

Sustainability of Solar Photovoltaic Systems: A Life Cycle Assessment Review

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Abstract

Solar photovoltaic (PV) systems are widely promoted as clean energy options, yet their sustainability remains difficult to judge when upstream manufacturing, storage, transport, and end-of-life burdens are not assessed alongside operational benefits. Existing studies have generated useful insights, but their conclusions are often fragmented by differences in system boundaries, functional units, storage treatment, and regional assumptions, making it harder to draw a clear and reliable sustainability picture. This study adopted a structured literature review approach to examine the life cycle assessment of solar photovoltaic systems. Relevant studies were sourced from Google Scholar, Scopus, ScienceDirect, and Web of Science. Eighty papers were initially considered, and after screening for relevance, 62 studies were retained and synthesized under key themes, including LCA application in PV systems, methodological trends, environmental hotspots, storage-related impacts, end-of-life management, and regional evidence gaps. The review shows that the main environmental pressures of PV systems are more consistently linked to manufacturing, storage systems, and end-of-life management than to electricity generation itself. It also shows that methodological inconsistency continues to weaken comparability across studies, while important evidence gaps remain for Africa and Nigeria, where local conditions are still poorly represented. Overall, PV should not be treated as inherently sustainable. Its sustainability depends on cleaner production, better storage choices, credible recycling and waste governance, and more context-specific life cycle assessment.

Keywords: Solar photovoltaic System, sustainability, environmental hotspot, Storage Systems, end of life

1. Introduction

Solar photovoltaic (PV) systems are often described as clean energy technologies, but that description becomes too simple once the full life cycle is considered. Electricity from PV may be low in direct emissions during operation, yet the system itself is shaped by a much wider chain of activities that begins with raw material extraction and component manufacturing and continues through installation, use, replacement, and end-of-life treatment. That is why life cycle assessment (LCA) has become so important in PV research: it allows the technology to be judged as a whole system rather than as an emissions-free device at the point of use [1]. This broader view has been strengthened by later review work showing that the environmental profile of PV depends heavily on methodological choices and on whether burdens outside the use phase are properly captured [2]. More recent sustainability-focused studies have pushed the argument further by showing that PV should not be assessed only through environmental indicators, but through a wider lens that also considers life cycle cost, social dimensions, and uncertainty across the system [3]. In the same spirit, recent work on decarbonization has argued that sustainability cannot be reduced to emissions reduction alone, because transitions that ignore governance quality, social equity, and economic resilience often weaken their own long-term legitimacy[4].

This wider perspective is especially important in countries like Nigeria, where the case for solar energy is strong but the conditions for sustainable deployment are far from automatic. Recent work on power distribution in Nigeria shows that weak infrastructure, supply shocks, inadequate capacity upgrades, and recurrent outages continue to undermine reliable electricity delivery, leaving many consumers exposed to unstable power access [5]. At the same time, Nigeria has substantial solar potential. A recent study on solar viability in Nigeria reports that the country receives nearly 290 days of sunlight annually, with solar insolation ranging from about 4.0 kWh/m²/day in the south to 7.0 kWh/m²/day in the north, making solar energy a realistic option for both decentralized and large-scale applications [6]. Even so, abundant sunlight does not settle the sustainability question. Contemporary PV LCA literature still shows wide variation in system boundaries, functional units, and inventory assumptions, which makes cross-study comparison difficult and weakens the reliability of broad claims about PV performance [7]. The problem becomes sharper when end-of-life is ignored or treated as a minor downstream issue, even though recent reviews show that waste management policy, toxicity concerns, and recovery pathways are now central to whether PV remains environmentally credible at scale [8]. Plant-level studies also continue to show that material-intensive components remain major contributors to life-cycle burdens, which means the real debate is no longer whether PV reduces emissions in principle, but whether its upstream and downstream burdens are being represented honestly enough to support sound sustainability decisions [9].

It is this tension that gives rise to the present review. Existing studies have generated valuable insights, but the evidence is still spread across different technologies, modelling choices, and

regional contexts, making it harder than it should be to draw a clear sustainability picture. Recent review work on renewable energy barriers also suggests that technical, economic, environmental, and policy constraints are deeply interconnected, and that more coherent synthesis is needed if renewable technologies are to support a balanced and effective energy transition[10]. Against that background, this paper reviews the life cycle assessment of solar photovoltaic systems in order to examine the major environmental hotspots, methodological trends, storage-related burdens, end-of-life issues, and regional evidence gaps that shape the sustainability of PV systems in practice.

2. Methodology

2.1 Review Design and Search Strategy

This review adopted a structured literature review approach to examine existing research on the life cycle assessment of solar photovoltaic systems. Relevant studies were sourced from Google Scholar, Scopus, ScienceDirect, and Web of Science using keyword combinations such as life cycle assessment, solar photovoltaic, PV systems, battery storage, end-of-life, recycling, and sustainability.

2.2 Study Selection and Synthesis

A total of 80 papers were initially considered during the literature search. After screening for relevance, 62 studies were retained for the review, while 18 papers were excluded because they were outside the scope of the study. Most of the excluded papers either did not focus directly on solar photovoltaic life cycle assessment, dealt with unrelated renewable energy systems or lacked sufficient relevance to the themes of environmental impacts, storage systems, end-of-life management, methodological trends, or regional sustainability concerns.

The selected studies were then examined and grouped into major themes, including LCA application in PV systems, methodological trends, environmental hotspots, storage-related impacts, end-of-life considerations, and regional evidence gaps. The findings were synthesized narratively to identify recurring patterns, major gaps, and sustainability implications.

A simple publication trend analysis was also carried out to show the yearly distribution of the reviewed studies. The result, presented in Figure 1, shows that most of the reviewed publications were produced in recent years, reflecting growing research interest in the life cycle sustainability of solar photovoltaic systems. The year-wise distribution of the reviewed publications is presented in Figure 1.

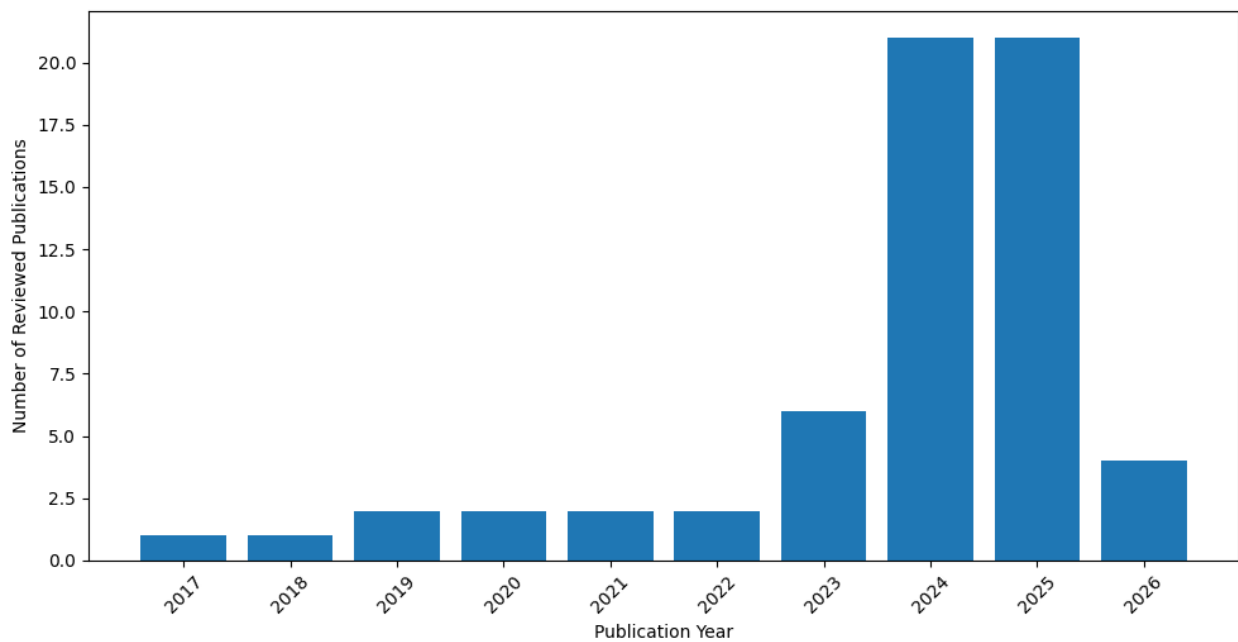


Figure 1. Distribution of reviewed publications by year.

3. Review of Life Cycle Assessment of Solar Photovoltaic Systems

3.1 Overview of LCA Application in Solar Photovoltaic Systems

Life cycle assessment has become central to solar photovoltaic research because the older assumption that PV is automatically “clean” is no longer enough on its own. Recent studies do not deny the low-carbon potential of photovoltaic electricity, but they show that this potential can only be defended when upstream manufacturing, balance-of-system components, replacement cycles, transport, and end-of-life management are all considered within the same analytical boundary[2].

For this reason, LCA in PV research now does much more than confirm that solar power is preferable to fossil-based generation at the point of use. It has become a way of testing how solid that environmental advantage remains once broader life-cycle realities are taken seriously. A comparative sustainability study of grid-connected PV in Northeast England showed that environmental performance cannot be discussed meaningfully if electricity generation is isolated from the wider life-cycle choices and sustainability criteria that shape it [11].

This shift has changed the main debate in PV LCA. The question is no longer whether PV deserves environmental assessment, but how that assessment should be carried out. A recent cross-continental review makes this problem clear by showing that differences in system boundaries, inventory choices, and methodological assumptions still limit comparability across studies, even when the technologies under discussion appear similar [7].

That lack of comparability is more than a technical inconvenience. It affects how conclusions are interpreted and how confidently they can be used. Earlier reviews had already pointed out wide variation in functional units, impact categories, technology scope, and hotspot attribution, warning that a growing body of studies should not automatically be mistaken for a coherent body of evidence [2]. A large literature, in other words, does not necessarily mean a settled literature.

Another change in the field is the move from module-focused analysis to more complete system-level assessment. This is important because once mounting structures, inverters, and supporting infrastructure are included, the environmental profile of a PV system can no longer be reduced to the panel alone. Work comparing rooftop and free-field PV structures shows that even elements often treated as secondary can noticeably alter total impact profiles, making narrowly framed assessments less convincing [12].

This point becomes even stronger in stand-alone and storage-coupled systems, where batteries can dominate the overall burden. Evidence from Burkina Faso shows that, in off-grid settings, batteries and PV modules account for the largest environmental contributions, while battery chemistry and disposal routes strongly influence final outcomes [13]. That makes it difficult to defend any broad claim that all PV configurations share roughly the same environmental profile.

It is also becoming harder to rely on climate change indicators alone when discussing PV sustainability. A detailed life-cycle study of a mono-Si PV plant shows that post-use management affects not only carbon outcomes but also human health, ecosystem quality, and resource depletion. The broader value of LCA in PV lies precisely in its ability to reveal trade-offs across several impact categories rather than support a single decarbonization narrative [9].

End-of-life concerns now sit much closer to the center of the debate than they once did. A systematic review of PV waste-management policy argues that end-of-life should not be seen simply as the last step in the system, but as one of the stages that will shape whether large-scale PV deployment remains environmentally credible, especially in places with weak waste regulation [8]. A separate review of silicon-panel recycling supports this view by showing that recycling technologies, material recovery, and policy design have become central to PV sustainability discussions rather than optional downstream additions [14].

There is also growing recognition that PV cannot be treated as environmentally identical across regions. An island-based assessment in Indonesia shows that transport limitations, infrastructure availability, and end-of-life pathways can significantly shift impact outcomes, meaning that regional conditions are part of the environmental result rather than background details [15].

Seen this way, contemporary PV LCA is better understood as a framework for qualifying sustainability claims rather than merely validating them. Even the expanding literature on end-of-life PV modules shows that treatment, reuse, recycling, and reverse-logistics issues are now part of the core research agenda, because large-scale deployment without credible waste pathways risks moving environmental burdens from the operation phase to the disposal phase [16].

Overall, the literature shows that LCA has become the main framework through which the environmental legitimacy of solar PV is examined, challenged, and refined. The more pressing issue now is not whether PV contributes to decarbonization, but whether PV systems are being assessed with enough methodological depth, regional realism, and end-of-life seriousness to support the sustainability claims often made on their behalf [11,7].

3.2 Methodological Trends in PV LCA Studies

One of the biggest methodological problems in photovoltaic life cycle assessment is not the lack of studies, but the lack of consistency across them. As interest in PV has grown, so too has the tendency to present it as a clean and sustainable energy solution. Yet recent reviews show that studies still vary widely in their functional units, system boundaries, database choices, and impact assessment methods, which makes broad comparisons less secure than they may first appear [7]. For sustainability research, that inconsistency is not harmless. If modelling choices are not aligned, then claims about environmental benefit become harder to trust.

A good example is the choice of functional unit. Reporting impacts per square meter of module area or per kilowatt-peak installed may be useful for comparing products, but those measures say less about the sustainability of electricity delivery over time. A functional unit based on electricity actually delivered, such as per kilowatt-hour, is more meaningful for sustainability analysis because it links environmental burdens to the service provided. This becomes especially important in places where solar yield, degradation, system losses, and operational disruptions vary substantially, since nominal capacity can exaggerate performance if real energy output is lower than assumed [17]. In effect, the choice of functional unit determines whether a PV system is being judged as a product or as a long-term energy service.

The same issue appears in the way system boundaries are drawn. PV systems are often described as sustainable because they produce electricity without direct emissions during operation, but that claim weakens once assessments exclude transport, mounting structures, inverter replacement, maintenance, or end-of-life treatment. Cradle-to-grave work on utility-scale PV systems has shown that these supposedly secondary components can materially influence total life-cycle burdens [18]. When the boundary is too narrow, important burdens are pushed out of sight, and the sustainability case becomes overstated.

A similar pattern emerges in large-scale plant studies that go beyond generic panel inventories and include real infrastructure and supporting systems. Once the actual configuration of a PV installation is represented, the environmental picture often changes, and so does the sustainability narrative attached to it. This suggests that simplified assessments may not only underestimate impacts but also point decision-makers toward the wrong mitigation priorities[19]. For sustainability-oriented research, incomplete modelling often leads to incomplete conclusions.

There is also a clear move toward parameterized and scenario-based modelling. Static PV LCAs that assume one lifetime, one irradiation profile, and one background context are increasingly inadequate for real-world decision-making. Agile LCA approaches for grid-tied systems argue for models that can respond to differences in location and deployment conditions rather than presenting a single result as universally representative [20]. That shift is important because sustainability is shaped by context; a system that performs well in one location may not deliver the same outcome elsewhere if material sourcing, waste management, or electricity mix differ.

Uncertainty is another issue that deserves more attention than it often receives. In many studies, it is treated as a technical appendix, yet uncertainty can directly weaken the strength of a sustainability claim. If the apparent superiority of one PV system over another depends heavily on assumptions that are poorly tested, then the conclusion is less robust than it looks. Recent work on decision-making under methodological uncertainty shows that different but plausible modelling choices can produce different rankings of environmental preference [21]. This makes transparency about uncertainty essential rather than optional.

End-of-life treatment has also become one of the most sensitive methodological areas. The way recycling credits, allocation rules, and recovery assumptions are handled can significantly alter final results [22]. That has implications beyond methodology, because sustainability claims about PV increasingly depend on whether systems are assessed through a circular-economy lens. Ignoring the way end-of-life is modelled leaves out one of the questions that now matters most in sustainable solar deployment: not only how electricity is generated, but how materials are managed after use.

This becomes even more relevant in studies of innovative manufacturing routes and emerging PV technologies. Process-level LCA work shows that inventory transparency, manufacturing yield assumptions, and scale-up modelling remain uneven, even though these factors can strongly influence whether a new technology appears environmentally preferable [23]. Newer technologies should therefore not be assumed to be more sustainable simply because they are more advanced. Their sustainability has to be demonstrated through credible assessment.

The demand for methodological rigor is even stronger in developing-country contexts, where foreign background datasets are often used to represent local systems. A review of LCA research in Nigeria shows that limited domestic inventories and weak contextual

representation remain major challenges [24]. A study may look methodologically sophisticated and still fail to capture local realities such as transport logistics, waste handling, grid conditions, and informal end-of-life pathways. In countries like Nigeria, methodological transparency also becomes a way of showing whether a study is genuinely relevant to local sustainability planning.

Across the literature, one point keeps returning: methodological transparency is not just good academic practice; it is the basis on which sustainability conclusions stand or fall. Weak functional units, truncated boundaries, vague uncertainty treatment, and generic end-of-life assumptions make it harder to defend the environmental credibility of PV systems. The field does not simply need more PV LCA studies; it needs studies that are explicit enough in their assumptions to support reliable conclusions about sustainable energy transitions, circular resource use, and environmentally responsible deployment [25].

3.3 Environmental Hotspots Across the PV Life Cycle

Recent literature makes it harder to sustain the view that photovoltaic systems are environmentally sustainable simply because they generate electricity without combustion. LCA evidence shows that the real test of PV sustainability lies in whether the major burdens across the life cycle are openly accounted for rather than hidden behind the use phase. These burdens are concentrated most strongly in manufacturing, storage, toxicity risk, and end-of-life management rather than in electricity generation itself [26, 27].

Manufacturing remains one of the most persistent hotspots. Studies on module production continue to show that the environmental profile of PV is shaped heavily by upstream material processing and assembly, not only by what happens after installation. A recent study on monocrystalline silicon module production in China found that the main burdens were linked to polycrystalline silicon extraction, cell production, and module assembly, reinforcing the argument that PV sustainability weakens when production remains resource- and energy-intensive [28].

That burden is not confined to carbon alone. A recent life-cycle sustainability assessment of PV module production showed that production-stage impacts also extend into resource use and other non-climate burdens, making it too narrow to describe PV as “green” only because it reduces operational emissions [29]. If module production remains materially intensive, then PV sustainability has to be treated as conditional rather than automatic.

The discussion becomes even more demanding when storage is included. In off-grid and hybrid systems, storage is not just an accessory; it is a core part of the environmental profile. An integrated off-grid energy-system study in Chile showed that storage lifetime can significantly shape life-cycle carbon outcomes, meaning that battery-related design choices alter the balance between cost and emissions even where solar penetration is high [30]. This

makes it difficult to separate the sustainability of PV from the durability and replacement pattern of the storage technologies that support it.

Toxicity also deserves a more central place in hotspot discussions. Reviews of photovoltaic-module toxicity assessment conclude that current and emerging PV technologies often contain hazardous and rare metals, while inconsistencies in testing procedures have sometimes masked the seriousness of possible waste-related risks [31, 32]. A technology that reduces operational emissions but generates poorly managed toxic waste cannot easily be presented as unambiguously sustainable, especially where hazardous-waste infrastructure is weak.

That concern deepens at end-of-life. Evidence from India shows that recycling crystalline-silicon panels at end-of-life can reduce impacts in future production by as much as 70% compared with landfill-oriented disposal pathways [33]. This means that post-use management is not a peripheral issue but one of the stages where PV sustainability is either preserved or compromised.

Newer recycling studies point in the same direction. A comparison of waste crystalline-silicon recycling routes found that greener solvent-based recycling processes can outperform traditional routes environmentally while also improving resource recovery, suggesting that end-of-life management now forms part of the environmental optimization of PV systems rather than remaining a downstream disposal issue [34]. The legitimacy of large-scale solar deployment increasingly depends on whether materials are recovered in ways that reduce future extraction and disposal pressure.

Policy-oriented waste literature has also pushed end-of-life closer to the center of sustainable energy debates. A strategic review of future solar-panel waste management argues that expanding PV capacity without matching growth in recycling and reuse systems risks replacing one environmental problem with another as waste volumes increase [35]. For countries pursuing rapid solar deployment, installation targets alone are not enough; sustainable deployment also requires credible material-recovery systems.

Transport, by comparison, is usually a secondary hotspot, though not an irrelevant one. A cradle-to-grave PV study from Mexico showed that transportation scenarios can still shift life-cycle outcomes meaningfully, especially when components travel long distances and end-of-life options remain weak [26]. Even so, the literature more often points to transport as a modifying burden rather than the core problem. The deeper sustainability pressures remain tied to production choices, storage dependence, toxicity, and waste governance.

The overall picture is clear enough. Environmental hotspots in PV systems are not evenly distributed across the life cycle, and they extend beyond greenhouse-gas emissions. They cluster around manufacturing intensity, storage durability, toxic-material risk, and end-of-life recovery, while transport usually plays a secondary but context-dependent role [27, 33, 30].

A sustainability-oriented aspect therefore points away from the claim that PV is inherently sustainable and toward a more careful conclusion: PV becomes sustainable only when these hotspot burdens are reduced through cleaner production, longer-lasting storage, safer toxicity control, and more circular end-of-life pathways.

3.4 Influence of Storage Systems on PV Life Cycle Impacts

Once storage is introduced, the sustainability case for photovoltaic systems becomes more conditional and harder to generalize. Batteries do not simply support PV operation; they reshape the whole life-cycle profile of the system by adding material demand, energy-intensive production, replacement cycles, efficiency losses, and end-of-life burdens. That is why it no longer makes sense to discuss PV sustainability only at the level of the module while treating storage as a neutral supporting technology. Reviews on lithium-based batteries have stressed that battery systems need to be assessed as full life-cycle products in their own right, not merely as devices that enable renewable electricity use [36, 37].

This point matters because storage often determines whether PV remains intermittent generation or becomes a dependable energy service. Once reliability is treated as part of sustainability rather than a separate technical issue, storage moves to the center of the discussion. Comparative work on stationary energy storage systems shows that lithium-ion, lead-acid, and hydrogen-based options differ substantially in their cradle-to-grave environmental profiles, which means that the sustainability of a PV system depends not only on solar generation but also on the chemistry and life-cycle behaviour of the storage technology chosen [38]. Storage choice is therefore not a minor design detail; it is one of the main factors shaping the environmental credibility of PV.

Lead-acid batteries bring this tension into sharp focus. Their continued use in many PV systems is often defended on the basis of lower upfront cost and wide market familiarity, but those advantages do not automatically translate into stronger sustainability performance. Cradle-to-grave evidence on industrial lead-acid batteries shows that their environmental profile is heavily influenced by material intensity and the quality of post-use treatment systems [39]. In contexts where replacement is frequent or recycling systems are weak, it becomes difficult to treat lead-acid storage as a straightforward sustainability solution.

Lithium-ion batteries are often presented as the more sustainable option because of their higher energy density and longer service life, yet the literature does not support an uncritical preference for them either. Reviews of lithium-ion battery recycling and life-cycle performance show that manufacturing burdens, raw material extraction, and recovery challenges remain substantial even when operational advantages are recognised [40, 36]. Lithium-ion storage may improve durability and efficiency, but it does not remove the need for careful sustainability scrutiny. In many cases, it shifts the burden profile rather than eliminating it.

Battery impacts are also strongly shaped by system design and operating conditions. A cradle-to-grave study of a large-scale LFP storage system found that environmental performance depends heavily on cycling behaviour, service lifetime, and actual use conditions rather than on chemistry labels alone [41]. A battery marketed as environmentally preferable can still weaken the overall sustainability case if it is badly sized, underused, or replaced too often.

The same point appears at residential scale. Work on residential battery systems shows that life-cycle greenhouse-gas performance depends on whether the battery is used in a way that genuinely displaces more carbon-intensive electricity over time [42]. Pairing a battery with PV, then, does not automatically improve sustainability. The battery has to deliver enough useful service across its life to justify the burdens created by its production, operation, and disposal.

This helps explain why PV-plus-storage systems often look more attractive in energy-access discourse than they do in life-cycle assessment. A study of residential photovoltaic systems with lithium-ion storage in Colombia found that battery-backed PV can contribute to sustainability goals, but only where system design and operating dynamics are properly aligned with service delivery [43]. Likewise, work on rooftop PV and battery storage in South Africa suggests that the environmental value of storage cannot be separated from technical and economic context[44]. These studies suggest that batteries do not automatically make PV more sustainable; they make the sustainability question more demanding.

Storage also complicates the circular-economy argument for solar deployment. Batteries create additional waste streams, more difficult recovery requirements, and stronger dependence on post-use governance systems. This is why IEA PVPS guidance recommends assessing residential PV-battery systems per kilowatt-hour of self-consumed electricity rather than by installed hardware alone, since storage changes the environmental profile of delivered electricity itself [45]. That framing is useful because it shifts attention from owning more technology to delivering more sustainable energy service.

This therefore points to a fairly consistent conclusion: storage is not a peripheral extension of photovoltaic systems but one of the main reasons simplified claims about solar sustainability become harder to defend. Batteries improve reliability and may increase the practical value of PV, but they also introduce burdens that have to be justified across the full life cycle. If chemistry choice, lifetime, replacement rate, recycling, and actual service contribution are ignored, then the sustainability of PV-plus-storage systems is being claimed too easily. A more defensible reading of the evidence is that storage does not make PV unsustainable by default, but it does make PV sustainability conditional on better design, longer service life, credible end-of-life management, and context-specific deployment decisions [46, 37].

3.5 End-of-Life and Recycling Considerations

End-of-life management can no longer sit at the margins of photovoltaic sustainability assessment, because it is one of the stages where the environmental promise of solar energy is either maintained or weakened. Recent review work argues that PV recycling is not merely a waste-treatment issue but a broader sustainability issue that spans environmental, economic, and social dimensions. Any review that claims to assess PV sustainability while giving little attention to end-of-life is therefore leaving out one of the most important parts of the picture [47].

A simple “install-use-discard” model is becoming increasingly difficult to justify for a technology promoted in the language of sustainable development. A value-chain analysis of solar PV end-of-life management shows that circular strategies such as recovery, refurbishment, and material recirculation are becoming central to sustainable business models rather than optional additions once a system is retired [48]. The question is no longer whether PV waste will emerge, but whether the sector is prepared to deal with that waste in ways that fit circular-economy principles.

Even recycling, however, cannot be treated as automatically beneficial. An LCA of a dedicated recovery process for crystalline-silicon panels showed that recycling can produce environmental gains, but those gains depend on how efficiently valuable materials are recovered and on whether new burdens are introduced through energy- or chemical-intensive treatment processes [49]. Calling a process “recycling” does not by itself make it a sustainability solution.

That is why several studies now insist that recycling must be judged against landfill and other disposal pathways on life-cycle terms rather than rhetorical ones. Evidence from India shows that recycling and reuse of recovered materials can significantly reduce impacts in future production compared with landfill-dominated disposal [33]. End-of-life decisions therefore matter well beyond the waste stage; they shape future production burdens and the longer-term environmental credibility of solar deployment.

The discussion has also broadened from recycling to reuse and life extension. Recent work on PV module reuse shows that many silicon modules are retired earlier than their technical lifespan would require, meaning that disposal is often driven by economic and market conditions rather than by physical failure alone [50]. A circular decision-making framework similarly argues that testing, repair, refurbishment, and redeployment can preserve embedded environmental value and reduce waste pressure more effectively than immediate disposal [51]. End-of-life, in this sense, should not be framed only as what happens after failure, but also as how unnecessary waste can be prevented before it occurs.

This broader circular perspective is strengthened by studies that connect PV recycling with the Sustainable Development Goals and with resource stewardship more generally. Research

on recycling photovoltaic modules within a circular economy framework shows that end-of-life strategies have implications not only for waste reduction but also for resource recovery, social responsibility, and more equitable sustainability pathways [52]. End-of-life governance therefore becomes part of the way the solar sector justifies its sustainability credentials.

At the same time, recycling quality and technology choice remain major practical concerns. Assessments of solar PV end-of-life recycling show that mechanical and recovery routes differ widely in their ability to separate and recover glass, silicon, aluminum, silver, lead, and encapsulant materials [53]. Scenario-based evaluations in South Korea likewise show that environmental outcomes change depending on the recycling pathway selected, which means that end-of-life modelling is one of the places where sustainability results can shift materially [54].

Policy has therefore moved closer to the heart of the end-of-life debate. A systematic review of photovoltaic waste policy argues that dedicated end-of-life management frameworks are no longer speculative future needs; they are already necessary if decarbonization goals are to remain compatible with responsible waste governance [8]. Without such frameworks, rapid PV expansion may repeat a familiar pattern in which low-carbon deployment outpaces the institutions needed to manage its material consequences.

The literature leaves little room for treating end-of-life and recycling as minor technical details. Landfilling weakens the sustainability case by locking in waste and preventing material recovery, while recycling, reuse, and circular design can strengthen that case only when they are supported by credible technology, sound policy, and realistic life-cycle accounting [55, 7]. A more defensible sustainability argument is therefore not that PV is sustainable because it is renewable, but that PV becomes sustainable only when its end-of-life pathway is governed as seriously as its electricity-generation phase.

3.6 Regional Trends and Evidence Gaps

A persistent weakness in the photovoltaic LCA literature is that it is often discussed as though it were globally representative, even though the evidence base is unevenly distributed across regions. Recent cross-continental synthesis shows that PV LCA studies exist across five continents, yet the literature is still shaped heavily by a limited set of methodological traditions and regional assumptions, which makes it risky to treat published findings as universally transferable without qualification [7]. Sustainability claims become weaker when they rely too heavily on evidence from places with stronger infrastructure, better waste systems, and more mature electricity networks than those found elsewhere.

One clear pattern is that the strongest body of evidence still comes from higher-income regions such as Europe, parts of Asia, and North America, where industrial inventories, reporting standards, and databases are better developed. While that concentration has helped the field grow technically, it has also shaped what is often treated as the “typical” PV system.

A review of renewable-energy LCA in Africa argues that this imbalance matters because African systems frequently operate under very different conditions, including longer supply chains, weaker formal recycling systems, and different downstream vulnerabilities than those embedded in many standard inventories [56]. Therefore, the problem is not just geographical imbalance; it is a gap in sustainability relevance.

This becomes especially visible when moving from well-documented grid-connected systems to off-grid and rural systems in developing countries. Much of the global PV LCA literature still uses grid-connected crystalline-silicon systems as the default case, even though this does not reflect the energy-access reality of many African settings. Work from Burkina Faso shows that once PV is assessed in the context of a developing country, hotspot structure, energy payback, and impact interpretation become more sensitive to local operating conditions and system design than generalized studies often suggest [57]. That makes blanket generalizations across regions much harder to defend.

The regional gap is not only geographical; it is also conceptual. In regions with strong grid infrastructure, PV is often evaluated as part of a decarbonized electricity mix. In many developing settings, by contrast, PV is more closely tied to energy access, storage dependence, and end-of-life governance. These differences matter because sustainability in one context may depend mainly on carbon displacement, while in another it may depend more on battery durability, affordability, and waste control. Work on integrated off-grid energy-system design supports this view by showing that climate-mitigation outcomes depend heavily on local design choices and service conditions rather than generic assumptions about renewable-technology performance [30]. Regional context changes not just the result, but the meaning of the result.

There is also growing evidence that Africa remains underrepresented in PV-specific life-cycle literature relative to the scale of the sustainability issues involved. [56] argue that the continent's LCA evidence base is still too thin to support confident generalization across different countries and technologies. This shortfall is especially important given the expected growth of PV deployment and the likelihood that many systems will operate in contexts where informal repair, weak logistics, and limited waste regulation shape life-cycle outcomes. A sustainability review that does not highlight this imbalance risks saying more than the literature can presently support.

For West Africa, the gap is even more pressing because rapid solar expansion is already raising future waste and governance questions faster than the literature is resolving them. Quantitative work on West African solar waste flows suggests that the region will face growing PV waste-management challenges as deployment accelerates, while institutional and technical capacity for end-of-life management remains limited [58]. One of the most serious evidence gaps, then, is not only the lack of more LCA case studies, but the lack of studies connecting deployment trajectories with realistic waste and circular-economy planning.

Nigeria illustrates this broader issue clearly. Although the country is central to African energy-transition debates, it remains thinly represented in up-to-date PV life-cycle literature relative to its population, energy-access needs, and likely market importance. Earlier Nigerian PV life-cycle research showed that regional solar radiation and operating context can significantly affect life-cycle metrics, which means national-level conclusions cannot simply be borrowed from foreign case studies without distortion [59]. More recent reviews of Nigerian LCA research show that the shortage of local inventories and context-specific datasets still limits the realism of environmental assessment in the country [24]. That is not just a technical inconvenience; it weakens confidence in sustainability-oriented policy.

Another regional issue is that local performance conditions often differ from what standard inventories assume. Analysis of sub-Saharan African PV performance shows that high operating temperatures, dust accumulation, and inconsistent policy support can all reduce system output and complicate long-term performance assumptions [60]. If actual yield is lower than assumed, then impacts per delivered kilowatt-hour rise accordingly. The evidence gap in Africa is therefore not only about having fewer studies; it is also about the mismatch between imported assumptions and local operating realities.

The literature also points toward a need for more regionally differentiated planning. A regional-planning study argues that solar PV development should be guided by both environmental and economic objectives rather than installation growth alone, because spatial variation strongly affects whether deployment is genuinely sustainable[61]. More solar capacity does not automatically mean more sustainability if systems are deployed, maintained, and governed under weak environmental conditions.

What emerges from this literature is a fairly consistent pattern: PV LCA evidence is concentrated in better-documented regions, while context-specific life-cycle knowledge remains underdeveloped for Africa, West Africa, and Nigeria in particular. That imbalance weakens the global sustainability narrative around PV because it encourages conclusions broader than the available evidence can safely support. A more defensible position is that PV may be globally important for decarbonization, but its sustainability still has to be demonstrated under regional conditions shaped by infrastructure quality, storage dependence, policy capacity, waste governance, and actual operating performance rather than assumed from studies conducted elsewhere [62, 3].

4. Synthesis of Findings and Future Directions

4.1 Major Insights and Evidence Gaps

The reviewed literature leaves little doubt that the environmental profile of solar photovoltaic systems is far more complex than the common description of PV as a uniformly clean energy technology. Across the studies examined, one of the clearest findings is that the environmental burden of PV is rarely concentrated in electricity generation itself. Instead, it

is more consistently associated with upstream manufacturing, storage systems, and end-of-life management. This pattern appears repeatedly across different system types and regional contexts, suggesting that the environmental strength of PV depends less on its zero-emission operation and more on how its materials, supporting technologies, and post-use pathways are handled over time. In practical terms, this means that the sustainability of PV cannot be judged credibly from the use phase alone.

A second major insight is that storage changes the meaning of PV sustainability in a fundamental way. Once batteries are introduced, especially in stand-alone and hybrid systems, the environmental discussion becomes more demanding. The reviewed studies show that batteries are not passive supporting devices but major determinants of overall system impacts. Their chemistry, service life, replacement frequency, and end-of-life treatment all influence whether PV remains environmentally favorable over its full life cycle. This is particularly important for off-grid systems, where storage is often indispensable. Under such conditions, the literature does not support the view that solar deployment can be treated as inherently sustainable without a parallel evaluation of battery performance and battery governance.

Another important finding is that end-of-life is no longer a minor downstream concern. The literature now treats recycling, reuse, refurbishment, and recovery as central to the sustainability case for PV rather than as optional extensions of it. This shift reflects a broader recognition that large-scale PV deployment without credible waste management and material recovery systems risks transferring environmental burdens into the future rather than resolving them. In that sense, the literature increasingly presents end-of-life as one of the points where the sustainability of PV is either strengthened or weakened most clearly.

The review also shows that methodological choices continue to shape PV LCA outcomes in powerful ways. Functional units, system boundaries, treatment of storage, recycling assumptions, and uncertainty handling all affect how results are interpreted. This remains one of the most persistent weaknesses in the field. The problem is not only that studies differ, but that these differences often make it difficult to compare results confidently across technologies, regions, and system configurations. As a result, methodological inconsistency still limits the extent to which individual studies can be synthesized into a stable body of evidence.

At the same time, the literature points to a clear geographic imbalance. Much of the available PV LCA evidence still comes from better-documented regions with stronger industrial inventories, stronger waste systems, and more established grid infrastructure. This leaves Africa, West Africa, and Nigeria especially underrepresented relative to the scale of the sustainability questions now emerging in those regions. The consequence is that global conclusions about PV sustainability are often broader than the evidence base can safely support. Many studies still rely on imported assumptions, foreign datasets, or context conditions that do not reflect the realities of developing-country deployment.

These gaps are not merely academic. They affect how confidently PV can be promoted as a sustainable solution in places where storage dependence is high, waste systems are weak, and actual operating conditions differ from those assumed in standard inventories. The literature therefore reveals two problems at once: the first is that PV sustainability is more conditional than popular narratives often suggest, and the second is that the evidence needed to evaluate those conditions remains unevenly developed across regions. For this reason, the strongest conclusion from the review is not that PV lacks sustainability value, but that its sustainability must be demonstrated more carefully, more contextually, and with greater methodological discipline than is often the case.

4.2 Sustainability and Policy Priorities

The literature reviewed in this paper points to a practical conclusion that is difficult to ignore: solar photovoltaic systems should not be treated as sustainable by default simply because they generate electricity without combustion. Their sustainability depends on how the full system is designed, produced, operated, and managed after use. This means that future discussions of PV deployment need to move beyond installation targets and electricity-generation metrics alone. A more credible sustainability approach must include attention to material intensity, storage requirements, toxicity risks, waste recovery, and long-term circularity.

One major priority is the need to improve upstream production practices. Since manufacturing remains one of the dominant hotspots in the PV life cycle, cleaner production processes, lower-carbon electricity inputs, and more resource-efficient material use are essential if PV is to retain a strong environmental advantage over time. This is particularly important for module production and other energy-intensive system components. Without progress in these areas, the environmental burden of PV may continue to be shifted upstream while sustainability claims remain focused too narrowly on the operational stage.

A second priority concerns storage. Because batteries increasingly determine the environmental profile of stand-alone and hybrid PV systems, policy and system design must pay closer attention to battery selection, durability, replacement strategy, and end-of-life treatment. Storage should no longer be treated as a simple technical add-on to solar deployment. It is now one of the main factors shaping whether PV systems can deliver reliable electricity without introducing new environmental and waste burdens that are difficult to manage later. This is especially relevant in developing-country settings, where battery replacement and informal disposal practices can weaken the long-term sustainability of otherwise promising systems.

End-of-life governance is another area that now demands stronger policy attention. The literature shows that recycling, reuse, and module life extension can improve the environmental profile of PV, but only when they are supported by credible infrastructure, realistic recovery pathways, and proper regulatory frameworks. In the absence of those

conditions, rapid solar deployment may create a familiar sustainability problem in which low-carbon expansion outpaces the systems needed to manage its material consequences. This suggests that waste regulation, recycling policy, and circular-economy planning should be treated as part of solar energy policy rather than as separate environmental matters.

The regional evidence gap identified in this review also points to an urgent research and policy priority. Countries such as Nigeria require more context-specific PV LCA studies built on local inventories, local operating realities, and realistic end-of-life assumptions. Without this, planning decisions will continue to depend too heavily on studies developed under different environmental, technical, and institutional conditions. For sustainability-oriented decision-making, this is a serious limitation. More local evidence is needed not only to improve academic understanding, but also to support better policy, better waste planning, and more reliable long-term deployment strategies.

There is also a need for greater methodological transparency in future research. Many of the disagreements across the literature do not come from fundamentally different technologies, but from different ways of modelling similar systems. Better reporting of assumptions, stronger justification of system boundaries, and clearer treatment of uncertainty would make the literature more useful for both scholars and decision-makers. More importantly, it would help ensure that sustainability claims about PV are based on evidence that can be compared, challenged, and trusted.

Looking ahead, the policy direction suggested by this review is fairly clear. Sustainable PV deployment will require more than expanding installed capacity. It will require cleaner production, more careful storage planning, stronger recycling and reuse systems, better local datasets, and policies that link energy transition goals with circular resource management. In that sense, the most meaningful path forward is not to ask whether PV is sustainable in general, but under what conditions it becomes sustainable in practice.

5. Conclusion

This review has shown that the sustainability of solar photovoltaic systems cannot be judged only by their low-emission operation. Across the literature, the main environmental pressures are more consistently linked to manufacturing, storage systems, and end-of-life management than to electricity generation itself. The review also shows that methodological differences in system boundaries, functional units, and end-of-life assumptions continue to weaken comparability across studies. In addition, important regional gaps remain, particularly for Africa and Nigeria, where local conditions are often poorly represented in the existing evidence base. Overall, the literature suggests that PV should not be treated as inherently sustainable, but as a technology whose sustainability depends on cleaner production, better storage choices, credible recycling and waste governance, and more context-specific assessment. Future studies should therefore focus on developing region-specific life cycle inventories, improving the representation of storage and end-of-life pathways under real

operating conditions, and generating more context-based evidence for Africa and other underrepresented regions.

References

- [1] Luu, L. Q., Doan, B. V., Nguyen, N. Q., & Nguyen, N. H. (2020). Life cycle assessment (LCA) of an integrated solar PV and wind power system in Vietnam. *Journal of Asian Energy Studies*, 4, 36–47.
- [2] Muteri, V., Cellura, M., Curto, D., Franzitta, V., Longo, S., Mistretta, M., & Parisi, M. L. (2020). Review on life cycle assessment of solar photovoltaic panels. *Energies*, 13(1), 252.
- [3] Tan, D., Wu, Y., Zhang, Z., Jiao, Y., Zeng, L., & Meng, Y. (2023). Assessing the life cycle sustainability of solar energy production systems: A toolkit review in the context of ensuring environmental performance improvements. *Sustainability*, 15(15), 11724.
- [4] Obuseh, E., Ebisine, E. E., Okieke, U. J., Aloamaka, C. A., & Anamonye, G. U. (2025). Sustainability of decarbonization: A systematic review of policy integration and regional realities. *Nigerian Journal of Sustainability Research*, 3(2), 77–95.
- [5] Jonathan, E. O., Ewere, O. E., Ezekiel, E. E., Onogharigho, O. A., & Okieke, U. J. (2025). Analysis of Oria Abraka 33/11 kV power sub-station: A case for sustainable power supply. *NIPES-Journal of Science and Technology Research*, 7(1), 204–218.
- [6] Oghenegare, A. J., Nkemdilim, E. J., Ewere, O. E., Donald, I., & Ekene, M. C. (2024). Renewable energy in Nigeria: A comprehensive examination of the viability of solar energy in Nigeria. *International Journal of Innovative Research and Technology*, 11(5), 2433–2438.
- [7] Ihoume, I., van Noord, M., & Augusto, A. (2026). Toward a transparent life cycle assessment of photovoltaic systems: Addressing regulatory and methodological challenges. *Environmental Impact Assessment Review*, 118, 108290.
- [8] Kwok, K. H., Savaget, P., Fukushima, S., & Halog, A. (2024). The necessity for end-of-life photovoltaic technology waste management policy: A systematic review. *Journal of Cleaner Production*, 461, 142497.
- [9] Leda, P., Piasecka, I., & Szala, G. (2025). Environmental life cycle assessment of the materials, components, and elements of a Mono-Si photovoltaic power plant. *Materials*, 18(12), 2748.
- [10] Obuseh, E., Eyenubo, J., Alele, J., Okpare, A., & Oghogho, I. (2025). A systematic review of barriers to renewable energy integration and adoption. *Journal of Asian Energy Studies*, 9, 26–45.

- [11] Li, T., Roskilly, A. P., & Wang, Y. (2018). Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England. *Applied Energy*, 227, 465–479.
- [12] Neumüller, A., Geier, S., & Österreicher, D. (2023). Life cycle assessment for photovoltaic structures—comparative study of rooftop and free-field PV applications. *Sustainability*, 15(18), 13692.
- [13] Badza, K., Sawadogo, M., & Soro, Y. M. (2024). Environmental impacts of a stand-alone photovoltaic system in sub-Saharan Africa: A case study in Burkina Faso. *Heliyon*, 10(19).
- [14] Preet, S., & Smith, S. T. (2024). A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook. *Journal of Cleaner Production*, 448, 141661.
- [15] Adiansyah, J. S., Agusdinata, D. B., & Putra, A. P. (2025). Environmental impacts of solar PV energy systems for small-island communities in Indonesia: A life cycle assessment approach. *Energy for Sustainable Development*, 85, 101651.
- [16] Mahmoudi, S., Huda, N., Alavi, Z., Islam, M. T., & Behnia, M. (2019). End-of-life photovoltaic modules: A systematic quantitative literature review. *Resources, Conservation and Recycling*, 146, 1–16.
- [17] Prabhu, V. S., Shrivastava, S., & Mukhopadhyay, K. (2022). Life cycle assessment of solar photovoltaic in India: A circular economy approach. *Circular Economy and Sustainability*, 2(2), 507–534.
- [18] Smith, B. L., Sekar, A., Mirletz, H., Heath, G., & Margolis, R. (2024). An updated life cycle assessment of utility-scale solar photovoltaic systems installed in the United States (No. NREL/TP--7A40-87372). National Renewable Energy Laboratory (NREL), Golden, CO, United States.
- [19] Cayuela, J. F., García, A. M., García, I. F., & Díaz, J. R. (2024). Life cycle assessment of large-scale solar photovoltaic irrigation. *Science of the Total Environment*, 954, 176813.
- [20] Gómez-Navarro, T., Stascheit, C., Díaz-Bello, D., & Vargas-Salgado, C. (2024). An agile life cycle assessment for the deployment of photovoltaic energy systems in the built environment. *Energy, Sustainability and Society*, 14(1), 60.
- [21] Marson, A., Zuliani, F., Fedele, A., & Manzardo, A. (2024). Life cycle assessment-based decision making under methodological uncertainty: A framework proposal. *Journal of Cleaner Production*, 445, 141288.

- [22] Krexner, T., Gronauer, A., & Kral, I. (2025). Comparison of four different end-of-life modelling approaches for an environmental life cycle assessment of agrivoltaic systems in Austria. *The International Journal of Life Cycle Assessment*, 30(12), 2925–2942.
- [23] Kiskira, K., Gerolimos, N., Priniotakis, G., & Nikolopoulos, D. (2026). Life-cycle assessment of innovative industrial processes for photovoltaic production: Process-level LCIs, scale-up dynamics, and recycling implications. *Applied Sciences*, 16(1), 501. <https://doi.org/10.3390/app16010501>
- [24] Isah, M. E., Wasah, A., & Matsubae, K. (2025). Life cycle assessment research and application in Nigeria. *The International Journal of Life Cycle Assessment*, 30(5), 880–895.
- [25] Loh, H. S., Phuang, Z. X., Mulya, K. S., Lee, C. T., Varbanov, P. S., & Woon, K. S. (2025). A systematic review of life cycle assessment reporting practices and transparency for mono-crystalline silicon photovoltaic systems. *Chemical Engineering Transactions*, 122, 97–102.
- [26] Daniela-Abigail, H. L., Vega-De-Lille, M. I., Sacramento-Rivero, J. C., Ponce-Caballero, C., El-Mekaoui, A., & Navarro-Pineda, F. (2024). Life cycle assessment of photovoltaic panels including transportation and two end-of-life scenarios: Shaping a sustainable future for renewable energy. *Renewable Energy Focus*, 51, 100649.
- [27] Rahman, M. M., Alam, C. S., & Ahsan, T. M. (2019). A life cycle assessment model for quantification of environmental footprints of a 3.6 kWp photovoltaic system in Bangladesh. *International Journal of Renewable Energy Development*, 8(2).
- [28] Sheng, X., Chen, L., Liu, M., Yuan, X., Wang, Q., Ma, Q., & Zuo, J. (2025). Environmental impact of monocrystalline silicon photovoltaic modules. *Resources, Conservation and Recycling*, 220, 108373.
- [29] Jiang, T., Yin, P., & Jin, Q. (2024). Performances of typical photovoltaic module production from the perspective of life cycle sustainability assessment. *Sustainable Energy Technologies and Assessments*, 64, 103703.
- [30] Viole, I., Valenzuela-Venegas, G., Sartori, S., & Zeyringer, M. (2024). Integrated life cycle assessment in off-grid energy system design—Uncovering low hanging fruit for climate mitigation. *Applied Energy*, 367, 123334.
- [31] Li, F., Shaw, S., Libby, C., Preciado, N., Bicer, B., & Tamizhmani, G. (2024). A review of toxicity assessment procedures of solar photovoltaic modules. *Waste Management*, 174, 646–665.

- [32] Petroli, P. A., Camargo, P. S. S., de Souza, R. A., & Veit, H. M. (2024). Assessment of toxicity tests for photovoltaic panels: A review. *Current Opinion in Green and Sustainable Chemistry*, 47, 100885.
- [33] Sharma, A., Mahajan, P., & Garg, R. (2024). End-of-life solar photovoltaic panel waste management in India: Forecasting and environmental impact assessment. *International Journal of Environmental Science and Technology*, 21(2), 1961–1980.
- [34] Duan, Y., Guo, F., Huang, Z., Gardy, J., Jiang, X., & Li, C. (2024). Life cycle assessment of recycling waste crystalline silicon photovoltaic modules: A comparison between traditional and green solvent recycling processes. *Chemical Engineering Journal*, 500, 157132.
- [35] Rathore, N., & Panwar, N. L. (2022). Strategic overview of management of future solar photovoltaic panel waste generation in the Indian context. *Waste Management & Research*, 40(5), 504–518.
- [36] Paul, D., Pechancová, V., Saha, N., Pavelková, D., Saha, N., Motiei, M., ... & Sába, P. (2024). Life cycle assessment of lithium-based batteries: Review of sustainability dimensions. *Renewable and Sustainable Energy Reviews*, 206, 114860.
- [37] Barbosa, J. C., Pinto, R. S., Serra, J. P., Gonçalves, R., Lizundia, E., Costa, C. M., & Lanceros-Mendez, S. (2025). Batteries and sustainability: The relevance of life cycle assessment. *Sustainable Energy Technologies and Assessments*, 82, 104488.
- [38] Stanchev, P., & Hinov, N. (2025). Comparative techno-economic and life cycle assessment of stationary energy storage systems: Lithium-ion, lead-acid, and hydrogen. *Batteries*, 11(10), 382.
- [39] Jasper, F. B., Baumann, M., Stumpf, M., Husmann, A., Riegel, B., Passerini, S., & Weil, M. (2025). Full life cycle assessment of an industrial lead–acid battery based on primary data. *Energy Advances*, 4(7), 910–929.
- [40] Domingues, A. M., & De Souza, R. G. (2024). Review of life cycle assessment on lithium-ion batteries (LIBs) recycling. *Next Sustainability*, 3, 100032.
- [41] Hemmati, M., Bayati, N., & Ebel, T. (2024). Life cycle assessment and costing of large-scale battery energy storage integration in Lombok’s power grid. *Batteries*, 10(8), 295.
- [42] Fett, D., Fraunholz, C., & Schneider, P. (2023). Life cycle greenhouse gas emissions of residential battery storage systems: A German case study. *Journal of Industrial Ecology*, 27(1), 182–195.

- [43] Hincapié, A., Sanint, E. Á., Dyner, I., & Aristizábal Cardona, A. J. (2025). Sustainability and environmental impact of residential photovoltaic systems with lithium-ion battery storage in Colombia: A system dynamics approach. *Management of Environmental Quality: An International Journal*, 1–24.
- [44] Makhubele, W. J., Thango, B. A., & Ogudo, K. A. (2025). Evaluating rooftop solar photovoltaics and battery storage for residential energy sustainability in Benoni, South Africa. *Processes*, 13(6), 1828.
- [45] Stucki, M., Götz, M., de Wild-Scholten, M., & Frischknecht, R. (2024). Environmental life cycle assessment of electricity from PV systems–2023 data update. *International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS)*.
- [46] Clemente, M., Maharjan, P., Salazar, M., & Hofman, T. (2025). Meta-analysis of life cycle assessments for Li-ion batteries production emissions. *The International Journal of Life Cycle Assessment*, 1–17.
- [47] Torrónategui-Chávez, G., Bustos-Terrones, Y., Tariq, R., Bassam, A., López, D. A. H., & Kurniawan, T. A. (2026). Recycling solar photovoltaic panels as an end-of-life scenario: Review considering environmental, economic, social, political, and educational dimensions. *Science of the Total Environment*, 1010, 181129.
- [48] AmrollahiBiyouki, Z., Zaman, A., Marinova, D., Minunno, R., & Askari Shayegan, M. (2024). Solar photovoltaics value chain and end-of-life management practices: A systematic literature review. *Sustainability*, 16(16), 7038.
- [49] Ansanelli, G., Fiorentino, G., Tammaro, M., & Zucaro, A. (2021). A life cycle assessment of a recovery process from end-of-life photovoltaic panels. *Applied Energy*, 290, 116727.
- [50] Basnet, R., Jones, L., Azmie, M. A., Jones, M., McCann, M., & Ernst, M. (2025). Advancing circular economy of silicon photovoltaics: Current status and challenges of PV module reuse. *Solar Energy Materials and Solar Cells*, 292, 113816.
- [51] Marinna, P., Laís, V., OR, P. F., & Ricardo, R. (2025). Circular solar economy: PV modules decision-making framework for reuse. *Journal of Cleaner Production*, 493, 144941.
- [52] Aşkın, A., Kılış, Ş., & Akinoğlu, B. G. (2023). Recycling photovoltaic modules within a circular economy approach and a snapshot for Türkiye. *Renewable Energy*, 208, 583–596.
- [53] Ali, A., Shahid, M., Qadir, S. A., Islam, M. T., Khan, M. W., & Ahmed, S. (2024). Solar PV end-of-life waste recycling: An assessment of mechanical recycling methods and proposed hybrid laser and high voltage pulse crushing method. *Resources*, 13(12), 169.

- [54] Kwon, S., Kim, H. J., Kim, S., & Hong, S. J. (2025). Sustainability impact evaluation of the recycling of end-of-life crystalline silicon solar photovoltaic panel waste in South Korea. *Sustainability*, 17(2), 431.
- [55] Celep, O., Deveci, H., & Yazici, E. Y. (2025). A comprehensive review on recycling end of life solar photovoltaic panels. *Waste Management*, 206, 115092.
- [56] Mukoro, V., Gallego-Schmid, A., & Sharmina, M. (2021). Life cycle assessment of renewable energy in Africa. *Sustainable Production and Consumption*, 28, 1314–1332.
- [57] Badza, K., Soro, Y. M., & Sawadogo, M. (2023). Life cycle assessment of a 33.7 MW solar photovoltaic power plant in the context of a developing country. *Sustainable Environment Research*, 33(1), 38.
- [58] Dong, D., Emem, O., Liu, L., Sen, B., Rasmussen, K., Edomah, N., ... & Liu, G. (2025). Solar photovoltaic development in West Africa will face million-ton waste challenges, and off-grid systems will dominate. *Environmental Science & Technology*, 59(39), 21102–21116.
- [59] Akinyele, D. O., Rayudu, R. K., & Nair, N. K. C. (2017). Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria. *Renewable Energy*, 101, 537–549.
- [60] Kichonge, B., & Mwakapoma, S. (2026). Photovoltaic system performance in Sub-Saharan Africa under environmental, technical and policy constraints. *Discover Sustainability*.
- [61] Yuan, J., Xu, X., Huang, B., Li, Z., & Wang, Y. (2023). Regional planning of solar photovoltaic technology based on LCA and multi-objective optimization. *Resources, Conservation and Recycling*, 195, 106977.
- [62] Li, Y., Gaffney, P. P., Zhao, F., Xu, X., & Zhang, M. (2025). Application of life cycle assessment to policy environmental impact assessment—A clean energy action plan case study in Qinghai Region. *Sustainability*, 17(1), 84.