic and hazardous Materials	Purpose/ application	Remark
First Generation	Crystalline Silicon (c-Si)	• Silane (SiH₄)	• Precursor for growing mono C-Si crystals	• Highly inflammable gas
		• Silicon Tetrachloride (SiCl₄)	• Byproduct of purification	• Highly toxic
		• Hydrochloric Acid (HCL)	• Produced by reaction of SiCl₄ with water	• Highly corrosive and toxic
		• Arsenic, Phosphine (PH₃)	• n-type doping	• Highly toxic
		• Hydrofluoric acid (HF)	• Surface texturing and cleaning	• High greenhouse potential (24.3 times that of CO₂)
		• Nitric Acid, Sulfuric Acid	• Byproduct of surface texturing process	• Highly toxic
Second Generation	Amorphous Silicon (a-Si)	• Silane (SiH₄)	• Deposition of a-Si films	• Highly inflammable gas
		• Arsine (AsH₃)	• Precursor for growing GaSa crystals and thin films	• Extremely toxic and can be fatal even at low concentrations
	Copper Indium Gallium Selenide (CIGS)	• Hydrogen Selenide (H₂Se)	• thin-film deposition	• highly toxic and flammable
		• Cadmium (Cd)	• Production of CdTe compound	• Cd is carcinogenic and highly toxic
Third Generation	Dye-sensitized cells Quantum Dot PV Cells (QDSC)	• Nitric-phosphoric acid	• Oxidative etching	• Highly corrosive and toxic
		• Titanium dioxide (TiO₂) nanoparticles	• Used as photoanode materials due to their wide band gap	• Potentially DNA damaging
		• Cadmium • lead	• As nanoparticles in the QD structure	• Highly toxic

Note: Lead is used in soldered joints in all technologies, hence a common element.

109 Evidently, the manufacturing process for CdTe-based thin-film modules is more straightforward and involves fewer toxic and corrosive chemicals than those for c-Si technologies.

Apart from the ecological footprint discussed above, several other technical parameters must also be considered when choosing a technological deployment. CdTe exhibits a lower temperature coefficient of power ($-0.21\text{ }^{\circ}\text{C}^{-1}$) compared to c-Si ($-0.48\text{ }^{\circ}\text{C}^{-1}$), suggesting superior performance in hotter climates (Virtuani et al., 2010). CdTe also demonstrates a higher irradiance absorption coefficient, utilizing a broader spectrum of light (400-850 nm) more effectively (Islam et al., 2022). Furthermore, CdTe offers greater flexibility for installations, such as building-integrated photovoltaics (Intal & Ebong, 2014), where c-Si is not suitable. Life cycle analysis reveals that CdTe modules require significantly less water during production (0.73 liter/kWh) compared to c-Si (7.2 liter/kWh) (Bošnjaković et al., 2023). While greenhouse gas emissions are comparable, if c-Si is 48% higher compared to that of CdTe (Bošnjaković et al., 2023). Further, CdTe features a shorter energy payback time and a lower cost per watt (0.4 USD/Watt) compared to c-Si (0.7-1.5 USD/Watt) (Bhandari et al., 2015, Scarpulla et al., 2023). These factors suggest that CdTe modules may offer economic and environmental advantages in specific deployment scenarios.

4.5 Chapter Summary

20 The growing volume of end-of-life (EoL) PV waste has begun to raise concerns among environmentalists and policymakers worldwide. This has drawn the interest of researchers to assess the impact of the disposal of such a heavy volume of PV module waste on the environment, as the constituent materials may leach into the soil and groundwater if not processed scientifically. Past research outcomes mostly favored the use of crystalline silicon solar PV modules, considering the ecotoxicity associated with EoL PV modules only. In the present work, the ecological footprint of the two most widely used technologies, i.e., crystalline silicon and CdTe, is analyzed holistically over the complete life cycle.

The findings of the present work reveal that CdTe technology uses and emits far fewer toxic and hazardous materials compared to crystalline silicon technology throughout its entire life cycle. Inevitable byproducts of the c-Si manufacturing process (SiCl_4) can cause severe harm to the ecology if not handled scientifically, but are often disposed of in landfills to reduce the cost of production. Similarly, byproducts like SF_6 have a high greenhouse potency. Hence, stricter regulatory control over the release of these gases to the atmosphere is advocated.

CdTe is found to be superior except for technical efficiency. However, since the initial cost and temperature coefficient of power of CdTe are found to be much lower than those of c-Si, a detailed cost-benefit analysis is recommended before choosing technology deployment. The installed capacity of solar PV is projected to increase exponentially; therefore, necessary precautions must be taken at all stages of the product life cycle, including manufacturing, to prevent health and environmental hazards on a large scale.

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CHAPTER 5

CRITICAL ANALYSIS OF GLOBAL PV WASTE MANAGEMENT POLICY FRAMEWORK

5.1 Preamble

As PV panels have a limited lifespan of 25-30 years, the end-of-life (EoL) waste stream is following the exponential rise in installed capacity, with only a temporal lag. And presently, the world has reached an inflection point, from which it will be afflicted by large-scale EoL waste generation unless it responds by building recycling infrastructure, establishing a regulatory framework, and raising public awareness. This chapter critically analyses the global status of regulatory frameworks for addressing this issue, revealing that they are inadequate to meet the required urgency, except in a few isolated regions. Those isolated efforts are also being rendered ineffective as waste streams slip into less-regulated regions and end up in landfills. The analysis reveals a pressing need to build global consensus on the urgency of the extended producer responsibility (EPR) policies, international cooperation, public awareness, and investment in recycling infrastructure to transition towards a circular economy in PV technology, which is essential to making the shade of PV energy truly green.

5.2 Introduction

End-of-life (EoL) management pathways for photovoltaic modules encompass a spectrum of strategies, including reuse, refurbishment, recycling, and final disposal. The choice among these depends not only on module conditions at retirement but also on prevailing regulatory environments, economic incentives, and available technological capabilities (Souza et al., 2024). As PV systems approach the end of their service lifetimes,

the mechanisms for processing modules after decommissioning will significantly affect their environmental and economic footprint (Celep et al., 2025). In practice, EoL routes often begin with collection systems that themselves vary in sophistication. In regions with robust extended producer responsibility policies, such as those influenced by the EU Waste Electrical and Electronic Equipment (WEEE) Directive, manufacturers or importers are responsible for facilitating structured collection and transport to licensed treatment facilities (Ali et al., 2023). In these settings, formal infrastructure ensures modules are documented, sorted, and either sent for disassembly or evaluated for potential reuse. By contrast, in jurisdictions lacking such frameworks, unregulated disposal or informal-sector recovery is more likely; such scenarios can lead to uncontrolled handling, increasing environmental risk (Sharma et al., 2024).

Re-use pathways typically require functional modules. Units retired due to system repowering or partial failure may still produce adequate power if cosmetic defects or slight efficiency drops are acceptable in secondary markets. However, ensuring compliance with electrical safety standards and reliability across diverse climatic conditions makes widespread second-hand deployment heavily dependent on testing protocols and recertification processes (Wang et al., 2024). Although this pathway is technically less resource-intensive than recycling, the economic viability of reuse is fragile; freight costs relative to residual energy yields often outweigh the benefits unless the end user faces high local electricity prices or lacks affordable alternatives. When direct reuse is not feasible, recycling becomes central. Material recovery from EoL PV panels captures scarce resources such as tellurium and indium, alongside abundant but energy-intensive inputs such as aluminum and high-purity silicon (Skarkos et al., 2025). For crystalline silicon (c-Si) modules, the most prevalent globally, mechanical dismantling combined with delamination is commonly used to recover aluminum frames and glass sheets before targeting the silicon cells themselves (Chen et al., 2024). Advanced techniques that achieve high-purity silicon recovery through thermal treatment followed by chemical etching can yield wafers comparable in quality to virgin material (Das & Sarmah, 2025).

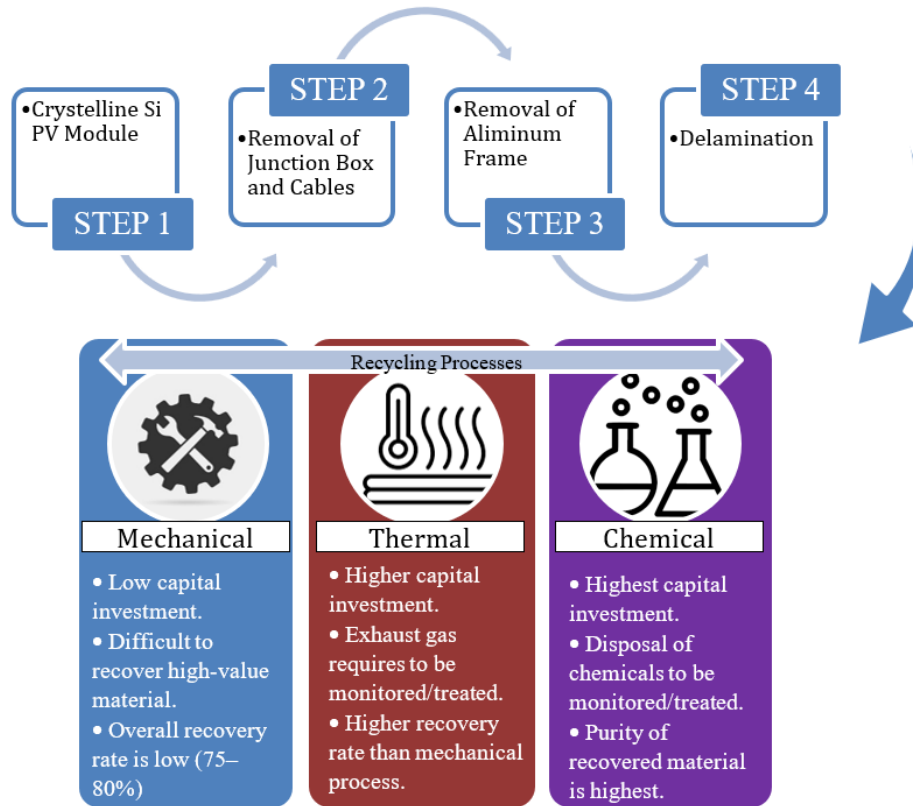


Fig. 5.1. The competitive merits of different recycling processes of PV modules.

These approaches can exceed 90% recovery rates for certain material streams, e.g., Li et al. (2025) reported a hydrometallurgical “step–leach–acid–etch” route that recovered intact wafers at 96.3% yield, with thickness $\sim 176 \mu\text{m}$, resistivity $\sim 1.07 \Omega \cdot \text{cm}$, surface roughness $< 1.55 \mu\text{m}$, and reflectivity 18.8%, indicating excellent wafer performance suitable for new devices.

However, they require capital-intensive equipment and careful process control to avoid secondary emissions during chemical use (see Fig. 5.1). While operationally mature for c-Si in some countries, scaling such systems globally remains challenging, especially in emerging markets (Sharma et al., 2024). Thin-film modules, such as cadmium telluride (CdTe), require more specialized approaches. Mechanical processing often serves as an initial step across various technologies, as it reduces volume quickly and simplifies subsequent treatments. However, without follow-on separation of hazardous materials, this route may merely shift risk from solid waste streams into fine particulates susceptible

to dispersion (Celep et al., 2025). Hence, various thermo-chemical processes are adopted, as illustrated in Fig. 5.2. However, safety considerations entail a financial burden across all technological pathways. Thermal decomposition stages must incorporate gas-capture systems capable of scrubbing acid gases, such as hydrogen fluoride, when fluoropolymer back sheets are processed alongside thin-film devices (Maghraby et al., 2025a). Chemical leaching under controlled conditions dissolves semiconductor layers, allowing cadmium and tellurium to be precipitated or electrolytically recovered (Ali et al., 2023). This processing must be enclosed with effluent treatment stages to prevent toxic releases. Industrial closed-loop systems have demonstrated recovery efficiencies above 90% for semiconductor content while retaining glass sheet integrity; nonetheless, these systems are not universally deployed due to both cost considerations and insufficient collection volumes in many regions (Das & Sarmah, 2025). Copper indium gallium selenide (CIGS) modules follow similar principles, though the selective leaching chemistry differs; indium recovery rates are critical given its scarcity, emphasizing the need to minimize impurity levels in recovered fractions so they can re-enter high-value manufacturing chains (Ali et al., 2023).

Pyrolysis offers another approach: applying elevated temperatures under an inert atmosphere degrades polymer encapsulants without oxidizing recovered metals or semiconductors; yet, here too, fume capture is essential, as decomposition products may include volatile organic compounds and acid gases if fluorinated back sheets are present (Wang et al., 2024). From a circular economy viewpoint, integrating multiple techniques sequentially yields the most comprehensive recovery profile: mechanical removal of bulk components, followed by thermal loosening of encapsulants, and targeted chemical extraction of semiconductor layers. Such hybrid processes strike a balance between high material retrieval and reduced reagent consumption compared to entirely chemical routes that start from intact panels (Das & Sarmah, 2025). They also facilitate the recovery of auxiliary materials, such as silver, from conductive pastes in c-Si cells, thereby helping offset processing costs. Nonetheless, capital amortization for small waste volumes remains a stumbling block; recurrent proposals suggest establishing regional

MECHANICAL	•Simpler and comparatively most economic process. •Difficult to sperate out high value items.
ETCHING	•Possible to recover high value material at high purity. •Energy intensive and poosibility of chemical emmission to environment.
VACUUM BLASTING	•Possibility of recovering the semiconductor layer. •Longer processing time and probability of metal particle emmissions to environment.
EROSION	•Chemical-free process, the glass material can be salvaged • Additional prepurification stage is necessary.
LEACHING	•Chemical intesive process. •Complete removal of metals is possible but precise control is required over the chemicals for effectiveness.
FLOATATION	•The process not chemical intensive. •Higher number of stages involved, including pre-purification stage.
TENSIDE CHEMISTRY	•Reusable chemical (tenside) is used. •Allows complete disintegration of metals from glass.

Fig. 5.2. Material recovery processes of PV modules.

demonstration facilities capable of processing diverse PV waste streams as both capacity-building exercises and economic proofs of concept (Wang et al., 2024).

Amorphous silicon panels offer somewhat lower inherent toxicity but still require encapsulant removal before semiconductor retrieval (Celep et al., 2025). A typical route involves thermal decomposition of EVA in inert atmospheres, followed by acidic stripping of silicon-based films from the glass substrate. Hydrofluoric acid and other fluoride-containing solutions are effective at dissolving residual silicon sub-oxides but demand

rigorous handling safeguards for workers and environments alike (Celep et al., 2025). Metal contacts embedded within TCO or back-contact structures are recovered via hydrometallurgical purification steps similar to those used for other thin-film chemistries (see Fig. 5.2). Hybrid processes combining mechanical, thermal, and chemical stages are gaining traction across thin-film types because they balance recovery effectiveness against reagent consumption (Das & Sarmah, 2025). For example, the SENSE project integrated waterjet cutting of CIGS substrates with pyrolysis to remove polymers, followed by chemical leaching that recovered metals from both CIGS and CdTe modules (Celep et al., 2025).

Disposal still accounts for a large share of current EoL outcomes where recycling infrastructure is absent or economically unviable (Sharma et al., 2024). Landfilling poses distinct hazards depending on the module chemistry: leachate from CdTe or CIGS modules under acidic landfill conditions may transport dissolved heavy metals into groundwater, unless engineered liners perform flawlessly over decades (Ali et al., 2023). Even c-Si panels pose contamination risks if lead-containing solders degrade over time. Incineration for volume reduction without prior segregation is generally discouraged because it can volatilize toxic elements into fly ash, requiring separate hazardous waste containment (Wang et al., 2024).

Circular economy is an absolute solution to the problem of materials recovered from PV waste and also reducing emissions, PV module recycling encounters practical difficulties: stubbornly complicated structures make separation very difficult; chemical treatments bring the problem of secondary pollution; and current logistics are incapable of economically gathering enough End-of-Life (EoL) panels for a commercially viable plant operation (Ndalloka et al., 2024). The key challenge is to integrate technical and environmental solutions with proper policy frameworks in very different political and legal contexts. Legislative and political diversity adds complexity to PV waste management. For example, under the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive, PV modules are specifically classified for regulated collection and recovery of key recyclable materials (European Union, 2012). On the other

hand, in the United States, categorization falls under the Resource Conservation and Recovery Act framework, where hazardous designation depends on results from toxicity characteristic leaching procedure (TCLP) tests; heavy metal-rich modules that fail TCLP are then treated more restrictively (Wang et al., 2024). Diverse regulatory frameworks complicate global standardization of technology-based strategies. Although policymakers can enforce collection and recycling through mandates, these activities, in the absence of subsidies or incentives, may soon become a financial burden for manufacturers or third-party operators (Singh et al., 2023).

The literature indicates that well-crafted economic policy can transform PV waste management into a profitable sector that advances resource-efficiency objectives. A recurring theme across various studies emphasizes the importance of combining stricter regulations with technological advancements as a dual approach (Das & Sarmah, 2025). Countries in the early stages of development stand to gain significantly by integrating these guidelines into emerging-market frameworks, rather than attempting to retrofit them later, when waste has already accumulated. By harmonizing global standards with local industry maturity-oriented implementation strategies, it is possible to achieve environmental objectives alongside the development of clean energy. The present article comprehensively reviews the current status of PV waste management policies in major economies and major consumers of PV technologies, a gap in the current literature. This will help policymakers compare their own position with that of the benchmark countries and take corrective action towards a greener, cleaner future.

5.3 Challenges of PV Waste Management Policy Enforcement

As discussed in Section 5.2, the rate at which PV module waste builds up is closely tied to product lifespan assumptions (25-30 years). This is further compounded by early retirements due to technological obsolescence, mechanical damage, or performance decline. Region-specific factors, such as degradation rates, climate stressors, and market policy changes, also contribute to the waste volume (Zaabi & Ghosh, 2024). Recent forecasting models estimate concentrated surges in decommissioning within major

20 markets such as China, the U.S., Japan, India, and Germany starting in the mid-2030s (Ali et al., 2024; Sharma et al., 2024). Policy-driven repowering, such as in feed-in tariff regimes, that replaces older modules with higher-efficiency ones, even when modules are still operational, maximizes revenue; however, it can increase disposal rates. This may lead to spikes in local waste volumes that could overwhelm existing collection capacity if not accounted for during policy implementation. Hence, regions with aging fleets will need recycling facilities sooner, while emerging markets might plan infrastructure buildouts aligned with strategies to augment PV installed capacity.

9 Studies suggest that improving the purity of recovered materials—such as high-quality glass, semiconductors, and precious metals—can open higher-value markets and boost profits (Wang et al., 2024). However, the financial viability of recycling depends on the value of the recovered material relative to processing costs. Also, facilities risk operating at a loss if commodity prices fall or transportation costs from dispersed collection points outweigh revenues. These logistical challenges are substantial; poor collection networks raise per-unit freight costs and increase environmental impacts by increasing fuel consumption. Developing countries face additional hurdles due to limited infrastructure for hazardous waste management, which poses environmental and financial risks (Celep et al., 2025).

51 Operationalizing a circular approach faces economic and infrastructural constraints. Studies indicate that, at present, the cost of recycling a single PV module can be an order of magnitude greater than landfill disposal fees (Sanathi et al., 2024; Granata et al., 2022; D'Adamo et al., 2023). This cost imbalance discourages voluntary participation in recycling unless policies create binding obligations or offer economic support mechanisms, such as subsidies, tax credits, or recycled-content requirements. Hence, subsidies are necessary to make dedicated plants commercially viable, especially for plants with throughputs below 8,000 t/yr (Yu et al., 2022). The estimated financial support required for the recycling facilities to break even at present is 200–350 €/t (Granata et al., 2022). Reviews of global practice highlight that harmonized implementation of extended producer responsibility (EPR) and PV-specific disposal fees

19

1 is essential to ensuring that producers pre-finance collection and recycling of future end-of-life modules (as in the EU WEEE system), for effective PV waste management (Chowdhury et al., 2020; Deng et al., 2019; Yu et al., 2022). This could enable cross-border transfer of PV waste, help mitigate disparities, and ensure that recycling facilities achieve the required scale for feedstock volume and receive the financial support mentioned above. However, implementing harmonized standards requires political consensus, which is often difficult to achieve outside tightly integrated regions, such as the EU.

8 Socio-economic impacts of streamlined and regulated PV waste management are also significant. Efficient recycling sectors could generate jobs in waste collection, logistics, process engineering, and downstream material markets (Zahra et al., 2024). However, inadequate infrastructure planning might leave recyclers unprepared for demand, resulting in overwhelmed facilities, stockpiling, or illegal disposal practices that undermine environmental goals. Current projections suggest that crystalline silicon (c-Si) installations will account for the largest share of decommissioned panels over the next few decades, primarily because of their dominant market share of about 97.4% (see Fig. 4.1). However, it is estimated that thin-film technologies may capture as much as 44.2% of the market share from the current level of 2.6% by 2030 (IRENA, 2016). Rapid growth in thin-film variants will lead to more diverse waste streams, necessitating flexible treatment systems capable of efficiently processing different architectures (Sanathi et al., 2024). Flexibility and adaptability are also required in the policy framework. Literature suggests that adaptable policies responsive to market shifts, rather than rigid regulations, improve resilience (Singh et al., 2023). Presently, the annual investment in the PV industry has crossed \$500 billion (Jäger-Waldau, 2025), which can be leveraged upon to plan the management of long-term waste streams, i.e., alongside new capacity additions, rather than at the waste generation stage (Das & Sarmah, 2025). Achieving this requires combining advances in recyclable design and the geographic planning of recycling facilities to align with regional retirements. Without this integration, environmental

management gaps will grow with solar capacity, threatening the sustainability goals that initially drove renewable energy expansion (Zaabi & Ghosh, 2024).

5.3 Global Status of PV Waste Management Policy Framework

As discussed in Sections 5.2 and 5.3, both the important aspects of PV technology – its deployment and lifecycle management are mainly driven by market forces and not well-thought-out policy frameworks. Whether promoting different technologies based on their competitive advantages or managing their growth sustainably, there is a significant gap in the policy paradigm. Most regions still lack PV-specific, binding policies for end-of-life (EoL) management; except the EU's WEEE Directive, which is the only operational supranational regime explicitly covering PV modules mandating EPR, while other major markets treat PV largely as generic e-waste or solid waste, if at all. This lackadaisical approach to regulation is probably based on the assumption that, since the power generation phase is non-polluting, the complete lifecycle, from mining to disposal, can be neglected. The large volume of related literature not only reveals that such an assumption is totally misplaced, it also raises alarm about the urgent need to study the isolated efforts implemented around the world and experience of their impact, and implement a harmonized policy framework across the globe, so that the efficiency of the well-regulated regions does not slip into the unregulated ones and nullifies the collective efforts. This chapter summarizes the regulatory efforts of major economies and all the countries with a significant share of installed PV capacity and highlights the dominant features (see Tables 5.1-5.3) that can influence the lifecycle management of PV technology in a sustainable way.

Amongst the countries that have implemented the specific PV waste management policy in some form (listed in Table 5.1), the EU is the only region with binding, PV-specific EPR obligations, via the revised WEEE Directive, which sets collection, recovery, and recycling targets for PV modules and places financial responsibility on producers. Updates to WEEE (and related national transpositions, such as Germany's ElektroG and the EAR register) require 85% recovery and 80% preparation for reuse/

Table 5.1

Countries with PV waste management policies in place

Country & Year	Policy Mechanisms and Frameworks	Key Features	Shortcomings	Reference
European Union (EU) 2012	WEEE Directive mandates Extended Producer Responsibility (EPR), mandatory collection (85%) & recycling targets (80%), eco-design requirements	Most comprehensive global framework; producer-financed take-back schemes, annual reporting, and the highest recycling targets; inspires global policy innovation in eco-design and circular economy.	Slow technology adoption in some member states, and enforcement varies by country.	(Yavuz et al., 2025)
Germany 2018	ElektroG regulation (WEEE compliance) - national registry (Stiftung EAR), producer responsibility, collection via 1,700+ collection points, and insolvency-proof guarantees.	Collected 7,865 tons in 2018; robust national registry and producer registration; mandatory B2B and B2C take-back systems	Recycling capacity needs expansion; some waste is exported for treatment.	(Röpke, 2022; Sharma et al., 2019)
France 2018+	WEEE compliance, dedicated recycling plant (ROSI, Veolia-operated), PV Cycle France partnership, national EPR scheme.	First European country with a dedicated silicon-based cell recycling facility (ROSI plant, 10,000 tons capacity annually); collected 1,555 tons in 2018.	Recycling infrastructure is still developing; it needs further capacity expansion.	(Komoto et al., 2022; EEA, 2025)
Italy 2014+	WEEE compliance, EPR, national collection and recycling schemes	Collected 1,350 tons in 2018; mature collection infrastructure	Relies partly on general e-waste infrastructure.	(Komoto et al., 2022, Sharma et al., 2019)
Spain 2015+	WEEE compliance, EPR, Royal Decree 2015 (producer responsibility for panels), no specific wind turbine recycling mandate	Producer responsible for panel recycling; collected 462 tons in 2018	Recycling infrastructure needs strengthening.	(García Vega, 2024; Komoto et al., 2022)
United Kingdom 2014+	WEEE Regulations, market-share-based collection financing, registration is required, and first-level treatment must occur in the UK.	Clear market-share financing (e.g., 10% market share = pay for 10% collection/recycling); flexible in treatment location beyond the first level.	Limited domestic PV recycling facilities and regulatory uncertainty post-Brexit.	(Komoto et al., 2022; Sharma et al., 2019)
Belgium 2014+	WEEE Directive compliance, EPR, and national collection systems.	Integrated into EU WEEE framework; clear EPR obligations.	limited large-scale dedicated PV recycling plants.	(Baldé et al., 2020; Clyncke et al., 2021)
Netherlands 2014+	WEEE Directive compliance, EPR, and national waste management system.	Effective waste collection infrastructure; small PV waste volumes (~1 kt in 2018) due to relatively recent installations.	Future waste surge expected; recycling capacity needs scaling.	(Baldé et al., 2020)
Austria 2014+	WEEE Directive compliance, EPR, and national collection schemes.	Part of robust EU framework; clear producer obligations.	Infrastructure scaling is needed.	(Komoto et al., 2022)

Sweden 2014+	WEEE Directive compliance (since 2014), Environmental Code Chapter 15, EPR, two approved collection systems for electronic waste, and research on recycling viability.	Early research on recycling economic and environmental viability; focus on thermal, chemical, and mechanical recycling methods; environmental impact studies underway.	Less than 10% of solar waste currently recycled; no dedicated PV recycling systems yet;	(Pérez Horno, 2024)
Norway 2014+	WEEE Directive incorporated, EPR, and national legislation alignment with EU standards.	Recycling facilities available; close collaboration with Nordic countries.	Small waste volumes; relies on regional cooperation.	(Sharma et al., 2024; Svedmyr et al., 2023)
Switzerland Pre 2014	SWICO RECYCLING scheme, EPR, independent take-back system.	One of the earliest adopters has a mature recycling infrastructure and high environmental standards.	High costs; limited scale compared to EU.	(Nain & Ancil, 2024)
Czech Republic 2014+	WEEE Directive incorporated into national law, EPR, waste registration system (ISPOP), and annual reporting required.	Clear registration and reporting obligations; integrated EU compliance.	Developing infrastructure; annual reporting by February 28; enforcement needs strengthening.	(Sharma et al., 2019; Hyży-Grimau, n.d.)
Poland 2014+	WEEE compliance, waste records in BDO Database, EPR, fines for non-compliance (5,000-1,000,000 PLN)	Mandatory waste records; clear penalties; annual return deadline March 15	Infrastructure for dedicated PV recycling limited; general e-waste treatment predominant.	(Hyży-Grimau, n.d.)
Hungary 2014+	WEEE compliance, waste declaration required (Government Decree 309/2014), EPR	Mandatory waste declarations for waste management activities or exceeding waste thresholds	Recycling infrastructure developing; enforcement varies.	Hyży-Grimau, n.d.)
Romania 2014+	WEEE compliance, EPR, monthly waste records required, annual reports due March 31, Environmental Manager training mandatory, GEO 92/2021 and GD 856/2002 regulations	Comprehensive monthly waste records; trained Environmental Managers required; significant projected PV waste increase (32,892 tons by 2033, up 2,336%); opportunity to become EU recycling leader	Enforcement inconsistent; infrastructure underdeveloped; national PV waste strategy needed; fines 20,000-40,000 lei.	(Andrei et al., 2024; Hyży-Grimau, n.d.)
Japan 2017+	Recycling Law, EPR, mandatory producer-funded take-back and recycling, government subsidies for recycling equipment, blockchain tracking (Ministry of Environment initiative)	Clear producer responsibility; government subsidizes recycling tech; blockchain for transparency; voluntary guidelines for proper disposal; processes a few thousand tons annually	E-waste system not always PV-specific; evolving collection targets; infrastructure developing; not yet mandatory recycling.	(Asian Power, 2024; Komoto et al., 2025)
South Korea 2018+	Extended Producer Responsibility (EPR), government-financed PV recycling centers.	Nationally uniform EPR policy; clear recycling goals; public-private partnerships;	Relatively small recycling market; infrastructure still developing.	Komoto et al., 2025

		government-financed infrastructure.		
China 2020 revision	National Solid Waste Law (2020 revision), incentives for recycling R&D, local pilot programs, ECOPV initiative (2020) for "PV green supply chain."	National policy framework supports R&D and circular economy; ECOPV established for green supply chain; local pilots;	Enforcement inconsistent regionally; lacks unified national EPR mandate; collection and recycling rates low.	(Ali et al., 2023; Asian Power, 2024)
Taiwan 2019	Solar Photovoltaic Panels Recycling System (PVIS), recycling fee (NT\$1,000/kW installation + NT\$0.0656/kWh), Bureau of Energy (BOE) collects fund, online registration system (PVIS), local treatment priority.	First-in-Asia comprehensive fee-based system; online registration (PVIS); fund for R&D, counselling, and treatment plants; 10,000 tons expected 2023, 100,000 tons by 2035; local treatment prioritized, Germany/Japan backup.	Infrastructure still scaling; relies on overseas treatment during disasters or capacity shortfalls; enforcement of developer compliance critical.	(Law.asia, 2025; MOENV, Taiwan, 2025)
Vietnam 2023	Circular 18/2023/TT-BTNMT (PV-specific waste management requirements), mandatory take-back	Among the first in Southeast Asia with PV-specific legislation, it mandates producers to take back	Early implementation stage; infrastructure and coverage still developing.	(GIZ, 2025)

recycling of PV modules. Despite this relative leadership, practical implementation lags: many facilities only recover bulk glass and aluminum, with limited recovery of high-value materials (Si, Ag, Cu), and large parts of Eastern and Balkan Europe still landfill PV modules because they are below the economic scale for recycling plants (Bošnjaković et al., 2023).

On the other hand, China has several overarching solid-waste and product-stewardship laws (e.g., National Solid Waste Law, GB/GB-T standards, and emerging EPR standards), but no clear, unified PV-specific EoL statute; PV modules are not consistently categorized, and responsibilities remain diffuse (Tembo and Subramanian, 2023). Policy focus has been on installation growth, with EoL policy and infrastructure years behind projected massive waste volumes of 26–134 Mt by 2050 (Wang et al., 2025). Recent work identifies an urgent need for region-specific recycling strategies, EPR enforcement, and better tracking of EoL flows (Babaei and Esfahani, 2024).

Table 5.2

Countries with partial implementation of PV waste management policy

Country & Year	Policy Mechanisms and Frameworks	Key Features	Shortcomings	Reference
18 The United States of America (no estimate available for holistic implementation)	Federal: RCRA (Resource Conservation and Recovery Act); State-level: EPR in Washington (2017), California (universal waste classification), Illinois, Oklahoma, Nebraska; EPA proposing universal waste rule for solar panels (2023).	Washington State mandates EPR; California reclassified panels as universal waste; EPA developing universal waste rule to improve recycling; flexibility allows state innovation.	No binding federal law; fragmented state-by-state coverage; recycling rates vary widely; many panels landfilled; inconsistent classification - hazardous vs. general waste.	(EPA, 2025; Ali et al., 2023)

Table 5.3

Countries in the drafting/deliberation/exploration stage (yet to be enacted)

Country & Year	Policy Mechanisms and Frameworks	Key Features	Shortcomings	Reference
14 India 2021-2022 (Pilot/EPR Rules)	E-waste Management Rules (amended 2022), EPR guidelines for PV (proposed, not enacted), pilot programs, joint EU-India R&D initiatives, landfill bans proposed, MNRE identifies PV recycling as a thrust area.	Developing EPR framework for PV; learning from EU; joint R&D calls with EU; landfill discouragement; Ministry of New and Renewable Energy (MNRE) prioritizes recycling R&D.	No mandatory EPR yet; collection/recycling rates extremely low; regulatory implementation lags sector growth; enforcement weak	Clyncke et al., 2021; Sharma et al., 2024
Singapore Pilot stage (2023+)	Developers must take back panels at end-of-life; landfilling discouraged but not banned; voluntary recycling; Sembcorp-Singapore Polytechnic pilot plant (2-year timeline), Etavolt initiative (NTU spin-off) for on-site regeneration and recycling.	Innovative pilot recycling plant by Sembcorp-Singapore Polytechnic (90%+ recycling rate); Etavolt offers on-site regeneration and mobile recycling; up to 5,000 tons waste expected within 2 years.	Recycling not compulsory; space constraints limit economies of scale; no dedicated large-scale facilities; no legislation mandates recycling.	Asian Power, 2024; Ha, 2020
Thailand NA	No specific PV waste management legislation; policy proposals under development; SWOT analysis compared to China.	Recognizes future waste challenge from floating solar; policy proposals being developed; learning from China's approach.	No enacted PV waste legislation; infrastructure non-existent; waste management framework urgently needed.	Ha, 2020; Meas, 2021

Malaysia NA	General e-waste regulations; no specific PV waste legislation; research advocacy for recycling laws.	Research institutions (UNITEN, University of Malaysia) advocating for PV waste policies; regional awareness growing.	No specific PV recycling laws; infrastructure absent; at risk of hazardous waste exposure.	Primus et al., 2025
Indonesia NA	ASEAN Circular Economy Framework; mandatory waste regulation policy anticipated when aggregate capacity threshold reached	ASEAN Circular Economy Framework provides regional guidance; policy expected when installation capacity reaches threshold	No specific PV waste management framework yet; infrastructure is undeveloped	Chen et al., 2022
Philippines NA	General e-waste under WEEE-like regulations; no dedicated PV waste management	General e-waste framework exists	No dedicated PV recycling legislation or infrastructure[33]	Gulagi et al., 2021)
Australia Enforcement targeted by 2025	National Product Stewardship Act, voluntary transitioning to mandatory stewardship, Australian PV Institute (APVI)/Product Stewardship Australia (PSA) initiatives, pilot take-back programs	Focus on market-based solutions; rapid transition from voluntary to mandatory stewardship; pilot programs operational; Victoria banned e-waste dumping (only state)	Not yet fully mandatory; inconsistent state-level readiness; limited recycling infrastructure.	Komoto et al., 2025; Logan, 2024.
New Zealand Enforcement targeted by 2025	Waste Minimization Act 2008, e-waste (including PV) designated as priority product (2020), TechCollect NZ developing regulated product stewardship scheme, regulations under consultation (2024/2025)	E-waste including PV designated priority product; co-designed product stewardship scheme in development; government consultation 2024/2025	No dedicated PV recycling facilities in New Zealand; may exclude or phase-in PV until infrastructure available; likely to require dumping, stockpiling, or export.	Logan, 2024. Obeka & Brent, 2025.
Brazil (NA)	General e-waste laws, net metering, social energy programs; no specific PV waste management legislation	Strong distributed generation growth (48%+); social inclusion focus; general e-waste framework	No dedicated PV waste legislation; recycling infrastructure underdeveloped; future waste surge anticipated	Souza et al., 2024
 10 Chile 2017+ (General EPR)	Law No. 20.920 (EPR framework for e-waste, batteries, packaging, etc.), implementing regulations for waste management, extended producer responsibility, technical-economic standards project for PV second life	EPR framework for multiple waste types; "Public Good" project developing technical/economic standards for PV second-life and recycling; aims for 30% recycling rate	No specific PV waste regulations yet; recycling rates currently <10%; PV-specific standards under development	Martínez et al., 2025
Colombia NA	Waste management regulated since 2015 (Law on environment and sustainable development), National Policy for Integrated Solid Waste Management (2016), draft	Comprehensive solid waste management policy; WEEE draft regulations; EPR for selected products (electronics, batteries, bulbs, pharmaceuticals)	No specific PV waste regulations; WEEE implementation incomplete; infrastructure developing	Calderón Márquez and Rutkowski, 2020; Cantillo and Quesada, 2022

	WEEE regulations, EPR for selected products			
Argentina 2017+ (General frame work)	General waste law, Energy Transition Law (Law 27,424, 2017) for renewable self-consumption, net metering, no specific PV waste management	Strong renewable energy promotion; net metering; general waste management	No specific PV waste legislation; recycling infrastructure absent	Savino and Titto, 2019
Mexico (NA)	General waste management, no specific PV waste legislation.	Renewable energy development slowing; focus on state-owned utilities	No PV waste recycling legislation; infrastructure absent.	Daniela-Abigail et al., 2021
South Africa	Extended Producer Responsibility (EPR) policy approach is under development, along with general waste management regulations	EPR policy approach being developed; makes manufacturers responsible for end-of-life waste; learning from international best practices.	No mandatory EPR yet; infrastructure limited; enforcement weak; policy development ongoing.	Lotter, 2024; Nahman, 2010; Moloi, et al., 2025
Morocco	General waste management; no specific PV waste legislation.	Large-scale solar projects (Noor complex); focus on utility-scale.	No specific PV waste management framework; limited small-scale PV.	Dahchour and Hajjaji, 2019; Elbroumi et al., 2025.
Egypt	General e-waste regulations (10 countries in Africa with e-waste legislation, including Egypt); no specific PV waste law	One of 10 African countries with e-waste legislation; large solar deployment planned	No specific PV recycling legislation; infrastructure underdeveloped; waste-to-energy projects emerging	Lema, 2024
Kenya	E-waste regulations, pilot programs for off-grid solar e-waste (UNEP DTU, University of Nairobi, Kenyatta University research project 2021-2023), EPR under consideration.	Regional hotspot for solar e-waste research; pilot collection and recycling schemes for off-grid solar devices; government engagement with Kenya Private Sector Alliance (KEPSA).	No mandatory PV waste management yet; informal recycling causes severe environmental consequences; infrastructure underdeveloped; policy development ongoing.	Mugendi, et al., 2023)
Nigeria	E-waste regulations (one of 10 African countries), E-Waste Guide for Stand-Alone Solar (ACE TAF support), used battery policy, Hinckley Recycling grant (\$50k-\$300k) for solar battery recycling.	EPR scheme in place; E-Waste Guide for Stand-Alone Solar developed; used battery policy requires registration, collection, recycling standards; Hinckley Recycling developing solar battery recycling facility; grant-funded capacity building.	EPR enforcement weak; infrastructure limited; informal sector dominates; solar battery recycling in pilot stage.	(Odeyingbo et al., 2025; Barnabas, 2025)
Ghana	E-waste regulations (one of 10 African countries with e-waste legislation), EPR scheme.	One of few African countries with EPR scheme for e-waste.	Infrastructure underdeveloped; enforcement weak; informal recycling predominant.	(Faibil et al., 2022)

Pakistan	No specific PV waste management legislation; awareness campaigns emerging; proposals for EPR policies, recycling infrastructure, public awareness, incentives for eco-design.	Massive solar boom (22 GW imported by 2024/2025); estimated 1.1-1.26 million tons waste in 25-30 years; calls for EPR, recycling infrastructure, public campaigns.	No legislation; no recycling infrastructure; 55-63 million panels will become waste; urgent need for policy and infrastructure development.	(Khan and Ali, 2022)
Bangladesh	General e-waste management; no specific PV waste legislation; focus on performance optimization and grid integration.	Hazardous Waste Management Rules (2021) have yet to be fully implemented or enforced.	No PV waste management policy; infrastructure absent; future waste surge expected.	Rahman, 2025; Babu et al., 2025)
Turkey	New Climate Law (drafted 2024/2025) prioritizing renewable energy, general waste management.	Ambitious solar targets (10,000 MW in 2022, 20,000 MW by 2030, 50,000 MW by 2050); Climate Law emphasizes green transition, emissions reduction; renewable energy priority.	No specific PV waste regulations yet; infrastructure needs development; grid integration challenges.	(Cé et al., 2025; Batmaz and Sisman-Aydin, 2025)
United Arab Emirates (UAE)	General waste management, waste-to-energy projects (e.g., Sharjah WTE plant), partnership between Averda and Dubai Municipality (2016 recycling center with solar panels), private sector recycling services (Escrappy, Greest, Planet Green).	Averda-Dubai Municipality recycling partnership (2016); private recycling companies operational (Escrappy, Greest, Planet Green); waste-to-energy projects; solar capacity targets (6 GW to higher); up to 5,000 tons PV waste anticipated.	No specific mandatory PV waste legislation; recycling voluntary; infrastructure limited; policy framework needed.	(Alhosani, 2025; ALqodsi, 2024)
2016+ (pilot stage)				
Saudi Arabia	General waste management; no specific PV waste legislation; focus on renewable energy development and waste-to-energy.	Large-scale solar development (FAS Energy projects, Benban Solar Park); waste-to-energy initiatives; renewable energy targets.	No specific PV recycling framework; infrastructure inadequate.	(Almaghrbi et al., 2025; MESIA, 2024)
NA				
Israel	General waste management; no specific PV waste legislation.	Strong solar deployment; focus on innovation.	No specific PV waste management framework.	(MESIA, 2024)
NA				

The USA has a different approach towards managing PV waste (see [Table 5.2](#)). Despite being a mature economy and having the second-highest installed capacity, there is no PV-specific law at the federal level; PV panels fall under general hazardous/solid waste rules (e.g., RCRA) or universal waste provisions. A few U.S. states (e.g., Washington, California) are piloting or adopting PV specific take back and recycling rules, but coverage and requirements differ widely ([Al-Aqqad and Menyhart, 2023](#)). As a result,

<10% of U.S. decommissioned panels are currently recycled; landfill remains cheaper than recycling (US\$1–5 vs US\$15–45/module) under current policies and economics (Peplow, 2022).

The status of other developing and emerging economies, e.g., much of Africa, Latin America, and South Asia (summarized in Table 4), is found to lack dedicated PV waste regulations and adequate infrastructure (Okoroigwe et al., 2020). The literature shows low awareness and virtually no planning for PV waste, despite recognition of its toxicity and environmental risks. Key challenges include a lack of specific regulations, weak data on waste volumes, insufficient incentives, and poor infrastructure.

5.5 Critical Analysis of the Policy Paradigm

Present systematic reviews show wide variations in the approach to PV EoL waste management. A handful of jurisdictions (EU and compliant nations) have PV-explicit policy, and the core of this policy is Extended Producer Responsibility (EPR). EPR is also at the center of the policy agenda in several other large consumers of PV technology, such as China, India, and Saudi Arabia. Where implemented, EPR can internalize EoL costs and fund collection and recycling, but experience shows producers often focus on compliance at the lowest cost, leading to bulk recycling (glass, aluminum) rather than high-value recovery (Peplow, 2022), and in countries with weak enforcement capacity, EPR obligations remain on paper, with limited collection (Wang et al., 2024). Hence, several other countries are skeptical about the merits of EPR implementation across the nations. For example, Australia and Jordan place more trust in product stewardship or public–private partnership models (PPP), which can be more politically and administratively feasible than strict EPR alone (Majewski and Dias, 2023). SWOT analyses and AHP-based decision frameworks conclude that hybrid models, combining government regulation, industry funding, and shared responsibilities, can outperform pure EPR in countries with immature regulatory systems.

On the other hand, many jurisdictions classify PV under generic e-waste or hazardous waste regulations without PV-specific requirements. Studies show this leads to

Ambiguity about whether PV is hazardous or non-hazardous, affecting how strictly it is handled. Inadequate characterization tests that don't reflect PV's complex leaching behavior, especially support an ecosystem with dominance of landfilling or simple shredding rather than advanced recycling. Very few regimes have landfill bans or fees specific to PV, or recycling subsidies significant enough to change behavior (Maghraby et al., 2024). Economic analyses show that recycling is currently more expensive than landfill, especially if high-value recovery is attempted, which, under current policy conditions, discourages investment.

5.5.1. Shortcomings in the present PV waste policy paradigm

Based on the present survey, the major shortcomings in global PV waste policy can be summarized as follows:

- (a) Insufficient coverage and lateness relative to the waste wave
 - Most policies have been formulated after large capacities were already installed and will reach EoL in the 2030s–2040s, leaving a regulatory lag.
 - Even in the EU, analysis suggests many member states lack sufficient infrastructure and may continue to landfill PV waste for decades.
- (b) Narrow focus on recycling, weak attention to higher-order circularity
 - Policies and research emphasize recycling, while repair, refurbishment, and reuse receive far less regulatory and institutional support, despite their higher circular value.
 - Behavioral and social modeling shows that reuse could only meet a fraction of future demand, so it must complement, not replace, recycling, but policy frameworks rarely co-optimize both.
- (c) Downcycling rather than high-value, closed-loop recovery
 - Most current practice is downcycling: recovering low-value glass and metals, with little recovery of high-purity silicon, silver, or rare metals.
 - Policy targets (in mass %) do not distinguish between low-value and high-value materials, so compliance does not guarantee circularity or resource security.

(d) Weak enforcement and institutional capacity

- Even where formal rules exist (e.g., parts of China, India, some U.S. states, Brazil), local enforcement and on-the-ground implementation are weak, especially for inspection, tracking, and illegal dumping control.
- Developing countries often lack data systems to monitor PV waste volumes and flows, undermining planning and compliance.

(e) Limited integration of environmental risk evidence

- Science indicates that leached Pb, Cr, Cu, Al from landfilled PV can reach or exceed hazardous limits under certain conditions, especially for crystalline-Si modules, but regulatory classifications and tests have not been systematically updated.
- Life-cycle assessments consistently show recycling beats landfill and incineration in GHG, toxicity, and resource-depletion metrics, but these findings are not yet embedded in binding performance standards or incentives.

(f) Neglect of social and ethical dimensions, especially in developing countries

- The developing countries risk becoming PV-waste hotspots, with low awareness, weak institutions, and high exposure to toxic impacts from informal recycling and dumping.
- Social-behavioral models demonstrate that public attitudes, trust, and incentives strongly affect participation in reuse/recycling schemes, yet policies rarely address these explicitly.

(g) Lack of harmonized international standards and cross-border governance

- There is no global treaty or harmonized standard specific to PV waste; transboundary movements of used modules and PV waste are governed indirectly via Basel and generic e-waste rules, which often lag behind actual trade patterns.
- This complicates producer compliance for global firms and creates loopholes for the export of problematic EoL modules to countries with weak regulations.

5.5.2 Good practices and recommended policy directions

Despite gaps, several promising policy directions appear across the literature:

- (a) Strengthening and regionalizing EPR and product stewardship: extending EU-style producer obligations, adapted to local capacities, and combining with PPP and product-stewardship schemes,
- (b) Explicit circular-economy strategies: integrating PV waste into national CE roadmaps (e.g., “6R” or “3R” frameworks; multi-level CLSC models) and embedding PV into cross-sector circular policies.
- (c) Linking policy to eco-design and design-for-recycling: incentivizing or mandating design changes to improve repairability, disassembly, and high-value recovery, though most jurisdictions have not yet moved beyond voluntary guidelines.
- (d) Using dynamic waste projections and spatial waste mapping: EU-wide and China-specific dynamic MFA studies are beginning to inform capacity planning for recycling plants and logistics.
- (e) Integration of LCA and techno-economic evidence into policy design: multiple LCAs and TEAs show that with appropriate policy support, recycling can be environmentally superior and potentially economically viable, especially when commodity prices and carbon costs are internalized.

5.6 Chapter Summary

For the deployment of energy technologies, the choice is made mostly based on economic parameters, especially the levelized cost of energy (LCOE). However, there is a significant disparity in the cost heads used to calculate the LCOE of different energy technologies. For example, the cost of a nuclear power project includes the handling and safe disposal costs of the spent fuel. The cost of coal-fired thermal plants includes the Flue Gas Desulphurization (FGD) system, a clean technology that removes sulfur dioxide from the exhaust flue gas. However, no such considerations are made for the end-of-life waste from solar photovoltaics, with the assumption that both its scale and environmental impact

can be neglected. The present article delves into socio-economic and environmental issues in detail and shows that such assumptions are completely misplaced.

The global photovoltaic ecosystem receives over USD 500 billion in annual investment; however, this investment is primarily directed toward building new capacity. Policies are primarily designed to accelerate PV deployment, such as feed-in tariffs, net metering provisions, renewable portfolio standards, and repowering (replacing older modules with higher-efficiency units before technical EoL). However, aspects of EoL waste management are completely neglected during project planning, except in the European Union. Core shortcomings include late and patchy adoption of PV-specific rules, weak enforcement, lack of economic incentives for high-value recycling, insufficient EPR (extended producer responsibility) outside the EU, and minimal attention to social and equity issues, especially in developing countries. Hence, a harmonized global standard mandating extended producer responsibility (EPR) and PV-specific disposal fees is hereby advocated to ensure that producers pre-finance the collection and recycling of future end-of-life modules, to retain the shade of PV truly green.

CHAPTER 6

EXPERIMENTAL INVESTIGATION OF EARLY FAILURE MODES OF PV MODULES

6.1 Preamble

As delineated in Chapters 3 and 4, PV waste management is a looming problem and a growing concern for environmental engineers and energy policymakers as early PV installations approach the end of their lifecycles. The cumulative PV waste generation is estimated to reach 8 million tons by 2030; however, interestingly, this humongous volume could be reduced by 79% if early failures are averted. Hence, improving PV reliability and preventing early failures are now more important than ever. One of the major contributors to the premature failure of PV modules is hotspot formation under partial shading and other mismatch conditions. In this chapter, the effectiveness of the hotspot-prevention mechanism integrated into a commercially available PV module is investigated across different PV array topologies. The findings reveal several limitations associated with the conventional bypass approach. Although the bypass diode partially fulfils its intended purpose in a string-array configuration, its effectiveness is entirely compromised when connected in a real-world installation, in a series-parallel (SP) or total cross-tied (TCT) array configuration.

6.2 Introduction

Solar photovoltaic technology presents multiple technical and environmental challenges that have raised concerns among environmentalists and policymakers worldwide, particularly given the rapid increase in installed capacity. First, the energy generated by solar PV systems is intermittent; therefore, large-scale battery storage

systems are necessary to manage daily fluctuations in production and demand and provide stable power. Although PV technology is environmentally safe during operation, most of the materials used in these batteries are hazardous and pose fire risks. Additionally, a proper global policy framework is lacking for the safe extraction of raw materials such as lithium and cobalt, as well as for their disposal or recycling after use. Second, solar PV systems are highly sensitive to environmental conditions, with past research showing that output varies significantly with wind speed, wind direction, dust composition, dust particle size, humidity, and irradiation levels (Alves dos Santos et al., 2021). To maintain optimal performance, PV installations need frequent cleaning with fresh water, which is scarce in many regions (Sarma and Singh, 2022). Thirdly, environmental factors such as partial shading conditions (PSC) also affect PV reliability, as well as efficiency and power output. PSC can result from uneven dust buildup on the module, inconsistent cleaning, bird droppings, leaves, or shading from nearby trees, electric towers, and low-lying modules of adjacent rows when the sun is at a low angle (see Fig. 6.1). In PSC, shaded cells become non-productive or less productive depending on shade intensity, and they can act as loads on the productive PV cells. This means that these cells start consuming or dissipating energy rather than generating it, causing their temperature to rise. Research shows that under PSC, cell temperatures can reach as high as 400 °C (Amerasekera et al., 1993).

Locational Factors Causing PSC	Deposition of Different Aerosols	Design Factors	Manufacturing Defects	Induced Defects	Environmental Factors Causing PSC
- Shadow of poles. - Shadow of transmission tower. - Shadow of building. - Shadow of tree. - Wind speed and direction - affects the aerosol deposition.	- Red soil. - Clay dust. - Normal city dust. - Fly ash from thermal power plants. - Micro dust from rice/wheat husk. - Desert sand. - Cement dust from construction sites. - Dust/ash from volcanic eruption.	- Self-shading at low sun elevation. - Low tilt angle-affects intensity of aerosol deposition. - Uneven irradiance on different facets in building integrated PV system.	- Micro cracks. - Mismatch in cell efficiencies.	- Potential Induced degradation of cells. - Light Induced degradation of cells. - Non-uniform reduction in transmittivity of top glass.	- Moving cloud. - Snow fall. - Bird dropping. - Fallen leaves. - Overgrown branches of neighboring trees. - Overgrown grass and weeds. - Bacterial/fungal growth due to high humidity. - Light precipitation (causing non-uniformity in aerosol deposition).

Fig. 6.1. Factors influencing partial shading and mismatch losses.

In addition to reducing efficiency and power output, higher temperatures compromise the PV system's reliability ([Mahamudul et al., 2016](#)). The temperature difference within the module can lead to cracking of the top glass, which, in severe cases, allows atmospheric oxygen to enter through the cracks and ignite the EVA sealant used in the modules.

To mitigate the risks associated with hotspot formation, virtually all commercially manufactured photovoltaic modules are equipped with an integral bypass mechanism. This bypass mechanism is strategically integrated at the module level to provide a parallel current path around non-productive cells or groups of cells. When functioning correctly, the bypass mechanism allows the module to divert photocurrent away from shaded or damaged cells, thereby preventing reverse bias conditions and the consequent heat generation that characterizes hotspot failures. This bypass function is fundamental to ensuring the longevity and reliability of photovoltaic installations, as it protects modules from accelerated degradation, potential fire hazards, and catastrophic failure modes ([Nunes et al., 2022](#)).

The prevailing industry standard for bypass circuit implementation relies on a single bypass diode connected in parallel with a series string of photovoltaic cells. This fundamental design approach has been universally adopted by photovoltaic manufacturers and project developers worldwide ([Amerasekera et al., 1993](#)). The simplicity and cost-effectiveness of this single-diode bypass circuit have made it the default choice across the industry, implemented without extensive verification of its practical effectiveness under real-world operating conditions. However, critical research has questioned the adequacy of this conventional approach. Studies by [Kim and Krein \(2015\)](#) demonstrated that standard bypass diodes do not completely eliminate hotspot formation but merely limit power dissipation by restricting the voltage across reverse-biased cells. This limitation means that while bypass diodes reduce the severity of hotspots, they cannot entirely prevent the heating phenomena that can lead to accelerated aging, cell encapsulation damage, and permanent module degradation. Despite the widespread deployment of this

bypass circuit architecture, a significant knowledge gap persists regarding its actual performance characteristics. Project developers and system integrators typically accept the manufacturer's claims regarding bypass circuit effectiveness at face value, relying on theoretical design principles and marketing assertions rather than empirical verification.

The absence of rigorous testing protocols represents a critical shortcoming in industry standards. International electrotechnical standards such as IEC 61215 (IEC, 2021), which establishes the primary testing and safety requirements for photovoltaic modules, contain only limited bypass diode testing requirements. Specifically, the bypass diode thermal test in IEC 61215 (designated MQT 18.1) simulates conditions at module temperature of 75°C with current flow at 1.25 times the short-circuit current for one hour. However, this standardized test does not comprehensively evaluate bypass circuit effectiveness under diverse partial shading scenarios, varying irradiance patterns, or different array configurations.

Consequently, no standardized test methodology exists to evaluate how well bypass circuits perform under varying degrees of shading, different patterns of light distribution, or integration into different array topologies. The literature similarly reflects this gap, with very few published studies systematically investigating the performance characteristics of bypass circuits under controlled experimental conditions (Sezgin-Ugranlı, 2025; Dhimish et al., 2024). To address this critical knowledge gap, a comprehensive experimental investigation of bypass circuit effectiveness has been undertaken. The research systematically evaluates commercial photovoltaic modules equipped with conventional single-diode bypass circuits. Multiple partial shading conditions are simulated in controlled laboratory environments. Additionally, the study examines how bypass circuit performance varies across different array topologies and electrical configurations, recognizing that module interconnection methods may influence bypass circuit operation and overall system resilience. This experimental validation approach aims to rigorously assess whether current industry practices adequately protect

photovoltaic modules against hotspot-induced failures and to identify any performance limitations or design improvements that may be warranted.

6.3 Theoretical Discussion of PV Module Failure Modes

The fundamental constituent element of any PV energy system is the PV cell, which is essentially a flat semiconductor diode with fingers and bus bars printed on the top surface to collect free electrons, and an Aluminum back contact at the bottom to collect holes upon irradiation with an electromagnetic wave (including sunlight). A number (typically 60, 72, or 96) of PV cells connected in series to constitute a PV module. In all commercially available PV modules, one bypass diode is connected in antiparallel with a group of cells (see Fig. 6.2), i.e., across each sub-panel, to provide an alternate path for current in case any cell or group of cells is shaded or non-productive due to defects.

The function of these bypass diodes is crucial; if they don't function effectively, the entire module may fail early, since it is not possible to replace a single cell or a group

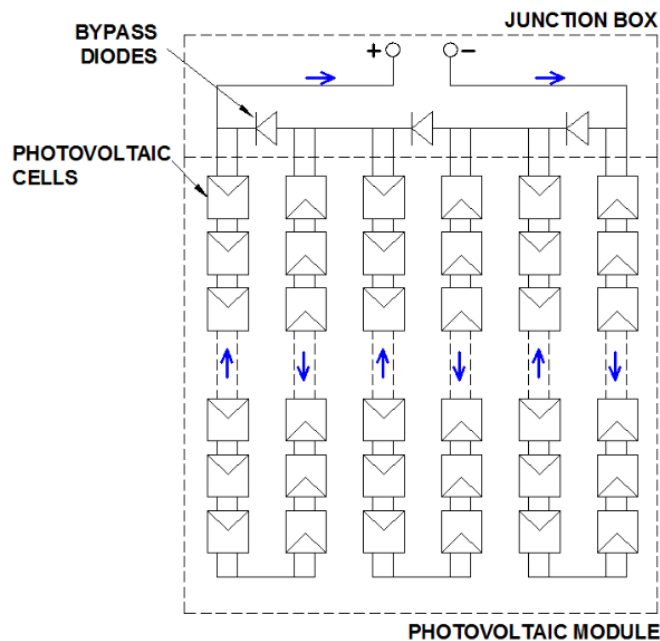


Fig. 6.2. Schematic diagram of the bypass arrangement provided in typical commercial PV Modules.

of cells in a module. The failure mode is discussed in the following paragraphs. When any cell or group of cells becomes non-productive or under-productive due to shading, defects, or other reasons, those cells are reverse-biased by the voltage developed in the productive cells. Now, if the applied reverse voltage is high enough to cause reverse breakdown in the shaded cells, reverse current flows through the shaded or non-productive cell, raising its temperature. This phenomenon may cause a thermal runaway when the reverse current flows through a narrow channel, in which case the temperature may rise to 400 °C (Amerasekera et al., 1993). The high thermal gradient within the module, caused by reverse breakdown, cracks the protective glass cover, eventually allowing atmospheric oxygen to enter the module. The sealing material EVA, in the presence of atmospheric oxygen and high temperature, catches fire in some cases (Guerriero et al., 2019). Another mode of failure is the failure of soldered joints at high temperatures. As discussed before, the PV modules are constructed by connecting a large number of PV cells in series. This connection is made by soldering the busbars of each cell to those of adjacent ones. The soldering alloys are suitable for withstanding temperatures between 200 and 300 °C; at higher temperatures, the joints may open or loosen, which can lead to internal short circuits and, eventually, fire.

Theoretical verification of the above narrative, based on the literature, may be carried out by calculating the reverse-bias voltage applied across the non-productive cell. The method for quantifying the reverse-bias voltage is described by Guerriero et al. (2019). As discussed in (Guerriero et al., 2019), the reverse bias voltage (V_R) across the shaded or non-productive cell may be calculated by $V_R = V_{PV}(N-1) + V_D$, where V_{PV} is the forward voltage generated in each PV cell, N is the number of PV cells in the sub panel (the group of cells, in antiparallel with which a bypass diode is connected), and V_D is the voltage drop in the bypass diode (which is generally 0.3 –0.5 V). The value of V_{PV} varies between 0.6 and 0.7 V for commercial crystalline silicon cells, and the values of N are 20, 24, and 32 for 60-, 72-, and 96-cell modules, respectively. By replacing these parameters, the magnitude of the reverse bias voltage across a shaded cell may be quantified as 12, 14, and 19 V, respectively, for the modules of the sizes described above.

Apparently, the reverse-bias voltage quantified in the paragraph above may seem harmless to PV cells, as, in theory, the reverse breakdown of any flat, defect-free p-n junction should occur at around 60 V (Sze and Gibbons, 1966). However, although the structure of PV cells is theoretically the same as that of a flat p-n junction, past research shows that the reverse-bias characteristics of PV cells differ substantially from those of basic p-n junctions. The reason behind this deviation is that a basic flat p-n junction undergoes several additional manufacturing processes to be converted to a PV cell (see Fig. 4.2). Which are, firstly, texturization of the top surface by alkaline etching or acid etching for improving receptivity of electromagnetic radiation; secondly, printing of fingers, busbars, and Al back contact for collection of free electrons and holes, respectively. Further, cofiring of the wafers at 750-870 °C for diffusing the front and rear contact with the Si substrate (Fraas, 2014). And during these processes, microdefects and micro-contamination with metallic particles are introduced in the semiconductor, which reduces the reverse breakdown voltage of the PV cells to a substantially lower level, and surprisingly, it almost overlaps with the reverse bias voltage generated in the PV module under PSC during operation (quantified in the previous paragraph). Interestingly, experimental investigations of the reverse-bias characteristics of PV cells reveal that the reverse breakdown of acid- and alkaline-texturized PV cells occurs at approximately -13 V (Bauer et al., 2009) and between -15 and -20 V (Sze and Gibbons, 1966), respectively. Hence, it is imperative that the extant hotspot prevention mechanism in commercial PV modules is ineffective at preventing reverse current through shaded or non-productive cells.

6.4 Environmental impacts and failure modes in real installations – Observations from Site Visit

Several rooftop and commercial installations were surveyed in the Indian capital city of New Delhi, and several installations were observed to be subjected to the unfavorable environmental conditions discussed in the previous section. At Installation 1 (see Fig. 6.3), it may be observed that the tree branches have grown close enough to cast



(a)



(b)

Fig. 6.3. Photographic survey of Installation I, (a) tree branches overgrown close enough to cast partial shading over the PV panels, especially during a low altitude of the sun, (b) Fallen dry leaves over the PV panels.

partial shading on the PV panels at a lower altitude of the sun. The dry leaves of the nearby tree are also found to be lying on the PV panels, which in turn will cause a partial shading effect. In another installation (see Fig. 6.4), the PV panels were found to be completely covered by dust and other aerosols after 15 days of exposure. During which the power



(a)



(b)

Fig. 6.4. Photographic survey of PV installation II, (a) the nonuniform dust deposition and bird droppings over PV panels after 15 days of exposure, (b) The closeup of animals' (monkeys') foot marks and bird droppings.

output from this installation was found to have reduced by 17%. More interestingly, aerosol depositions were not uniform across the modules, and this non-uniformity was caused by animal movement (monkeys in this case) and bird droppings (see Fig. 6.4). The observed abnormalities in the real installations were further studied using infrared thermography to validate their impact (see Figs. 6.5 (a) and 6.5 (b)). In all cases (defect or PSC due to bird droppings or dust), the temperature of the affected area is observed to be higher than the average module temperature. This implies that the affected areas were dissipating power generated by the other productive cells in the module, and that the reverse-bias current was flowing through them. Hence, it is quite evident that the protection circuit, which is provided in all the commercial modules, which is supposed to bypass the string current when any cell is unproductive, was not working effectively and needs improvement. To investigate the behavior of the protection mechanism in greater detail under different partial shading scenarios and array configurations, a test setup was built with a 3×3 array of PV modules. The description of the setup, design of the experiment, and the results are presented in the following sections.

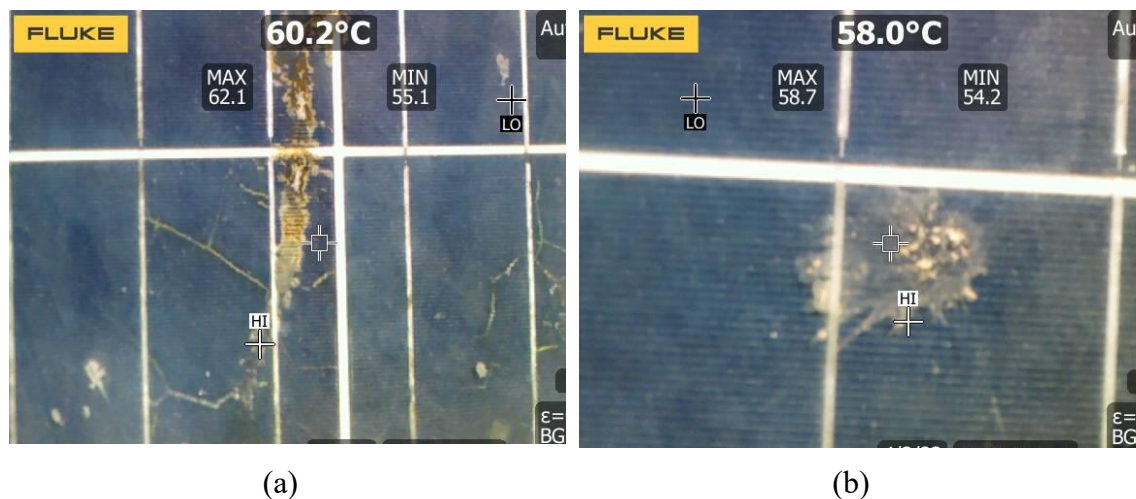


Fig. 6.5. Infrared thermographic image of the abnormalities in the PV modules while in operation, (a) the image of a damaged PV module, (b) the image of a dried bird dropping.

6.5 Experimental Setup and Design of Experiment

Every large-scale PV plant is constructed first by connecting several PV modules in series to form a string. The length of the string depends on the plant design voltage, as the string voltage increases with string length. Large-scale PV plants are designed for 1 kV or 1.5 kV voltage levels, depending on the selected inverter rating. Further, several strings of equal numbers of modules are then connected in parallel, depending on land availability. And the installed capacity of the plan increases with the number of strings in parallel. This arrangement is called a series-parallel (SP) array (see Fig. 6.6(a)), and this basic configuration is used in most large-scale installations. However, past research reveals that the performance of the arrays can be substantially improved by modifying the basic SP array by interconnecting the strings, which are bridge-link (Fig. 6.6 (b)), honeycomb (Fig. 6.6 (c)), and total cross-tied (TCT) (Fig. 6.6 (d)). The performance in the modified array configurations improves under partial shading and other mismatch conditions, due to the redundant paths available in them, which allow the bypass path. And since TCT has the highest degree of redundancy and interconnections, this array is reported to be the best performing under partial shading conditions (Belhachat and Larbes, 2015).

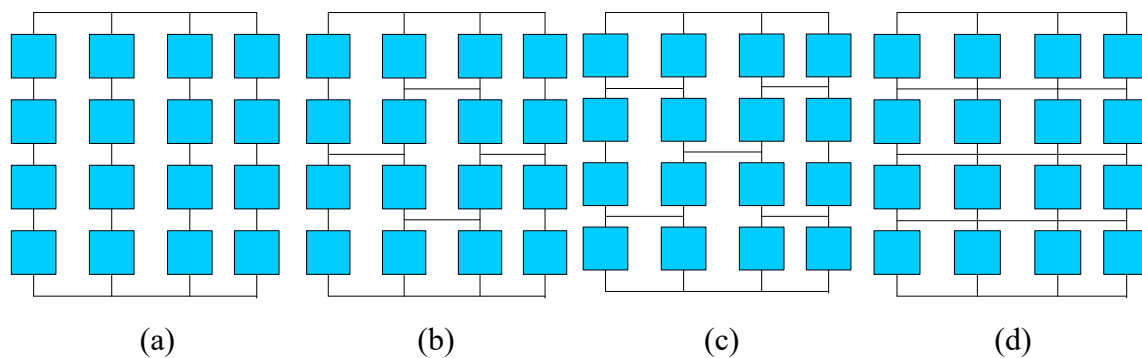


Fig. 6.6. Different PV array configurations (a) series-parallel, (b) bridge-link array (c) honeycomb, and (d) total cross-tied array.

However, reconfiguring PV arrays in real-world applications is extremely difficult, both technically and commercially, especially for utility-scale PV projects. On the other hand, those do not add any value under normal operating conditions; on the contrary, the array

with no cross ties, i.e., a conventional Series-Parallel (SP) array, is observed to yield the highest fill factor under normal operating conditions (Wang and Hsu, 2011). Secondly, additional cross-ties increase project costs and reduce the reliability of the PV system as the number of joints increases. Due to the above factors, in commercial PV plant design, SP arrays are invariably implemented for large-scale projects, whereas string arrays are used for small-scale projects.

In the present research work, an experimental setup was developed in the present work to carry out a comparative study of the efficacy of the bypass diodes in the two most commonly used array configurations used in real installations, i.e., a string and an SP array and the array with highest degree of redundancy, i.e., TCT, in preventing the hotspot formation in the shaded cells (see Fig. 6.7). The experimental study was mainly focused on establishing the efficacy of the bypass diode in preventing the hotspot formation in the series and SP, and TCT array configurations under PSC. For this purpose, the bypass current (i.e., the current through the bypass diode) was measured by disconnecting (desoldering) the bypass diode and connecting an ammeter (A_1) in series with it (see Fig. 6.8) while different PSCs were created by covering a different number of cells. A variable resistive load (R_l), another ammeter (A_2), and a voltmeter (V_l) were connected to the array terminals to establish the power outputs of the arrays, as well, for the complete operating range, i.e., from the short circuit voltage (i.e., $V_{SC} = 0$) to the open circuit voltage (V_{OC}). The bypass current was superimposed onto the arrays' outputs under different PSCs to gain deeper insights into the behavior of the bypass diodes across operating points. Additionally, the thermal response of the shaded cells was simultaneously observed using a thermal imaging camera with 640×480 infrared resolution. The modules (refer to Table 6.1 for detailed specifications) were first connected in a 3×1 series string configuration, and varying numbers of cells (from 1 to 4) were shaded sequentially to create partial shading conditions (PSC). The same steps were later repeated on a 3×3 array of SP array configuration by connecting three such (i.e., 3×1) strings in parallel. Next, each string was interconnected to form a TCT array (see Fig. 6.6). The experiment was conducted under natural solar irradiance to simulate an environment closer to real applications.

Table 6.1

Specification of the module used in the experimental study

Parameter	Specification	Parameter	Specification
Model	EIL 40	Open circuit voltage (V_{oc})	22.0 V
Maximum power at STC (P_{max})	40.0 W	Current at maximum power (I_{mp})	2.2 A
Short circuit current (I_{sc})	2.4 A	Voltage at maximum power (V_{mp})	18.0 V

Note: Specified values are at STC (i.e., the irradiance of 1000 W/m^2 , AM 1.5, Temperature 25°C)

However, the experiment was conducted in a fixed time slot every day to minimize the variation in the irradiance level and ambient temperature to the extent practically possible. All dependent and independent variables, such as natural irradiance, ambient temperature, and current and voltage at the PV array terminal, were recorded to analyze the results and draw meaningful conclusions. Care was taken to choose a fixed time slot each day for conducting the experiment to ensure that variations in incident irradiance and ambient



(a)



(b)

Fig. 6.7. The experimental setup used to investigate the effectiveness of the bypass diode in different configurations (a) The 3×3 PV array, and (b) measurement of bypass current.

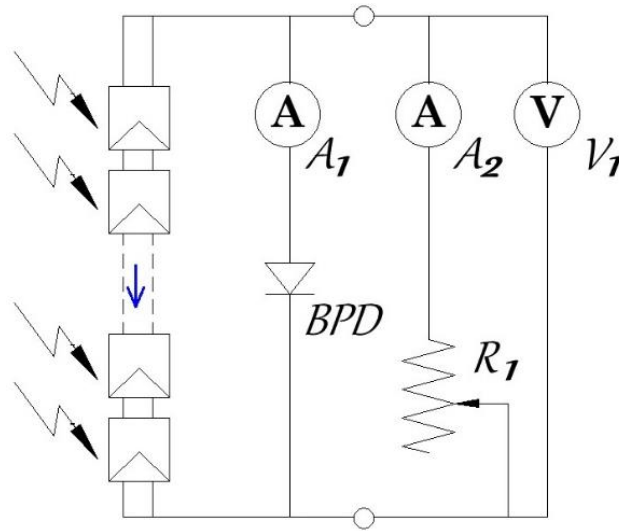


Fig. 6.8. Schematic Diagram of the proposed experimental setup.

conditions remained within reasonable limits. The recorded natural irradiance ranged from 905 to 957 W/m², and the ambient temperature ranged from 28.5 to 31 °C during data collection. Infrared thermography was used to record the thermal behavior of all the cells under partial shading conditions. The application of infrared thermography started in this space in 1990 and slowly gained huge popularity as it is a non-contact and non-invasive method, and it also enables the investigation of the defects, especially the hotspots, in a very short span of time, without needing to take the system offline, *i.e.*, without affecting the generation or disturbing the electrical connections. Hence, this method is currently hailed as one of the best for detecting high-temperature zones (hot spots) in PV modules and thereby identifying microcracks, defects, and mismatches due to PSC.

6.6 Results and Discussion

6.6.1 Results of String array configurations under PSC

To compare the effectiveness of the bypass circuit across different configurations and shading scenarios, the PV modules were first interconnected to form a 3×1 string, and shading scenarios were simulated by covering the modules in steps of 1 cell at a time. When 1 cell was shaded, a negligible current was observed through the bypass diode (see

Fig. 6.9), indicating that the bypass diode remained in the OFF state over the operating range (0 to V_{OC}) and the bypass path was inactive. Hence, the open-circuit voltage (V_{OC}) was the highest (i.e., 50.1 V) among all shading scenarios. In this case, the observed V_{OC} of the string is the cumulative V_{OC} of all three modules, as no module was bypassed. However, since the bypass path was non-functional, the string current had to flow through the shaded cell, forcing it to undergo reverse breakdown. This observation was corroborated by the thermographic image of the module (see Fig. 6.10). The thermographic investigation revealed that when only 1 cell was shaded, a hot spot was generated in it. The temperature in the shaded cell increased to 80.7 °C from a normal operating temperature of 43.2 °C (i.e., 86.8% higher) than that of the unshaded cells in the same module (see Fig. 6.10(a)). The bypass diode got activated in the series string only after the shading of 2 or more cells. The performance characteristics, superimposed with the bypass diode current characteristics of the string, when 2 and 3 cells were shaded, are illustrated in Figs. 6.11(a) and 6.11(b), respectively. It may be observed from the aforementioned figures that the profile of the string current matches perfectly in both cases, i.e., 2-cell and 3-cell shading scenarios. This implies that the bypass diode was conducting throughout the operating range (i.e., from 0 V to the open-circuit voltage). However, it is interesting to note that the string current exceeded the bypass diode current in both cases, and this difference remained nearly constant from the short-circuit condition to the maximum power point. This implies that though the shaded cells did not undergo reverse breakdown, a part of the string current was conducted through the shaded cells, overcoming their shunt resistances. This shunt current varied between 10.8 to 12.1% at different operating points and for different shading conditions (see Table 6.2).

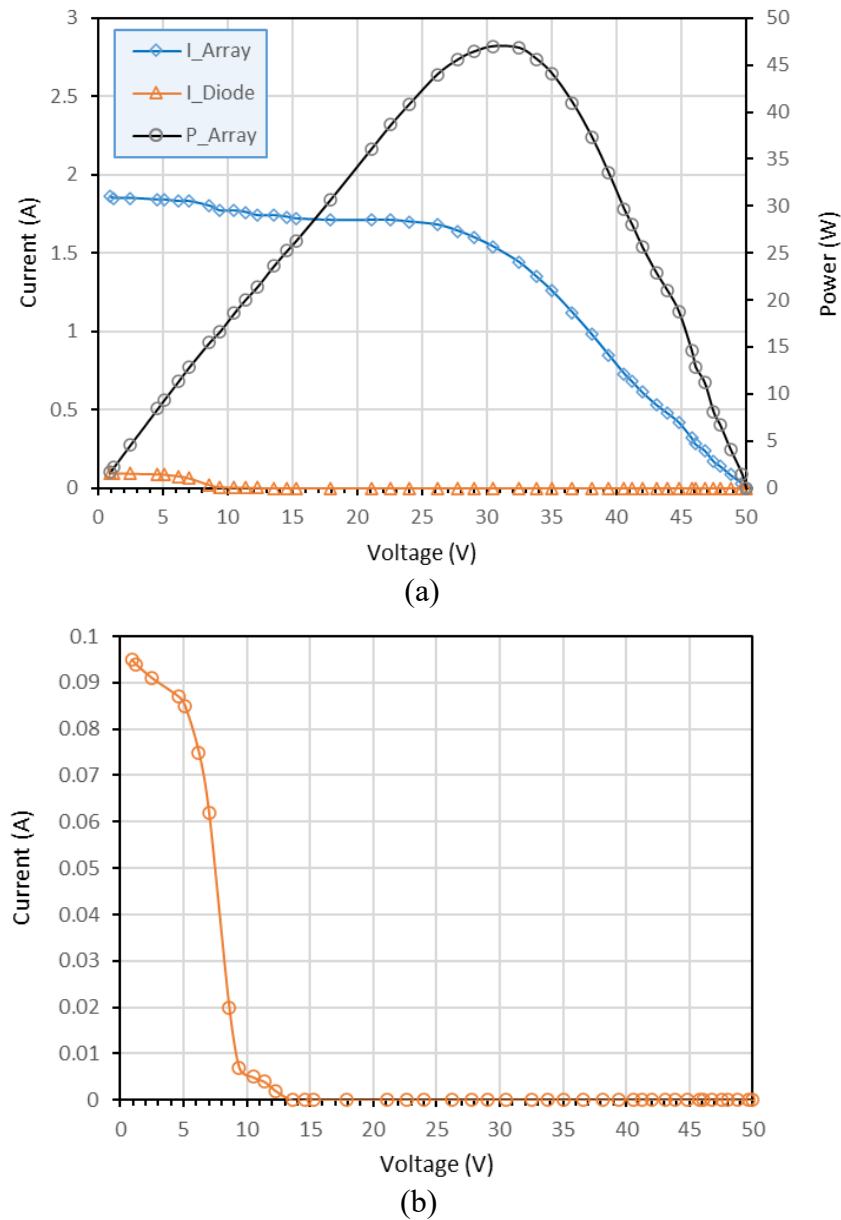
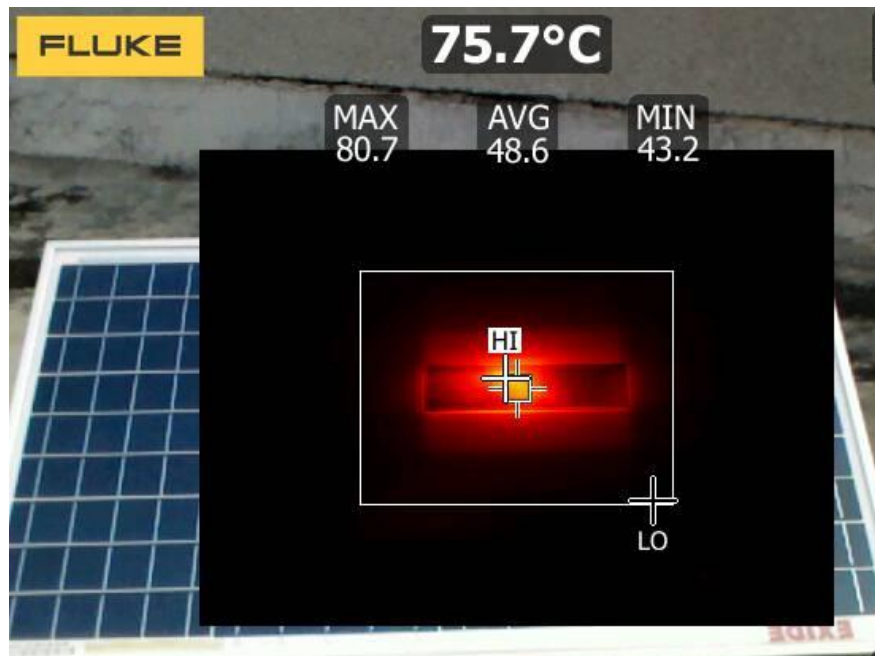
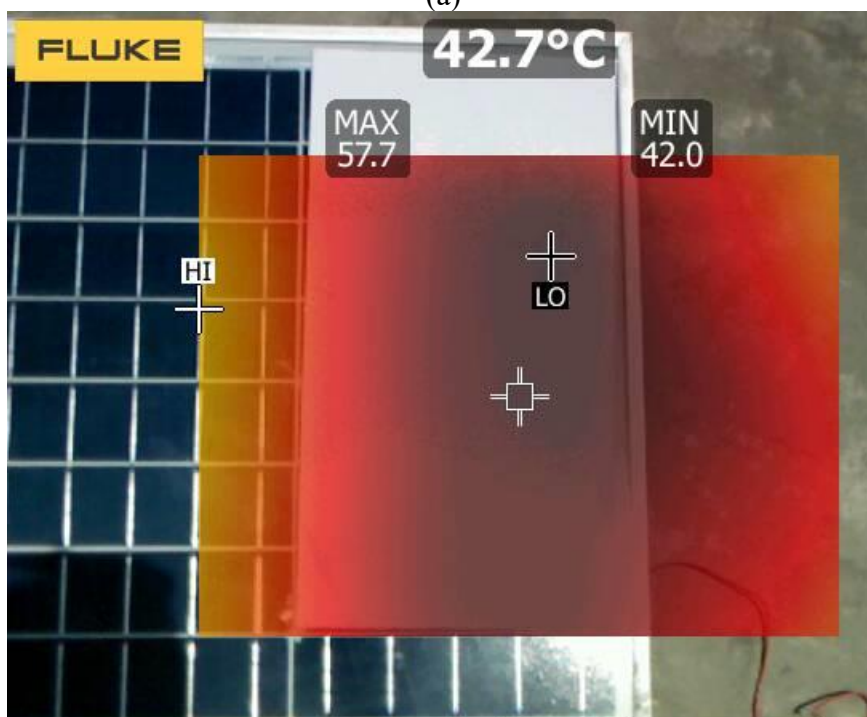


Fig. 6.9. Performance characteristics of 3×1 string under PSC, with one cell shaded, (a) Superimposed plot of all 3 parameters, (b) enlarged plot of bypass current.

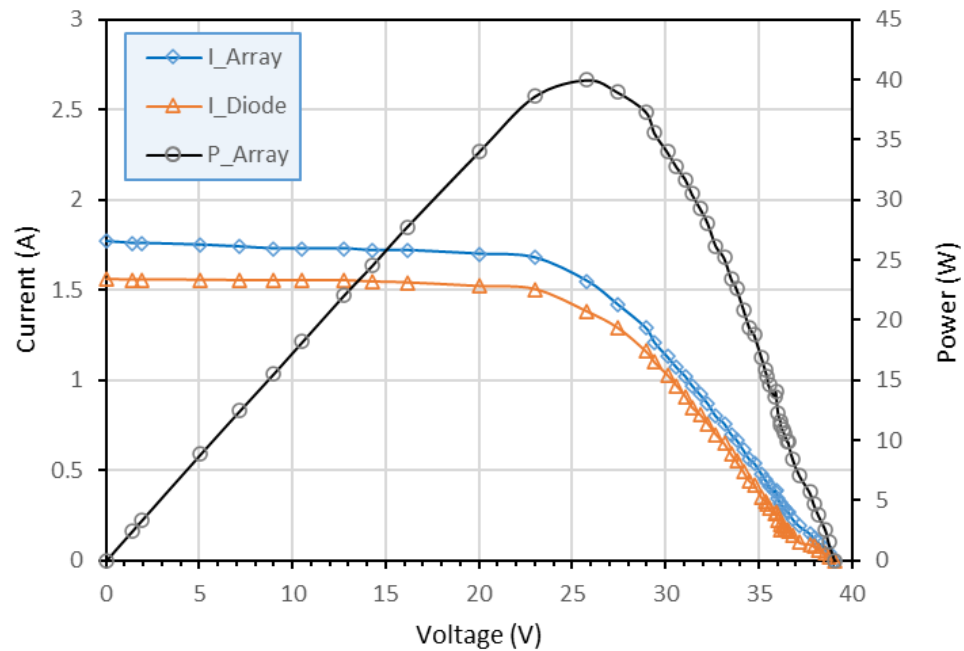


(a)

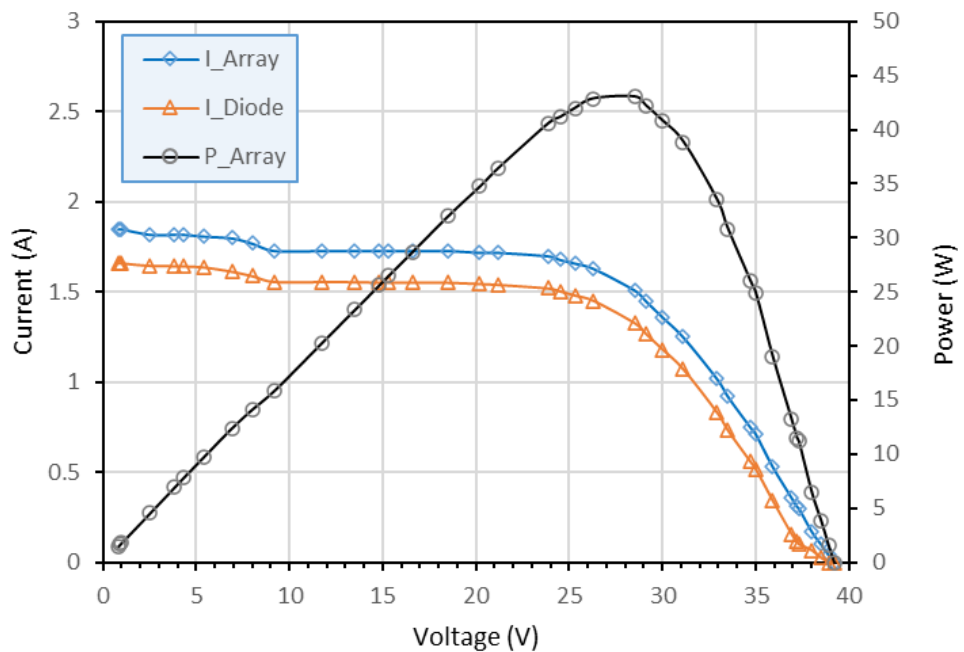


(b)

Fig. 6.10. Thermographic image of PV module under different shading conditions, (a) under single cell shading, and (b) under multiple cell shading



(a)



(b)

Fig. 6.11. Bypass circuit characteristics superimposed on performance characteristics of 3×1 string under PSC, (a) with 2 cells shaded, and (b) with 3 cells shaded.

6.6.2 Results of TCT Array Configuration

In the second stage of the study, the above experiment was repeated on a 3×3 TCT array by interconnecting 3 strings similar to and including the string used in the first stage of the experiment. The shading strategy was kept the same as followed for a 3×1 string as well, *i.e.*, a different number of cells were shaded in a step of 1 cell at a time. Under single-cell shading, the observations were similar to those on the single string, *i.e.*, the bypass diode was non-conducting in this shading scenario (see Fig. 6.12). This forced the shaded cell to undergo reverse breakdown, and the string current conducted through the shaded cell. The thermographic investigation was also carried out in this case, which corroborated the above observation as well (see Fig. 6.13(a)). It may be observed in Fig. 6.13(a) that the temperature of the cell increased to 81.6°C from the normal operating temperature of 44.2°C , under the single cell shading scenario. A small leakage current was observed to be flowing at the voltage range of 0 to $\approx 12\text{ V}$, as may be observed in Fig. 6.12(b), which was also observed in the case of a single string.

From the experimental result of single cell shading, it is quite evident that the present protection circuit does not protect the panel, neither in a single string nor in the TCT array, unless an area of more than one cell is shaded or becomes non-productive due to other factors. This apparently seems to be acceptable since the module is made of a large number of cells, and the existing circuit will be able to protect the module in all other cases. However, it is worth noting that there are many possibilities in which only one cell or lesser area may be shaded, such as falling of dry tree leaves, and bird droppings (refer Fig. 6.4). And protection of single cell shading scenario is also needs to be viewed with equal importance

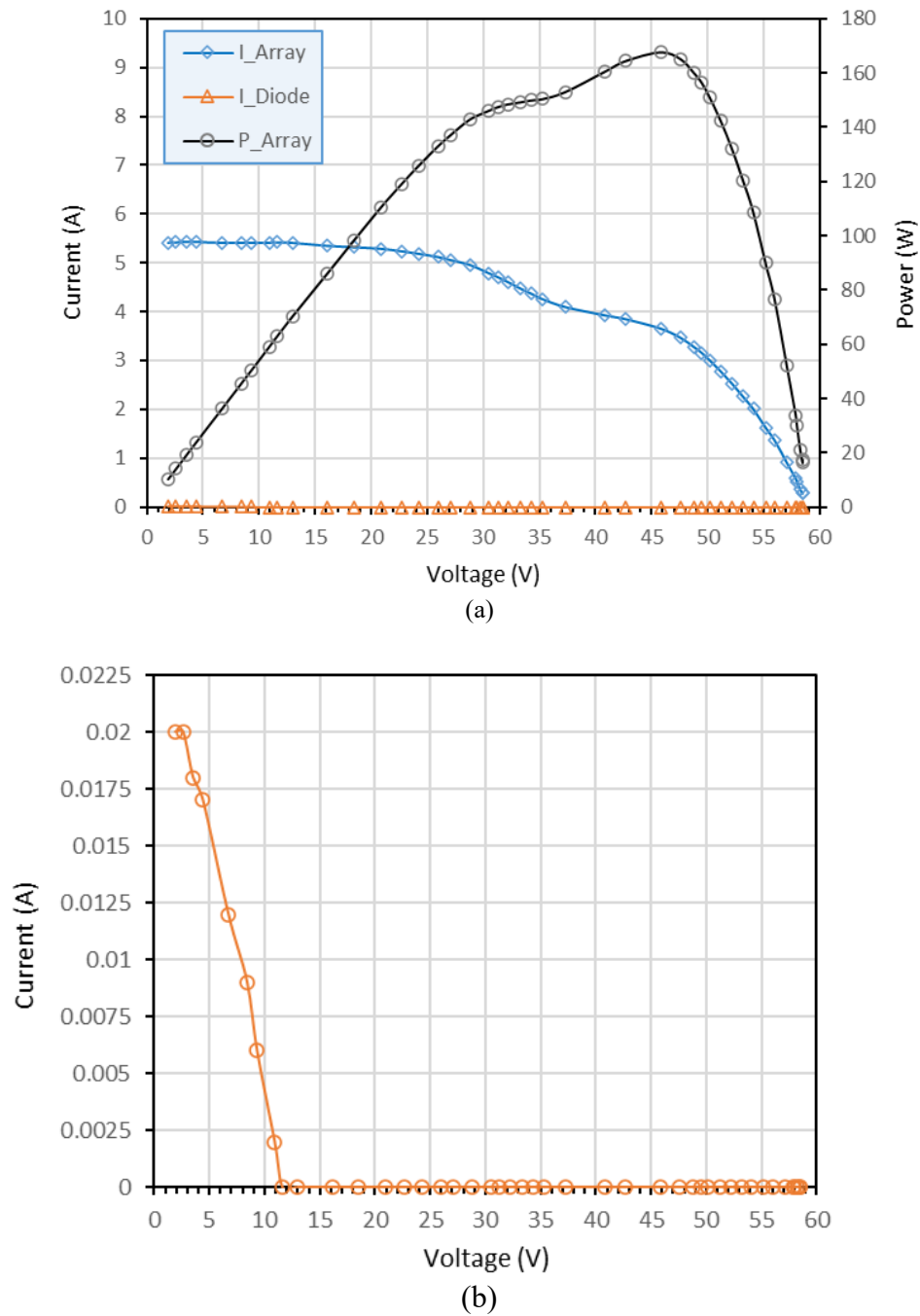


Fig. 6.12. Performance characteristics of 3×3 TCT array under PSC, under single cell shading, (a) Superimposed plot of all 3 parameters, and (b) enlarged plot of bypass current.

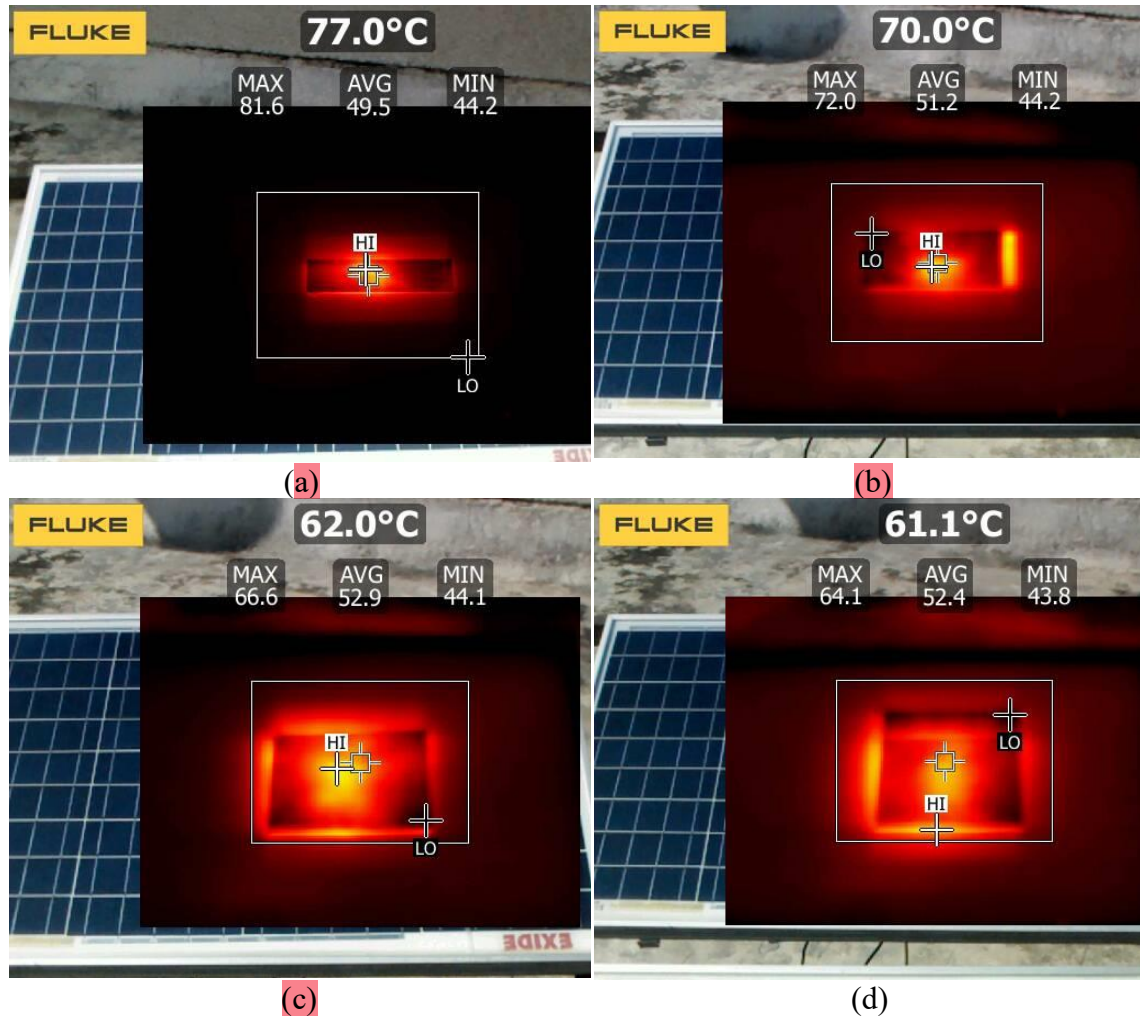


Fig. 6.13. Thermographic image of PV module of 3×3 TCT array at MPP, under (a) single cell shading, (b) two cells shading, (c) three cells shading, and (d) under four cells shading scenarios.

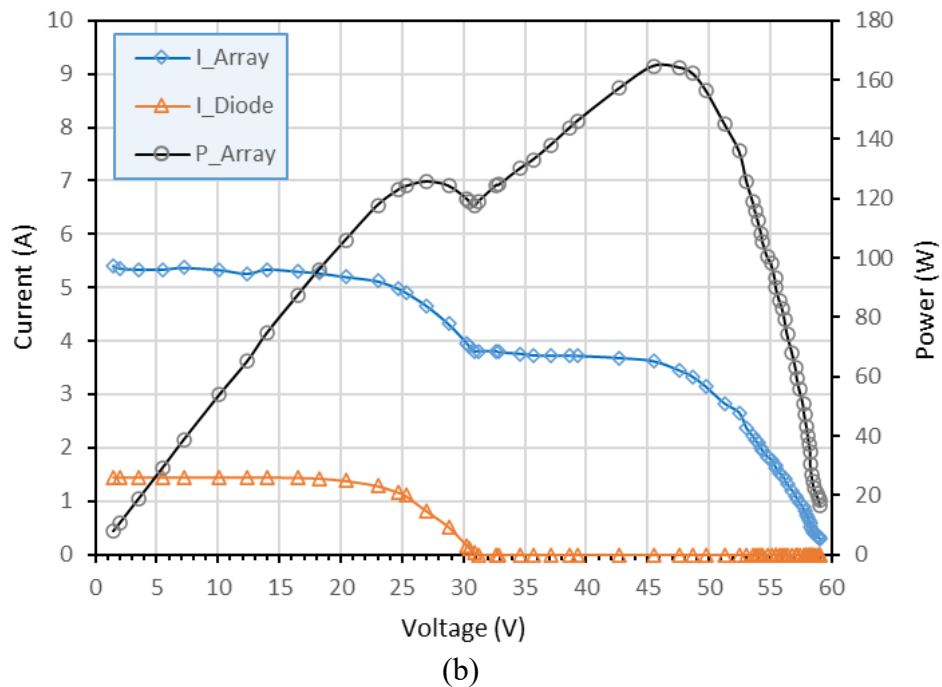
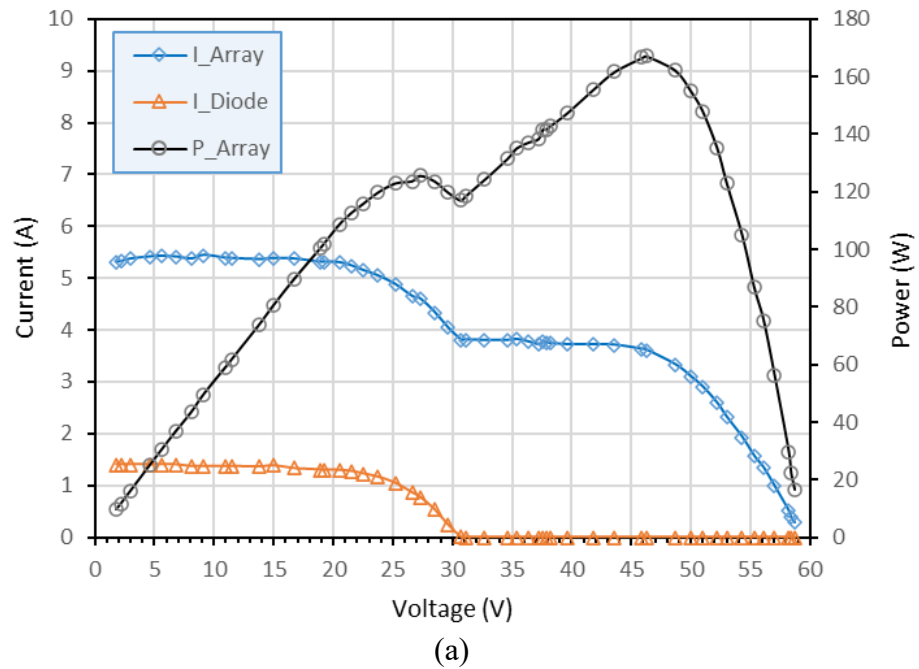


Fig. 6.14. Bypass circuit characteristics superimposed on performance characteristics of 3×3 TCT array under PSC, (a) under 2 cell shading, and (b) under 3 cell shading scenarios.

as it is not feasible to repair a single cell in case it gets damaged, however, small the affected area may be. Hence, under the present protection scheme, the complete module is vulnerable to early failures. The performance characteristics of the array, under 2-cell shading and 3-cell shading scenarios, are illustrated in Figs. 6.14(a) and 6.14(b), respectively. The bypass diode current is also superimposed in the performance characteristics curves to establish the nature of the correlation between the performance characteristics and the operation of the bypass circuit. It is interesting to note that, unlike in the single string, the bypass current profile did not follow the array current throughout the voltage range; it started following the array current profile only after nearly half the voltage of the maximum array voltage (*i.e.*, $\approx 30\text{V}$). It is also worth noting that the point at which the bypass diode started operating is far away from the point at which the array produced maximum power (*i.e.*, MPP). And this phenomenon was observed for all the shading scenarios except 1 cell shading scenario (in which the bypass path did not conduct at all). To understand the implication of this observation, at this point it will be worth recalling the fact that PV modules are always operated as close as possible to the MPP by the MPP tracking (MPPT) algorithm. Hence, it is quite evident that under real-world scenarios, the bypass path in the TCT arrays will be non-operational, even when it is under partial shading conditions, irrespective of the area covered by the partial shading.

To investigate the thermal impact of the phenomenon discussed in the paragraph above, thermographic images were captured for all the shading scenarios, *i.e.*, shading of 1-4 cells, at the operating point (*i.e.*, at MPP), and the images are presented in Figs. 6.13(a)-6.13(d), respectively. It may be observed that the thermal profile of the PV cells is entirely different from that observed for the single string under similar shading scenarios. In the case of the TCT array, hotspots were created in all shading cases (*i.e.*, 1-4 cells) when the array was operated at MPP, whereas in the single-string case, a hotspot was created only in the single-cell shading scenario. It is also worth noting from the Figs. 6.13(a)-6.13(d) show that the hotspot temperature decreased as the number of shading areas increased, after exposing the module to the partial shading condition for the same duration (≈ 30 min). The temperature in the shaded cell increased to 81.6°C from the

normal operating temperature of 44.2 °C under a single-cell shading scenario. Whereas the temperatures under the 2, 3, and 4-cell shading scenarios increased by 27.8, 22.5, and 20.3 °C, respectively, from the module's normal operating temperature. The decrease in the hotspot temperature with the increase in the shaded area may be attributed to the fact that the reverse bias voltage decreases with the more extensive coverage of partial shading. In all the shading scenarios, from 2-cell shading onwards, the hotspot was not observed in the shaded cells when the array was operated away from MPP and in the region closer to the short-circuit condition. This can be attributed to the bypass diode activating in this region, as shown in Table 6.3, which quantifies the difference between the array current and the bypass current at different operating points. From Table 6.3, it may be observed that although the bypass path carried 25-27% of the string current in the short-circuit region, no current was carried at MPP in all shading scenarios. Hence, thermographic observations of lower temperatures in shaded cells in non-MPP regions lead only to a false interpretation of hotspot mitigation, as in real-world scenarios, the array will always be operated at MPP. Based on the results and performance characteristics, along with thermographic images, it is evident that the hotspot prevention circuit in commercial PV modules behaves differently in a single-string and in a TCT. The contrasting behavior of the hotspot protection circuit in a single string and in the TCT array is graphically juxtaposed in Figs. 6.15 and 6.16. Fig. 6.15 illustrates the percentage of bypass current in

Table 6.3

Comparison of array current versus bypass current in 3×3 TCT array

Operating Point	1 cell Shaded			2 cell Shaded			3 cell Shaded			4 cell Shaded		
	String Current (A)	Bypass current (A)	Difference (%)	String Current (A)	Bypass current (A)	Difference (%)	String Current (A)	Bypass current (A)	Difference (%)	String Current (A)	Bypass current (A)	Difference (%)
MPP	3.66	0	100%	3.61	0	100%	3.62	0	100%	3.6	0	100%
Short Circuit	5.41	0.02	99.6%	5.31	1.406	73.5%	5.41	1.45	73.2%	5.36	1.37	74.4%

the total array/string current in the short-circuit region. It may be observed that, in both configurations, the bypass circuit effectively and bypassed the string current. The thermographic investigations also reveal that the hotspot was effectively prevented. However, this is a false indication of the hotspot mitigation as the arrays are operated at MPP and not at the short circuit region. The contrasting behavior of the bypass circuits of single strings and the TCT array at MPP is graphically illustrated in Fig. 6.16. Which is the true picture of the effectiveness of the bypass circuits, as the arrays will always operate at MPP in a real-world scenario.

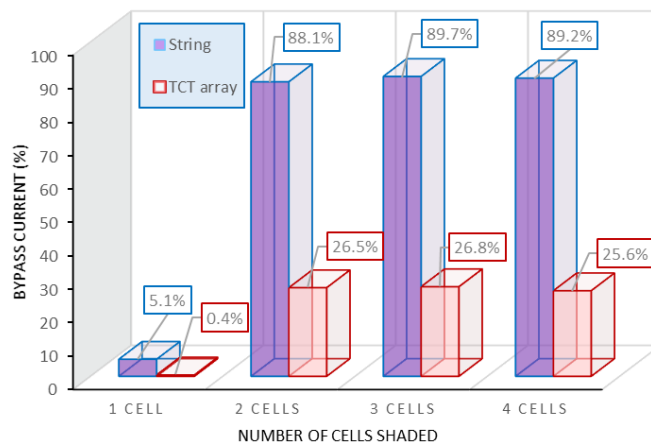


Fig. 6.15. Comparison of bypass current as percentages of the string current in a single string and TCT array, at short circuit region.

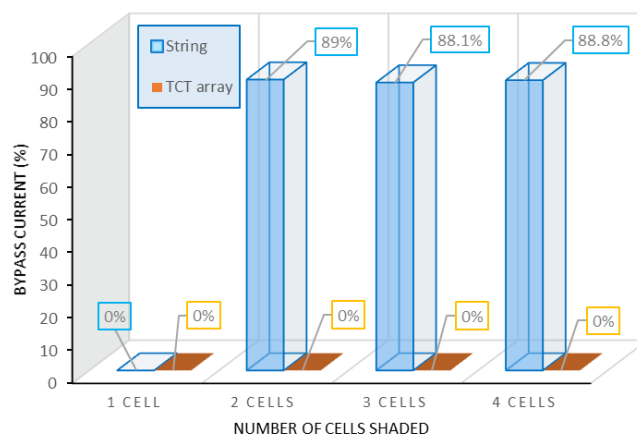


Fig. 6.16. Comparison of bypass current as percentages of the string current in a single string and TCT array, at maximum power point (MPP).

As evident from Fig. 6.16, close to 90% of the string current was bypassed in the single string at MPP, in all shading cases except the single cell shading scenario. However, in real-world scenarios, PV arrays are rarely built with a single-string configuration. But in the case of the TCT array, the bypass current remained 0 at MPP across all shading cases, resulting in hotspot generation in the shaded cells. Hence, in real-world scenarios, the extant hotspot prevention mechanism is ineffective for the TCT array, which has been found to be the best-performing topology in the literature. So, disruptive innovation is needed to make the bypass circuit effective, preventing early failures and thereby limiting PV waste generation in the near future.

6.6.3 Results of SP Array Configuration

In case of SP configuration as well, the Bypass diode was observed to have remained non-conducting when a single cell was shaded (see Fig. 6.17). And similar to the case of a single string, a small leakage current conducted through the bypass diode (see Fig. 6.17(b)) as well, near the short-circuit region. The value of the leakage current was 0.091 A, whereas the short circuit current of the array was 5.62 A (See Table 6.4). An infrared image of the shaded cell was also captured for the SP array, revealing hotspot formation with a temperature rise of 24.7 °C above the normal operating temperature. The above observations

Table 6.4

Comparison of array current versus bypass current in 3×3 SP array

Operating Point	1 cell Shaded			2 cell Shaded			3 cell Shaded			4 cell Shaded		
	String Current (A)	Bypass current (A)	Difference (%)	String Current (A)	Bypass current (A)	Difference (%)	String Current (A)	Bypass current (A)	Difference (%)	String Current (A)	Bypass current (A)	Difference (%)
MPP	4.731	0	100	3.989	0	100	3.319	0	100	3.137	0	100
Short Circuit	5.62	0.091	98.4	5.743	1.728	69.9	5.553	1.542	72.2	4.85	1.43	70.5

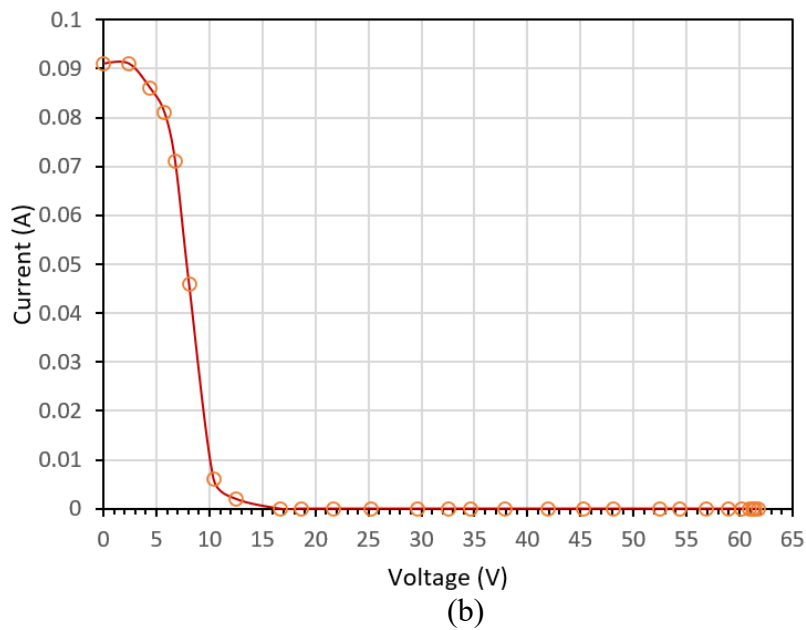
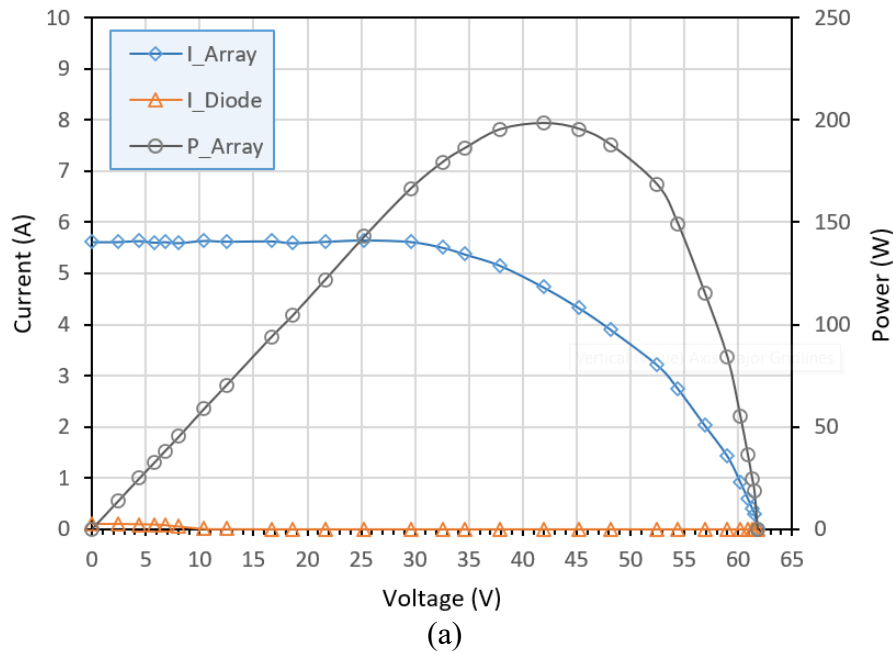


Fig. 6.17. Performance of SP array under single cell shading condition (a) bypass current superimposed on the electrical performance of the array, (b) bypass current-enlarged view.

imply that in the single-cell shading scenario, the bypass diode failed to conduct, and hence reverse breakdown occurred in the shaded cell, in the SP array, as well as similar to the string and TCT array configurations.

However, a major shift in the bypass diode's behavior across shading scenarios in two or more cells may be observed when the string is converted to an SP array. The response of the bypass circuit was observed to be in direct contrast to that of the string array when a 3×3 SP array was configured using 3 such strings, in two or more cell shading scenarios. In these scenarios, the bypass diode remained in the OFF state until a point well beyond the global MPP (GMPP). The GMPP was observed at 41.8, 46.2, and 47.3 V, respectively, for two cells, three cells, and four-cell shading scenarios, whereas the bypass diode was observed to conduct in the operating range from 0 to 37.81, 38.9, and 38.6 V, respectively (see Figs. 6.18-6.20), for the above shading scenarios. This implies that at the GMPP, the bypass diode remained OFF in all shading cases. The difference between the array current and the bypass current was much larger compared to the string array. For the two-, three-, and four-cell shading scenarios, this difference was observed to be 9.9%, 72.2%, and 70.5%, respectively (see Table 6.4). This difference is larger than the values recorded for the string array because in the SP array, there were three such parallel strings, and the bypass diode bypassed the current of only one string, *i.e.*, the string subjected to partial shading.

As the bypass diode didn't conduct at GPP, it is of great interest to study the thermal response of the shaded cells as well. For this purpose, infrared images were captured under all shading scenarios by operating the array at GMPP for approximately 300-350 seconds. The thermal images (see Figs. 13(a)–13(d)) reveal that the temperature of the shaded cells increased significantly across all shading scenarios, whereas in the string array, the hotspot temperature was observed only with single-cell shading. It may be observed from Fig. 13 that the temperature increased to 70.7, 67.5, and 64.2 °C under two-cell, three-cell, and four-cell shading scenarios, respectively.

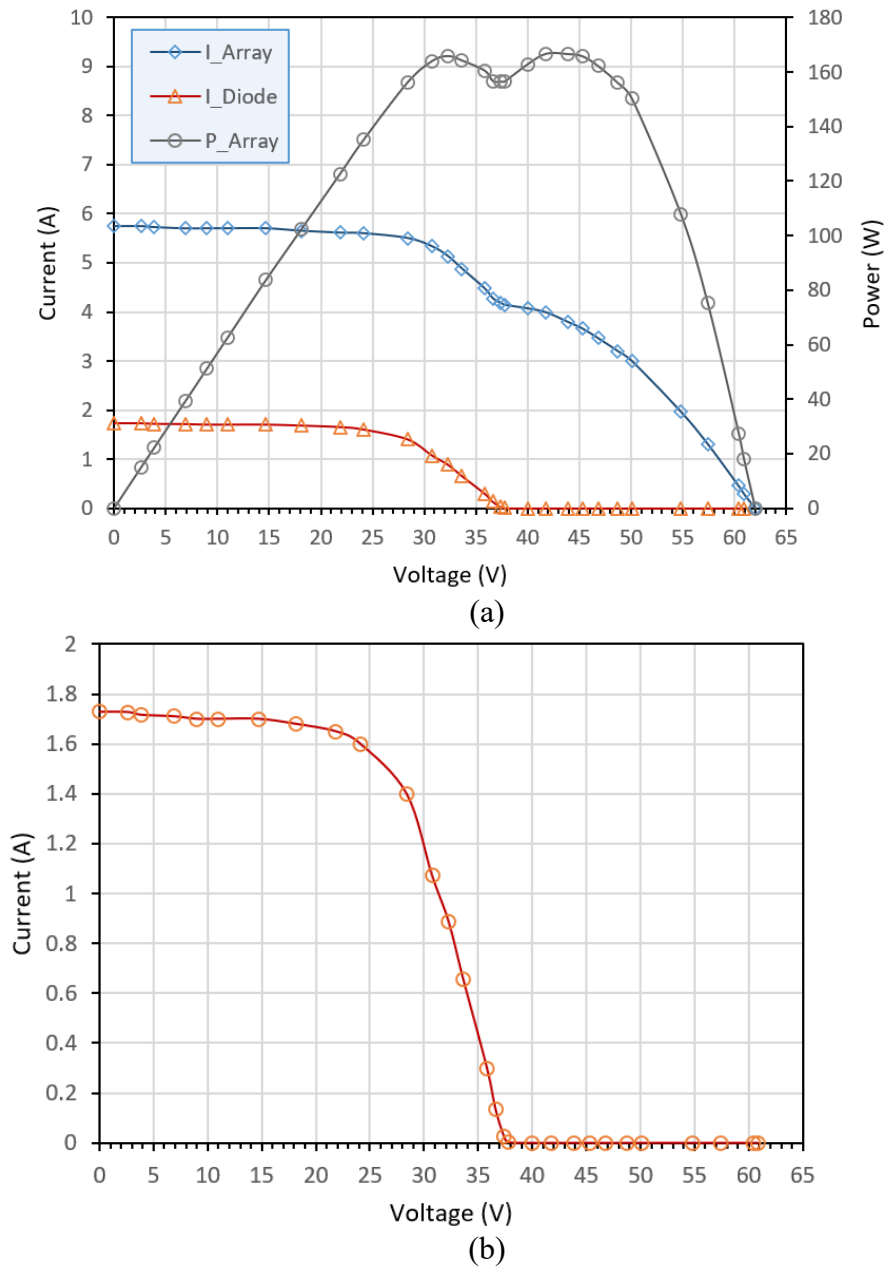


Fig. 6.18. Performance of SP array under two cells shading condition (a) bypass current superimposed on the electrical performance of the array, (b) bypass current-enlarged view.

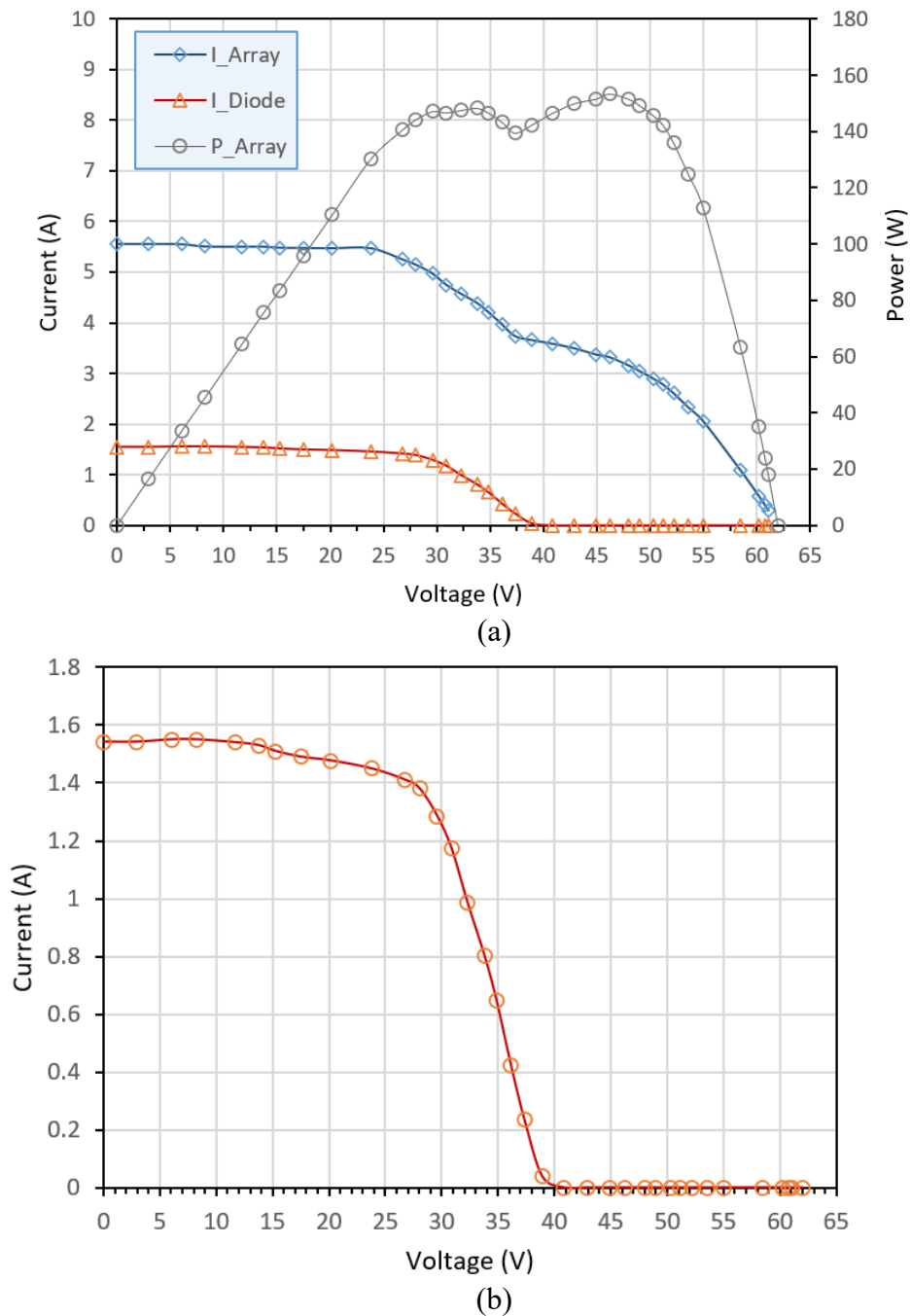


Fig. 6.19. Performance of SP array under three cells shading condition (a) bypass current superimposed on the electrical performance of the array, (b) bypass current-enlarged view.

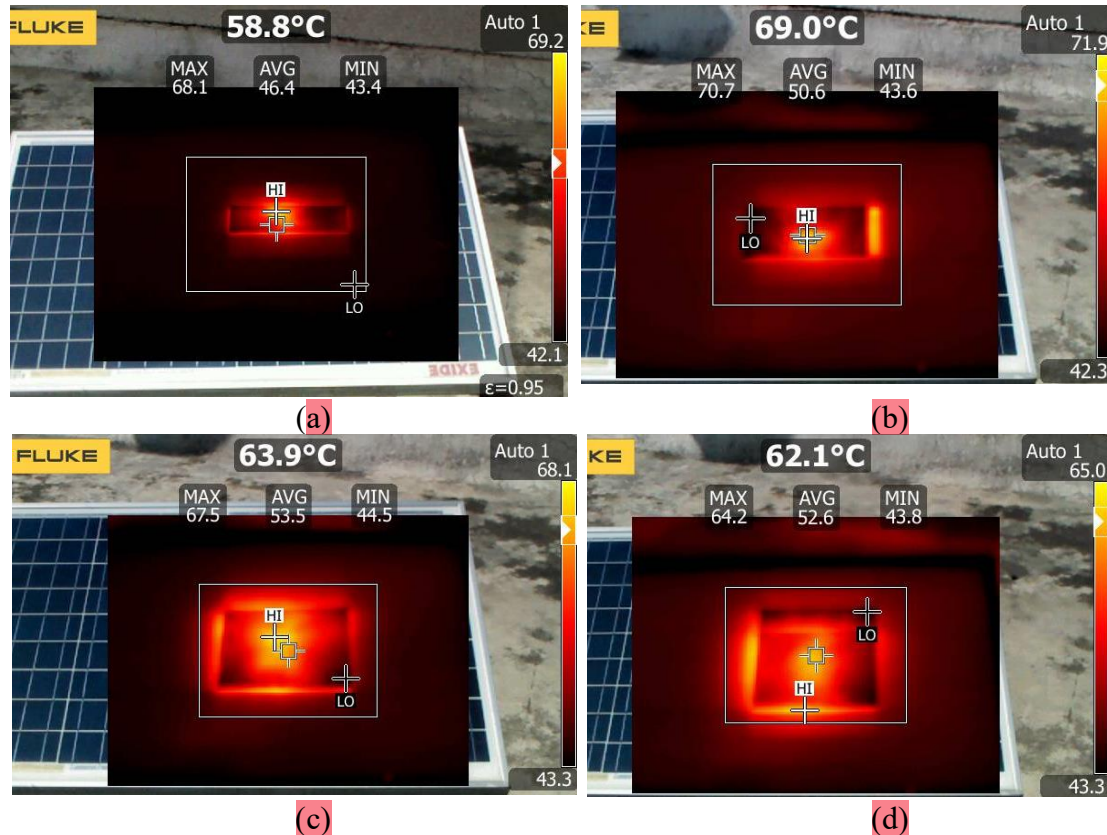


Fig. 6.20. Thermal images of the partially shaded module at MPP in the series-parallel configuration under (a) single-cell shading, (b) two-cell shading, (c) three-cell shading, and (d) four-cell shading scenarios.

6.7 Chapter Summary

In this chapter, the effectiveness of the hotspot prevention mechanism is experimentally investigated, as hotspots are a primary cause of early failures in PV modules. The results of the experimental study revealed several shortcomings in the extant hotspot-mitigation circuit in commercial PV modules, thereby explaining its ineffectiveness in averting early failures.

Firstly, the bypass diode does not conduct when a single cell is shaded in none of the array configurations considered in the present work: single-string, total cross-tied, and series-parallel. This suggests that in the case of single-cell shading, the cell is bound to

undergo reverse breakdown and heat up, irrespective of the array configuration. Though the affected area in this case is small relative to the entire power plant, it cannot be overlooked, as a single cell cannot be repaired in the event of failure, leaving the entire module vulnerable. Secondly, for shading of two or more cells in a single string, the bypass diode conducts at the operating point (MPP); however, in a TCT or SP array, it operates near the short-circuit region rather than at MPP. Hence, while the bypass mechanism works perfectly in a single-string configuration, in real-world scenarios the bypass diode will be non-functional in two- or more-cell shading scenarios, as a single string is seldom used in large PV plants.

Based on the findings of the experimental study, it may be concluded that disruptive innovation in the hotspot prevention mechanism and the MPPT algorithm is the need of the hour. The simple Schottky may be replaced with solid-state switches whose operation can be controlled by an intelligent algorithm to activate the bypass path at the operating point (i.e., at MPPT), thereby making the protection circuit effective. This will help avert early failures of PV modules due to hotspots, thereby reducing PV waste volume, avoiding environmental pollution, and helping keep the shade of PV energy truly green.

CHAPTER 7

CONCLUSION, FUTURE SCOPE, AND SOCIAL IMPACT

1.1 Conclusion

The present research demonstrates that while solar photovoltaic (PV) technology has emerged as the dominant pathway for global energy decarbonization, its long-term sustainability is challenged by several technical, environmental, economic, and policy-related issues. The rapid expansion of PV installations has occurred without commensurate attention to end-of-life (EoL) management, recycling infrastructure, grid integration challenges, and long-term environmental consequences. The analysis reveals that the global renewable energy transition has become disproportionately dependent on solar PV, while other renewable technologies with significant potential remain comparatively underutilized. Consequently, concerns related to intermittency, grid stability, and the impending accumulation of large volumes of PV waste are becoming increasingly significant.

A comprehensive life-cycle assessment of the two most widely deployed PV technologies—crystalline silicon (c-Si) and cadmium telluride (CdTe)—revealed that environmental impacts extend far beyond EoL waste. Although c-Si modules dominate the global market, their manufacturing process generates environmentally harmful by-products such as silicon tetrachloride (SiCl_4) and sulfur hexafluoride (SF_6), which can cause severe ecological damage if not managed appropriately. CdTe technology was found to exhibit a lower overall ecological footprint despite its lower conversion efficiency, highlighting the need for technology selection frameworks that consider life-cycle sustainability in addition to technical performance.

The study further establishes that current economic assessment methodologies underestimate the true cost of solar electricity by excluding EoL collection, recycling, and disposal expenses. Unlike conventional and nuclear power generation technologies, where pollution-control and waste-management costs are incorporated into project economics, PV deployment largely ignores future waste liabilities. The economic analysis indicates that recycling costs remain substantially higher than landfill disposal costs, creating a significant barrier to circular-economy implementation. Existing policy frameworks, except those within the European Union, remain inadequate due to weak enforcement mechanisms, limited Extended Producer Responsibility (EPR) provisions, insufficient recycling incentives, and lack of attention to social equity considerations.

Technical investigations into hotspot formation and mitigation mechanisms revealed important shortcomings in existing protection strategies employed in commercial PV modules. Experimental results showed that bypass diodes fail to provide adequate protection under several practically relevant shading conditions, particularly in large-scale array configurations. This inadequacy contributes to premature module failures, reduced system reliability, and accelerated generation of PV waste. Firstly, the bypass diode does not conduct when a single cell is shaded in none of the array configurations considered in the present work: single-string, total cross-tied, and series-parallel. This suggests that in the case of single-cell shading, the cell is bound to undergo reverse breakdown and heat up, irrespective of the array configuration. Though the affected area in this case is small relative to the entire power plant, it cannot be overlooked, as a single cell cannot be repaired in the event of failure, leaving the entire module vulnerable. Secondly, for shading of two or more cells in a single string, the bypass diode conducts at the operating point (MPP); however, in a TCT or SP array, it operates near the short-circuit region rather than at MPP. Hence, while the bypass mechanism works perfectly in a single-string configuration, in real-world scenarios the bypass diode will be non-functional in two- or more-cell shading scenarios, as a single string is seldom used in large PV plants. The findings highlight that ensuring the sustainability of solar PV requires not only effective waste management but also improvements in module reliability and operational lifetime

which will enable restricting PV waste generation in the present scenario of under capacity of solid waste management facilities.

Overall, the research concludes that achieving genuinely sustainable solar energy requires a holistic life-cycle approach encompassing responsible manufacturing, improved reliability, environmentally sound EoL management, robust recycling infrastructure, and globally harmonized regulatory frameworks. Without such measures, the environmental benefits of PV deployment may be partially offset by the ecological and social burdens associated with its life cycle.

1.2 Future Scope

The findings of this research identify several areas requiring further investigation and technological development. First, comprehensive techno-economic studies are needed to develop methodologies for incorporating EoL management costs, recycling obligations, and environmental externalities into the Levelized Cost of Energy (LCOE) framework. Such approaches would enable more realistic comparisons among competing energy technologies.

Second, further research is warranted to optimize PV technology selection using integrated assessments that simultaneously consider efficiency, economic performance, environmental impacts, resource utilization, and long-term sustainability. In particular, detailed cost-benefit analyses comparing crystalline silicon, CdTe, and emerging photovoltaic technologies should be undertaken to support informed deployment decisions.

Third, substantial innovation is required in PV recycling technologies to improve material recovery rates while reducing recycling costs. Research should focus on developing economically viable high-value recycling processes capable of recovering critical materials at industrial scale. Parallel efforts are needed to establish circular-economy models that integrate collection, refurbishment, reuse, remanufacturing, and recycling within the PV value chain.

Fourth, future studies should investigate policy mechanisms capable of accelerating circularity in the PV sector. These include harmonized global Extended Producer Responsibility (EPR) frameworks, PV-specific disposal fees, recycled-content mandates, deposit-refund systems, and international standards governing collection and recycling practices.

Fifth, the technical findings related to hotspot formation indicate the need for disruptive innovation in module protection systems. Future research should explore intelligent bypass architectures employing solid-state switching devices, advanced sensing technologies, artificial intelligence-based diagnostics, and adaptive Maximum Power Point Tracking (MPPT) algorithms capable of preventing hotspot formation under real-world operating conditions.

Finally, broader energy-system research is required to reduce excessive dependence on a single renewable technology. Future energy planning should investigate optimal portfolios combining solar PV with wind, hydro, geothermal, biomass, energy storage, and smart-grid technologies to improve system resilience, reliability, and sustainability.

1.3 Social Impact

The outcomes of this research have significant implications for society, public health, environmental protection, and sustainable development. Solar PV is widely regarded as a clean and environmentally benign energy source; however, the findings demonstrate that sustainability cannot be evaluated solely during the operational phase. Environmental risks associated with raw material extraction, manufacturing emissions, premature module failures, and improper EoL disposal have the potential to affect ecosystems and communities on a large scale if left unaddressed.

The anticipated growth of PV waste poses risks of soil and groundwater contamination through the uncontrolled release of hazardous substances from discarded modules. Such impacts are likely to be most severe in developing countries, where recycling infrastructure, regulatory enforcement, and waste-management capabilities

remain limited. Consequently, vulnerable populations may disproportionately bear the environmental and health burdens of the global energy transition, raising important issues of environmental justice and social equity.

Implementation of effective recycling systems and EPR-based regulatory frameworks would not only mitigate environmental risks but also create new economic opportunities through the establishment of recycling industries, secondary material markets, and green employment. Development of a circular PV economy can reduce dependence on virgin raw materials, improve resource security, and support sustainable industrial growth.

Improved module reliability and enhanced hotspot prevention mechanisms would further contribute to societal benefits by extending asset lifetimes, reducing waste generation, lowering lifecycle costs of electricity production, and increasing public confidence in renewable energy technologies. At a broader level, adoption of life-cycle-based policies and sustainable manufacturing practices can ensure that solar PV remains a genuinely green technology capable of supporting climate-change mitigation without transferring environmental burdens to future generations.

Therefore, the social significance of this work lies in its contribution toward developing a more responsible, equitable, and sustainable photovoltaic ecosystem that balances energy security, environmental protection, economic viability, and societal well-being.