



END-OF-LIFE LCA OF SOLAR PV MODULES: RECYCLING PROCESS, INDIA VS CHINA COMPARISON, AND DESIGN IMPLICATIONS

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ABSTRACT

The fast development of the solar photovoltaic (PV) installations has raised prompting questions on how to handle the end-of-life (EoL) PV waste. This paper provides an assessment of the environmental effects of the recycling of crystalline silicon (c-Si) PV modules on a Life Cycle Assessment (LCA) framework, and a comparative analysis between India and China. The collection, transportation, pre-treatment, and recycling are considered as the system boundaries, where the functionality of any unit was determined as 1 tonne of EoL PV modules. The findings reveal that the Indian situation has more environmental impacts because of the low infrastructure, unproductive processing technologies, and low material recovery rates. However, the situation is different in China, where the performance is better due to high-level recycling technologies, better recovery rates, and favourable policy frameworks. The paper also identifies the importance of using chemical processes to extract valuable materials like silicon, silver and the difficulties that pertain to the removal of polymer. Moreover, it is defined that the module design can be regarded as one of the factors of recyclability and that the glass-glass module exhibits better environmental performance than the glass-back sheet layout. The results highlight the significance of technology promotion, policy facilitation, and design-to-recycle principles to facilitate the sustainability of the PV recycling systems.

KEYWORDS: *Life Cycle Assessment (LCA), Photovoltaic (PV) Waste Recycling, Crystalline Silicon Solar Modules, Material Recovery Processes, Circular Economy in Renewable Energy*

1. INTRODUCTION

The increase in the number of solar photovoltaic (PV) systems across the world has played a key role in the global adoption of renewable energy systems due to the pressing demand to minimise greenhouse gases and reliance on fossil fuels. The falling price of PV technologies has expedited large-scale application of PV technologies in both developing and developed economies over the last decade due to the favourable policy environments. This expansion has, however, led to a commensurate rise in the amount of photovoltaic waste, especially because early-generation modules are nearing the end of their lifespan of operation, which in most cases is between 20 and 30 years. It is projected that the amount of waste from PV will increase significantly over the next few decades, posing significant problems to the environment and resource management unless dealt with properly. The recent research on photovoltaic waste production within the framework of sustainable energy transition is informative of the immediacy of the need to design the most effective end-of-life (EoL) management systems to address the newly emerged source of waste (Nieto Morone et al., 2025).

Efficient EoL management is important not only in the reduction of environmental effects but also in facilitating the recovery of valuable materials like silicon, silver and aluminium that are needed in the production of new PV modules and other electronics used during production. The existing methods of disposal, like landfills and informal recycling, are unsatisfactory and usually lead to huge wastage of resources and environmental degradation through the release of hazardous wastes. An in-depth discussion of photovoltaic waste management underlines that sustainable approaches are necessary to reduce such effects and promote the objectives of the circular economy, especially under conditions of growing material requirements and the scarcity of natural resources (Babaei and Nasr Esfahani, 2024). In addition, technological inefficiency, the absence of standardisation of the process, and inadequate infrastructure are all interconnected with the constraints of current recycling activities, making them difficult in terms of material salvage and lowering the overall system efficiency.

In this regard, there is an increased requirement of scientifically sound evaluation techniques to determine the environmental efficacy of PV recycling systems. The Life Cycle Assessment (LCA) has become a relatively reliable instrument in terms of measuring environmental effects at various phases of a product lifecycle and has allowed gaining a complete perspective of environmental trade-offs, which are linked to recycling processes. The emergence of new practices in recycling technologies and evaluation techniques in the recent past has placed emphasis on the need to combine LCA with process-based evaluation to get a more detailed and precise analysis of sustainability results (Sanathi et al., 2024). Also, the use of technology in PV recycling, such as advanced methods of collecting the materials, enhanced separation, and process optimisation strategies, contributes even further to the necessity of a thorough environmental assessment to make decisions (Martínez et al., 2024).

Irrespective of these developments, there are still some major gaps in research, especially regarding region-specific comparison studies and closer examination of the chemical recovery processes. The literature available does not tend to provide an in-depth analysis of the comparison of the recycling systems within different nations, with a particular tendency to compare the recycling systems between the developing and the developed economies, where the infrastructure, policy, and technological advancement may greatly impact the recycling performance. In addition, module design has not been thoroughly investigated in relation to its impact on recyclability, even though it has an impact on how efficiently materials can be separated, as well as the overall environmental impact. The Ecodesign concept, aimed at enhancing product design to increase environmental sustainability and add to recycling performance, has been called one of the factors to improve the effectiveness of the PV module lifecycle performance and a decrease in the environmental burden (Ding et al., 2026).

The given research is expected to fill these gaps by assessing the environmental effects of PV recycling modules through the LCA framework, with particular attention paid to comparing India and China in terms of the recycling systems. The paper further investigates the chemical mechanisms of the process of recovering materials and the impact of the design of modules on the efficiency of recycling. The research is informed by strategic questions on the differences in the environmental impacts of the two regions and the determination of the key contributors of the major environmental impacts.

The originality of the paper is in the complex approach that combines LCA and the analysis of chemical processes with region-specific comparison. The study also offers a thorough analysis of PV recycling systems by integrating the experiences of the principles of the circular economy and life-cycle analysis. Current studies highlight how the concept of a circular economy is necessary to enhance better sustainability in the photovoltaic systems, specifically by committing to the better use of recycling and reuse measures that can expand the material lifecycles and lower the generated wastes (Don et al., 2025). Besides, the discussion of the use of innovative reuse and reconditioning strategies also suggests other avenues to prolong PV module lifecycle and decrease the amount of waste production, which will be seen as the contribution to long-term sustainability objectives (Bahramimirood et al., 2025). All these views are of importance in enhancing the knowledge on sustainable PV waste management and the need to integrate solutions to the rising environmental issues.

1.1 Literature Review

The solar market all over the world is dominated by crystalline silicon (c-Si) photovoltaic modules, which are characterized by high efficiency, lengthy working life and high usage in residential, commercial and industrial applications. These modules normally have several layers such as glass, ethylene-vinyl acetate (EVA), silicon cells, silver, and aluminium, which are strongly glued together to make them last and operate in different environmental conditions. Nonetheless, this multilayer design is quite difficult to recycle especially when it comes to separating materials and efficiency of recovery. Detailed surveys of crystalline silicon solar panels recycling have documented how recycling technologies have transformed through simple deconstructive methods to innovated material recovery methods and pointed out that the challenge requires continuous innovation to manage the challenge (Chen et al., 2024). The worldwide PV waste situation has become an issue of growing interest in recent years, and research shows that its rate of growth is fast paced, as the installed capacity is keeping growing across the globe. This increase in amount of waste that is being produced requires effective waste management initiatives that would allow proper utilisation of resources and reduce environmental effects. Recycling systems and policy frameworks that have been developed worldwide are also key in the management of PV waste as evidenced by the attempt by the international community to come up with standardised recycling practices and regulatory frameworks (Komoto et al., 2025). Moreover, the design requirements of PV modules have been provided to enhance recyclability and mitigate the environmental effects, and the significance of sustainability considerations at the design stage so that the material should be easily recycled (Bilbao et al., 2021).

The current recycling techniques used in PV may be divided into broad factors as mechanical, thermal and chemical methods, each with its benefits and drawbacks. There are mechanical processes that deal with dismantling and shredding of modules, which allow recovery of bulk materials like glass and aluminium. Thermal treatments that eliminate polymer layers like EVA are usually linked with the high energy consumption and emissions, but they are not always linked with these issues. It allows the recovery of high-value materials like silicon and silver with greater accuracy and purity with the help of chemical processes, which include leaching and purification. Recent technological developments in recycling methods have offered new methods of silicon reclamation and reuse, including use in energy

storage (lithium-ion batteries), and thus the material reuse has expanded far beyond the manufacturing of PV (Wang et al., 2024). Moreover, multiset recycling systems combining various methods of processing have been reported to be more efficient and less harmful to the environment and are more productive when scaled to large volumes (Wei et al., 2025).

There has been an increasing number of papers that have been devoted to assessing the environmental effects of PV recycling using life cycle assessment, which shows its significance as a decision-support tool. Through these studies, energy-consuming processes, specifically thermal and chemical treatments always appear to be significant contributors to environmental effects, although the effectiveness of material recovery is also important in enhancing a more sustainable result. Detailed analyses have highlighted the importance of the enhanced recycling technologies to make the process more sustainable and lessen emissions related to the processing of PV wastes (Celep et al., 2025). Moreover, the available studies on sustainable recycling methods emphasize the necessity of incorporating technological innovation with environmental analysis to deliver the best results and foster the goal of a circular economy (Akhter et al., 2024).

In spite of these developments, there are still several research gaps that restrict the efficiency of the existing recycling systems of PV. The major weaknesses of current research include insufficient study of the process of chemical recovery, especially concerning its efficiency, scalability and environmental impact. Recent studies have noted the possibility of improved recycling methods to enhance material recovery and minimise the environmental cost; nonetheless, additional studies are needed to authenticate these methods on an industrial level and make them economically viable (Chen and He, 2025). Furthermore, little emphasis is given on the comparative studies between various regions, which are critical to comprehending how infrastructure, policy and technological capabilities can affect recycling performance.

The other gap is associated with the fact that the module design has a potentially significant impact on recyclability and the overall system efficiency. The implementation of the design-for-recycling concepts has been discovered as one of the major measures of enhancing the efficiency of recycling and the complexity of the processing process, as well as the environmental impacts. It has been demonstrated that simplified module designs, better material choices, and modular design methods can make a massive contribution to recyclability and energy consumption during processing (Frischknecht et al., 2023). The results show that there is a necessity to incorporate design issues in PV lifecycle management to ensure long-term sustainability.

Overall, the literature shows that even though much has been done in terms of PV recycling technologies and environmental evaluation, more studies are necessary to close the existing gaps and create more sustainable and efficient recycling systems. Tightly coupled with the introduction of enhanced technologies, better policy frameworks, and design innovations, the future of a set of efficient and environmentally sustainable PV garbage management will become possible.

2. METHODOLOGY

2.1 Goal and Scope Definition

The current research uses a tool of Life Cycle Assessment (LCA) to critically analyze the environmental effects of the end-of-life (EoL) of crystalline silicon (c-Si) photovoltaic (PV) modules. The main aim is to measure and compare the environmental performance of the processes involved in recycling the PV modules in India and China, and also to investigate the contribution of technological development and recovery of the materials. To provide consistency and comparability in the various recycling situations, the functional unit is established as the treatment of 1 tonne end of life PV modules, which is a standardised basis that is frequently used in industrial and environmental assessment.

A cradle-to-recycling model is used as the system boundaries, which include all the key steps of the EoL management of PV modules. These phases involve the gathering of decommissioned units, delivery to recycling centres, pre-treatment procedures including dismantling and elimination of aluminium frames and junction boxes, and after that, the recycling procedures of such units through mechanical, thermal and chemical treatments. The last phase in the specified demarcation is the recovery of precious materials, including glass, silicon, and metals, including silver and copper. The detailed recycling stages and material recovery pathways are illustrated in Figure 1.

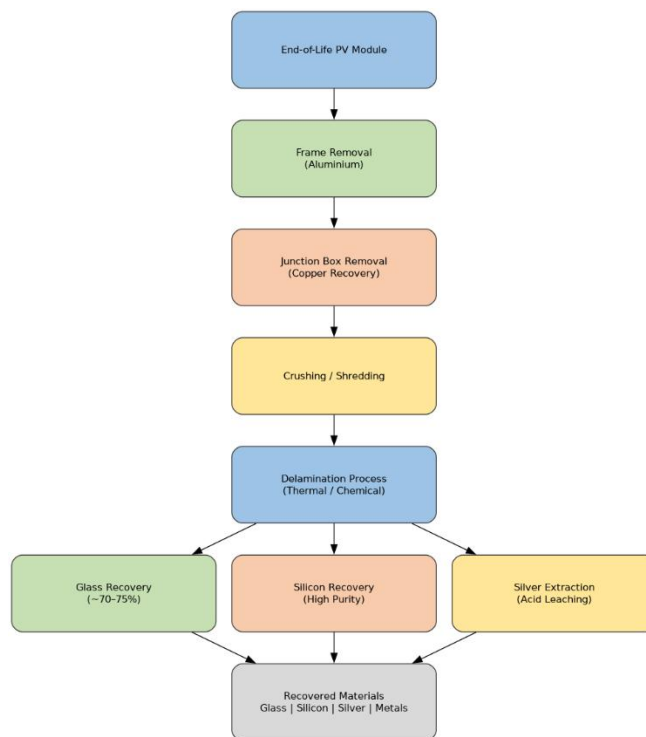


Figure 1. Detailed process flow showing sequential recycling steps and recovery of glass, silicon, silver, and metals from c-Si PV modules

Other processes, which are outside the scope of the system, like reuse, secondary production or end-of-life disposal of the remaining waste, are not considered as part of the system to ensure that the scope of the system is limited to the efficiency of recycling and the direct environmental impact of recycling.

2.2 Life Cycle Inventory (LCI)

The step of Life Cycle Inventory (LCI) is the full gathering of the input and output values related to every stage of the recycling of the PV modules. The information used in this research comes from a mix of peer-reviewed journal articles, technical reports, and existing LCA databases, including Ecoinvent, making it reliable and consistent in terms of methodology. The composition of the material of crystalline silicon PV modules is a crucial aspect of the inventory analysis. Typically, these modules consist predominantly of glass, accounting for approximately 70–75% of total weight, followed by aluminium frames, silicon solar cells, conductive metals such as silver and copper, and polymeric materials including ethylene-vinyl acetate (EVA) and back sheet layers.

Besides the material inputs, data on the energy consumption at every stage of the recycling process are also added to the inventory. These are energy demands involved in mechanical shredding, thermal delamination processes to strip off polymer layers and chemical treatment methods to obtain high-value material like silicon and silver. The emissions

produced in these processes, such as greenhouse gases and process-specific pollutants is also included in the inventory. Since available data differ and places differ, several assumptions are used to make comparisons across scenarios. These are the assumptions, such as standardised transportation distances, averaged through recycling efficiencies given on the industrial practices as reported, and representative energy mixes as aligned to Indian and Chinese electricity grids. Although these assumptions might create some uncertainty, it is in line with the conventional LCA practices and is required to make a comparative evaluation.

2.3 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) phase is the process that entails conversion of inventory data to environmental impact indicators. The important categories of impacts are chosen in this research depending on their relation to the PV recycling and sustainability of the environment. The main category of impact associated is Global Warming Potential (GWP) that is used to measure the amount of greenhouse gas emissions related to recycling and energy use. Moreover, total energy consumption is used to measure the energy intensity of recycling process and resource depletion is measured to evaluate the level to which material recovery is applied in the preservation of natural resources.

The evaluation is done by applying a standardised impact assessment methodology, e.g. the ReCiPe method, that offers a complex framework of transforming inventory data into environmental impact indicators. The inventory data is characterised by the factors of characterisation to measure the contribution of each process to the categories of impacts selected. The method will allow a systematic and similar assessment of environmental effects in various recycling conditions, and, as a result, the sustainability performance is analyzed in a robust way.

2.4 Scenario Development

Two different scenarios are created to reflect regional differences of the PV recycling system in India and China. The Indian situation can be viewed as a reflection of the present situation in PV recycling infrastructure, marked by the low formal recycling facilities, increased use of manual labour, and comparatively low technological development. As a result, reduced material recovery efficiencies and increased environmental effects are presumed in this case.

In comparison, the China case study is a more progressive and industrialised system of recycling, which is enabled by properly developed infrastructure, greater rates of automation, and enhanced regulatory measures. The processes of recycling in this case are also presumed to have a better recovery of valuable materials like silicon and silver as well as enjoying the advantage of better energy efficiency. The scenario modelling is applied to these differences in technological capability and policy support so that the comparative evaluation of environmental impacts can be achieved. These scenarios can be developed in order to have a better insight into the role of the regional factors on the sustainability of the PV module recycling and to identify the possible avenues of the enhancement of the recycling system in the emerging economies.

3. RESULTS

3.1 LCA Results for India

Life Cycle Assessment (LCA) of the chosen situation in India shows that the environmental impacts in all the categories were rather high in Global Warming Potential (GWP), energy consumption, and resource depletion. The main causes of these high impacts are that little formal recycling infrastructure has been developed and even today, recycling processes are still being performed manually or semi-mechanised. Recycling operations in most of the cases are conducted in decentralised or informal arrangements, which are not optimised in terms of processes and energy efficiency. As a result,

the GWP of recycling operations is greatly affected by the consumption of a carbon-intensive energy source, especially the fossil-based electricity that fuels the recycling process, meaning that the emissions are more severe at such critical recycling operations as pre-treatment, thermal delamination, and material recovery. The overall system boundary and recycling stages considered in the analysis are illustrated in Figure 1.

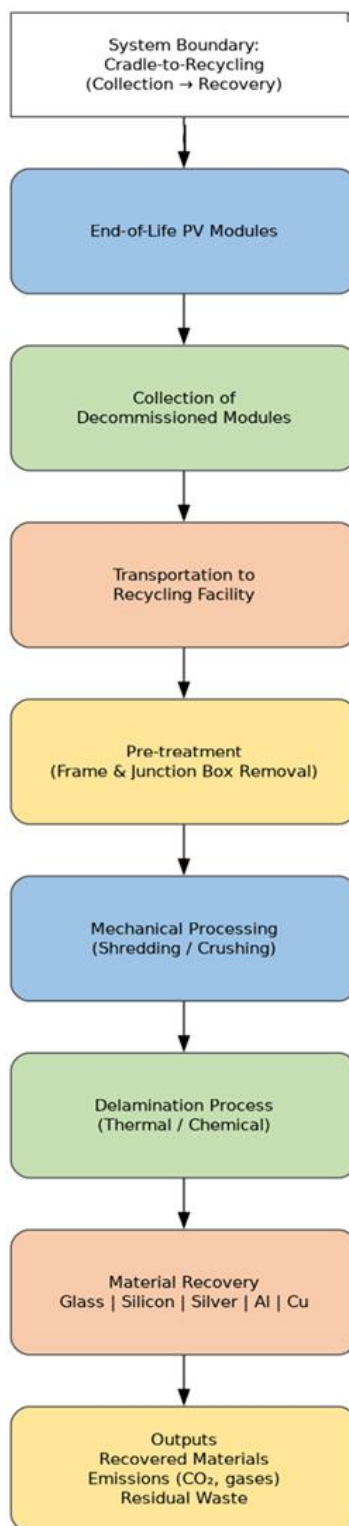


Figure 2. System boundary and life-cycle stages of end-of-life c-Si PV module recycling from collection to material recovery

Energy-consuming processes are mostly high in processes involving the removal of polymeric constituents like ethylene-vinyl acetate (EVA), and in this case, inefficient thermal treatments are commonly used without proper heat recovery systems. The lack of controlled processing conditions is also another factor that promotes energy losses and high emissions. Also, the recovery rate of valuable materials, such as silicon and silver, is still relatively low because of the technological limitation and the lack of full separation. In many cases, the failure to recover fractions that are layered completely causes contamination of the recovered ones, making them of poor quality and reuse.

Consequently, the positive environmental impact of recovery of materials is diminished and primary sources of materials extraction are more relied upon to satisfy material demand. It does not only add to the upstream environmental burdens but also devalues the possibility of recycling as a strategy in the circular economy. Overall, the findings indicate that the existing PV recycling system in India is typified by reduced efficiency, increased emissions, and low material recovery, which requires introducing technological advances and enhancements to the regulatory frameworks. Table 1 provides a comparative analysis of the end-of-life management alternatives, which clearly shows that recycling has an upper hand over landfill and incineration techniques about environmental and resource benefits.

Table 1. Comparative Assessment Of End-Of-Life Management Options For Crystalline Silicon Photovoltaic Modules, Including Landfill, Incineration, And Recycling, Based On Environmental Impact, Resource Recovery, And Sustainability Performance

Parameter	Landfill	Incineration	Recycling
Global Warming Potential (GWP)	High	Very high	Low
Resource recovery	None	Minimal	High
Energy consumption	Low	High	Moderate
Environmental impact	Long-term pollution risk	Air emissions, toxic release	Reduced emissions and resource conservation
Material recovery	Not possible	Limited (metals only)	Glass, silicon, silver, aluminium
Sustainability level	Very low	Low	High

3.2 LCA Results for China

The LCA outcomes of the China scenario, on the contrary, illustrate much better environmental performance of all the impact categories taken into consideration. GWP values of PV modules recycling are significantly lower as it implies the vast use of the modern and energy-saving recycling techniques. The recycling plants in China are also industrial scaled with automated and integrated processing units, which lead to greater accuracy in the separation of materials and to a high rate of recovery of major materials like silicon, silver, aluminium, as well as glass.

Controlled thermal processes and extensive chemical treatments optimize the consumption of energy and minimize the total energy required during delamination and material recovery processes. Examples of these include the effective removal of polymer layers with minimum wastage of energy through regulated thermal decomposition procedures and selective recovery of highly purified metals through chemical leaching. Moreover, the inclusion of comparatively clean energy sources in the electricity grid also helps in decreasing the emitted emissions, thus, decreasing the total carbon footprint of recycling processes.

The high recovery efficiencies do not only help in minimising the environmental impacts but also improve the conservation of resources as the resources do not necessitate the extraction of virgin materials. The fact that it can recycle high-purity silicon and silver also contributes to the economic value of the recycling process and makes it more sustainable and business-friendly. These findings demonstrate efficiency of well-developed recycling infrastructure, excellent policy support, and technological development in creating sustainable PV waste management in China.

3.3 Comparative Analysis (India vs China)

Comparative analysis of the India and China case indicates that there are significant differences in the environmental performance, process efficiency and recovery of material outcome. China scenario always rates higher than the India scenario in all the impact categories that are evaluated such as GWP, energy consumption, and efficiency of the recovery of the resource. Such differences can mainly be ascribed to technological capability variation, process optimisation and development of infrastructure.

In both cases, energy-intensive processes, namely, thermal delamination and chemical treatment processes, are defined as the major contributors to the environmental impacts. The two areas however differ greatly in the efficiency and control of these processes. In the Indian case, the more energy used and the less material recovery efficiency leads to a greater number of environmental burdens. Inefficient processing does not only contribute to increased emission but also the effectiveness of recycling activities is affected.

Conversely, the China case has the advantage of optimised process design, new technologies, and increased rates of recovery that all contribute to minimised emissions and energy consumption. Automation of the systems ensures that the processing conditions remain constant hence enhancing efficiency and the quality of the output. The analysis also highlights the need to have an efficient recovery of the material to reduce the environmental impacts. The conservation of resources is a direct result of higher recovery rates since the demand of primary raw materials will be low, hence decreasing the environmental impacts upstream in the mining and processing of the materials.

Generally, the comparison shows the paramount importance of the use of technology and policy assistance in enhancing the sustainability of PV recycling systems, especially in developing economies. Table 2 provides a comparison of the recycling systems characteristics in India and China and shows that there are high disparities in the infrastructure, level of technological development and the performance of the recycling systems in terms of the environment.

Table 2. Comparative Assessment Of Photovoltaic Module Recycling Systems In India And China, Highlighting Differences In Infrastructure, Policy Support, And Environmental Performance

Parameter	India	China
Recycling infrastructure	Limited, emerging	Advanced, industrial scale
Processing type	Manual / semi-mechanised	Automated, optimized
Material recovery efficiency	Low-moderate	High
Policy support	Developing (nascent EPR)	Strong regulatory framework
Recycling capacity	Low (early-stage growth)	High (scaling with industry)
Environmental performance	Higher emissions	Lower emissions

3.4 Impact of Module Design (Glass-Glass vs Glass-Back sheet)

The findings also demonstrate how the design of PV modules has a great impact on the results of recycling and the environment. Glass has been shown to be more recyclable with a relatively easy structural composition and a greater percentage of recoverable compounds especially glass. The layer of polymer back sheets is not complex, which makes the recycling process simpler and does not require energy-consuming delamination treatments and allows separating the materials more efficiently.

Consequently, glass-glass modules are linked to a decreasing amount of energy used, fewer emissions, and higher recovery efficiency, which are more acceptable in a sustainable end of life. Conversely, glass back sheet modules pose significant problems in the recycling of the module because they have multilayer polymeric materials that are hard to isolate, and which, in most cases, must be subjected to thermal or chemical treatments to be removed. These extra processing measures consume more energy and emit more, thus becoming an added cause of environmental impact. A

comparative evaluation of module designs across key recycling parameters is shown in Figure 3.

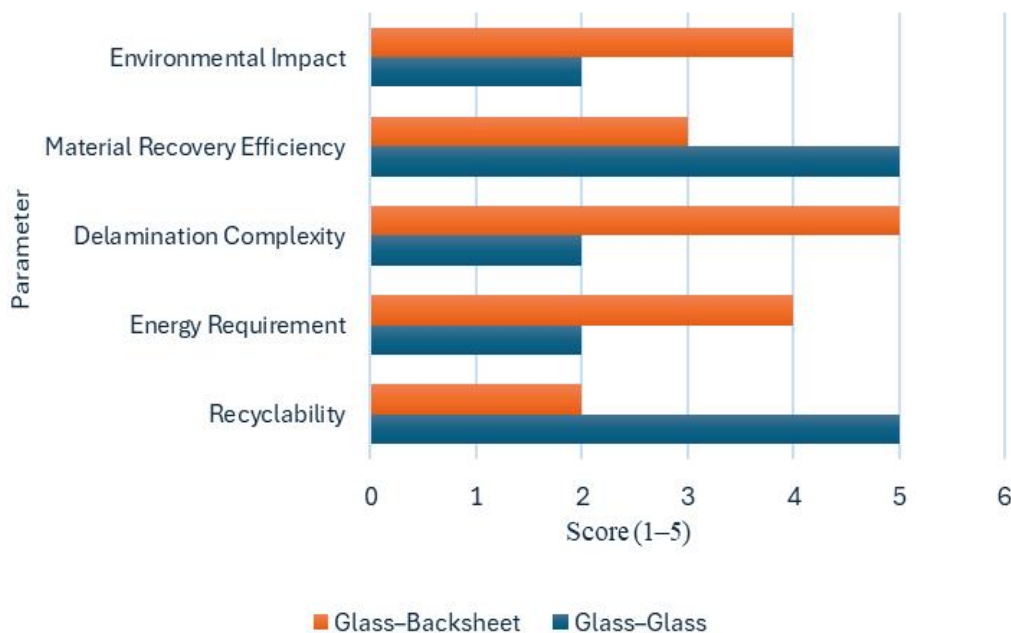


Figure 3. Comparison Of Glass–Glass And Glass–Back Sheet Pv Modules Based On Recyclability, Energy Requirement, Delamination Complexity, Recovery Efficiency, And Environmental Impact

Moreover, partial segregation of the back sheet materials may also have adverse implications on the quality of the reclaimed materials, especially the glass and silicon, and hence, diminish their reuse capabilities. The findings highlight the need to consider design-to-recycle (DfR) principles during the production of PV modules. Recovery properties of the major materials in crystalline silicon PV modules are summarised in Table 3, and glass materials make the most contribution to mass, and silicon makes the highest value recovery possible despite its lower mass content.

Table 3. Comparative Material Recovery Characteristics Of Glass And Silicon In Crystalline Silicon Photovoltaic Modules, Including Mass Share, Recovery Efficiency, And Environmental Significance

Parameter	Glass	Silicon
Mass share in module	70–75 wt.%	3–5 wt.%
Typical recovery practice	Recovered as cullet (downcycled)	Requires thermal and chemical recovery processes
Best recovery yield (reported)	92–93%	95–96%
Purity and market value	Low–medium (construction use)	High (refined for solar-grade reuse)
Process complexity	Low	High
Environmental benefit	Large volume recovery, moderate impact reduction	Highly avoided environmental burden per unit

By prioritising material simplicity, ease of separation, and recyclability, future PV module designs can significantly enhance recycling efficiency and reduce environmental burdens.

4. DISCUSSION

Through the outcome of the current research, it is evident that technological development and infrastructure are quite important in defining how photovoltaic (PV) module recycling systems perform in the environment. The relatively greater environmental effects that were witnessed in the Indian case can be explained by the lack of formal recycling infrastructure, the use of informal processing structures and the use of inefficient technologies that consume more energy and produce more emissions. These outcomes can be compared to the earlier research, which highlights the necessity to implement a circular economy framework in India to improve the utilisation of resources and diminish the negative impact on the environment (Prabhu et al., 2022). Also, the lack of clear regulatory standards and formal waste management systems has led to inefficiencies in recycling, another issue that has been pointed out by the research on the policy and institutional gaps in the PV waste management (Jain et al., 2022). As it is assumed that the volume of PV waste will increase in India, it is necessary to enhance the recycling efficiency to reduce the adverse effects on the environment in the long term (Sharma et al., 2024).

In comparison, the situation in China is characterised by much better environmental performance, which can be explained by the utilisation of sophisticated recycling technologies, the scale character of the operations, and favourable policy frames. The effectiveness of optimised recycling systems is indicated by the lower Global Warming Potential (GWP) and lower energy consumption, which is present in this scenario. These results are consistent with the LCA studies conducted worldwide, which have noted that technological efficiency and system-level optimisation would help to minimise the environmental impact of PV recycling (Mao et al., 2024). Also, the systematic regulatory framework in China and experience acquired through international experience, e.g., the European Union, have resulted in such effective recycling systems (Wang et al., 2024).

The major element of PV recycling is the reuse of valuable resources, specifically silicon and silver, which are important in increasing the efficiency of the resources and less reliance on the main raw materials. Recycling methods like integrated thermal and hydrometallurgical processes have been demonstrated to increase the efficiency of recovery and purities of the materials, thus improving the environmental and economic performances (Lyberatos, 2022). This is because the recovery of silicon by the chemical purification process provides a significant saving on the primary production of silicon taking a lot of energy, and the extraction of silver by the acid leaching and precipitation technology is economically beneficial. High efficiency and minimum environmental impacts have been observed to be realised by sustainable chemical recovery processes, thus becoming the key in future recycling strategies (Deng et al., 2021).

The leaching of polymers, specifically of ethylene-vinyl acetate (EVA) is still a significant problem in PV recycling because it has a high encapsulation characteristic. Conventional thermal processes are energy-consuming and contribute to the increase in emissions, but the chemical process is a more efficient and greener alternative. The latest developments in chemical purification methods have proved to be more efficient in EVA separation, thus saving energy and improving material recovery (Brenes et al., 2023). On the same note, alternative approaches to the problem have been suggested as low-energy chemical delamination methods that would effectively enhance the efficiency of recycling and mitigate the environmental effects (Vaněk et al., 2023). These advancements determine the need to incorporate chemical-based processes into PV recycling processes to make the whole process more sustainable.

The ecological value of PV recycling is not limited to the reduction of emissions but has a major impact on the resource's preservation and the establishment of the circular economy. Recycling processes lower the need for virgin materials and reduce the negative effects of materials processing and mining on the environment by recovering the high-value materials, including silicon, aluminium, and silver. It has been revealed that PV waste management

approaches are the approaches that can effectively contribute to the proper achievement of sustainable resource utilisation and environmental-burden reduction (Al Zaabi & Ghosh, 2024). In addition, the literature on all aspects of PV recycling technologies also focuses on the necessity of constant innovation and refinement of recycling methods to meet new challenges and improve the system efficiency (Preet & Smith, 2024).

Despite these developments, there are still various technological issues especially concerning separation of the materials, optimisation of the process and scalability. It has been stated that hydrometallurgical practices are promising methods of enhancing recovery efficiencies and minimizing environmental effects though they should be expanded on a larger scale as more research and development are required (Luo et al., 2021). Also, recent research indicates the necessity to develop unified and scalable recycling mechanisms that would be able to process growing amounts of PV waste without losing economic sustainability (Badran & Lazarov, 2025). The design of efficient metallic recycling methods, especially of crystalline silicon solar cells, would also play an essential role in improving the total recycling efficiency and minimizing losses of materials (Lin et al., 2023).

The policy and regulation systems are fundamental in facilitating sustainable PV recycling systems. This is because the differences found between India and China highlight the effectiveness of good governance, enforcement of regulations and financial incentives that should be used to enhance recycling efficiency. It has been proven in international studies that the policies like the extended producer responsibility (EPR) and the organized waste management policies are a key to proper collection, processing, and recycling of PV modules (Ali et al., 2023). Such policies can raise the level of recycling and help to shift to the circular economy in the emerging markets.

In general, the conclusion of this research demonstrates that technology, policy, and system design are interrelated and that they influence the sustainability of PV module recycling. The relative comparison of India and China has shown that the strengthening of recycling infrastructure, the use of modern technologies, and supportive policy frameworks are needed to ensure that environmental effects are kept to the minimal and the resources are recovered with maximum. The insights will serve as the starting point of future research and policy development to realize sustainable end-of-life management of PV modules.

5. CONCLUSION

This paper gives a thorough analysis of the environmental performance of photovoltaic (PV) module recycling systems by a Life cycle Assessment (LCA) approach with a preferential emphasis given to India and China. The findings indicate that technological capability, development of infrastructures, and policy frameworks are significant factors in determining the efficacy of recycling and effects on the environment. Higher emissions and lower material recovery are the features of the Indian scenario because there are few formal recycling systems and ineffective methods of their processing. By comparison, China scenario has better sustainability results, which are supported by high-tech technologies of recycling, industrial level operations, and efficient regulatory environment. Critical position of chemical processes in the enrichment of valuable materials like silicon and silver is also noted in the analysis to contribute in preservation of resources and to reduce reliance on primary raw materials. Also, the results highlight the significance of module design in the process of defining the capability of being recycled, as the simpler modules, e.g. glass-glass modules have a great potential in terms of energy saving and material recovery. Although these insights are made, the study is constrained by use of secondary data and assumptions that are made regarding recycling effectiveness and energy consumption. The way forward in future studies should consider the creation of improved recycling technologies and the accuracy of data as well as the large-scale implementation plans. In general, this paper highlights that to have an effective end-of-life management of PV modules, there is a need to integrate technological innovation, policy formulation, and sustainable design.

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