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Book

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1/2025

Life Cycle Assessment Practices for PV Technologies

Systematic Literature Review

Zeena Patel

Ilmenauer Schriften zur
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Life Cycle Assessment Practices for PV Technologies:
Systematic Literature Review

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List of Acronyms

a-Si	Amorphous Silicon
CA	Citric Acid
CdTe	Cadmium Telluride
CdS	Cadmium Sulfide
CED	Cumulative Energy Demand
CIGS	Copper Indium Gallium Selenide
CML	Centrum voor Milieukunde Leiden
c-Si	Crystalline Silicon
Cu₃AsS₄	Enargite (copper arsenic sulfosalt mineral)
CZTS	Copper Zinc Tin Sulfide
DSSC	Dye-sensitized Solar Cell
EPBT	Energy Payback Time
EROI	Energy Return on Investment
FTO	Fluorine-doped Tin Oxide
FU	Functional Unit
GaAs	Gallium Arsenide
GWP	Global Warming Potential
GHG	Green House Gas
H₂O₂	Hydrogen Peroxide
IEA	International Energy Agency
IEA PVSP	International Energy Agency Photovoltaic Power Systems Program
InGaP	Indium Gallium Phosphide
INR	Indian Rupee
ITO	Indium Tin Oxide
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCoE	Levelized Cost of Electricity
mc-Si	Multi-crystalline Silicon
Mono-Si	Mono-crystalline Silicon
MoOx/Al	Molybdenum Oxide/Aluminum
NZE	Net Zero Scenario
O&M	Operation and Maintenance

OPV	Organic Photovoltaic
PET	Polyethylene Terephthalate
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSC	Perovskite Solar Cell
PV	Photovoltaic
QDPV	Quantum Dot Photovoltaic
SETAC	Society of Environmental Toxicology and Chemistry
SHJ	Silicon Heterojunction
Si	Silicon
SLR	Systematic Literature Review
SustEnMat	Sustainable Energy Materials
TMGa	Trimethyl-Gallium
TMIn	Trimethyl-Indium
TOPCon	Tunnel Oxide Passivated Contact
USD	United States Dollar
(Zn (O, S))	Zinc Oxysulfide
Zn₃P₂	Zinc Phosphide

1 Introduction

The continuing growth of the global population has significantly intensified the demand for energy. Our dependency on fossil fuel-based power for energy generation substantially contributes to climate change, underscoring the need to develop new approaches using renewable sources. According to the International Energy Agency (IEA), by 2025, sustainable power solutions, including Photovoltaics (PVs), are projected to influence 35% of the world's electricity generation [1]. In addition, PV energy production increased significantly to 320 TWh, with an increase of 25%, reaching an overall capacity of 1600 TWh. This upward trend corresponds to the forecast performed by the Net Zero Emissions Scenario (NZE) for 2023 to 2030 [2]. To uphold this growth pace of PVs, continuous research on increasing solar cell efficiency and economical viability is needed. Moreover, improvement in public policies and an alliance of the public and private sectors could play an important role in developing modern PV technologies.

The PV technologies were initially categorized into first, second, and third generation. First-generation PV includes traditional silicon-based solar cells. At that instant, solar cells were at a premium cost but had optimal efficiency. To minimize the cost, the second generation, thin-film technologies, came forth with a minor decline in efficiency relative to the first generation. As the name implies, it requires less space and fewer materials with mostly the same efficiency levels as silicon-based technologies. Furthermore, to maintain lower cost and streamlined productivity of solar cells, the third generation was brought into practice [3]. However, this concept is enhanced by [4] with the detailed categorization of solar cells under three generations, as shown in Figure 1.

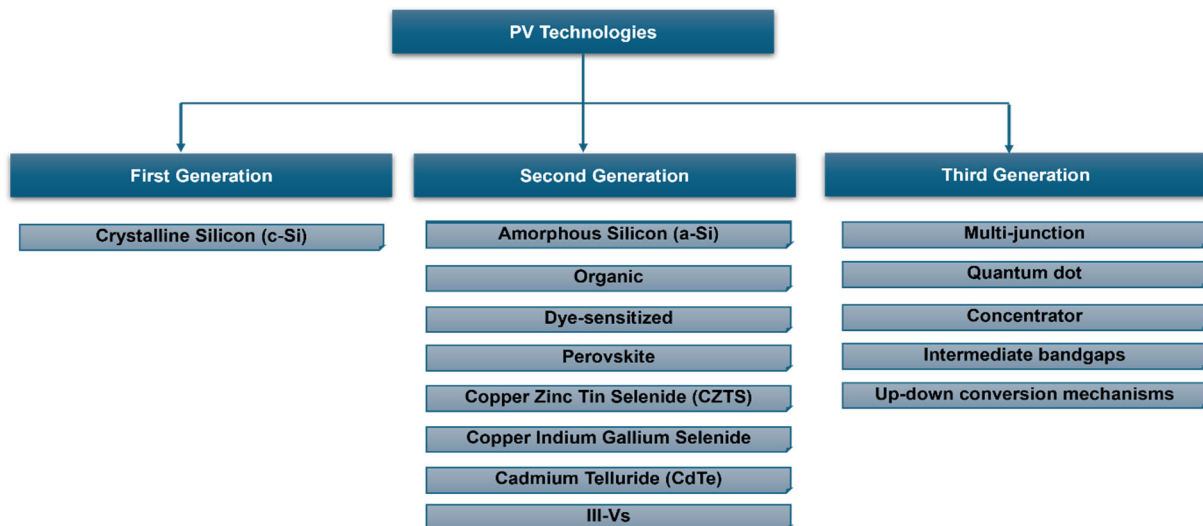


Figure 1: Categorization of PV technologies by [4]

To analyze whether these innovative technologies lead to green energy production, it is crucial to understand the environmental impacts associated with the production chain of PVs. Life cycle assessment (LCA) is a rigorous assessment that helps measure long-term environmental effects and invest in a green future. Nowadays, combating climate change is a global concern. Multiple public institutions have initiated policies to overcome this challenge. Therefore, the concept of LCA is significant in evaluating environmental impacts [5]. The International Organization for Standardization (ISO) has defined the guideline on conducting LCA as a decision method [6]. LCA is structured into four key stages. The definition of goals

and scope involves establishing the objectives and defining the boundaries of the study to provide a clear framework. The second step, Inventory Analysis, focuses on the collection of data, including input and output of materials, waste, energy, and emissions, which are significant for further assessment. The third stage, Impact Assessment involves converting the inventory data into an anticipated environmental impact. It does not only cover climate change but several other impacts like toxicity, resource depletion etc. Finally, the Interpretation step synthesizes the findings and suggests measures to overcome those identified impacts [7].

Additionally, Life Cycle Costing (LCC) is frequently coupled with LCA to assess also the economic efficiency of products and services. By analyzing costs throughout the entire life cycle, LCC serves a critical function in supporting informed decision-making and identifying strategies to streamline costs at each stage of the product's life cycle [8]. Therefore, this study aims to provide a systematic review of existing LCA and LCC studies for PV cells, encompassing both state-of-the-art fabrication techniques and prospective LCAs of emerging technologies. Furthermore, this study particularly presents a comprehensive overview of the recent development in the LCA of III-V solar cells. The focused inclusion of III-V technologies was motivated by their relevance to the *Carl Zeiss-funded SustEnMat (Sustainable Energy Materials) project* at TU Ilmenau, which prioritizes advanced materials for sustainable energy applications, while still considering the broader PV landscape. Despite the relatively modest investment of time and resources in their research and development, III-V/Si tandem or multi-junction cells have already showcased efficiencies surpassing 47.6% at the laboratory scale, with the record attributed to the Fraunhofer Institute for Solar Energy Systems [9]. III-V materials are composed of elements from groups III and V of the periodic table, for example, including gallium, indium, arsenic, and phosphorus. If arsenic is released into the environment, it can pose significant environmental risks, as arsenic is a toxic substance with potential harmful effects on ecosystems and human health [10]. Indium and gallium are considered as rare and critical materials characterized by their limited availability and high economic value. The scarcity and cost of these elements underscore the importance of developing effective strategies for recycling III-V PV systems to reduce the dependency on these critical resources [11]. This serves as the main impetus for the current systematic literature review (SLR).

To systematically explore the life cycle assessment of photovoltaic technologies, this review begins by outlining the Methods and Materials (Chapter 2), detailing the study selection and analysis process along with interpretation strategies. Chapter 3 then present both results of descriptive and content analyses, including in-depth assessments of different PV generations and life cycle costing. Following this, the Discussion (Chapter 4) highlights key publication trends, identifies methodological gaps and comparative analysis with existing literature, and reflects on study limitations. Finally, the Conclusion (Chapter 5) synthesizes the main findings and offers perspectives for future research.

2 Methods and Materials

To conduct the SLR, this study utilized the widely recognized approach for meta-research [12]. The process involves three different stages:

1. Objectives derivation
2. Research strategy and study selection
3. Interpretation

2.1 Objectives Derivation

This study seeks to examine recent academic research and future implications on the application of LCA and/or LCC within the PV sector. In this context, the review intends to address specific research questions, which are outlined below:

1. What kind of evolutions can be observed in the application of LCA and/or LCC within PV cells, particularly concerning the volume of the publications over time and the technologies assessed?
2. Are there any variations among the LCA studies based on methodology, and if so, what are the reasons for these variations?
3. What are the main challenges in implementing LCA for PVs?

2.2 Research Strategy and Study Selection

The research strategy for this study is designed to systematically explore and analyze the key factors influencing the application of LCA and LCC in the PV industry. To initiate the search process, a comprehensive brainstorming session was conducted to identify the relevant keywords. The initial search was performed using the terms “Life cycle assessment (LCA)”, “Life cycle costing (LCC)”, and “Photovoltaics (PV)”. However, to refine the search and focus specifically on III-V semiconductor materials due to SustEnMat project focus, additional keywords were incorporated, such as “semiconductor”. This approach resulted in a larger volume of studies, with more irrelevant studies. To obtain a comprehensive dataset, three primary themes were identified: 1) LCA and LCC, 2) III-V materials, and 3) PV technology. The final search string, incorporating these themes, is provided in Table 1, with a filter applied to include only publications in English language. While this emphasis on III-V semiconductors guided the search string (detailed in Table 1), the study also provides a broader overview of PV technologies including other materials as well, ensuring a comprehensive analysis of the PV landscape.

Search string	(“Life cycle Assessment” OR “Life cycle Costing” OR LCA OR LCC) AND (“Semiconductor*” OR “III-V” OR Indium OR Gallium OR Arsenic) AND (“Solar*” OR “Photovoltaic*” OR PV)
Publication language	English

Table 1: Scientific approach for research strategy

To systematically initiate the study selection, PRISMA (Preferred Reporting items for Systematic Reviews and Meta-Analyses) as a conceptual model can be used [13]. This process mainly involves three phases, called identification, screening, and inclusion, as shown in Figure 2. PRISMA is a predefined model, and to conduct research for this study, the PRISMA model has been modified according to the research needs.

During the identification phase, a query mentioned in Table 1 was run in the “Scopus” database. Using this defined query, the Scopus database yielded 197 relevant studies, which formed the base for the subsequent screening phase. The screening phase was essential in streamlining the initial collection of articles, ultimately narrowing it down to a more targeted and relevant set of studies. A comprehensive review of the abstracts from all 197 identified

publications was conducted, during which studies not aligned with the scope of the research were excluded. As a result, 81 articles were found to be directly pertinent to the focus of this investigation, forming the core set for in-depth analysis and evaluation.

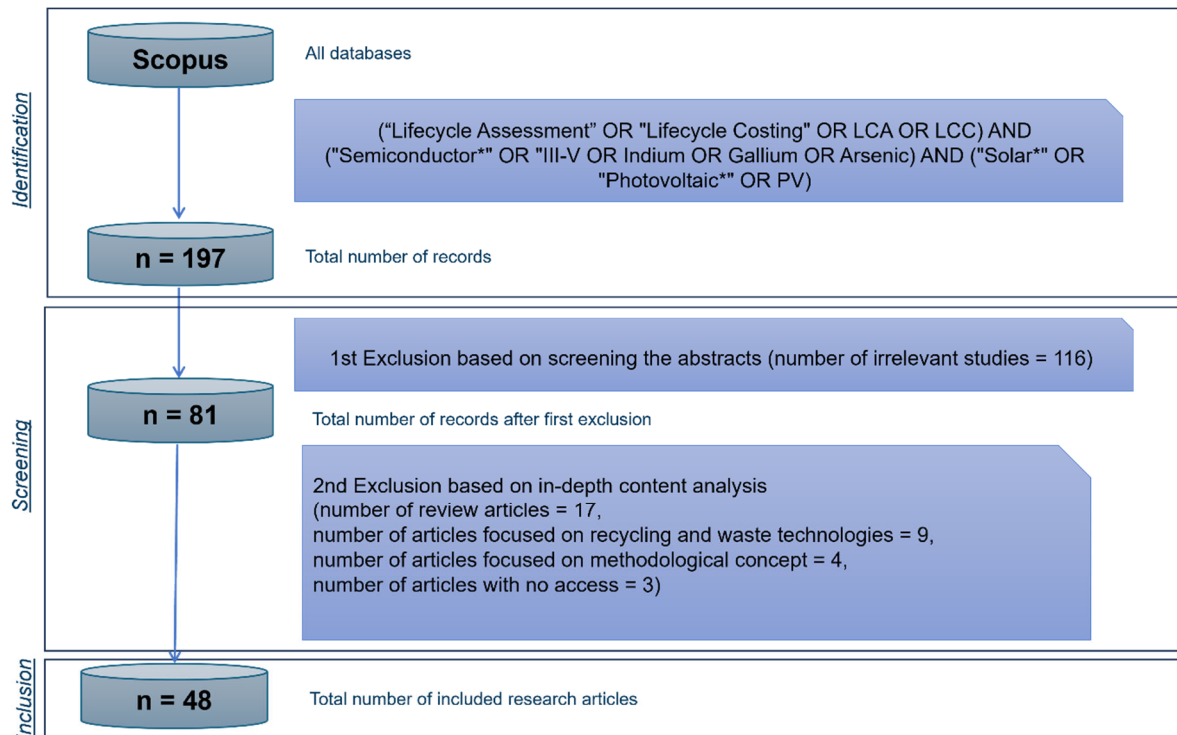


Figure 2: Schematic illustration of inclusion and exclusion criteria in PRISMA model

Finally, a rigorous and systematic evaluation of the remaining studies represented the final stage of the inclusion process. At this phase, the significance of each article in contributing to a holistic view of life cycle assessment was critically examined. Rather than merely quantifying the number of relevant studies, this stage focused on a qualitative appraisal of each publication's scholarly impact and relevance to the research domain. Following an in-depth analysis of the full content of all 81 selected studies, it was determined that 48 of them encompassed complete life cycle assessment investigations, making them suitable for further examination. As illustrated in Figure 2, the other 33 studies were deemed ineligible for inclusion in the subsequent SLR based on several predefined exclusion criteria. Firstly, review articles were excluded as it seems not suitable to conduct a re-review of existing review papers. Secondly, studies that primarily focused on recycling and waste management technologies but did not present comprehensive LCA analyses were also excluded. Thirdly, articles that concentrated predominantly on methodological concepts of LCA, rather than on the practical application of LCA in the PV sector, were excluded. Although the theoretical and methodological aspects of LCA are crucial, they did not align with the focus of this review, which aimed to synthesize the applied LCA studies. Lastly, studies that were not accessible free of charge were excluded. Combining these exclusion criteria, it ensured that only relevant, accessible, and complete LCA studies were considered in the subsequent analysis.

2.3 Interpretation

Following the completion of the research strategy and study selection process, 48 articles were included, and the SLR proceeded with two distinct analytical approaches: descriptive analysis and content analysis. The descriptive analysis was conducted with the first research question in mind, aiming to identify trends in the application of LCA and/or LCC in the PV industry. For this purpose, various data points were extracted from the Scopus database, including the type of source of publication, and country of publication. This data provided insights into temporal and geographical trends, as well as the academic and professional dissemination of LCA and/or LCC studies within the PV industry. A more detailed presentation of this analysis can be found in Section 3.1 of the results, which provides a comprehensive overview of these trends. In parallel, a content-based analysis was conducted to answer the second and third research questions, focusing on the methodological differences and challenges encountered in LCA studies within the PV sector. This analysis, detailed in Section 3.2, delves into various approaches and methodologies employed in the reviewed studies, exploring the range of technologies assessed in these studies, the functional units, system boundaries, different software utilized, different methods used, and the impact categories evaluated across different cases. The content analysis further highlights the challenges other scientists have faced when applying LCA.

The results from both the descriptive and content analyses are subsequently discussed in the discussion section. In this part, the findings are critically interpreted and compared with existing reviews, and the implications for future research and practice were explored. The discussion aims to synthesize the trends identified through the descriptive analysis with the insights from the content analysis, highlighting areas where methodological standardization is needed and where future studies could address gaps in the existing literature. Together, these two analytical approaches provide a holistic understanding of the current state of LCA and/or LCC applications in the PV sector.

3 Results

As outlined in Section 2.3, this section seeks to analyze the extracted data through two approaches: descriptive analysis and content-based analysis.

3.1 Descriptive Analysis

A total of 81 studies were identified after the first exclusion criterion. These studies were classified into the following categories: review articles (17 studies), articles focused on recycling and waste management technologies (9 studies), articles discussing methodological concepts and publications without full access (7 studies), and LCA studies (48 studies).

Furthermore, based on data extracted from Scopus, as presented in the supplementary document, the 48 included LCA studies were analyzed to examine trends in publication over time, as depicted in the column chart in Figure 3. The distribution of these publications across different journals is illustrated in Figure 4, while Figure 5 provides an overview of the studies, categorized according to the country of the first author's affiliated institution.

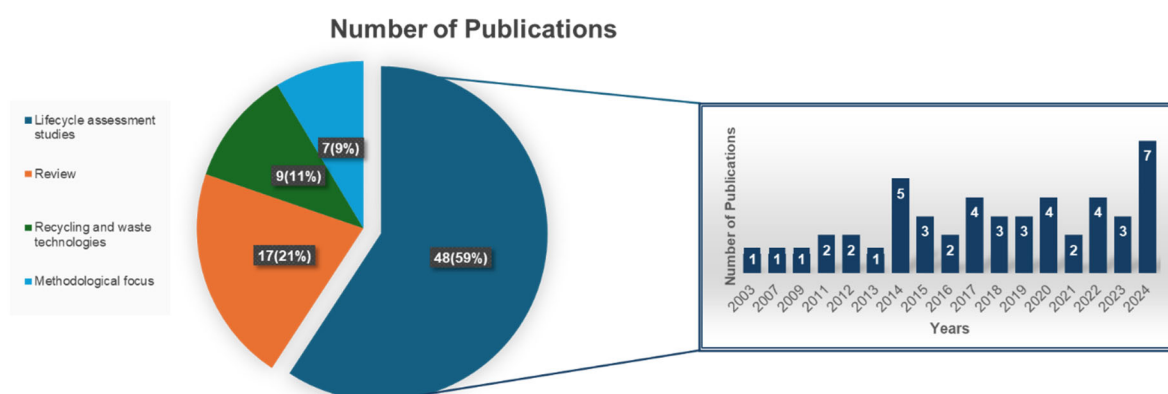


Figure 3: Bibliometric Analysis: distribution of publications by theme (pie-chart) and distribution of publications over years of LCA studies

The column graph in Figure 3 illustrates that the first article on the LCA of PV systems was published in 2003. This aligns with the release of ISO technical guidelines for conducting LCA in June 1997 [14]. However, a study by [15], which evaluated energy payback time and greenhouse gas emissions, was published in October 1997. While this study was included in the study selection process, it was excluded from the SLR as it did not provide a full four-stage LCA according to ISO standards. Despite this, the adoption of LCA methodology could have been plausible as early as 1997, given that the Society of Environmental Toxicology and Chemistry (SETAC) established a code of practice for LCA methodology during that period [16]. In addition, the number of studies remained relatively low until 2014. A noticeable increase in the number of publications occurred in 2014, with the highest number of studies recorded in that year. Overall, the chart demonstrates a steady increase in LCA studies on PV systems, with significant growth in recent years, particularly in 2024.

According to Table S1 of the supplementary document, out of 48 included studies, 40 are research articles, while the remaining 8 are conference papers. A clear distinction emerges between journals with a disciplinary focus on PV and those centered on LCA. Within the PV-specific domain as described in Figure 4, *Progress in Photovoltaics: Research and Applications* ($n = 6$) and *Solar Energy* ($n = 5$) were the most frequently represented, reflecting their central role in disseminating application-driven research within the field. Conversely, journals grounded in LCA methodology, such as the *Journal of Cleaner Production* ($n = 6$), *International Journal of Life Cycle Assessment* ($n = 3$), and *Journal of Industrial Ecology* ($n = 3$), were prominent among LCA-focused literature. This distribution underscores the interdisciplinary nature of LCA research in the PV sector, with substantial contributions stemming from both domain-specific engineering journals and environmental assessment outlets.

Based on the geographical distribution of publications, as shown in Figure 5, researchers in North America and Europe are significant scientific contributors in the field of LCA of PVs. Authors from the United States (USA) emerged as a leading contributor, accounting for 29% of total publications, followed by the Netherlands with 16%. These two countries significantly outpace others in terms of research output. Within the Netherlands, it is noteworthy that 6% of the publications (three articles) are from Leiden University, a key institution in the field [17][18][19]. Leiden University is particularly renowned for its contributions to LCA research, with the Institute of Environmental Sciences (CML) at the university having developed the CML 2001 LCA methodology, a widely used framework in environmental impact assessment [20].

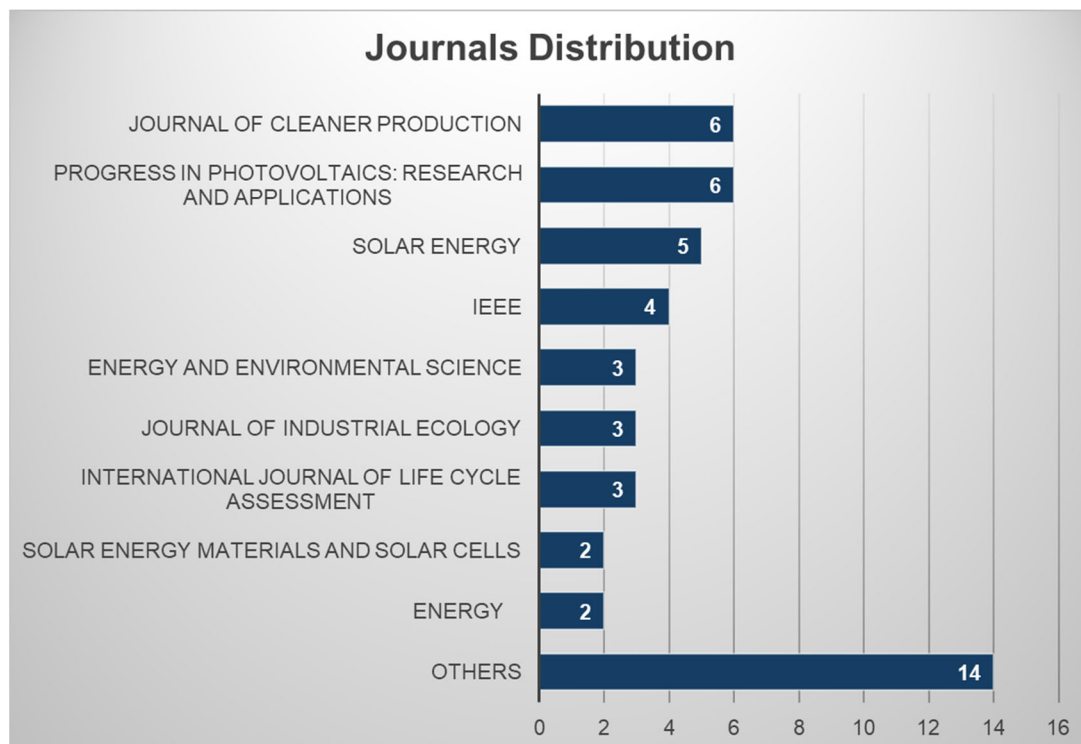


Figure 4: Bibliometric Analysis: distribution of publication sources

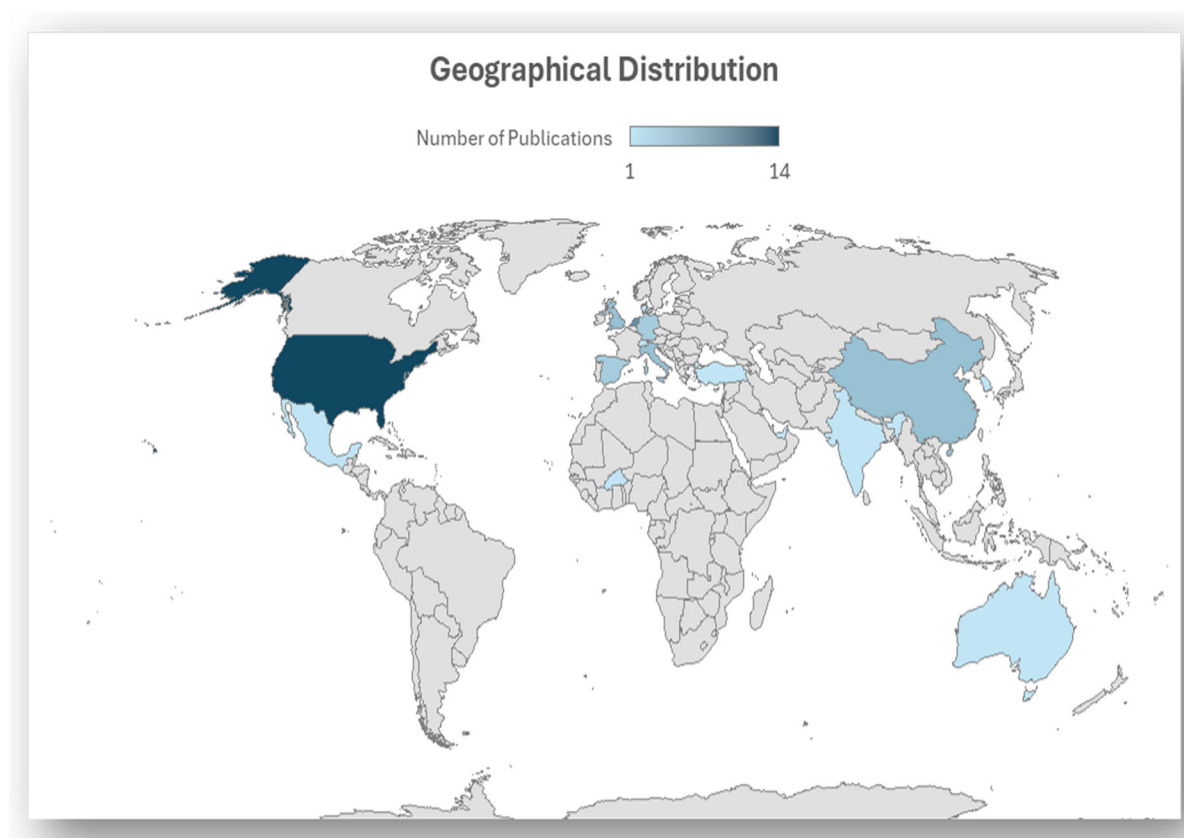


Figure 5: Bibliometric Analysis: geographical distribution of publications

Other notable contributions from Europe include Germany, Italy, and the United Kingdom, each contributing approximately 6% to 8%. Overall, Europe as a continent demonstrates strong research engagement collectively in 45% of the total publications. In Asia, notable contributions originate from China, the Republic of Korea, India, and the United Arab Emirates, comprising around 15% of the total, with authors from China being the most prominent contributors in the region. Overall, these patterns highlight the dominance of Western countries in scientific output, with emerging participation from key Asian nations, indicating the growing global interest in the research of LCA of PVs.

3.2 Content Analysis

In this section, all 48 studies are systematically analyzed with a focus on the products assessed and the four key phases of the LCA framework as outlined in section 1. Additionally, in Section 3.2.1, an overview is provided regarding the type of PV technologies for which the LCAs were conducted, categorizing them into first-, second-, and third-generation PV systems.

Moreover, it becomes crucial to analyze the results within and across the generational groups. Examining the LCA outcomes for first-, second- and third-generation photovoltaic technologies independently in section 3.2.2, allows for the identification of generation-specific environmental hotspots, performance patterns, and methodological consistencies or discrepancies. This comparative approach highlights the progression in material choices, manufacturing processes, and system efficiencies. Such stratified analysis enhances the interpretive depth of the study, facilitating more precise, generation-specific sustainability assessments and guiding future research directions.

Besides environmental analysis, only few studies integrate broader economic analysis, such as LCC, to provide a more comprehensive understanding of economic and environmental trade-offs [21][22][23]. This represents a significant research gap in the field of life cycle costing (LCC) of photovoltaic systems. Moreover, two studies adopted the Levelized Cost of Energy (LCoE) calculation to compare the lifetime costs of electricity generation [24][25]. The detailed economic analysis can be found in section 3.2.3.

3.2.1 Overview

As an initial step, an overview of the different PV systems investigated across the reviewed publications was developed, as illustrated in Figure 6. In this context, the classification of PV technologies presented in Figure 1 was used as a reference framework to ensure consistency in categorization. Notably, two studies assessed both first and second-generation technologies and were therefore counted in both categories [26][27].

The analysis from Figure 6 indicates that second-generation technologies dominate the research landscape, comprising approximately 58% of the total studies. Within this group, around 50% of the studies focused on Cadmium Telluride (CdTe) and perovskite solar cells (PSCs), highlighting their prominence due to high absorption coefficients and low material requirements. The remaining studies in this category addressed a broader array of technologies, including organic polymer solar cells (OPVs), Copper Indium Gallium Selenide (CIGS), Copper Zinc Tin Sulfide (CZTS), Cu_3AsS_4 , and III-Vs semiconductors. Notably, no studies were found evaluating dye-sensitized solar cells (DSSCs) or amorphous silicon (a-Si), indicating a decline in research focus on these materials within LCA context. This may be attributed to the relatively low power conversion efficiencies of a-Si and DSSC [9]. Third

generation technologies constituted approximately 26% of the publications, with a strong emphasis on tandem architecture. About 85% of these studies involved tandem configurations incorporating perovskite and III-Vs in combination with silicon, reflecting current trends aimed at surpassing efficiency limits of single-junction cells. The remaining third-generation studies covered more experimental technologies, including quantum dot solar cells, and nanowire-based PVs. Lastly, first-generation PV systems, mainly based on multi-crystalline silicon (mc-Si), account for about 16% of the studies, reflecting their established presence and ongoing relevance in environmental impact assessments. Specific information regarding PV type can be found in Table S2 in the column of the goal of the study.

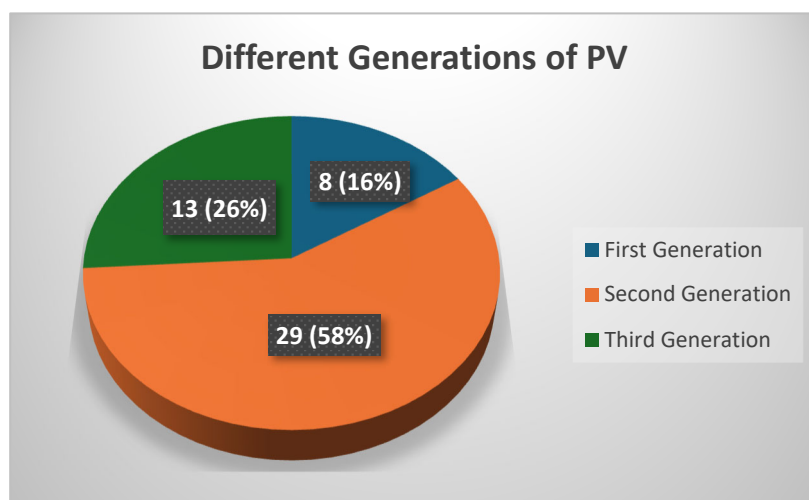


Figure 6: Distribution of PV product systems assessed in LCA studies

The 48 selected studies were evaluated against the criteria outlined in Table S2 (goal & scope definition of selected LCA studies) and Table S3 (Lifecycle inventory databases, software, LCIA and impact categories for selected case studies) in the supplementary document, with particular emphasis on the four key phases of the LCA framework. The results of this analysis can be found in section 3.2.2. Within the goal and scope phase, the analysis compares the functional units and system boundary definitions employed across the studies. Additionally, table S3 was examined to investigate the methodological frameworks employed in the selected studies. This table encompasses choices pertaining to LCI analysis, including the selection of databases, software, LCIA methodologies, and integrated environmental and economical assessment approaches with corresponding indicators. This comparative analysis is essential for elucidating methodological heterogeneity and identifying divergences in assessment practices across reviewed studies.

Lastly, the interpretation phase was examined to assess whether the studies applied any systematic approaches for results interpretation, particularly following the guidelines provided by the ISO. According to ISO 14044:2006, the interpretation phase begins with identifying key factors influencing results, such as methodological choices, assumptions, and major contributors across life cycle stages. This step is closely linked to evaluating results through three essential checks: completeness, sensitivity, and consistency, ensuring robustness and transparency in the assessment [6]. Table S2 records whether individual studies performed sensitivity analysis, scenario analysis, or uncertainty analysis, thereby offering a comparative overview of the interpretive rigor adopted within the reviewed literature.

3.2.2 Life Cycle Assessment of Photovoltaics: Phase Specific Results

Phase 1: Goal and Scope Definition

A rigorous comprehension of the assessed product and goal underlying LCA studies necessitates a precise definition of both the functional unit (FU) and system boundaries as a first phase of LCA. As stipulated by ISO 14040, the FU serves as a standardized quantitative measure of a product system's performance, acting as the reference parameter that harmonizes the system's input and output exchanges, thereby enabling consistent comparison between different product scenarios. Concurrently, ISO 14040 defines system boundaries as the set of processes, systems, and life cycle stages included within LCA and the criteria used to determine which unit processes are part of the product system.

- **System Boundary**

While analyzing Table S2, the selected literature demonstrate heterogeneous adoption of system boundaries, encompassing cradle-to-gate (raw material extraction to manufacturing), cradle-to-use (including the operational phase, though often omitted in PV studies), cradle-to-grave (spanning the full life cycle to final disposal at the end of functioning), and cradle-to-cradle (closing loop by reincorporating end-of-life products as a raw materials, represented by single study only from selected studies). Additionally, single-stage boundaries, isolating phases such as manufacturing, end-of-life treatment, or land filling and recycling, are recurrent. As depicted in Figure 7, cradle-to-gate boundaries accounted for 38% of the studies, followed closely by cradle-to-grave frameworks at 33%. Cradle-to-use boundaries represented 17%, while cradle-to-cradle approaches were scarcely adopted, comprising only 2%. The remaining 6% of studies implemented single-stage system boundaries, focusing on isolated life cycle phases. Additionally, three studies focused on LCC; as shown in Table S2, two of these did not define system boundaries, while one adopted the same boundaries as its corresponding LCA.

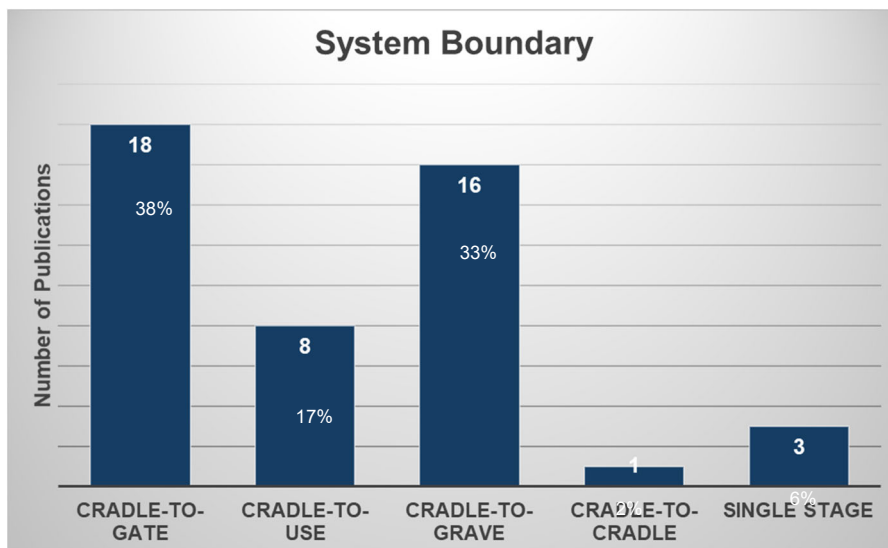


Figure 7: System boundary definitions from selected studies

- **Functional Unit**

Functional units across the studies varied, with the most common being 1 kWh/MWh (allowing comparison of energy outputs [28] [29]), 1 kWpeak/Wpeak (for assessing rated

power under standard conditions [29]), and 1 m² (for evaluating material intensity [29] [30]), while others, such as 1 kg of waste, 1 kg of III-V precursors, 20 ml of nanoparticles were grouped under “others”. One study did not report its FU, and two focused only on conventional LCC.

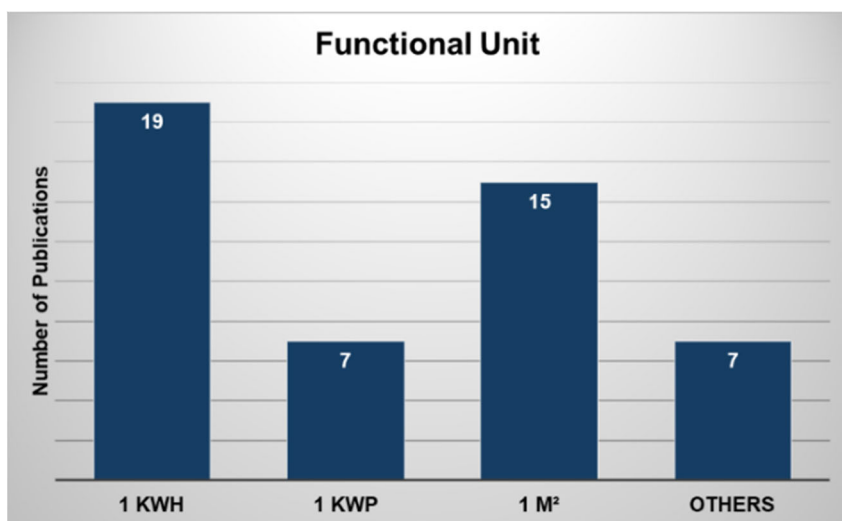


Figure 8: Functional units from selected studies

Phase 2: Lifecycle Inventory

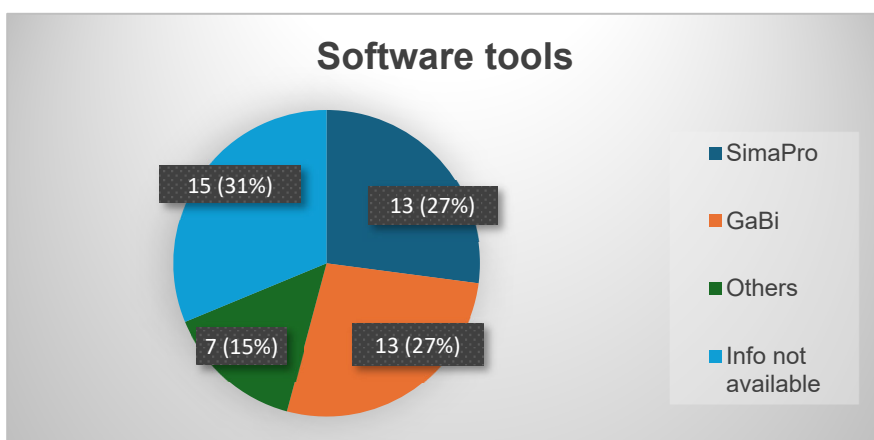


Figure 9: Utilization of LCA tool in case studies

Following the analysis of the first phase of LCA, the second phase, LCI, was examined to assess data sourcing practices and methodological rigor. In this phase, a strong reliance on secondary data was observed, with the Ecoinvent database used in 30 studies, GaBi database in four, and literature-based data in five cases. Notably, only three studies integrated primary data with secondary sources, reflecting a critical underuse of site-specific, process-level data. This is particularly concerning novel or location-sensitive systems, where generic databases may not accurately represent real-world conditions. Furthermore, ten studies failed to disclose their data sources entirely, revealing a significant transparency gap. These findings underscore the need for improved data reporting and greater incorporation of primary data to enhance the accuracy and contextual relevance of LCA results. Moreover, as part of the second phase of LCA it is necessary to examine software used in different case studies. A striking observation

from the reviewed studies, also described in Figure 9, is the dominance of GaBi and SimaPro, each used in 13 publications, suggesting a clear preference for these two LCA software tools. However, in 15 cases, the software used was not disclosed.

Phase 3: Lifecycle Impact Assessment

Building on the inventory phase, the third phase of LCA, LCIA, was analyzed, focusing on the selection of LCIA methods (Figure 10) and associated impact categories. While CML 2001 emerged as the most frequently applied method ($n = 16$), followed by Cumulative Energy Demand (CED) ($n = 10$) and ReCiPe ($n = 8$), a substantial number of studies ($n = 13$) did not specify which methodology was used. This lack of disclosure undermines reproducibility and hampers meaningful comparison across studies. Although some studies employed integrative approaches by combining multiple LCIA methods ($n = 14$), the rationale for such decisions was rarely articulated. These findings highlight the pressing need for standardized and transparent reporting of LCIA methods to enhance the consistency, reliability, and interpretability of LCA results.

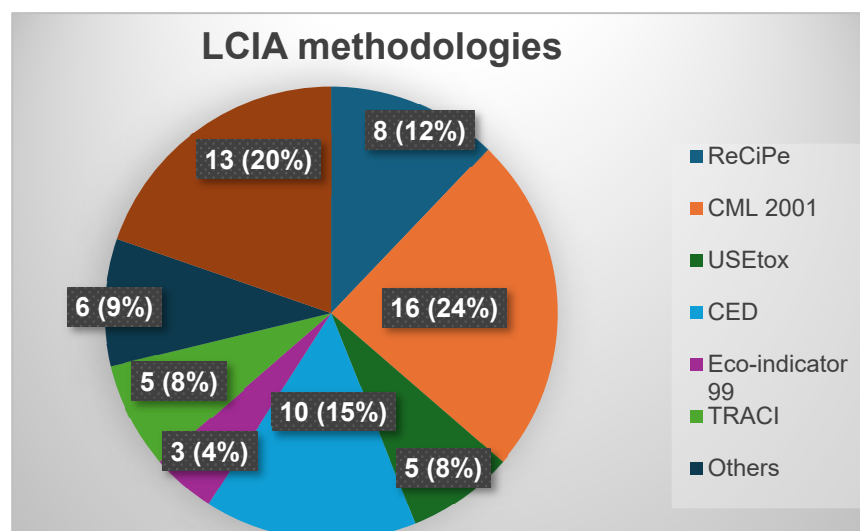


Figure 10: Different methodologies of LCIA used in case studies

Furthermore, as a core component of the LCIA phase, the selection and application of impact categories were also examined to understand how environmental burdens are characterized and compared across studies as shown in Figure 11. Among the most frequently assessed impact categories, Global Warming Potential dominated the selected studies ($n = 41$), reflecting its continued centrality in environmental assessments. However, it is noteworthy that toxicity-related categories, such as EcoToxicity Potential ($n = 35$), Human Toxicity Potential ($n = 26$), and Terrestrial Toxicity ($n = 24$), were also widely considered, indicating growing recognition of health and ecosystem impacts beyond carbon emissions. Similarly, resource-related categories like Abiotic Depletion (Mineral and/or Fossil) ($n = 30$) were more prevalent than expected, suggesting increasing attention to material scarcity and long-term resource sustainability. Despite this breadth, none of the studies provided a rationale for the selection of impact categories. This absence of justification reveals a critical methodological gap, limiting the transparency, comparability, and contextual relevance of findings. These results highlight the need for clearer reporting standards and selection criteria to guide impact category inclusion in LCA studies.

In addition to environmental indicators, several energy-related indicators were identified. CED was reported in 18 studies, Energy Payback Time (EPBT) in 17 studies, and Energy Return on Investment (EROI) in three studies. From an economic perspective, LCC was conducted in three studies, while Levelized Cost of Energy (LCoE) was assessed in two studies.

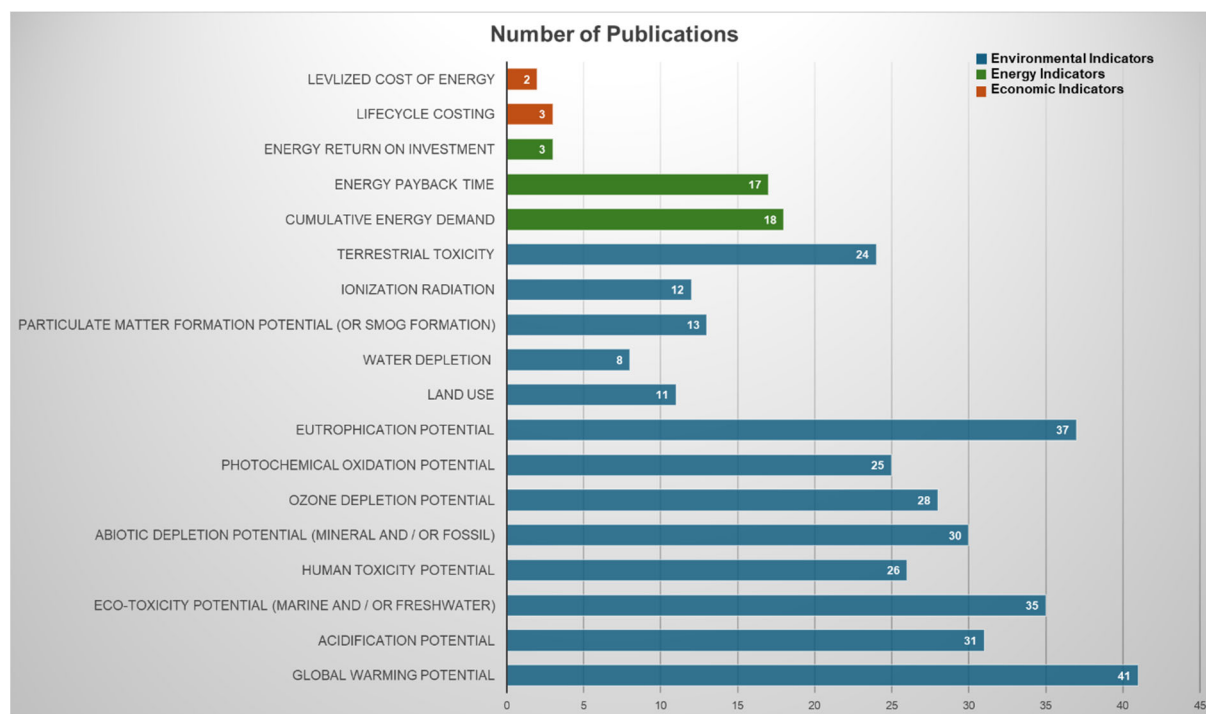


Figure 11: Evaluated indicators of Environment, Energy, and Economics

Phase 4: Interpretation

Lastly, the interpretation phase was also analyzed across the selected studies from the data extracted in Table S2, to assess how results were communicated, and conclusions were drawn. The chart in Figure 12 illustrates the distribution of visualization methods employed in LCA related publications, specifically focusing on how studies communicate sensitivity and uncertainty analyses. The predominance of “No visualization” ($n = 26$) highlights a critical gap in the transparent reporting of model variability and result reliability. Sensitivity analysis ($n = 11$) and uncertainty analysis ($n = 5$) are employed to a lesser extent, while a combined approach integrating both ($n = 4$) remains also limited, despite its potential to enhance interpretive robustness. Scenario analysis ($n = 2$) appears as a marginal method. These findings underscore the need for improved transparency in LCA communication practices, particularly through visual tools that facilitate stakeholder understanding of methodological assumptions and data limitations.

Furthermore, the assumptions made regarding key model parameters, such as the operational lifetime and conversion efficiency of PV, play a critical role in conducting accurate and meaningful LCAs of PV technologies [29]. Most studies commonly assume a PV lifetime of 25 or 30 years, which aligns with guideline provided by IEA PVSP (International Energy Agency Photovoltaic Power Systems Program) [29]. However, conversion efficiencies vary significantly depending on the specific PV type, geographical location, and operating conditions. These variations directly influence the environmental impact results and should be carefully considered when modelling and interpreting LCA outcomes.

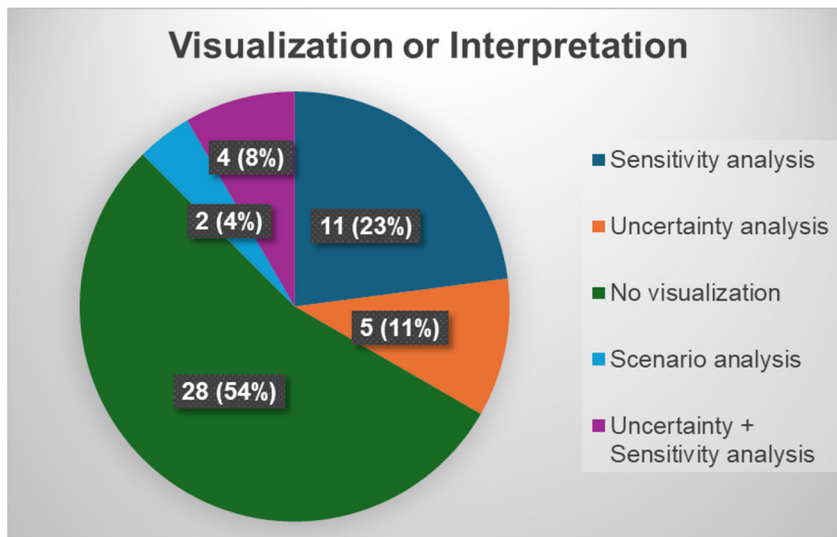


Figure 12: Visualization approaches of selected LCA studies

3.2.3 Life Cycle Assessment (LCA) of Solar Cell Technologies

After analyzing 48 case studies based on LCA phases it is necessary to understand the outcome of the LCA. Therefore, the detailed analysis on environmental profiles of different technologies based on three generations are described in three subchapters (3.2.3.1, 3.2.3.2 & 3.2.3.3). The life cycle assessment of PV technologies across first-, second-, and third-generation systems reveals nuanced environmental, energetic, and economic profiles, driven by differences in material use, production processes, deployment geography, and recycling strategies, with each generation's section concluding with a brief summary of the key findings.

3.2.3.1 Life Cycle Assessment of First-Generation Solar Cell

In this first-generation comparative analysis of PV technologies, as categorized before, 8 out of 48 studies were examined to evaluate the environmental performance of conventional solar cell systems through LCA. These case studies have highlighted the critical role of production geography, material composition, and waste management strategies in determining the overall environmental performance of PVs.

One of the most significant findings from existing studies is the influence of regional production geography on greenhouse gas (GHG) emissions. For example, silicon modules produced in China, where electricity generation heavily relies on coal, emit roughly double the GHGs compared to modules manufactured in Europe [31][32]. Conventional crystalline silicon modules (c-Si) produced in China emit approximately 46 g CO₂eq/kWh, whereas modules manufactured in Europe benefit from a cleaner energy mix. Furthermore, energy performance metrics reflect this disparity: mono-crystalline silicon (mono-Si) modules manufactured in China demonstrate EPBT ranging from 0.42 to 0.91 years, and EROI valued between 12.6 and 16.9, with European-made equivalents achieving even higher EROIs of up to 22 [32][33].

Meanwhile, material choices also affect environmental impacts. Plastic-encapsulated PV modules, which are c-Si cells encapsulated in polymer materials instead of traditional glass, emerge as promising low impact alternatives, emitting slightly less GHGs during production (45 g CO₂eq/kWh) and demonstrating a 57% reduction in emissions during the disposal phase compared to conventional glass-encapsulated c-Si cells. Moreover, recycling also plays a

significant role in mitigating environmental burdens and an increase in recycling rates by 15% correlates with a 5.3% reduction in overall emissions, which highlights the growing significance of the circular economy principles [31].

Despite their favorable EPBTs, mono-Si modules are associated with high human toxicity and marine eco-toxicity impacts due to intensive use of silver paste, electricity, and glass in their manufacturing process [33]. In contrast, mc-Si modules, particularly those deployed in regions like Mexico, exhibit GHG emissions of 47.2 g CO₂eq/kWh, which is comparable to conventional glass-based silicon PV modules (46 g CO₂eq/kWh), but mc-Si modules demonstrate improved end-of-life outcomes through recycling compared to landfill [31][34][35]. However, Chinese-produced mc-Si still poses a high domestic environmental burden, with 94% of life cycle GHG emissions originating from local industries [36]. In addition, key stages of manufacturing mc-Si cells, such as production, cell processing, and module assembly are identified as high-impact processes, especially concerning climate change and human toxicity indicators, emphasizing the need for targeted mitigation strategies within these stages [35].

Furthermore, geographical deployment also plays a decisive role; locations with higher solar irradiation, such as Greece and Tibet, yield markedly lower emissions per unit of electricity generated, thereby enhancing the overall environmental performance of PV installations [31][33]. Policy mechanisms such as carbon tariffs, estimated between €105-129/ton CO₂, have been proposed to compensate the carbon emissions across manufacturing regions [32].

Ultimately, no single PV technology dominates all environmental indicators. Among the currently studied first-generation technologies, plastic and recycled mc-Si modules show the most balanced environmental profiles, whereas mc-Si modules may become more sustainable through improvements in material and cleaner energy sourcing.

3.2.3.2 Life Cycle Assessment of Second-Generation Solar Cell

The second-generation PV technologies were analyzed based on environmental and energy performance attributes from 27 studies. Second-generation PV technologies, such as CdTe, CIGS, perovskites, CZTS and OPVs have attracted increasing interest due to their potential for lower environmental impacts, reduced energy consumption during manufacturing, and better adaptability to novel applications compared to conventional silicon-based systems. However, each of these technologies presents a unique set of environmental trade-offs and opportunities for improvement.

CdTe Solar Cells

Among second-generation technologies, CdTe PV has consistently shown the most favorable environmental and energy performance metrics. LCAs from multiple studies reveal that extending the operational lifespan of CdTe panels from 30 to 50 years, under average solar irradiance conditions, can reduce carbon emissions by nearly 40% and increase the EROI from 67 to 177. Improved module durability, aided by a decreasing degradation rate (from 0.3% to 0.2% annually), reinforces these gains [24] [25]. Moreover, CdTe also has the shortest EPBT among commercial PVs, at approximately 1.47 years, which is significantly lower than mono-Si's 1.95 years [37].

While CdTe excels in categories such as global warming potential and cumulative energy demand, its freshwater ecotoxicity and human toxicity scores remain relatively high due to cadmium content. Nonetheless, implementing recycling processes, specifically for cadmium,

substantially mitigates these issues, reducing toxicity-related impacts by over 90% with only marginal increases (4–5%) in other categories like global warming potential and abiotic resource use [27].

Further environmental benefits are anticipated through a cradle-to-cradle recycling approach, where CdTe modules at end-of-life could become a significant secondary source of tellurium by 2045. This strategy not only conserves resources but also reduces the energy and environmental footprint of future module production [38]. Regional LCAs, such as those conducted in Malaysia, demonstrate strong performance even in markets with different grid compositions, with CdTe showing significantly lower GHG emissions compared to ribbon and amorphous silicon [39].

Perovskite Solar Cells (PSCs)

PSCs exhibit remarkably low EPBT values — as low as 0.21 years, making them highly promising from an energy investment perspective [40]. However, this figure is based on a future-oriented scenario that uses graphene transparent electrodes instead of the conventional indium tin oxide (ITO). In current state-of-the-art PSCs using ITO electrodes, EPBT values are generally higher, typically ranging between 0.35 and 0.5 years [41]. Despite these promising energy metrics, their overall environmental sustainability remains a challenge. The short operational lifespan of PSCs significantly impacts on their overall GHG emission performance, highlighting the need for improvements in stability and durability. Manufacturing processes further contribute to environmental burdens, especially due to high electricity use and the use of materials such as indium and silver in electrode layers, which are either resource-intensive or associated with toxicity concerns. However, the study [40] explores graphene electrodes as a potential alternative to reduce such material-related impacts, though these are not yet industrially scalable.

These challenges are not unique to PSCs and apply broadly across photovoltaic technologies. As part of wider efforts to mitigate such impacts, strategies like using green solvents, alternative electrode materials, and improved encapsulation techniques are being explored. For example, replacing silver contacts with molybdenum oxide/aluminum (MoO_x/Al) and ITO with fluorine-doped tin oxide (FTO) has shown potential for reducing toxicity impacts in multiple PV technologies, including PSCs [42]. Further innovations, such as graphene-enhanced architectures, have also demonstrated approximately 20% lower environmental impact relative to traditional perovskites [43]. Nonetheless, most studies agree that improvements in durability, material substitution, and clean manufacturing energy sources are critical for perovskites to become a viable and sustainable option.

Organic Photovoltaics (OPVs)

OPVs offer manufacturing flexibility and lightweight designs but currently struggle with low efficiency and long energy payback periods. For example, modules with only 1% efficiency show EPBTs of up to 10 years, mostly due to energy-intensive electrode fabrication processes like roll-to-roll sputtering. However, at modest efficiency improvements (3–5%), EPBTs can decrease to 1–2 years [44].

The major environmental burden in OPVs stems from the use of ITO electrodes, which account for nearly 87% of embedded energy and experience significant material loss (65%) during etching [45]. This has led researchers to advocate for ITO alternatives, both for environmental and economic reasons, to improve material efficiency and reduce reliance on scarce elements like indium.

CIGS Solar Cells

CIGS modules display balanced environmental profiles, particularly when produced with cleaner electricity sources. Several studies highlight that shifting from cadmium sulfide (CdS) to zinc oxysulfide (Zn (O, S)) in buffer layers not only eliminates cadmium toxicity but also improves end-of-life recyclability [46]. CIGS modules manufactured in regions like New York, where cleaner grid electricity is available, demonstrate GHG emissions as low as 12.6 g CO₂-eq/kWh, comparable with or better than CdTe under similar conditions [47].

CIGS waste contains valuable metals at concentrations higher than natural ores, with approximately 600 ppm of gallium and 90 ppm of indium. Among various extraction methods, leaching using a combination of citric acid (CA) and hydrogen peroxide (H₂O₂) has proven most effective, achieving over 90% recovery of both Ga and In within 1 hour at 80 °C. This CA + H₂O₂ approach also demonstrated the lowest carbon footprint, estimated at just 0.1 kg CO₂-equivalent per kilogram of CIGS treated [48].

Other Emerging Thin-Film Technologies

Several non-toxic and earth-abundant alternatives are under development to further reduce environmental impacts:

- Zinc phosphide (Zn₃P₂) and CZTS are gaining attention for their low toxicity and availability. While they may have slightly higher energy and water demands than CdTe, they offer significantly lower ecotoxicity and material risk profiles [49].
- Copper-arsenic chalcogenides (e.g., Cu₃AsS₄) also show promise but raise concerns due to potential environmental impacts linked to arsenic content, highlighting the need for careful material selection [50].
- Comparisons with GaAs indicate that shifting to single-crystalline silicon can reduce the energy use by over 95%, underscoring the environmental advantages of more established PV technologies [51].

Additionally, precursor materials like trimethylgallium (TMGa) and trimethylindium (TMIn), used as group III elements in III-V compound semiconductors, have been found to have significantly higher GHG emissions than previously assumed, especially in the absence of solvent recovery, revealing the urgent need for updated LCA data in this area [52].

While second-generation solar technologies offer substantial environmental benefits over traditional silicon modules, especially in terms of energy payback and emissions, each comes with specific challenges. CdTe leads in overall environmental performance, CIGS offers strong recyclability prospects, perovskites show outstanding potential but require durability improvements, and OPVs benefit from flexibility but need efficiency and material improvements. Progress in recycling, greener materials, and cleaner energy inputs will be pivotal in maximizing the environmental sustainability of next-generation solar energy systems.

3.2.3.3 Life Cycle Assessment of Third-Generation Solar Cell

Third-generation solar technologies, including tandem, III-V, organic, and quantum dot-based photovoltaics, which surpassing the Shockley–Queisser single-junction limit, offer promising performance enhancements but present complex environmental trade-offs. Among tandem configurations, PSC/silicon tandems incorporating tunnel oxide passivated contact (TOPCon) technology (PSC/TOPCon) — a multilayer silicon-based cell featuring an ultrathin

tunnel oxide layer and doped polysilicon to enhance surface passivation and carrier selectivity — generally outperform GaAs-based systems (GaAs/SHJ) in terms of global warming potential (GWP), toxicity, and metal depletion. This advantage stems largely from the high energy demand and toxic material use in GaAs wafer production. However, reusing GaAs wafers can substantially reduce their environmental footprint, highlighting the importance of circular material use [23]. The environmental impacts of silicon-PSC tandem solar cells are higher, and these configurations exhibit higher GWP, EPBT, CED, and EROI compared to other perovskite-based tandem devices [53]. These impacts are primarily attributed to the energy-intensive production of silicon wafers, which contributes to 77% higher CED in silicon-based perovskite tandems. Therefore, it is critical to revisit the manufacturing process of silicon to reduce the environmental footprint.

Therefore, material substitutions, such as using aluminum electrodes instead of gold or silver — have shown potential in lowering climate and toxicity impacts [54]. Additionally, organic tandem solar cells stand out with significantly lower GWP, energy demand, and toxicity impacts compared to traditional technologies like mc-Si and CdTe, making them highly favorable from an environmental standpoint [55].

III-V tandem cells, especially those using GaAs and InGaP top absorber structure with silicon bottom cell, demonstrate shorter EPBTs and improved performance across several environmental categories. Yet, they are associated with higher toxicity risks due to arsenic, phosphine gas, and gold usage. Mitigation strategies include upgrading gas treatment systems and exploring less harmful materials [17] [19] [23] [56]. Importantly, the electricity source used during manufacturing significantly influences environmental outcomes. Using renewable electricity instead of fossil-based energy can reduce climate impacts by up to a factor of five, although toxicity impacts remain due to the persistent use of hazardous materials [57]. Further focusing on quantum dot technologies, it has shorter EPBT than most other PV techniques except CdTe PVs, with a GWP of 25 kg CO₂eq/m² [58].

In summary, third-generation solar cells offer high efficiency and low EPBTs, but their sustainability relies on reducing toxic materials, cleaner manufacturing, and better recycling. Tandem and organic designs are especially promising, though further innovation is needed to minimize environmental impacts.

3.2.4 Life Cycle Costing of Photovoltaics

In parallel with the environmental profile, a comparative analysis of LCC was conducted across the studies as discussed earlier in section 3.2. Only three studies were conducted on LCC out of 48 studies, highlighting a significant gap in the integration of LCC with LCA. LCC is an analytical method employed to determine the comprehensive economic impact of a project throughout its operational lifespan. Within the framework of federal energy management, LCC serves as a critical tool for evaluating the cost-effectiveness and long-term viability of energy and water conservation initiatives in federal facilities [59].

LCC can be divided into three different types — conventional, environmental, and societal LCCs. Each approach varies in scope: the conventional method focuses on direct economic costs within the product lifecycle; the environmental approach incorporates both economic and environmental costs, while the societal perspective extends further to evaluate social impacts alongside economic considerations [60]. In this comparative evaluation, key methodological features were assessed from selected studies, including the type of PV technology, key cost

drivers considered while conducting the economic assessment, calculated costs, and location of the LCC study as described in the supplementary table.

The scope and system boundaries perspectives of these three studies have been analysed. The LCC assessment of two PV tandem cells (GaAs/SHJ and PSC/TOPCon) in China has adopted a cradle-to-grave approach, encompassing raw material extraction, manufacturing, installation, operation, maintenance, and end-of-life management, while excluding electricity distribution and consumption phase [23]. In contrast, the full-lifecycle approach for CdTe PV cells in India was adopted by [21], but uses a more conventional financial evaluation structure, placing greater focus on component-specific costs (capital, maintenance, replacement, and salvage value). Moreover, material-related LCC was carried out for CIGS and CdTe cells using a material flow analysis model [22]. It applies a closed loop model that tracks material flows from production to end-of-life recycling, omitting broader system costs such as installation or operation and maintenance (O&M).

With a focus on the economic indicators, LCC of PV tandem cells includes a broader range of cost categories such as materials, manufacturing energy, balance of system components, O&M, and end of life costs [23]. While LCC of CdTe PV has also addressed various costs, it has also integrated energy-based indicators like LCOE, offering an energy-economic perspective. In contrast, material-based LCC of CIGS and CdTe has narrowed down its focus to raw material costs, scrap rates, tolling charges, and recycling/disposal expenses, which helps to dive deep into material efficiency and critical material dependence [[22]].

The findings marked differences in economic viability. PSC/TOPCon is significantly more cost-effective (23.7 USD (United States Dollars) /MWh) than GaAs/SHJ (135 USD/MWh), primarily due to lower material and processing costs. However, it also notes that reuse of GaAs wafers can potentially reduce the cost gap [23]. CdTe systems show strong regional feasibility, with an estimated LCOE of 9.85 INR (Indian Rupee)/kWh [21]. Material utilization strongly influences life cycle costs: under high-efficiency scenarios, CdTe costs 61.1 million USD/GWp, while CIGS reaches 179.6 million USD/GWp, with both rising substantially at lower efficiencies. These results emphasize the importance of high efficiency and recycling in minimizing material-driven costs, especially for scarce elements like indium and tellurium [22].

From *the methodological standpoint*, [23] presents a system-level integration of environmental and economic metrics, while [21] applies a classical LCC framework enhanced by energy-based indicators for climate-specific analysis. In contrast, [22] emphasizes material flow risks and scarcity-driven costs. Moreover, studies utilized secondary data sources for prices like literature and ecoinvent. Notably, the studies highlight promising areas for cost reduction through material reuse, efficiency improvements, and better recycling; no unified conclusion can be drawn across all studies regarding the most economically viable technology. Future research should focus on methodological harmonization and expanded sustainability criteria.

4 Discussion

In this section, the interpretation of results with respect to the original research are highlighted, comparison with excluded review articles during study selection process (section 2.2) are included and the limitations of the study are discussed.

4.1 Trends in LCA of PV Technologies: Publication Dynamics

The current study represents the first known effort to provide a comprehensive descriptive analysis of LCA studies within the PV sector. Unlike previous literature that may focus on specific methodological advancements, this study takes a wide perspective to map the evolution and current state of LCA adopted globally [61][62]. Notably, the application of LCA on PV technologies has shown growth over time. A clear upward trend in LCA-related publications within the PV sector is observed, with a sharp rise beginning in 2014 and reaching its highest count in 2024. This trend aligns with a prior study conducted for various sectors, including energy, which has reported a temporal increase in LCA studies of the energy sector after 2011 due to rising awareness regarding climate change and circular economy [63].

Furthermore, considering the geographical distribution in this study, the United States emerges as a leading contributor to LCA-related publications in PV technologies. This observation is consistent with findings reported by [64], which identifies the USA as having the highest number of LCA studies focused on renewable energy sources. Moreover, the findings of the current study highlight that Europe plays a significant role in advancing LCA research in PV technologies. Notably, the Netherlands stands out as the second-highest contributor after the USA. Other European countries, such as Italy, the UK, Spain, and Germany, also demonstrate active engagement. This strong European presence reflects the region's commitment to sustainability. This contribution may reflect the EU legislation, such as the Eco Design Directives, which mandates calculating greenhouse gas emissions and transparent LCAs of PV modules to establish a market presence [65]. Including a wider array of regional contexts is crucial for understanding regional environmental impacts. Expanding geographical representation will strengthen the global applicability of LCA and enhance the reliability and relevance of its outcomes across diverse policy and market settings.

Regarding the LCC of PVs, this study identified that only three publications have conducted such analysis, underscoring a significant research gap in the broader economic assessment of the PV sector. The limited emphasis on LCC can be partly explained by the prevalent use of LCOE as a standard economic indicator among policymakers, investors, and market analysts. LCOE is widely recognized for its ability to provide clear, comparable insights into the cost effectiveness of renewable energy technologies across the broader market [66][67]. Due to its direct relevance to decision-making and market assessments, it is often prioritized over more detailed and nuanced methodologies like LCC. Nevertheless, future research should explore the full spectrum of economic assessment metrics applicable to PV beyond LCOE. A broader evaluation framework could support more comprehensive and context-specific economic analysis, ultimately facilitating informed decision-making in sustainable energy planning.

In a nutshell, descriptive analysis highlights the necessity for addressing current research gaps concerning geographical context and economic assessment. Moreover, the study indicates that while second-generation PV technologies are frequently evaluated within the LCA framework (Figure 6), desensitized solar cell (DSSC) technologies remain largely underrepresented in such assessments. This gap highlights the need for further LCA studies focused on emerging PV technologies to ensure comprehensive sustainability evaluations across all technological variants.

4.2 Methodological Gaps & Material-Driven Novel Insights

This section represents the clear gaps derived from evaluating key methodological components of LCA, including the definition of the system boundaries and functional unit, the selection of impact categories, and the choice of visualization techniques. Furthermore, it represents the comparison of the results of this study with existing review articles.

This study extends the methodological scope of earlier reviews [61] [62] by incorporating a broader and more recent set of PV-related LCA studies, revealing key evolutions in how system boundaries, functional units, and impact categories are defined and applied. While [61] primarily addressed traditional metrics such as 1 kWh and 1 m², the current study includes a wider range of application-specific functional units (e.g., 1 kg of CIGS waste), reflecting a shift toward more granular and material-oriented assessments critical for next-generation PVs.

In terms of system boundaries, cradle-to-gate remains the most common, but the limited use of cradle-to-grave highlights ongoing constraints in capturing full lifecycle impacts despite IEA PVSP recommendations [29]. Moreover, inconsistencies in reporting LCI databases, software tools, and LCIA methodologies persist, with nearly one-third of studies omitting essential methodological details. While CML 2001 remains dominant, the selective use of impact indicators, even within the same method, signals a lack of harmonization. Notably, the ReCiPe method, despite its policy relevance, remains underused [68][69].

Moreover, GWP is the most frequently assessed category, whereas the inclusion of other categories remains inconsistent. Lastly, sensitivity analysis underlines the need for stricter methodological alignment. Compared to earlier reviews, this study emphasizes the necessity of transparent, standardized reporting to enable reliable cross-study comparisons and policy applicability.

Furthermore, LCA of PV technologies reveal clear generational distinctions. First-generation c-Si modules generally demand the most embodied energy and exhibit the longest EPBT, whereas second-generation thin films and third-generation emerging PV systems require substantially less material input and energy input. For example, [70] emphasized that thin-film PV (including OPV; PSC, quantum-dot, etc.) has a median EPBT of about 1.34 yr and median GWP is around 49 kg CO₂-eq/m². This study supports that trend, particularly for OPV and perovskite systems built on thin substrates (e.g., flexible polyethylene terephthalate (PET) or ultra-thin glass), which demonstrate substantially lower embodied energy than c-Si.

However, despite favorable embodied energy metrics, broader environmental indicators reveal a more complex sustainability profile. Notably, the deviations on GWP are evident. Specifically, GWP for PSCs is slightly higher than values reported in [62][71]. This variation is primarily due to the incorporation of recent data on lead sequestration processes and revised assumption of lifetimes. These results highlight the dynamic nature of life cycle inventory data and the importance of regularly updating environmental assessments in line with technological and manufacturing advancements.

A critical gap in LCA of PVs is toxicity assessment. Out of the 48 case studies reviewed, only about half included human toxicity impact categories in their life cycle assessments. While first-generation silicon modules are largely non-toxic and recyclable, second-generation thin films & third generation tandems involve toxic elements like cadmium & lead. Again, PSCs are distinguished by their incorporation of lead, a highly toxic heavy metal, which results in a significantly higher potential human toxicity. The previous study [71] identifies antimony and bismuth as less toxic alternatives to lead in perovskite. This review extends that understanding

by highlighting that, without end-of-life and recyclability, antimony and bismuth do not inherently yield superior environmental outcomes. These outcomes show the complex balance between toxicity, performance, and how easily the materials can be recycled.

Moreover, material criticality has emerged as a pivotal concern for PVs. Second-generation thin-film technologies such as CdTe and CIGS introduce heightened material criticality through reliance on minor and by-product metals including tellurium, indium, gallium, and selenium, elements with limited natural abundance and constrained geopolitical supply chains [72]. This study extends this view by providing LCA of recycling strategies for elements like tellurium, indium and gallium. For example, tellurium recovery from end-of-life CdTe modules is becoming essential to support long-term scalability, as projected demand by 2045 may outpace current primary production capacities. Recycling efforts also utilize recent methods enabling over 90% recovery of indium and gallium using low-impact processes.

While recycling of critical raw materials is increasingly recognized as essential for reducing supply risk and environmental impact, recovery alone is not sufficient. To fully realize circularity in PV technologies, recent research emphasizes the importance of integrating material selection with end-of-life strategies at the design stage. As highlighted in [70], a safe-and-sustainable-by-design approach is crucial — one that prioritizes non-toxic, earth-abundant alternatives and facilitates recyclability through thoughtful material and architectural choices. This review advances current understanding by not only identifying recyclable critical raw materials such as indium, but also by examining how their recoverability influences key sustainability metrics. For example, replacing conventional ITO/FTO layers with aluminum-doped zinc oxide or carbon-based electrodes can not only reduce critical metal dependency but also lower embedded energy and toxicity.

4.3 Limitations of the Study

Despite efforts to ensure a comprehensive and rigorous approach, this systematic literature review is subject to several limitations throughout the various instances, including research strategy, study selection process, descriptive and content-based analysis. Firstly, as mentioned in Table 1, a specific search string was employed to retrieve relevant publications. While this approach ensured a focused and systematic search process, it may have inherently excluded studies that used alternative keywords or terminologies. Furthermore, only articles published in the English language were considered, potentially excluding significant research published in other regional languages. Additionally, the literature search was limited to Scopus database, which, although comprehensive, does not encompass all available academic sources. As a result, relevant studies in other databases such as google scholar and web of science may have been omitted. These limitations highlight the need for broader search strategies in future review to ensure more inclusive and representative coverage of the literature.

Another limitation arises from the screening and inclusion phase. Although a structured approach was applied, the initial relevance assessment was based solely on the author's interpretation of abstracts, which may introduce subjective bias. Relevant studies may have been inadvertently excluded due to insufficient detail in abstracts, particularly if the study's focus on LCA of PV systems was not clearly articulated.

In content analysis phase, the methodological aspects of LCA were primarily focused. While this provides valuable insights into how LCA is applied across various studies, the review lacks a detailed analysis in technical characteristics of PV technologies. This analysis covers

the conversion efficiencies and life expectancies but other aspects such as performance ratio, degradation rate, curtailment and direct & alternate current ratio, and back-up systems as given in [29] were not systematically reviewed. The absence of this dimension limits the review's ability to connect methodologies in LCA with physical behavior. Including such analysis would enhance the understanding of how technical PV system characteristics drive environmental outcomes and could help inform more accurate and context-specific LCA modelling in future research.

5 Conclusion

This study provides state-of-art for application of LCA on PV technologies. It explores current practices, identifies key challenges and future research. The review highlights the importance of LCA in understanding the environmental impacts of PV systems and guiding sustainable technology development.

The descriptive analysis shows a noticeable increase in related publications over the years, with significant rise in 2024, reflecting growing research interest. This reflects a growing interest among researchers in evaluating the environmental performance of solar systems. The increase may be attributed to rising global sustainability goals, policy pressures, and technological advancements in the PV sector. Overall, this trend underscores the expanding role of LCA as a vital tool in guiding the sustainable development of photovoltaic technologies.

This review synthesizes recent LCA studies on photovoltaic technologies, highlighting methodological inconsistencies, gaps in toxicity assessment, and limited end-of-life modelling. It extends prior work by incorporating updated data on material durability, toxic material management, and critical raw material recovery. The findings emphasize that material substitution alone is insufficient; environmental benefits depend on recyclability and integration into circular design strategies. Advancing standardized methods, expanding LCA scope, and incorporating LCC are essential to support the sustainable development of next-generation PV systems.

Addressing these challenges offers clear opportunities for future research. Standardizing the functional units and system boundary definitions would greatly enhance comparability and reproducibility. Expanding cradle-to-cradle studies is critical to capturing end-of-life impacts and circular economy potentials of PV technologies. Increasing the availability and use of primary data from real-world PV operations would reduce dependency on secondary sources and improve data quality. Additionally, broadening the scope of impact categories beyond GWP and energy metrics to include economical and social dimensions would provide a more holistic sustainability assessment. The SustEnMat project focuses primarily on resource depletion and toxicity impacts. Future work will evaluate resource-related impacts in greater detail, incorporating broader resource categories and advanced characterization methods. Finally, greater compliance with ISO standards, particularly regarding sensitivity and uncertainty analyses, is essential to strengthen confidence in LCA results and support decision-making in PV technology development and policy formulation.

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Supplementary Document

The supplementary document supporting this study is available from the corresponding author upon request.



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