

Life Cycle Sustainability Assessment of Solar Energy Systems: A Review Work

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Abstract

The rapid growth of solar energy systems worldwide is crucial for achieving climate goals. However, fully understanding their sustainability requires looking beyond their low emissions during operation. This publication provides a chance to review how the Life Cycle Sustainability Assessment (LCSA) framework has been applied to solar photovoltaic energy systems and thermal technologies. It gathers findings from the three pillars of sustainability: environmental, economic, and social. It focuses on Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social LCA (S-LCA). The review outlines methodologies, key indicators, and impacts related to processes from raw material extraction to end-of-life management. The results highlight significant climate benefits, including low lifecycle greenhouse gas emissions and improved energy payback periods. However, environmental challenges still exist in manufacturing, the use of essential materials and waste generation. Regarding economic factors, costs have decreased due to technological improvements but they are still affected by balance-of-system components and decommissioning costs. On the social front, solar energy boosts job creation and expands energy access. Yet there are ongoing issues related to labor practices in supply chains and effects on local communities. Major challenges include inconsistent methods, a lack of data for S-LCA, and regional variations. This review reiterates the significance of incorporating multiple-approach evaluation to make analytic decisions, which finally have made an economic impact and sustainably promote solar energy transition in the 21st century.

Keywords

LCSA, Renewable Energy, Environmental Life Cycle Assessment LCA, LCC, Social Life Cycle Assessment (S-LCA), End-of-Life Management

1. Introduction

1.1. The Imperative for Sustainable Energy Transitions

The global shift towards sustainable energy systems is an indispensable pillar for meeting international climate targets, such as the Paris Agreement's 1.5°C goal, and achieving the United Nations Sustainable Development Goals (SDGs), most importantly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [1] [2]. The working concept for decarbonizing the power sector, which accounts for a significant section of global greenhouse gas (GHG) emissions, needs the rapid and widespread deployment of renewable energy technologies [3]. Among these, solar energy systems, encircling photovoltaic (PV) modules for electricity generation and solar thermal technologies for heat production, have witnessed unique growth. This increasing growth is empowered by dramatic cost reductions (often described by Swanson's law of learning curves), inherent modularity, and scalability, making solar a leading candidate for primary energy supply in numerous national strategies [4] [5].

1.2. The Holistic Sustainability Challenge of Solar

While justifiably acknowledged for their near-zero operational emissions, solar energy systems come with environmental, economic, and social impacts across their value chain. A narrow focus on the actions of GHG savings risks perpetuating a form of "burden shifting", where solving a climate problem triggers issues in other domains, such as resource depletion, ecosystem damage, or social inequity [6]. Therefore, globally branding solar energy as universally "green" or "clean" is a global fallacy. Its true sustainability profile must be rigorously evaluated across the entire life cycle, from the extraction of important raw materials and natural resources (e.g., graphite, aluminum, silicon, indium) and energy-intensive manufacturing, through life long operations, to final abandonment and end-of-life (EoL) management [7] [8]. This entire perspective is critical to ensure that paradigm shift in the renewable energy is sustainable, resilient, and just.

1.3. Life Cycle Sustainability Assessment (LCSA) as an Integrative Framework

To address this multi-faceted challenge, Life Cycle Sustainability Assessment (LCSA) has emerged as the overarching analytical framework for industrial ecology. As conceptualized by Kloepffer [9], LCSA integrates three complementary pillars:

- Environmental Life Cycle Assessment (LCA): Evaluates potential environmental impacts (e.g., global warming potential, water use, ecotoxicity) using standardized ISO 14040/44 principles.
- Life Cycle Costing (LCC): Assesses all economic costs associated with a product system over its life cycle, from a private (financial) or societal (socio-economic) perspective.
- Social Life Cycle Assessment (S-LCA): Analyzes the social and socio-economic

impacts on stakeholders (e.g., workers, local communities, consumers), guided by UNEP/SETAC [10] guidelines.

LCSA does not merely conglomerate these characterizations but seeks a synergistic integration to avoid sub-optimization and support balanced decision-making [11]. Applying LCSA to solar power systems gives way for a comparative analysis of technologies, identifies environmental and social “flashpoints”, informs policy design, and guides technological advancement that gears toward more sustainable roadmaps.

1.4. Scope and Objective of This Review

This paper presents a comprehensive and critical review of the application of the LCSA framework to solar energy systems. We synthesize findings from a broad corpus of literature to map the methodological landscape, consolidate key results, and identify critical pathways for future research. Specifically, this review aims to:

Map the methodological approaches, system boundaries, and key sustainability indicators used in LCA, LCC, and S-LCA studies for solar PV and solar thermal technologies.

- Synthesize consensus findings on environmental flashpoints, economic drivers, and social considerations, while highlighting regional variations due to factors like grid mix, manufacturing location, and policy context.
- Identify persistent methodological challenges and critical research gaps, particularly in the underdeveloped domain of S-LCA, the integration of circular economic strategies at EoL, and the harmonization of data for robust comparative analysis.
- Provide structured recommendations for advancing robust, integrated sustainability assessments to inform coherent energy policy, industrial strategy, and sustainable system design.

To visually frame the scope of this review and the interconnected pillars of LCSA for solar energy, **Figure 1** presents a conceptual framework diagram. **Table 1** summarizes key performance indicators (KPIs) used in life cycle sustainability assessment (LCSA), structured across the three core pillars: environmental, economic, and social. The selected indicators and their corresponding units, such as global warming potential (GWP), levelized cost of electricity (LCOE), and social impact metrics are widely adopted in sustainability evaluations to ensure a comprehensive and standardized assessment of energy systems [12]–[14].

Figure 1 organizes a multi-faceted analysis by connecting three core pillars with specific product phases and key research themes, as depicted in the conceptual framework of the systematic review [12] [15].

The Sustainability Pillars (Three-Pillar Approach): On the left, a Venn diagram (or similar overlapping structure) defines the scope, identifying the integrated pillars of sustainability assessment [12] [13]. Environmental life cycle assessment (LCA) analyzes environmental impacts, with particular emphasis on emissions and material efficiency [13]. Economic life cycle costing (LCC) evaluates direct

monetary costs and long-term financial feasibility [16]. Social life cycle assessment (S-LCA) examines impacts on people, communities, and labor conditions, drawing from established social assessment frameworks [14].

Table 1. Key Sustainability indicators for solar energy systems UNEP & SETAC [63]; UNEP/SETAC [10].

Pillar	Key Performance Indicators (KPIs)	Common Units/Metrics
Environmental (LCA)	Global Warming Potential (GWP), Energy Payback Time (EPBT), Cumulative Energy Demand (CED)	gCO ₂ eq kWh/Years MJ
Economics (LCC)	Levelized Cost of Electricity (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR)	\$/kWh, Currency (\$), Percentage (%)
Social (S-LCA)	Human Rights, Health and Safety, Local Employment, Community Engagement	Qualitative, Scales, Accident Rates, Jobs/MW

Product/Technology Life Cycle Phases: In the center column, grey rounded rectangles map how these pillars apply across different stages of the life cycle, tracing the progression from raw material extraction through manufacturing, use, and end-of-life management [15]. This life cycle perspective ensures a comprehensive evaluation of sustainability impacts over time [12].

Key Research Themes: The right column outlines the major themes synthesized in the review, including methodological approaches, comparative analysis of results, identification of regional variations, and assessment of existing challenges and research gaps [12] [17]. These themes provide critical insights into the current state and limitations of life cycle sustainability assessment studies.

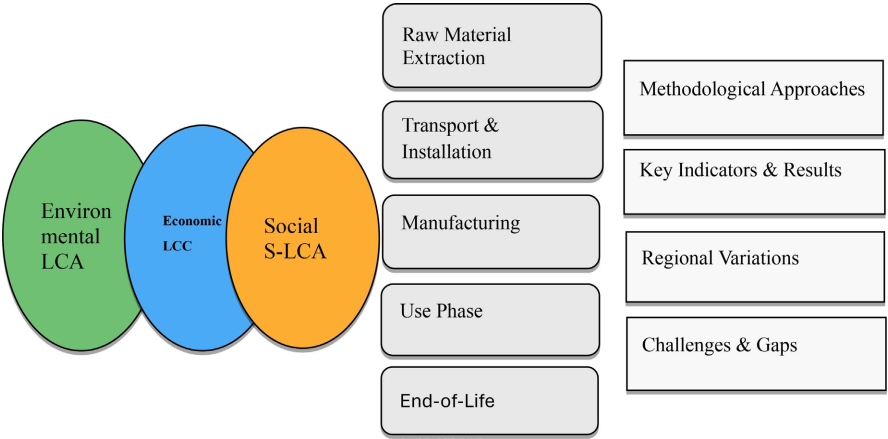


Figure 1. Conceptual framework for reviewing life cycle sustainability assessment (LCSA) of solar energy systems. UNEP & SETAC [63]; Finkbeiner *et al.* [18]; Onat *et al.* [12]; Sala *et al.* [19].

2. Methodology

This review employs a systematic narrative approach to synthesize and critically

evaluate the literature on Life Cycle Sustainability Assessment (LCSA) of solar energy systems. The approach used combines a structured and transparent literature selection process with qualitative synthesis, making it well suited to a research field characterized by methodological heterogeneity.

The methodological workflow adopted in this study is illustrated in **Figure 2**, which outlines the sequential steps followed in conducting the review.

This review is conducted as a narrative (critical) review structured by a purposive search and citation-tracking (snowball) process, rather than as a fully registered systematic review; it does not follow a pre-registered protocol (e.g., PROSPERO), report a PRISMA-style record-screening funnel, or use dual-reviewer screening with inter-rater agreement, and claims of comprehensiveness elsewhere in this paper should be read with that scope in mind. The search was conducted across Scopus, Web of Science and ScienceDirect using combinations of the terms “life cycle sustainability assessment”, “life cycle assessment”, “life cycle costing”, “social life cycle assessment”, “photovoltaic”, “solar thermal”, and “concentrated solar power”, restricted to publications from 2008-2024 in the English language, and supplemented by citation tracking from key review articles. The search strategy was informed by predefined keywords and is broadly consistent with the International Reference Life Cycle Data System guidelines [15], which supports transparency in study identification. The full list of the 22 technology-specific studies underlying **Figure 3** and Sections 3 - 5, together with each study’s assigned technology category, is provided in supplementary table in **Appendix**.

Rather than reporting a formal PRISMA-style funnel of records identified, screened, and excluded at each stage, this review draws on a purposive narrative sample of studies identified through the search and citation-tracking process described above. This sample comprises 22 technology-specific studies applying at least one LCSA-related method (E-LCA, LCC, or S-LCA) to a solar PV or solar thermal technology, which forms the evidence base synthesized in Sections 3 - 5, including the technology distribution reported in **Figure 3**; this is supplemented by a further set of framework, standards, and institutional-report references used for conceptual and contextual grounding but not counted toward the technology distribution. Eligibility criteria for the 22 technology-specific studies required that a study: 1) Be a peer-reviewed journal article (grey literature, theses, and non-academic sources were excluded to maintain methodological consistency); 2) Apply at least one LCSA-related method to a solar PV or solar thermal technology; 3) Report primary or secondary quantitative or qualitative sustainability indicators rather than purely technical performance data. Because included studies used varying functional units, this review synthesizes results primarily at the level of the technology category (e.g., c-Si PV, thin-film PV, CSP), using per-kWh-generated indicators (e.g., g CO₂-eq/kWh, \$/kWh) as the common basis for comparison where studies reported them, and noting explicitly where a study’s original functional unit (e.g., per module, per installed kWp, per m² of collector area) required this conversion or where comparability was consequently limited. The selected

studies were then critically evaluated based on key methodological attributes, including system boundaries and functional units as defined in ISO standards [13], as well as life cycle stages and sustainability indicators spanning environmental, economic, and social dimensions. The integration of social impact considerations further reflects established S-LCA frameworks [14], ensuring a balanced and comprehensive assessment.

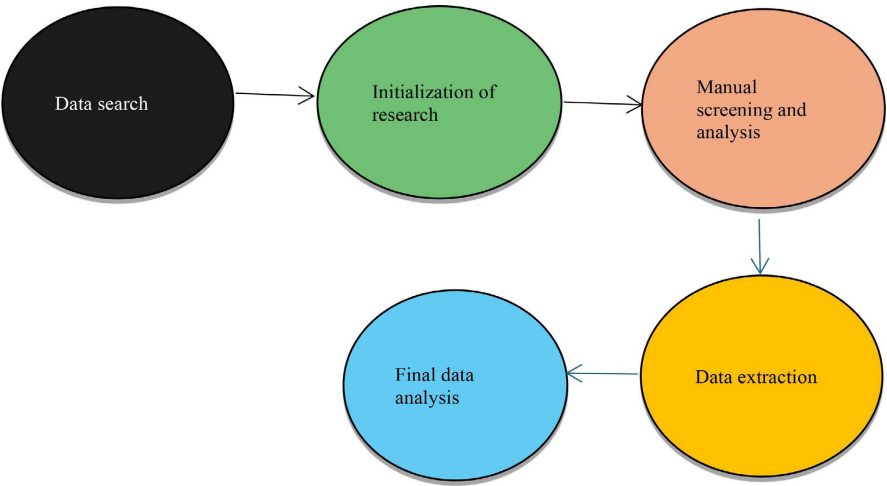


Figure 2. Schematic workflow for the study.

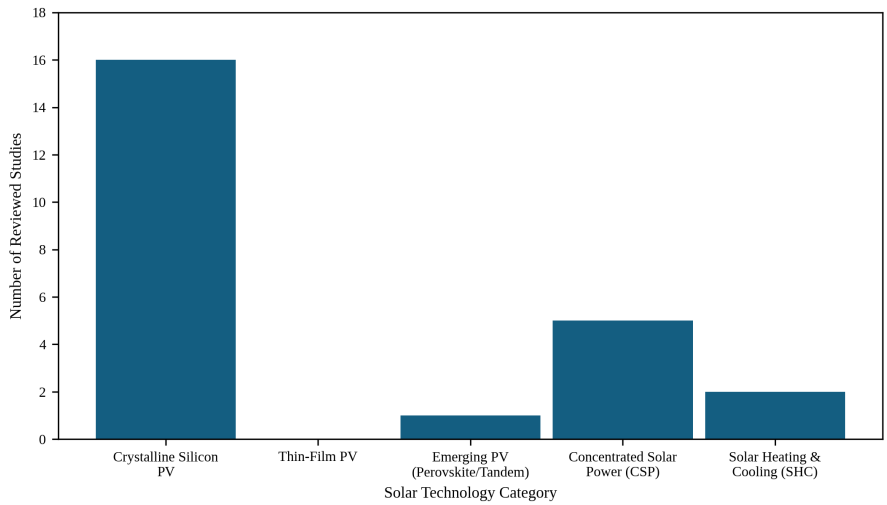


Figure 3. Distribution of reviewed studies across major solar energy technologies discussed in this review.

Subsequently, a structured data extraction and qualitative synthesis process was employed to capture essential information from each study, including solar technology types, analytical framework, geographical scope, and performance indicators. Rather than relying on statistical aggregation, the analysis emphasizes interpretative synthesis to identify recurring methodological patterns, dominant indicators, regional variations, and existing research gaps, as recommended in LCSA

review studies [17]. This integrative approach enables a holistic understanding of sustainability performance across the life cycle of solar energy systems while aligning with contemporary multi-dimensional evaluation frameworks [12].

The workflow presented in **Figure 2** provides a clear visual representation of the research process and reinforces the transparency and coherence of the review methodology.

3. Overview of Solar Energy Systems

The transition toward a decarbonized global energy environment is strongly dependent on the scalability, technology development, and sustainability performance of solar energy technologies, which are globally acknowledged as critical components of low-carbon energy transitions [20] [21]. Nonetheless, all solar technologies derive energy from a universal primary source, that is solar radiation emitted from the sun. This phenomenon forms the fundamental basis of solar energy conversion systems [22]. However, different solar knowhows vary significantly in terms of material composition, energy conversion mechanisms, manufacturing complexity, and operational characteristics [23]. These scientific distinctions play a critical role in shaping their respective environmental, economic, and social impacts when evaluated within a Life Cycle Sustainability Assessment (LCSA) framework, which integrates life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) [12] [18].

3.1. Photovoltaic (PV) Technologies

Photovoltaic (PV) technologies constitute the most widely deployed category of solar energy technologies, characterized by the direct conversion of incident photons into electricity through the photoelectric effect [20] [22]. Commercial PV technologies are commonly classified into distinct “generations”, a categorization based primarily on the type of semiconductor materials used and the technological maturity of the systems [24] [25]. First-generation technologies typically include crystalline silicon-based cells, while second and third-generation technologies comprise thin-film and emerging materials with different efficiencies, costs, and scalability potentials [23] [24].

3.1.1. Crystalline Silicon (c-Si) Systems

Crystalline silicon remains the dominant PV technology, accounting for more than 95% of global module production. It is largely divided into monocrystalline and polycrystalline silicon technologies.

- **Monocrystalline silicon (mono-Si):**

These cells are produced from high-purity single-crystal silicon ingots. They offer the highest commercially available conversion efficiencies, typically in the range of 20% - 24%. However, their manufacturing process, particularly the Czochralski crystal growth method is energy-intensive, resulting in higher embodied energy and influencing their energy payback time (EPBT) during the early life-

cycle stages [26].

- **Polycrystalline silicon (multi-Si):**

They are cells manufactured by melting silicon feedstock and casting them into square molds. This process carries minimal energy and it's more cost-effective, but results in lower output efficiencies outcome, generally between 17% and 20%. In recent years, polycrystalline technology has undergone a steady decline in market share due to the rapid adoption of high-efficiency mono-PERC (Passivated Emitter and Rear Cell) technologies, which combine higher performance with reducing production costs [27].

3.1.2. Thin-Film Technologies

Thin-film photovoltaic (PV) technologies are generally based on the deposition of one or more thin semiconductor layers onto substrates such as glass, plastic, or metal, enabling reduced material usage and flexible applications compared to conventional crystalline silicon systems [22] [25]. The most commercially established thin-film technologies include cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), both of which have attained remarkable market penetration due to their relatively lower manufacturing costs and competitive performance indicators [23] [24].

Sustainability profile, owing to decreased material thickness and lower processing temperatures, thin-film PV systems generally exhibit a lower carbon footprint and shorter EPBT compared to crystalline silicon technologies. Nevertheless, the reliance on limited or hazardous elements, such as cadmium and tellurium raises concerns related to resource availability, toxicity, and end-of-life management. These issues highlight the importance of effective recycling systems and circular economic approaches within an LCSA perspective [28].

3.1.3. Third-Generation PV Technologies

Third-generation photovoltaic technologies, particularly perovskite solar cells (PSCs) and tandem configurations such as perovskite-on-silicon, represent some of the most actively researched areas in photovoltaic innovation due to their rapid efficiency improvements and scalability potential [25] [29]. These advanced technologies depict significant potential for achieving high power conversion efficiencies while enabling low-cost manufacturing through solution-based processing methods, such as spin-coating and printing methods [23] [30]. Their emergence reflects a paradigm shift in solar cell development, with tandem architectures in particular offering pathways to surpass the efficiency limits of single-junction silicon-based systems [29].

Irrespective of their quality, significant challenges remain, most especially regarding long-term operational stability, degradation under environmental stressors, and concerns surrounding the hazardous propensities of lead-based components. As a result, their sustainability performance remains largely theoretical and subject to ongoing technological reviews [31].

Of the $N = 22$ technology-specific studies included in this review (supplementary table in **Appendix**), **Figure 3** illustrates their distribution across major solar energy technologies: 16 addressed crystalline silicon (c-Si) or general PV, 5 addressed concentrated solar power (CSP), 2 addressed solar heating and cooling (SHC), and 1 addressed emerging PV (perovskite/tandem) technologies; notably, no included study addressed thin-film PV specifically, which we treat as an identified evidence gap rather than an omission. Category totals sum to more than 22 because one cross-cutting study [32] addresses multiple technologies and is counted in every applicable category. The Emerging PV (perovskite/tandem) count is represented by Tian, Stranks, & You (2020) [31]. A full list mapping each included study to its technology category is provided in supplementary table in **Appendix**. To satisfy the peer-reviewed journal article eligibility criterion stated above, three institutional/technical reports previously counted among the 22 included studies [25] [33] [34] have been replaced in supplementary table in **Appendix** and in **Figure 3** counts by peer-reviewed studies covering equivalent ground: Bolinger, Wiser, and O’Shaughnessy [5] on PV cost learning, Tsanakas *et al.* [35] on PV end-of-life recycling and circularity, and Palacios *et al.* [36] on CSP thermal energy storage, respectively. The three original reports are retained in the reference list as supplementary technical context but are no longer counted among the 22 core included studies. Crystalline silicon photovoltaic (PV) systems and concentrated solar power (CSP) dominate the reviewed literature, reflecting their technological maturity and widespread commercial deployment, which have led to extensive life cycle sustainability assessment (LCSA) studies [20] [23]. In contrast, emerging technologies such as perovskite and tandem solar cells are represented by markedly less research, and thin-film PV by none at all in the studies meeting our eligibility criteria, indicating their relatively early stage of LCSA-specific evaluation and limited availability of long-term performance data.

This disparity is largely due to key technical and sustainability challenges associated with emerging PV technologies. For example, perovskite solar cells, although highly efficient in laboratory conditions, face significant issues related to long-term operational stability under environmental stressors such as moisture, heat, and ultraviolet exposure [29] [30]. In addition, concerns about the use of lead-based materials raise environmental and social sustainability issues within LCSA frameworks, particularly under environmental LCA and social S-LCA dimensions [12] [37]. These limitations contribute to the scarcity of robust, long-term datasets required for comprehensive sustainability assessment.

3.2. Solar Thermal Systems

In contrast to photovoltaic systems, solar thermal technologies capture solar radiation and convert it into thermal energy, which can be utilized directly for heating applications or indirectly for electricity generation through thermodynamic cycles [20] [22].

3.2.1. Concentrated Solar Power (CSP)

Concentrated Solar Power (CSP) systems operate by using mirrors or lenses to concentrate solar radiation onto a receiver, thereby producing high temperature heat that drives a thermodynamic cycle, typically a steam or gas turbine connected to an electrical generator [20] [38]. CSP technologies are particularly notable for their ability to incorporate thermal energy storage, which enhances dispatchability and enables electricity generation even in the absence of direct sunlight [39].

Thermal Energy Storage (TES) has comparative advantage of CSP systems is their ability to integrate thermal energy storage, typically using molten salts. This capability enables electricity generation during periods of low or no solar radiance, thereby providing dispatchable renewable power and enhancing grid stability [40].

Material intensity, with this innovation CSP installations are highly material-intensive, requiring appreciable quantities of steel, concrete, glass, and heat transfer fluids (HTFs). From an LCSA standpoint, environmental impacts are often concentrated in the construction and infrastructure phases, as well as in the production and management of HTFs [41] [42].

3.2.2. Solar Heating and Cooling (SHC) Systems

These technologies convert solar radiation into heat energy for applications such as domestic hot water production, room heating, space cooling, and industrial process heat. Common collector designs include flat-plate collectors and evacuated tube collectors.

Though technically less complex than CSP systems, SHC technologies play a critical role in sustainability by directly displacing fossil-fuel-based heating, which continues to account for a substantial percentage of global final energy usage. Their life-cycle sustainability benefits are particularly echoed in locations with high heating demand and limited access to low-carbon thermal energy sources [43]. Most especially region that experience winter seasons and very low temperature regimes.

3.2.3. Life-Cycle Sustainability Synthesis for CSP and SHC

Compared with PV, the LCSA evidence base for CSP and SHC is considerably smaller (Section 3.1, **Figure 3**), but the available studies point to a distinct sustainability profile rather than simply a data gap. Environmentally, CSP's life-cycle GWP is generally reported in a broadly similar range to c-Si PV per kWh generated, but with a different distribution of burden: impacts are concentrated in the construction and infrastructure phase (steel, concrete, and mirror/receiver manufacturing) rather than in upstream cell processing, and the heat transfer fluids (HTFs) and molten-salt thermal storage systems used to enable dispatchability introduce additional material-intensity and, in some HTF formulations, toxicity and fire-safety considerations during operation and end-of-life [36] [41] [42]. Economically, CSP's high capital expenditure and reliance on thermal energy storage generally yield a higher levelized cost of electricity than utility-scale PV, though this is partly offset by CSP's dispatchability value, which is not captured

by LCOE alone. Socially, CSP plants are typically utility-scale, land-intensive installations concentrated in high-irradiance, often water-scarce regions, raising water-use and land/community-impact considerations (via cooling and mirror-washing needs) that are less pronounced for distributed PV. SHC systems, in contrast, are comparatively low-impact and low-cost across all three pillars given their mechanical simplicity, and their principal sustainability contribution is the direct displacement of fossil-fuel-based heating rather than competitive electricity-sector metrics; however, the LCSA literature on SHC remains sparse, particularly for the economic and social pillars, and this review's conclusions for SHC should accordingly be treated as provisional. Overall, given that the reviewed evidence base is predominantly PV-focused, the comparative statements above for CSP and SHC are necessarily less granular than those provided for PV in Section 4, and are flagged as a priority area for future synthesis (Section 6).

3.3. Comparative Technical and Material Metrics

The sustainability performance of solar energy systems is closely linked to their raw material sources, conversion rates, and operational duration (as shown in **Table 2**).

Table 2. Summarizes key technical and material metrics commonly considered in LCSA studies of solar technologies.

Technology	Primary Materials	Average Efficiency	Operation Duration
Monocrystalline Si	High-purity silicon, silver, aluminum	20% - 24%	25 - 30 years
Thin-film (CdTe)	Cadmium, tellurium, glass	16% - 19%	20 - 25 years
Concentrated Solar Power	Steel, concrete, molten salts	15% - 20%	>30 years
Perovskites (emerging)	Organic-inorganic halides	~25% (laboratory)	<5 years (current)

These metrics provide salient basis for comparing sustainability trade-offs across solar technologies and serve as foundational inputs for environmental, economic, and social life-cycle assessments.

4. Life Cycle Sustainability Assessment: Environmental, Economic, and Social Dimensions

This section applies the Life Cycle Sustainability Assessment (LCSA) framework introduced in Section 1.3 to solar technology systems, addressing in turn its three constituent, methodologically distinct pillars across all life cycle stages, from raw material extraction and manufacturing to operation and end-of-life management. Environmental Life Cycle Assessment (E-LCA), covered in Section 4.1, is confined to environmental impacts and highlights benefits such as low greenhouse gas emissions during operation, while also capturing upstream impacts like resource extraction and ecosystem disturbance; it does not itself encompass economic or social impacts. Economic life cycle costing (LCC), covered in Section 4.2, separately assesses the full cost structure, emphasizing high initial investment but

long-term cost efficiency. Social LCA (S-LCA), covered in Section 4.3, separately considers factors such as job creation, labor conditions in supply chains, and community impacts. Collectively, these three independently conducted assessments show that while solar technologies significantly support decarbonization, their broader ecosystem and societal impacts must be carefully managed to ensure truly sustainable energy transitions.

4.1. Environmental Life Cycle Assessment

The environmental performance of solar energy systems is widely recognized as a fundamental driver of the global transition toward low-carbon energy systems [1]. Unlike conventional fossil-fuel-based power generation, solar technologies produce little to no direct emissions of greenhouse gases (GHGs), sulfur dioxide (SO₂), or nitrogen oxides (NO_x) during the operational phase [44]. However, comprehensive Environmental Life Cycle Assessment (E-LCA) studies demonstrate that these environmental benefits are not entirely impact-free, as significant environmental burdens are shifted to up-stream processes such as raw material extraction and manufacturing [45], as well as downstream end-of-life management stages [46].

4.1.1. Global Warming Potential and Carbon Payback Time

The Global Warming Potential (GWP) of solar photovoltaic (PV) systems is arguably lower than that of conventional fossil-fuel technologies (Table 3). Typical life-cycle emission intensities for coal-fired electricity (~820 g CO₂-eq/kWh) and natural gas (~490 g CO₂-eq/kWh) far exceed those of modern silicon-based PV systems, which generally range between 20 and 50 g CO₂-eq/kWh over their full life cycle [1] (Table 4).

Table 3 illustrates the influence of regional solar irradiance on the environmental performance of photovoltaic (PV) technologies, as measured by Carbon Payback Time (CPBT) and Energy Payback Time (EPBT). The results clearly demonstrate that PV systems installed in high-irradiance regions, such as the Middle East, achieve significantly shorter payback times compared to those deployed in lower-irradiance regions like Europe. This is primarily due to higher annual energy yields, which accelerate the offset of embodied carbon and energy invested during manufacturing [45].

For crystalline silicon (c-Si) systems, CPBT decreases from approximately 2.5 years in Europe to about 1.2 years in the Middle East, while EPBT reduces from 2.0 to 1.3 years. This trend reflects the strong dependence of life cycle performance on solar resource availability, where increased irradiance enhances electricity generation without proportionally increasing embodied impacts [46]. Similarly, thin-film CdTe technologies exhibit even lower payback times, with CPBT and EPBT values dropping to as low as 0.5 years in high-irradiance regions. This improved performance is attributed to lower material intensity and reduced energy requirements during manufacturing [47].

Overall, the table underscores the critical role of geographic context in Environmental Life Cycle Assessment (E-LCA), demonstrating that identical technol-

ogies can exhibit markedly different sustainability outcomes depending on installation location. This site-dependence highlights the importance of incorporating regional parameters, particularly solar irradiance, into LCSA modeling and policy decision-making [45] [46].

Table 3. Influence of solar irradiance on carbon and energy payback time of PV technologies, Fthenakis *et al.* [45]; Muteri *et al.* [47].

PV Technology	Region	CPBT (Years)	EPBT (Years)
c-Si	Europe	2.5	2.0
c-Si	Middle East	1.2	1.3
CdTe	Europe	1.0	0.9
CdTe	Middle East	0.5	0.5

Table 4 highlights the comparative environmental performance of solar photovoltaic (PV) systems relative to conventional fossil fuel-based electricity. The results show that coal and natural gas exhibit significantly higher life-cycle greenhouse gas emissions, with values of approximately 820 and 490 g CO₂-eq/kWh respectively, compared to much lower ranges for c-Si (20 - 50 g CO₂-eq/kWh) and CdTe PV (15 - 35 g CO₂-eq/kWh), confirming the strong climate mitigation advantage of solar technologies [1] [6].

However, PV systems introduce trade-offs in other impact categories. While they produce negligible SO₂ and NO_x emissions during operation, their life cycle involves higher abiotic depletion potential due to reliance on critical materials such as silver, silicon, tellurium, and indium [45] [48]. Additionally, carbon and energy payback times for PV systems range from 0.5 to 2.8 years and 0.5 to 2.0 years respectively, demonstrating relatively rapid environmental recovery compared to their operational lifetimes [47].

Overall, the table underscores that although solar PV systems offer substantial reductions in air pollutants and greenhouse gas emissions, their environmental profile is influenced by upstream material extraction, land use requirements, and end-of-life considerations, reinforcing the need for circular economy strategies and improved resource efficiency [44].

A key indicator in E-LCA is Carbon Payback Time (CPBT), which is the time required for a solar energy system to offset the greenhouse gas emissions generated during its manufacturing, transportation, and installation. This occurs when the clean electricity produced replaces emissions from conventional fossil-fuel-based power generation. In recent research, it is indicated that CPBT values for silicon-based PV technologies have significantly reduced, driven by improvements in cell performance and the improved decarbonization of electricity grids in manufacturing regions. Current estimates place CPBT in the range of 0.5 to 2.8 years, depending on installation site irradiance and the energy mix of the manufacturing country [45] [46]. Unless otherwise stated, the CPBT and EPBT values reported in this section assume: displacement of the local grid-average electricity

mix at the installation site (rather than a marginal or fossil-only mix); a module operating lifetime of 25 - 30 years with an annual performance degradation rate of approximately 0.5% - 0.8%; and an end-of-life scenario in which modules are landfilled or recycled according to the disposal pathway assumed by the source study, rather than a harmonized EoL scenario across studies. Because source studies vary in these assumptions, particularly the displaced electricity mix and assumed degradation rate, the ranges reported here should be read as indicative rather than directly comparable across studies; this variability is a key driver of the divergence in published payback estimates [7].

Table 4. Comparative environmental indicators of solar PV and conventional electricity systems, IPCC [1]; Nugent & Sova-cool [6]; Fthenakis *et al.* [45]; Tawalbeh *et al.* [44].

Indicator	Unit	Coal	Natural Gas	c-Si PV	CdTe PV
GWP (Life Cycle)	g CO ₂ -eq/kWh	820	490	20 - 50	15 - 35
Carbon Payback Time	Years	N/A	N/A	0.5 - 2.8	0.5 - 1.0
Energy Payback Time	Years	N/A	N/A	1.2 - 2.0	0.5 - 1.0
Abiotic Depletion Potential (ADP)	kg Sb-eq/kWh	Moderate	Low	High (Ag, Si)	High (Te, In)
SO ₂ Emissions	g/kWh	8	1.2	~0	~0
NO _x Emissions	g/kWh	3.2	0.9	~0	~0
Land Use	m ² /MWh	Low	Low	Moderate	Moderate
Toxicity Potential	CTUe/kWh	High	Medium	Medium	Medium

4.1.2. Energy-Intensive Manufacturing and Silicon Purification

Upstream production is the most energy-intensive phase of the solar PV life cycle. Specifically, for c-Si technologies, converting metallurgical-grade silicon into solar-grade polysilicon, mostly through the Siemens or Fluidized Bed Reactor (FBR) process and requires temperatures exceeding 1100°C.

Energy Payback Time (EPBT) measures the period required for a system to generate a considerable amount of energy equivalent to that consumed across its life cycle. Thin-film technologies such as CdTe exhibit EPBT values for less than one year, extremely due to lower processing temperatures and low material use. In contrast, c-Si PV systems typically exhibit EPBT values ranging from 1.2 to 2.0 years [47].

Chemical usage and toxicity risks of Silicon wafer production depend on hazardous substances, comprising hydrofluoric acid for surface cleaning and silane gas for deposition processes. In the absence of acceptable environmental controls, these substances expose risk into the environment, making chemical management critical consideration within E-LCA studies [44].

4.1.3. Critical Materials and Resource Depletion

As solar energy technology increases towards terawatt-scale capacity, resource depletion and material criticality have emerged as leading environmental concerns. A lot of solar power depends on materials that are geologically limited, energy-

intensive to extract, or concentrated in geopolitically sensitive territories.

Silver (Ag) is widely used for front-side alloy in crystalline silicon cells. With all the strategic efforts to reduce silver content, the solar PV sector is currently making assiduous use of 10% of global silver demand, which is raising concerns about long-term supply challenges [48].

Indium and tellurium elements are particularly used for CIGS and CdTe thin-film technologies, respectively. As by-products of zinc and copper mining, their global supply is inherently inelastic and intertwined with higher cumulative environmental burdens [49].

From an Environmental Life Cycle Assessment (E-LCA) perspective, these trends are often reflected in elevated Abiotic Depletion Potential (ADP) values, as solar technologies rely on critical minerals and metals for their production [48]. While solar systems significantly reduce dependence on fossil fuel resources, they can increase pressure on material resource availability, particularly for elements such as silver, indium, and tellurium [49]. These dynamic underscores the importance of adopting recycling-oriented approaches and circular economy strategies to mitigate long-term resource constraints and environmental impacts [44].

4.1.4. Land Use and Biodiversity

The spatial footprint of solar energy systems particularly utility-scale PV installations introduces trade-offs between climate mitigation benefits and eco-environmental impacts. Utility-scale PV typically needs more land per unit of electricity generated than centralized fossil-fuel plants. This can contribute to habitat destruction, soil compaction, and alterations to local hydrology and microclimates [44].

Large-scale solar installations could change surface albedo by replacing reflective natural surfaces with darker panel arrays. In arid and semi-arid regions, this change may enhance heat absorption and contribute to localized “heat-island” effects, which should be considered in regional and ecosystem-level environmental assessments [1] [50].

4.1.5. Waste Generation and End-of-Life Management

The end-of-life (EoL) phase represents one of the fastest-growing research areas in solar E-LCA. With typical operational lifetimes of 25 - 30 years, the first large wave of decommissioned PV modules is expected to peak in the late 2030s. Global cumulative of waste generation of PV waste is projected to reach approximately 78 million tons by 2050, posing significant waste management challenges if not addressed with effective recycling regulations and policies [33].

In respect of recycling limitations, although glass and aluminum frames constituting about 85% of module mass are potentially recyclable, the recovery of high-value materials such as silicon, silver, and copper remains technically challenging and economically constrained in the absence of encouraging regulatory policies.

Indiscriminate disposal may contribute to the leaching of chemically hazardous

substances, including lead and cadmium, into soil and groundwater reservoir. These impacts are significant to both E-LCA toxicity categories and broader sustainability considerations [51].

4.2. Economic Life Cycle Costing

The economic scalability of solar energy systems has undergone a significant transformation over the past decade. Once regarded as a high-cost technology dependent on substantial subsidies, solar photovoltaics (PV) are now among the least expensive sources of electricity generation in many global markets [52] [53]. Within the Life Cycle Sustainability Assessment (LCSA) framework, the economic dimension is evaluated using Life Cycle Costing (LCC), which provides a comprehensive assessment of costs across the entire system life cycle [54]. Unlike simplified capital expenditure (CAPEX) approaches, LCC adopts a cradle-to-grave perspective by accounting for costs associated with raw material extraction, manufacturing, transportation and installation, operation and maintenance, and end-of-life management [54].

4.2.1. Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) is the standard metric for evaluating grid-connected solar economics. It represents the average net present cost of generation per unit of total lifetime output. By using consistent financial assumptions such as discount rates and capacity factors, LCOE allows for a direct comparison between different energy technologies.

Recent cost trajectories illustrate the rapid decline in solar electricity costs. For example, Lazard's Levelized Cost of Energy Analysis [52] reports that the LCOE of utility-scale solar has fallen by approximately 80% - 90% since 2010, this has consistently reflected manufacturing scale-up, supply-chain optimization, and improved module performance. These reductions are usually interpreted through learning-curve dynamics, often associated with Swanson's Law where cumulative deployment and technological experience drive systematic cost declines [27].

4.2.2. Cost Structure across the Life Cycle

Solar energy projects generally exhibit a front-loaded cost profile, where most investment occurs before commissioning, followed by relatively low but non-trivial operational costs. In an LCC context aligned with **Figure 4**, these costs are best interpreted according to their dominant life-cycle stages.

1) Capital Expenditure (CAPEX) and Installation Costs

CAPEX typically includes PV modules, inverters, mounting or racking systems, cabling, and the broader balance of system (BOS) components, with installation labor, permitting, and grid interconnection. Material sensitivity remains relevant to CAPEX. Volatility in input prices (e.g., silver, aluminum, polysilicon) can influence module and system costs, though large-scale manufacturing and vertical integration particularly in Asia-Pacific, where supply chains have moderated some cost variability through economies of scale [53].

2) Operation and Maintenance Costs

Solar PV systems are often described as low maintenance compared to thermal generation. However, LCC models must include operation and maintenance to avoid underestimating lifetime costs.

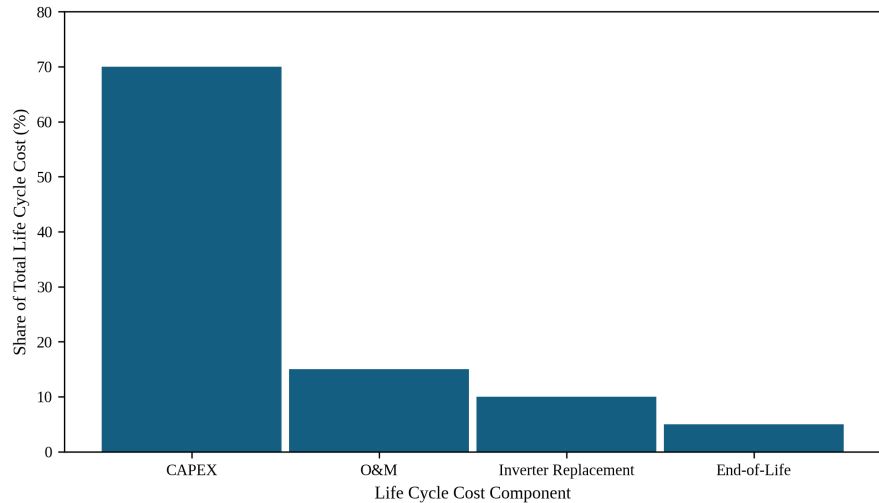


Figure 4. Illustrative life cycle cost structure of a utility-scale solar Photovoltaic (PV) system (composite estimate); general cost-component context from Lazard [52] and IRENA [53].

- Routine operation and maintenance: cleaning (notably in dusty regions where soiling losses are high), vegetation control, inspections, monitoring, and minor repairs.
- Inverter replacement: While PV modules are commonly warrantied for 25 - 30 years, inverters typically require replacement after 10 - 15 years. At least one replacement cycle is often assumed in utility-scale LCC models and may represent a significant mid-life reinvestment [54].

3) End-of-Life Costs

Generally, end-of-life (EoL) costs are often excluded from solar economic appraisals. As early PV installations approach retirement, decommissioning, transport, recycling, and disposal costs are increasingly included in LCC boundaries.

Importantly, EoL can represent both liability and opportunity. Decommissioning and compliant of waste handling are costs, but recovery of high-value materials (e.g., aluminum, copper, silver, silicon) may partially offset expenditures, depending on recycling technology maturity and regulatory frameworks. Mandatory recycling regimes such as the EU's WEEE Directive are accelerating the integration of EoL requirements into economic models and project finance assumptions [51].

4.2.3. Long-Term Economic Sustainability

The long-term cost trajectory of solar energy is typified by **experience curves**, where costs decline with cumulative production as manufacturing efficiency improves, supply chains mature, and performance increases.

- Efficiency gains transition from polycrystalline to advanced monocrystalline architectures (e.g., PERC and N-type technologies) increases energy yield per unit area. This reduces land, racking, and BOS requirements per kW installed, improving project economics and lowering LCOE [27].
- Bifacial PV technologies can improve energy yield by approximately 5% - 15%, often with modest CAPEX increases. This can strengthen investment returns by improving lifetime energy generation and enhancing key financial metrics such as IRR under suitable site conditions [55].

4.2.4. Market Design and Policy Influence

Economic sustainability is notable not only by internal project costs but also by policy design, market rules, and broader externalities. Subsidies and incentives instruments such as investment tax credits, feed-in tariffs, and concessional finance have historically reduced investment risk and accelerated deployment. As solar approaches or achieves grid parity in many contexts, policy support has increasingly shifted toward competitive auctions and market-based procurement mechanisms [53].

Grid integration and storage of solar technology penetration dominates; the market value of solar electricity can decline during periods of high daytime generation (often described through the “duck curve” dynamic). Consequently, modern LCC studies increasingly incorporate Battery Energy Storage Systems (BESS) and assess complementary metrics such as the Levelized Cost of Storage (LCOS) to evaluate firm, dispatchable, or time-shifted solar supply [52] [56].

4.2.5. Economic Comparison: PV versus Concentrated Solar Power (CSP)

Although PV currently leads in low-cost electricity generation, Concentrated Solar Power (CSP) retains an economic niche in systems where dispatchability is valued. Higher base cost of CSP generally exhibits higher LCOE than PV due to the complexity and cost of heliostat fields, receivers, and thermal power blocks.

System value of dispatchability when LCC frameworks incorporate the ability of CSP to provide electricity beyond daylight hours through thermal energy storage, CSP can deliver higher system value in certain grid contexts particularly where evening peak supply, capacity adequacy, or firm renewable generation commands a premium [34].

4.3. Social Life Cycle Assessment (S-LCA) of Solar Energy Systems

While the environmental and economic benefits of solar energy are widely recognized, its social implications are a crucial yet developing focus of the Life Cycle Sustainability Assessment (LCSA) framework. Social Life Cycle Assessment (S-LCA) specifically examines the real and potential social effects, both beneficial and harmful on stakeholders across a product’s entire lifespan. For solar technology, this means evaluating its influence on workers, local communities, and consumers worldwide to guarantee that the shift towards renewable energy is not only environmentally sound but also socially equitable [32].

4.3.1. Labor and Human Rights in the Supply Chain

The global solar supply chain is both complex and geographically concentrated, especially in the upstream stages of silicon mining and wafer production. Social Life Cycle Assessment (S-LCA) studies have raised concerns about working conditions in this sector, pointing to significant risks to occupational health and safety during quartz mining and the chemical processing of silicon. Furthermore, the industry's rapid expansion in certain regions has led to serious allegations regarding forced labor and inadequate wages in polysilicon manufacturing [57].

Another critical dimension involves material criticality and the potential for conflict minerals. The solar industry's reliance on resources like silver, cobalt, and copper links it to mining sectors frequently associated with human rights abuses in developing nations. A robust S-LCA seeks to trace these "socio-economic footprints" to ensure that the Global North's pursuit of decarbonization does not inadvertently perpetuate labor exploitation in the Global South [58].

4.3.2. Community Impacts and Land Rights

The large-scale deployment of utility-scale solar farms necessitates vast land areas, which frequently brings them into competition with agriculture and Indigenous territories. In rural and developing regions, converting communal land for solar energy can directly displace local communities and their livelihoods. To assess these impacts, Social Life Cycle Assessment (S-LCA) frameworks utilize metrics like "Community Engagement" and "Cultural Heritage Protection" to evaluate how such projects affect local autonomy and self-determination [10].

This dynamic gives rise to a "Green-on-Green" conflict, highlighting an inherent tension between achieving global climate objectives and preserving local ecosystem services. S-LCA helps identify these trade-offs and promotes solutions like agrivoltaics, the co-location of agriculture and solar power as a socio-technical approach to maintain food security while advancing clean energy generation [59].

4.3.3. Just-Transition and Job Creation

On the positive side, the solar industry serves as a significant driver of global employment. The International Renewable Energy Agency [53] reports that the solar photovoltaic (PV) sector accounts for the largest share of renewable energy jobs worldwide. A key socio-economic advantage lies in the nature of the work itself, unlike the highly mechanized and centralized operations of fossil fuel extraction, solar installation and maintenance generate decentralized, local employment opportunities. Social Life Cycle Assessment (S-LCA) captures this benefit by evaluating the Local Content of projects, the extent to which they hire and train local workers rather than relying on imported labor [60].

For a social transition to be truly sustainable, however, it must be underpinned by investment in technical and vocational education. Accordingly, S-LCA studies are increasingly adopting Human Capital Development as a key performance indicator (KPI) for the solar sector, recognizing that skills development is essential to sustaining long-term industry growth and equitable access to opportunity.

4.3.4. Human Health and Safety

The social pillar also encompasses the health impacts on populations near manufacturing and recycling facilities. Toxic Leaching and Public Health as discussed in the E-LCA section, improper end-of-life management can lead to the leaching of lead and cadmium. From an S-LCA perspective, this is a Public Health impact. Vulnerable communities located near informal recycling centers are at the highest risk, making formal, regulated recycling a social imperative [51].

Operational Safety during the operational phase, solar systems are generally very safe. However, large-scale installations must manage fire risks and electrical hazards to protect both workers and neighboring residents.

4.3.5. Energy Democracy and Equity

A final theme in solar S-LCA is the concept of Energy Justice. This examines who has access to the benefits of solar energy. Energy Access in sub-Saharan Africa and South Asia, small-scale solar home systems (SHS) are transforming social life by providing lighting for education and power for healthcare, directly contributing to UN Sustainable Development Goals (SDGs) related to poverty and health [61]. Affordability in respect of S-LCA assesses whether the economic gains of solar (low LCOE) are being passed down to low-income consumers or if the solar divide is widening between those who can afford the upfront CAPEX and those who cannot.

5. Integrated Life Cycle Sustainability Assessment for Solar Energy Systems

The central objective of Life Cycle Sustainability Assessment (LCSA) is to go beyond the parallel execution of Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) toward a coherent, decision-oriented sustainability profile. For solar energy systems, such integration is essential because their widely acknowledged environmental advantages particularly in climate change mitigation must be evaluated alongside economic viability and social implications across global supply chains. An integrated LCSA framework enables the systematic identification of trade-offs and synergies among the three sustainability pillars and supports more balanced energy policy and investment decisions [12] [19] [62].

5.1. Trade-Off Analysis

Integrated Life Cycle Sustainability Assessment (LCSA) explicitly recognizes that sustainability performance is inherently multi-dimensional and cannot be adequately captured by a single metric [12] [19]. Solar photovoltaic (PV) systems, for example, typically exhibit low life-cycle greenhouse gas emissions, yet may involve high upfront capital costs and dependence on critical minerals such as silver, indium, and tellurium [1] [48]. Similarly, large-scale solar deployment can stimulate employment and local economic development while simultaneously raising concerns related to land use, biodiversity impacts, and end-of-life

management [44] [53].

Table 5 summarizes the key sustainability trade-offs associated with solar photovoltaic (PV) systems across environmental, economic, and social dimensions within the Life Cycle Sustainability Assessment (LCSA) framework. While solar PV provides substantial environmental benefits through low life-cycle greenhouse gas emissions, it also creates upstream pressures linked to critical material extraction such as silver, indium, and tellurium [1] [44].

Economically, the table highlights declining levelized cost of electricity (LCOE), improving the competitiveness of solar energy, although high upfront capital costs remain a barrier in many contexts [53]. Socially, solar deployment contributes to job creation in manufacturing and installation but may also introduce labor risks within raw material supply chains [63]. Overall, the table emphasizes that while solar energy is broadly sustainable, its benefits are accompanied by important system-level trade-offs that must be managed through circular economy and responsible sourcing strategies.

Table 5. Sustainability trade-offs in solar energy systems identified through integrated Life Cycle Sustainability Assessment (LCSA), UNEP & SETAC [63]; IRENA [53]; IPCC [1]; Tawalbeh *et al.* [44].

Sustainability Dimension	Positive Outcomes of Solar PV	Potential Trade-offs/Impacts
Environmental	Low lifecycle GHG emissions	Critical material extraction (Ag, In, Te)
Economic	Declining LCOE and improved cost competitiveness	High upfront capital costs
Social	Job creation in installation and manufacturing	Labor risks in mining supply chains
Land Use	Renewable electricity generation	Land occupation and biodiversity pressure
Circular Economy	Growing recycling technologies	Limited PV end-of-life infrastructure

Recent studies explain that optimizing one sustainability dimension often leads to sub-optimization in another. For instance, minimizing levelized cost of electricity (LCOE) may favor manufacturing in regions with lower production costs but weaker environmental or labor regulations, thereby shifting burdens along the supply chain. Integrated LCSA therefore provides a framework for identifying such burden-shifting effects and informing policy trade-offs in renewable energy transitions [12] [19].

This **Figure 5** illustrates the integrated framework of Life Cycle Sustainability Assessment (LCSA), showing how sustainability is evaluated through three core pillars, that is environmental (LCA), economic (LCC), and social (S-LCA) [9] [11]. The inner sections represent these three dimensions, while the surrounding layers detail their respective impact categories such as ecosystem and biodiversity impacts for LCA, financial performance for LCC, and social well-being factors including health, labor conditions, and governance for S-LCA [19] [62]. Overall, the figure emphasizes that achieving sustainability in solar energy systems requires a balanced assessment of environmental impacts, economic performance,

and social outcomes within a unified framework [10].

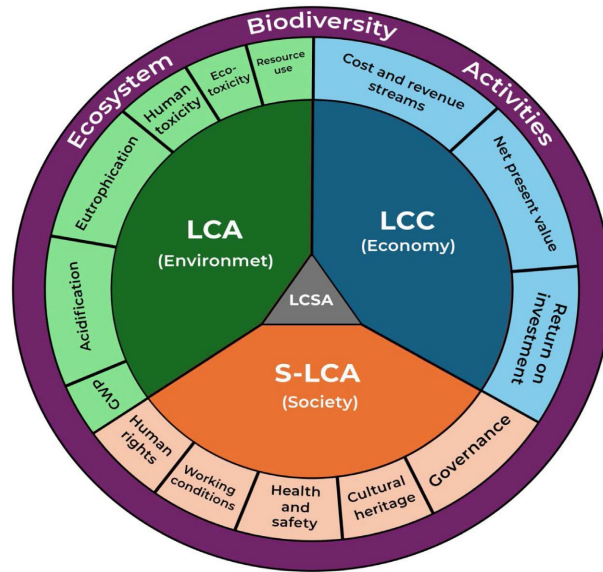


Figure 5. Integrated sustainability trade-off framework for solar energy systems.

5.2. Multi-Criteria Decision Analysis (MCDA)

Because LCSA produces heterogeneous indicators expressed in different units. Multi-Criteria Decision Analysis (MCDA) has become a primary tool for integration and interpretation. MCDA enables normalization, weighting, and aggregation of diverse indicators while making underlying value choices explicit. In solar energy assessments, MCDA is widely applied to compare technology options, evaluate siting alternatives, and support strategic planning.

Common MCDA methods used in solar-related LCSA include the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and outranking approaches such as PROMETHEE. These tools help decision-makers incorporate stakeholder priorities such as climate mitigation, affordability, or local employment into structured evaluation processes. Recent scholarship highlights that MCDA-enhanced LCSA is particularly valuable in policy contexts where transparent and participatory decision support is required [62] [64].

5.3. Persistent Methodological Challenges

Despite increasing methodological sophistication, several challenges continue to constrain robust LCSA integration. These highlights may include:

- Indicator weighting and subjectivity. Weighting schemes in MCDA are inherently normative, reflecting societal values rather than purely technical criteria. Different stakeholder groups may prioritize climate benefits, economic returns, or social equity differently, leading to divergent outcomes. Transparent reporting and sensitivity analysis are therefore essential to ensure credibility [64].

- Data gaps and inconsistency. Environmental LCA data for solar technologies are relatively mature, but S-LCA datasets remain limited in geographic coverage and sectoral resolution. Social indicators often rely on proxy or qualitative data, increasing uncertainty. LCC data are similarly sensitive to local financing conditions and market volatility. These disparities complicate cross-pillar comparability [10].
- Regional variability. Solar sustainability performance is strongly dependent on context. Environmental benefits depend on the carbon intensity of the displaced electricity mix, economic outcomes on financing conditions and solar irradiance, and social impacts on land-use patterns and labor standards. Consequently, results from one region cannot be universally generalized [19].
- Temporal dynamics. Different assessment components operate on different time horizons. Climate impacts may be modeled over 100 years, financial analyses typically span 20 - 30 years, and social impacts may include intergenerational considerations. Integrating these timelines remains an open methodological question.

5.4. Emerging Directions for Integrated LCSA

Recent literature proposes several pathways to strengthen integrated LCSA for solar energy systems:

- Standardization of S-LCA methods and databases tailored to energy technologies to improve data consistency [10].
- Probabilistic and scenario-based MCDA, allowing explicit treatment of uncertainties in future costs, recycling rates, and technological learning.
- Dynamic and spatially explicit LCSA models that incorporate evolving grid mixes, technological progress, and regional characteristics.
- Participatory approaches, where stakeholders contribute to indicator selection and weighting, thereby enhancing legitimacy and policy relevance [62] [64].

These developments align with broader sustainability and technological trends that emphasize transparency, stakeholder engagement, and systems thinking.

5.5. Section Synthesis

Integrated LCSA typifies the most inclusive framework currently available for measuring the sustainability of solar energy systems. By linking environmental performance, economic viability, and social implications, it enables better informed, policy directions and balanced decision making. Nevertheless, integration remains challenged by subjective weighting choices, data limitations, and strong regional dependencies. Solving and giving credence to these issues is critically important to ensuring that the rapid global scale-up of solar energy contributes effectively to long-term sustainable development goals. Continuous methodological refinement and improved data infrastructures will be technically pivotal to advancing LCSA as a robust decision-support tool for the clean energy transition.

6. Challenges and Research Gaps

Despite the growing body of literature on Life Cycle Sustainability Assessment (LCSA) of solar energy systems, several methodological and empirical challenges continue to limit the robustness, comparability, and policy relevance of current studies. Addressing these gaps is essential for advancing LCSA as a decision-support tool for sustainable energy transitions.

6.1. Methodological Harmonization

One of the most frequently cited challenges is the limited harmonization of LCSA methodologies. While the environmental Life Cycle Assessment (E-LCA) pillar benefits from relatively mature ISO standards (ISO 14040/44), the economic (LCC) and especially social (S-LCA) components remain less standardized. Differences in system boundaries, functional units, allocation rules, and impact assessment methods reduce comparability across studies [62] [65].

Recent research emphasizes the need for integrated and consistent methodological frameworks that align the three pillars under unified system definitions and temporal scopes. Without such alignment, trade-off analysis risk reflecting methodological artifacts rather than true sustainability performance [12].

6.2. Insufficient Social Impact Data

Social Life Cycle Assessment remains the least developed pillar of LCSA for solar energy systems. Many studies rely on qualitative indicators or proxy datasets due to limited availability of site-specific social data. Issues such as labor conditions in PV supply chains, community acceptance of large solar installations, and equity in energy access are often treated superficially or omitted altogether [10] [66].

Furthermore, social indicators are highly context-dependent, making universal metrics difficult to apply. This creates uncertainty in cross-regional comparisons and limits the operationalization of S-LCA in policy frameworks. Advancing databases and standardized social indicators is therefore a priority area.

6.3. End-of-Life Management and Circularity

End-of-life (EoL) management of photovoltaic (PV) systems represents another critical research gap. Although projections show rapidly increasing volumes of PV waste in the coming decades, uncertainties remain regarding recycling technologies, recovery rates, and economic feasibility [35] [67].

Many LCSA studies still assume simplified or idealized EoL scenarios, which may underestimate environmental burdens or overstate circularity benefits. More realistic modeling of collection systems, material recovery efficiencies, and secondary markets for recycled materials are required. Integrating circular economy principles into LCSA frameworks is dominantly recognized to capture long-term sustainability value [68].

6.4. Underrepresentation of Developing Countries

A notable geographical imbalance exists in the LCSA literature, with a strong con-

centration of case studies in Europe, North America, and parts of East Asia. Developing regions particularly in Africa, Latin America, and parts of South Asia remain underrepresented [65].

This gap is problematic because sustainability performance is strongly influenced by regional electricity mixes, regulatory contexts, labor markets, and waste management infrastructure. Without region-specific assessments, global conclusions about solar sustainability may be biased or incomplete. Expanding empirical studies in emerging solar markets is therefore essential for equitable energy planning.

6.5. Future Research Directions

In order answer these critical challenges, next research should focus on:

- Standardized and harmonized LCSA supports that ensure consistency across pillars and studies
- Improved social LCA databases and context-sensitive indicators
- Integration of circular economy principles, particularly for PV end-of-life management
- Region-specific assessments that reflect local socio-economic and environmental conditions
- Coupling LCSA with decision-support tools such as multi-criteria decision analysis (MCDA) to enhance policy relevance

Advancing these areas will strengthen the credibility and applicability of LCSA in guiding sustainable solar energy deployment and broader energy transition strategies.

7. Conclusions

This review has examined the sustainability performance of solar energy systems through the lens of Life Cycle Sustainability Assessment (LCSA), integrating environmental, economic, and social dimensions across the full life cycle. The evidence synthesized indicates that, relative to fossil-based energy systems, solar technologies generally deliver significant environmental benefits, particularly in terms of greenhouse gas (GHG) emission reductions, lower operational-phase impacts, and declining life cycle energy and carbon intensities as technologies mature [3] [69]. From an economic perspective, continued cost reductions in photovoltaic (PV) modules and balance-of-system components have improved life cycle cost competitiveness, reinforcing solar energy's role in least-cost decarbonization pathways [23].

However, the review also underscores that solar energy systems are not impact-free. Upstream material extraction, energy-intensive manufacturing processes, land use, and end-of-life (EoL) management introduce environmental and socio-economic burdens that must be carefully managed. Critical materials demand and PV waste streams are projected to grow substantially, making circular economy strategies such as design for recyclability, extended producer responsibility, and

improved material recovery central to long-term sustainability [21] [67].

On the social dimension, the literature reveals persistent gaps in robust Social LCA (S-LCA) applications, particularly regarding labor conditions in global supply chains, community-level impacts, and issues of energy justice and equitable access. The limited availability of high-quality, site-specific social data constrains comprehensive assessments and weakens comparability across studies [10] [66].

A key conclusion of this review is that methodological integration remains a frontier for LCSA. While many studies apply the three pillars in parallel, fewer achieve true integration and systematically evaluate trade-offs and synergies. Approaches that combine LCSA with multi-criteria decision analysis (MCDA) and scenario analysis show promise for supporting policy and planning, especially under conditions of uncertainty and regional variability [12] [65].

Strengthening integrated LCSA methodologies through harmonized system boundaries, standardized indicators, improved databases, and transparent weighting procedures will enhance the reliability of sustainability evaluations. Such advances are essential for informing policymakers, investors, and planners as solar energy scales globally.

Overall, solar energy systems represent a cornerstone of sustainable energy transitions, but maximizing their sustainability benefits requires continuous improvement in material efficiency, recycling infrastructure, and social performance assessment. A mature, integrated LCSA framework can serve as a critical decision-support tool to guide solar deployment pathways that are not only low-carbon, but also economically viable and socially responsible.

Author Contributions

All authors contributed equally to the conceptualization, literature search, data extraction, analysis, and writing of this manuscript. All authors read and approved the final version for submission.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix. Supplementary Table

Included Studies (N = 22) Mapped to Technology Category

This table lists the 22 technology-specific studies underlying the evidence base synthesized in Sections 3-5 and the distribution reported in **Figure 3**. Each study's primary technology category is listed, along with any additional categories it was also counted toward where it addressed more than one technology (per the counting rule stated in Section 3.1). Full citation details for each study are given in the References list above.

#	Study	Primary Category	Also Counted In
1	Fthenakis, Leccisi, & Raugei (2020) [45]	PV (c-Si/general)	-
2	Branker, Pathak, & Pearce (2011) [54]	PV (c-Si/general)	-
3	Bhandari, Collier, Ellingson, & Apul (2015) [7]	PV (c-Si/general)	-
4	Deng, Chang, Ouyang, & Chong (2019) [67]	PV - crystalline silicon	-
5	Bolinger, Wiser, & O'Shaughnessy (2022) [5]	PV (c-Si/general)	-
6	Guzik, Burkowicz, & Szlugaj (2022) [49]	PV (c-Si/general)	-
7	Tsanakas <i>et al.</i> (2020) [35]	PV (c-Si/general)	-
8	Mann <i>et al.</i> (2014) [26]	PV (c-Si/general)	-
9	Muteri <i>et al.</i> (2020) [47]	PV (c-Si/general)	-
10	Mahmoudi <i>et al.</i> (2019) [51]	PV (c-Si/general)	-
11	Tawalbeh <i>et al.</i> (2021) [44]	PV (c-Si/general)	-
12	Bonilla-Alicea & Fu (2022) [70]	PV (c-Si/general)	-
13	Vartiainen, Masson, Breyer, Moser, & Medina (2020) [27]	PV (c-Si/general)	-
14	Weselek <i>et al.</i> (2019) [59]	PV (c-Si/general)	-
15	Yu <i>et al.</i> (2022) [28]	PV (c-Si/general)	-
16	Baharoon, Rahman, Omar, & Fadhl (2015) [40]	CSP	-
17	Palacios, Barreneche, Navarro, & Ding (2020) [36]	CSP	-
18	Pelay, Luo, Fan, Stitou, & Rood (2017) [42]	CSP	-
19	Pihl, Kushnir, Sanden, & Johnsson (2012) [41]	CSP	-

Continued

20	Milousi <i>et al.</i> (2019) [46]	SHC/solar thermal	-
21	Zafar, Stojceska, & Tassou (2024) [32]	Cross-cutting	PV, CSP, SHC
22	Tian, Stranks, & You (2020) [31]	Emerging PV (perovskite/tandem)	-

Notes

This table reflects a revision from an earlier draft in which Feldman *et al.* (2022), IRENA (2016), and Mehos *et al.* (2020)—institutional/technical reports rather than peer-reviewed journal articles—were counted among the 22 included studies, inconsistent with the “peer-reviewed journal article only” eligibility criterion stated in Section 2. They have been replaced above by peer-reviewed studies covering equivalent ground: Bolinger, Wiser, & O’Shaughnessy (2022) on PV cost learning (replacing Feldman *et al.*), Tsanakas *et al.* (2020) on PV end-of-life recycling and circularity (replacing IRENA 2016), and Palacios *et al.* (2020) on CSP thermal energy storage (replacing Mehos *et al.*). The three original reports remain in the reference list as supplementary technical context but are no longer counted among the 22 core included studies. Study #12, Bonilla-Alicea & Fu (2022) [70], similarly replaces Mulvaney (2024) [58], a political-ecology review of solar supply chains rather than an applied LCSA study; [58] remains in the reference list and is cited in Section 4.3.1 as contextual support.

Thin-Film PV: no study in this table addresses thin-film PV (e.g., CdTe, CIGS) specifically. This is reported in Section 3.1 as an identified evidence gap rather than an omission.

Emerging PV (perovskite/tandem): the study addressing this category is Tian, Stranks, & You (2020) [31], a dedicated life-cycle assessment of perovskite-silicon and perovskite-perovskite tandem solar cells (Science Advances, 6(31), eabb0055), also cited directly in Section 3.1.3. The perovskite-specific citations used elsewhere in Section 3.1 (Kojima *et al.*, 2009; Green *et al.*, 2022; Babayigit *et al.*, 2016) remain technical/background references on efficiency and toxicity, not LCSA studies, and are therefore not counted in this table.

Category assignment was made from each study’s title and stated scope; the authors should verify each assignment against the full text before final submission.