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A Systematic Review of Life Cycle Assessment Reporting Practices and Transparency for Mono-Crystalline Silicon Photovoltaic Systems

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Mono-crystalline silicon (mono-Si) PV modules account for around 70 % of global c-Si production, making robust environmental assessments essential. Life Cycle Assessment (LCA) is widely used for this purpose, yet inconsistent data reporting limits transparency and comparability. While prior reviews have explored environmental impacts and parameter trends, none have systematically evaluated reporting quality in mono-Si PV LCAs. To address this, the current review conducted a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-guided review of 32 mono-Si PV LCA studies published from 2019 to 2024. Each was assessed using the ISO 14040/14044 framework and IEA guidelines, with a focus on key elements such as functional unit, system boundary, data sources, software, characterization models, and data quality analysis. The review applied both a descriptive summary of common practices and a grading rubric to evaluate reporting transparency. Results reveal major inconsistencies, with fewer than half of the studies meeting international standards. This underscores the urgent need for harmonized reporting protocols in mono-Si PV LCA literature.

1. Introduction

The global push for decarbonization has placed photovoltaic (PV) systems at the forefront of clean energy transitions. Among PV technologies, crystalline silicon (c-Si) modules accounted for about 98 % of total production in 2024, with monocrystalline silicon (mono-Si) dominating (Fraunhofer ISE, 2025). Their widespread deployment demands robust environmental assessment across the full life cycle, from raw material sourcing to end-of-life management. Life Cycle Assessment (LCA) is the benchmark method for quantifying environmental burdens and enabling sustainability comparisons (Liu et al., 2024). Despite its broad adoption, inconsistencies in LCA implementation—particularly in PV literature—remain challenging. Key elements such as functional unit, system boundaries, data sources, and characterization methods are often poorly defined or inconsistently justified. This lack of standardization undermines transparency, reproducibility, and comparability, especially as LCA influences policy and investment decisions. Previous reviews have mainly evaluated PV LCAs from a performance perspective, summarizing metrics like EPBT, GHG emissions, and efficiency (Gerbinet et al., 2014), but offer limited methodological insight. Muteri et al. (2020) discussed functional units and boundaries without structured quantification. Cellura et al. (2024) reviewed diverse PV technologies, diluting relevance to mono-Si despite its global dominance. To date, no review has systematically analyzed methodological practices or reporting transparency focused exclusively on mono-Si. To address this, the present study conducts a PRISMA-guided systematic review of 32 mono-Si PV LCA studies published between 2019 and 2024. Following ISO 14040/44 and IEA PVPS Task 12 guidance, the review applies a dual-stage analytical framework. The first

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stage identifies common practices in key methodological areas; the second applies a grading rubric to evaluate transparency across six elements: functional unit, system boundary, data sources, software, characterization method, and data quality analysis. By combining practice mapping with standardized reporting assessment, this dual-stage approach offers both descriptive and normative insights. It highlights current PV LCA trends while identifying critical transparency gaps, key to improving reproducibility and cross-study comparability.

2. Methodological Framework: PRISMA-Guided Screening and Dual-Stage Assessment for Mono-Si PV LCA Studies

A systematic review via the PRISMA method (Figure 1) was conducted using the Scopus database for studies published between 2019 and 2024 on the LCA of PV systems. This five-year range also reflects recent advancements in PV manufacturing, LCA software, and updated methodological guidelines, ensuring both relevance and methodological comparability. Review articles, conference papers, retracted works, and non-English publications were excluded. Studies were further screened to include only those focused solely on PV systems, excluding those that combined PV with other energy technologies or referenced PV only as a generic electricity source. Papers that mentioned LCA without applying it as a core methodology were also removed. To ensure quality, only articles indexed in the Web of Science with a 2023 Impact Factor were considered, with a focus on journals in the top 50 % by impact factor. Finally, the selection was narrowed down to 32 studies that specifically analyzed mono-Si PV systems to ensure technological consistency.

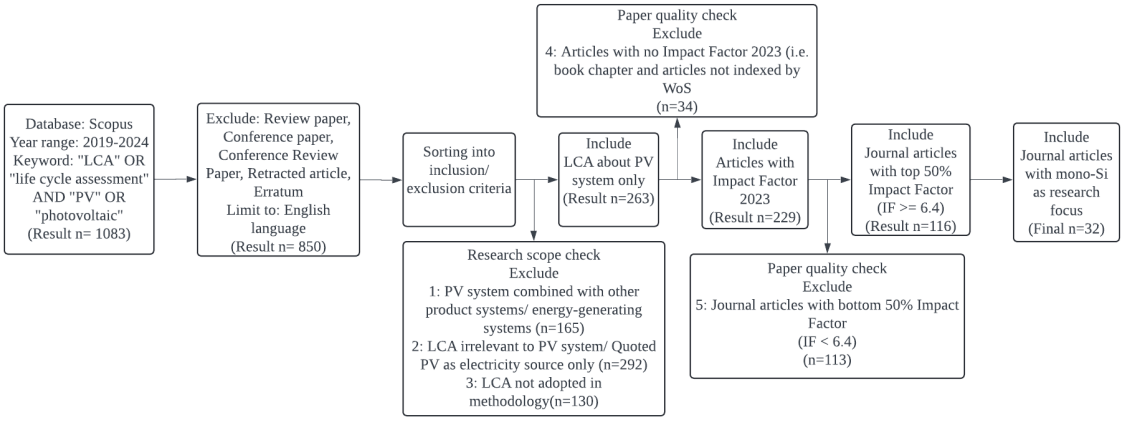

Figure 1: PRISMA screening and selection process for mono-crystalline silicon PV LCA studies

Table 1: Grading rubric for data reporting quality

LCA Elements	0	1	2
Functional unit	Not stated	Stated with no explanation on the choice of functional unit and/or inappropriate functional unit being used.	Stated with explanation on the choice of functional unit and the appropriate functional unit being used.
System boundary	Not stated	Stated with no explanation on exclusions of process/ material. No schematic diagram.	Stated with explanation on exclusions of process/ material. Have a schematic diagram.
Data collection method	Not stated	Stated	-
Software	Not stated	Stated with no explanation of choice	Stated with an explanation of choice. Or did not use software with an explanation
Characterization method	Not stated	Stated with no explanation of choice	Stated with an explanation of choice. Or did not use the characterization method with an explanation
Data quality analysis	Not stated	Stated	-

This study adopts a two-stage review framework to evaluate both methodological practices and reporting quality in recent LCAs of monocrystalline silicon (mono-Si) photovoltaic (PV) systems. The review draws on two key standards: ISO 14040/14044, which define the general LCA structure (goal and scope definition, inventory analysis, impact assessment, and interpretation), and the IEA PVPS Task 12 guidelines, which offer PV-specific

methodological recommendations. The ISO standards stress transparency and consistency across all LCA phases. The IEA Task 12 guidelines support this by providing harmonized expectations tailored to PV LCAs, including best practices for degradation modelling, allocation procedures, and assumption reporting. In the first review stage, common methodological practices across 32 selected studies are identified and assessed (Table 2) for alignment with ISO and IEA guidelines. In the second stage, a grading rubric (see Table 1) is applied to evaluate the transparency of reporting across six core LCA elements.

3. Results and Discussion

3.1 Common Practice

Table 2 indicates common practice of studied papers. The total count of elements exceeds 32 because some studies reported multiple methodological configurations (e.g. multiple functional units). For details on how each study addressed individual LCA elements, see the matrix table (Loh et al., 2025). Section 4.2.3.2 ISO 14044 requires the FU to be clearly defined and aligned with the goal and scope of the study. (ISO 14040:2006, 2006) IEA PVPS Task 12 further recommends using kWh of AC electricity delivered to the grid for PV systems, especially for comparative and system-level analyses. Most studies used kWh or MWh, consistent with IEA guidance. Five studies used m² as the FU, three within cradle-to-gate and two within cradle-to-cradle scopes. In these cases, the choice is consistent with IEA recommendations, which consider m² appropriate when assessing production or end-of-life (EoL) processes. Some studies applied kW_p as the FU in comparative analyses across PV technologies. This introduces bias, as kW_p reflects rated capacity but not actual energy yield or system performance. This explains why IEA guidelines limit the use of kW_p to evaluating electrical components (e.g., inverters). Yuan et al. (2024) compared mono-, multi-, and amorphous Si modules using kW_p without normalization for performance differences, making their results difficult to interpret. Many studies lacked explanations or failed to match the FU to the system boundary. Thus, greater consistency in defining and justifying FUs would enhance transparency and enable future comparability across PV LCA literature.

Table 2: Common Practice of Studied Papers

LCA Element	No. of LCA studies	LCA Elements	No. of LCA studies	LCA Elements	No. of LCA studies
Functional Unit		Cradle-to-cradle only	1	efootprint	2
Electrical energy generation	14	End of life (No recycling/ recovery)	0	Activity-Browser	1
Area of panel	5	Not stated	1	Not stated	7
Nominal power	5			Characterization	
PV system component	3	Data Collection Method		Method	
Mass of panel	2	Database	30	ReCipe	8
LCA life stage	2	Journal article	25	CML	7
Others	5	Report	20	ILCD	4
Not stated	0	Primary data	11	IPCC	3
		Others	5	EF	2
System Boundary		Not stated	0	IMPACT	2
Cradle-to-gate	7	Time-related data	16	Others	4
Cradle-to-grave only	7	Geographical data	30	Not stated	7
Cradle-to-grave and Cradle-to-cradle	6	Software		Data Quality Analysis	
End of life (Recycling/ recovery)	4	Sima Pro	14	Sensitivity analysis	15
Cradle-to-use	3	OpenLCA	6	Uncertainty analysis	1
		Gabi	2	Not stated	17

System boundary (SB) defines which life cycle stages are included in an LCA and must align with the study's goal and scope. IEA PVPS Task 12 recommends a cradle-to-cradle model, yet many reviewed papers diverged from this approach. 18 studies used general terms like "manufacturing" or "disposal" rather than standardized boundary definitions; these were reclassified for consistency without changing their meaning. Only six studies adopted a cradle-to-cradle approach, though this does not indicate poor practice. For example, Müller et al. (2021) used a cradle-to-gate plus end-of-life (EoL) model, excluding the use phase due to the minimal expected differences between systems, showing that boundaries can be modular and tailored. Among the reviewed studies, none modelled end-of-life (EoL) scenarios that excluded recycling or material recovery processes.

Cradle-to-grave boundaries were found only in pre-2022 publications, suggesting a shift toward circularity and better access to EoL inventory data, likely influenced by policy changes and improved modelling tools.
All reviewed studies addressed data collection, though the scope and completeness varied. Time-related data coverage was partially reported in 16 studies, typically limited to specific sources. Guillén-Lambea et al. (2023) documented the vintage of their Ecoinvent dataset, justifying its use based on software compatibility. Geographical coverage was more consistently reported, with 28 studies identifying country-level data sources and 16 specifying city or district-level origins. This detail enabled certain studies, such as those by Oteng et al. (2023), to refine transport distances and logistics emissions, thereby improving spatial accuracy.
IEA PVPS Task 12 emphasizes the importance of documenting the software used to ensure transparency regarding assumptions, methods, and database compatibility. SimaPro emerged as the dominant tool, largely due to its integration with the Ecoinvent database, broad methodological range (e.g., CML, ReCiPe), and strong alignment with European practices. Prior studies (Herrmann and Moltesen, 2015) have highlighted its strengths in handling multi-regional datasets and detailed process modeling. OpenLCA has been featured in four studies and remains a widely available, free option. However, its limited documentation and calculation errors for varying impacts may have hindered broader adoption (Mulya et al., 2022).
For characterization, ReCiPe was the most commonly used method (8 studies), followed by CML (7 studies) and ILCD (4 studies). ReCiPe's integrative design supports both midpoint and endpoint indicators, whereas CML is preferred for midpoint-focused assessments of traditional impacts, such as global warming and acidification. Seven studies did not explicitly report any characterization method. Zhu et al. (2024) and Dong et al. (2024) substituted formal methods with calculations of carbon payback time (CPBT) or energy payback time (EPBT). Though not formal LCIA methods, these metrics were supported by equations and used as performance indicators. In some cases, GHG emissions were reported without explaining the impact assessment method, raising concerns about reproducibility. This review highlights that clear documentation and equations for custom metrics are essential to ensure that results remain traceable and credible for comparison and meta-analysis.
Data Quality Analysis, though critical, is often overlooked in PV LCAs. ISO 14044 stresses the importance of sensitivity and uncertainty analyses in assessing robustness. The scope of the sensitivity analysis varied. Herceg et al. (2022) studied system lifetime and degradation rates, while Pimentel Pincelli et al. (2024) explored alternative LCI datasets. Fthenakis and Leccisi (2021) evaluated different electricity mixes. This variety aligns with ISO guidance that data quality assessment should reflect each study's specific goal and scope.

3.2 Data Reporting Quality

Figure 2 illustrates the data reporting quality of mono-Si PV system LCA studies in this review.

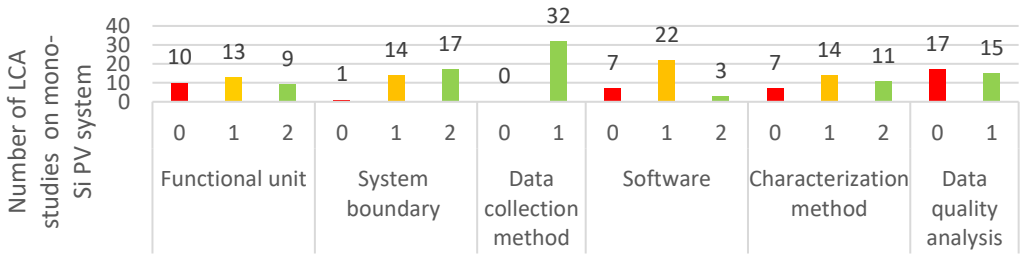

Figure 2: Data reporting quality of mono-Si PV system LCA studies, categorized by key elements and grades

For FU, studies scoring 0 in our rubric mentioned a unit (e.g., per m² or kWh) only in the Results, without defining it in the Goal and Scope. Li et al. (2022) listed energy and GHG emissions per life stage without a normalization basis. Wang et al. (2024) referenced m² as a denominator but omitted a formal FU. Although its system boundary spans production, integration, operation, transmission, and retirement, it excludes BOS components. Without a clear FU, it is unclear whether all system elements were consistently considered. Conversely, several studies demonstrated strong practices. Kabayo et al. (2019) used "1 MWh of electricity averaged over 2012–2016" to account for inter-annual variability. Herceg et al. (2022) justified the use of DC electricity based on system design and delivery point, demonstrating how FU can reflect specific system configurations.
Regarding transparent system boundary (SB) reporting, ISO recommends schematic diagrams to illustrate unit process flows and boundaries. This review found these diagrams valuable, especially for complex or comparative systems. Dong et al. (2024) effectively used visuals to differentiate configurations. High-scoring studies also provided clear explanations for exclusions, such as marginal BOS components (Müller et al., 2021), negligible use phases, or EoL stages excluded due to uncertainty or data gaps, as in Le et al. (2024) and

Bahlawan et al. (2020). These justifications generally align with ISO's transparency requirements and reflect sensitivity to methodological limits. Such clarity is essential, as inconsistent or undefined system boundaries can lead to misleading comparisons by conflating results based on fundamentally different life cycle scopes.
In data collection, none of the studies employed a structured rubric to assess quality according to ISO 14044. This is a methodological gap, as ISO recommends evaluating data quality based on time, geography, representativeness, and uncertainty. Future studies could benefit from frameworks such as the Ecoinvent pedigree matrix, which assesses six quality dimensions (e.g., reliability, correlation, temporal and geographical relevance), or the ILCD Data Quality Rating (DQR), which provides standardized scores across key indicators.
For software, only three papers gave reasons for their tool selection, and these were superficial. Klugmann-Radziemska and Kuczyńska-Łażewska (2020) cited SimaPro for compatibility with European datasets but did not elaborate on its technical suitability. No study has conducted a comparative software assessment, though such comparisons are essential. Iswara et al. (2020) found that the same input data can yield different results across tools like SimaPro and OpenLCA, due to variations in characterization factors, sub-compartment mapping, and LCIA implementation. Even under harmonized conditions, Lopes Silva et al. (2019) observed considerable variability, underscoring the need for transparent reporting of software choice and assumptions.
Only 11 studies justified their choice of characterization method. Oteng et al. (2023) selected a region-specific approach to align with local impact conditions, while Phuang et al. (2022) opted for ReCiPe, citing its combination of CML-IA midpoint and Eco-indicator 99 endpoint benefits. Though rare, such justifications represent best practice by aligning method selection with study scope.
Of the 32 studies reviewed, 15 conducted data quality analysis. Only one used a Monte Carlo simulation for uncertainty analysis. The other 17 did not report any form of data quality evaluation. This limited adoption reveals a methodological shortfall, despite ISO and IEA guidelines stressing the need for data quality analysis to support robust LCA interpretation. While both ISO 14044 and IEA PVPS Task 12 describe DQA methods as optional and context-dependent ("if needed"), this flexibility is intended to accommodate diverse study goals, not to justify its omission without explanation. In this review, studies that failed to even acknowledge DQA were scored accordingly, in line with ISO's broader principle of transparent and complete reporting.

4. Conclusions

This study reviewed 32 mono-Si PV LCA studies published between 2019 and 2024 using a dual-stage framework aligned with ISO 14040/44 and IEA PVPS Task 12. The analysis revealed significant variation in methodological practices and widespread shortcomings in reporting transparency. The most frequently used functional unit—kWh electricity—aligned well with IEA recommendations, but justification was often lacking. System boundary definitions also varied, with limited use of visual schematics or clear exclusion criteria. Software and characterization methods were often reported without rationale, affecting the traceability of results. Sensitivity analysis was more commonly applied than uncertainty analysis, but both were inconsistently documented. While these inconsistencies highlight a need for better reporting, they do not imply that there is only one correct way to conduct a PV LCA. The flexibility of the LCA framework remains a strength, allowing for context-specific choices in functional unit, system boundary, and software, so long as these choices are clearly justified and aligned with the study's goal and scope.

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