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**Sustainability and Environmental Impact Assessment of Solar
Energy Systems: A Comprehensive Review**



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Sustainability and Environmental Impact Assessment of Solar Energy Systems: A Comprehensive Review

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Abstract

Purpose: The increased adoption of solar energy systems has positioned solar photovoltaic (PV) technology as a major renewable energy solution for achieving sustainability and reducing environmental impacts associated with electricity generation. This study aims to evaluate the environmental performance and sustainability of solar PV systems using a life cycle assessment perspective.

Methodology: This research employs a comprehensive literature review of existing life cycle assessment studies on solar photovoltaic systems. The analysis examines key sustainability indicators including energy payback time, greenhouse gas emissions, energy return on energy invested, resource efficiency, and end-of-life management across different PV technologies and system configurations. Comparative assessment with fossil fuel-based electricity generation is also conducted to contextualize environmental performance.

Findings: The review demonstrates that solar PV systems provide significant environmental benefits over their operational lifetime despite manufacturing-related impacts. Technological advancements and improved production processes have reduced life-cycle emissions and energy requirements. Large-scale and building-integrated PV systems show strong sustainability potential in commercial buildings and urban developments. However, challenges remain in PV recycling, circular economy integration, and standardization of life cycle assessment methodologies.

Unique Contribution to Theory, Policy and Practice: This study synthesizes life cycle sustainability evidence for solar PV systems and identifies critical research gaps related to recycling, circular economy implementation, and assessment standardization. The findings provide decision-support insights for policymakers, researchers, and commercial infrastructure developers seeking to enhance sustainable energy adoption.

Keywords: *Solar photovoltaic systems, Sustainability assessment, Life cycle assessment, Energy payback time, Greenhouse gas emissions, Environmental impact*

1. Introduction

The world's energy industry is at a crossroads; climate change and environmental degradation will create new barriers to the long-term availability of resources. While traditional fossil fuel-based energy systems have fueled the global economy, they have also created massive amounts of greenhouse gases (GHGs), and caused significant air quality problems and ecological damage. Additionally, as global energy demands increase due to growing populations, urbanization, and increased industrial production the environmental impact of producing energy has reached unsustainable levels. Meeting these challenges will require a fundamental change toward cleaner energy options that satisfy increasing demands with reduced negative environmental and social impacts (Peng et al., 2013).

In addition to reducing GHG emissions, sustainability in the energy industry encompasses efficient use of resources, environmental stewardship, and resilient energy delivery systems. Renewable energy technologies are emerging as key contributors to the clean energy revolution providing pathways to de-carbonize electric power generation and provide alternatives to finite natural resources (Fthenakis & Kim, 2011) Among the renewable energy technologies available, solar energy technologies have been gaining momentum because of their abundant supply, decreasing cost of equipment, and flexibility of application to both large scale utility and small scale distributed applications. Solar Photovoltaic Systems have become a common place component of both residential and commercial energy portfolios and play a significant role in both national and regional energy plans (Wall et al., 2012).

Although solar energy systems offer many positive aspects once operational, solar energy systems do not exist in a vacuum and there are a number of environmental impacts associated with the life cycle of solar energy systems including energy intensive manufacture of PV modules, extraction of materials used in PV modules, chemical usage, system installation, land use changes, transportation of modules to site, maintenance of systems and finally disposal or recycling of systems at the end of their useful life (Hernandez et al., 2014) Therefore, as the deployment of solar energy systems increases globally, it is essential to understand and manage the environmental impacts of solar energy systems so they may produce real and sustained sustainability benefits (Zuo & Zhao, 2014).

Therefore, it is essential to evaluate the environmental impacts of solar energy systems using comprehensive assessment tools such as life-cycle assessments. A life-cycle assessment (LCA) is a widely accepted method of evaluating the environmental impacts of a product or service throughout its entire life-cycle including energy consumption, greenhouse gas emissions, and other environmental indicators. LCAs allow for meaningful comparisons to be made between different types of solar energy and traditional electricity generation technologies, and supports evidence based decision making by policymakers, developers, and researchers. As solar photovoltaics continue to evolve as a responsible and effective option for meeting future energy demands,

rigorous environmental assessments will continue to be essential to ensuring that the transition to sustainable energy continues unabated (Latunussa et al., 2016).

2. Life-Cycle Assessment Framework for Solar Energy Systems

A life-cycle assessment is an established methodology for examining environmental effects of products, technologies, and systems through the entirety of their life cycle. Within the context of solar energy systems, a life-cycle assessment methodology offers a methodical and clear-cut way to quantify energy usage, greenhouse gas emissions and other environmental parameters from the extraction of materials to the final stages of end-of-life management of photovoltaic (PV) technologies. The methodology is required to ensure that any claims made about the sustainability of deploying solar energy can be evidenced by both comparative and comprehensive evidence.

2.1 Methodological Basis of Life-Cycle Assessments

Life-cycle assessments rely upon widely accepted international standards to describe the foundational principles, requirements and methods for conducting environmental analyses. The typical steps involved in an LCA include: goal and scope; life-cycle inventory; life-cycle impact assessment; and the interpretation of the results (Fthenakis & Raugei, 2017) In most cases, the goal of the solar PV study will involve determining the environmental performance of a particular PV technology; the comparison of two or more system designs; or the benchmarking of solar-generated electricity compared to conventional energy supplies (Wall et al., 2012) The scope is used to define the underlying assumptions, data quality requirements and methodological selections that establish the assessment.

The life-cycle inventory phase of an LCA involves establishing quantitative information relative to material inputs, energy consumption, emissions and waste flows associated with all phases of a photovoltaic system (Hu et al., 2016) During the life-cycle impact assessment phase, the information collected during the life-cycle inventory phase is transformed into environmental effects using characterization factors to connect the inventory flows to environmental effects. The interpretation phase is used to synthesize the results obtained from the prior steps, identify the predominant impact contributors, and evaluate the uncertainty in order to derive strong conclusions.

2.2 System Boundaries in Solar PV Studies

An important component of an LCA is the establishment of system boundaries which defines which processes are considered within the assessment. For solar photovoltaic systems, system boundaries frequently include raw material extraction and processing, module and balance-of-systems manufacture, transportation, installation, operation and maintenance, and end-of-life treatment such as recycling or landfilling. Some studies have adopted a cradle-to-gate approach to focus on the environmental impacts associated with manufacture of the photovoltaic modules,

while others have conducted more extensive cradle-to-grave assessments to examine the full environmental profile of the system throughout its operational lifespan.

The boundaries selected for an LCA has a significant effect on the outcomes of the assessment and should be well-justified. Broadly defined system boundaries are preferred in studies focused on sustainability because they allow for the consideration of long-term environmental benefits associated with electrical generation and the capture of end-of-life recovery opportunities. This is particularly true for large-scale and commercial photovoltaic installations where the long duration of the service life of the photovoltaic equipment and the large cumulative amount of electrical energy generated increases the sustainability advantages of the installed system.

2.3 Functional Units and Comparative Analysis

The functional unit is the reference point for measuring and comparing the environmental effects resulting from the life-cycle assessment of a product or system. In solar PV studies, the functional unit is usually defined as the total electrical energy generated per unit of electrical energy, i.e., kilowatt-hours of electricity delivered to the grid (Hu et al., 2016) Normalizing the measurement of environmental effects by this type of functional unit enables the comparison of different photovoltaic technologies, system configurations, and alternative electrical energy supply options.

The selection of the appropriate functional unit is critical to ensure that comparisons among alternatives are valid and transparent. Electrical energy-based functional units are particularly useful for comparing solar PV systems with electrical energy supplied from fossil fuels and other forms of renewable energy. Additionally, they enable the evaluation of several key sustainability metrics, including energy payback time and life-cycle greenhouse gas emissions per unit of electrical energy generated.

2.4 Environmental Impact Categories Relevant to Solar PV Life-Cycle Assessments

Life-cycle impact assessment transforms the quantitative data collected during the life-cycle inventory phase into qualitative environmental indicators that represent the possible adverse environmental impacts caused by the production and use of solar photovoltaic systems. Commonly assessed environmental impact categories in solar PV studies include: climate change potential, energy demand, resource depletion, and emissions of air pollutants. Indicators of climate change potential, typically measured as greenhouse gas emissions per unit of electrical energy generated, are central to evaluating the degree to which solar PV contributes to reducing carbon dioxide levels (Kittner et al., 2016).

Other environmental impact categories that may be evaluated in addition to those mentioned above include: water usage, land occupation, and toxicity-related indicators, which may be more applicable to evaluating the manufacturing processes and end-of-life management of solar photovoltaic systems. Collectively, these environmental impact categories provide a complete picture of the environmental performance of solar energy systems and provide the necessary

information to make informed decisions regarding technology selection, system design and sustainability practices.

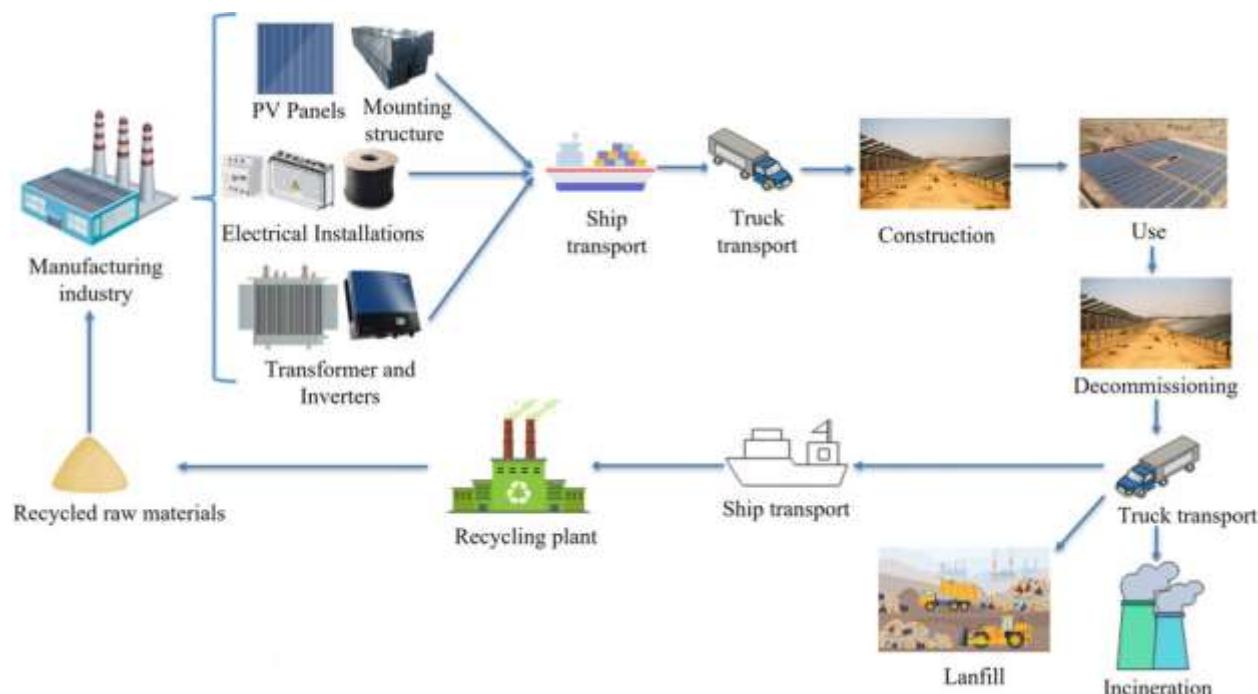


Figure 1. Life-Cycle Assessment System Boundary for Solar Photovoltaic Systems

This figure illustrates the cradle-to-grave life-cycle stages of a solar photovoltaic system, including raw material extraction, manufacturing of PV components, transportation, construction and installation, operational use, decommissioning, and end-of-life pathways such as recycling, landfill, and incineration. It defines the system boundaries applied in life-cycle assessment studies and highlights material and energy flows across the entire photovoltaic value chain.

3. Environmental Impacts of Solar Energy Systems

The Environmental Impact of Solar Photovoltaic Systems

Solar photovoltaic (PV) systems produce electricity without generating greenhouse gases (GHGs) during normal operation; however, the total environmental impact of the systems is determined by all phases of the system's life cycle including manufacturing,

transportation/installation, operation, and end-of-life management. For this reason, it is essential to evaluate the environmental performance of solar PV systems through a life-cycle assessment (LCA) to fully capture and compare the impacts of the solar PV systems to other electricity generation alternatives.

3.1 GHG Emissions

The majority of the greenhouse gas emissions attributed to solar PV systems occur during the initial upstream stages of the life cycle; specifically, in the extraction and processing of the raw materials needed for the modules and the manufacturing process itself. Additionally, the energy intensive nature of processes used to purify silicon, create wafers, and assemble modules accounts for the majority of the life-cycle GHG emissions (Fthenakis & Kim, 2011) However, technological advancements in the solar PV manufacturing process, the increasing efficiency of manufacturing processes and the greater use of renewable electricity to meet the electrical needs of production facilities have greatly decreased the GHG emissions attributed to solar PV systems. Furthermore, LCA analyses show that the GHG emissions from solar PV systems per unit of electricity produced is significantly less than that from fossil-fuel based electricity generation supporting the role of solar PV systems in GHG emission reduction and climate change mitigation.

3.2 Energy Payback Periods

The energy payback time (EPBT) is an important measure of the environmental effectiveness of solar PV systems. EPBT represents the length of time required for a solar PV system to produce the same amount of energy as was used to manufacture, transport and install the system. As a result, modern solar PV systems generally have a shorter EPBT than their useful lifespan and will continue to produce net positive energy for many years after the EPBT has been met. A decreasing EPBT reflects the improvements made in module efficiency, manufacturing processes, and system design and contributes to the increased sustainability of deploying solar energy (Raugei et al., 2017).

3.3 Water Usage and Resource Consumption

Compared to traditional thermal power plants, water usage in solar PV systems is generally very low. During the operational phase, most of the water used by solar PV systems is related to cleaning and maintaining the modules. Manufacturing is the primary source of water usage for solar PV systems. Dry processing methods and improved cleaning methods are being developed to reduce the amount of water used during manufacturing and cleaning processes. Overall, solar PV systems are a preferred option for water-scarce locations due to the low water usage requirements. Improving the efficiency of solar PV systems reduces the use of raw materials and is also improving the sustainability of solar PV systems (Fthenakis & Raugei, 2017).

3.4 Land Use and Material-Related Impacts

The land use impacts associated with solar PV systems depend upon the size and location of the solar PV systems. Utility-scale solar PV systems often require large amounts of land, which can potentially cause ecological damage if the land use planning is poor. Roof-top and building-integrated PV systems reduce the need for land use because they utilize existing structures in urban and commercial areas (Latunussa et al., 2016) The material-related impacts associated with solar

PV systems include the extraction and processing of the metals, glass and semiconductor materials used in the manufacturing process. End of life waste management of solar PV systems also includes material-related impacts. Recyclable and closed-loop recycling approaches are being developed to recover valuable materials and reduce the environmental impacts associated with the disposal of solar PV systems at the end of their life.

Life Cycle Assessment of Solar Photovoltaic Systems

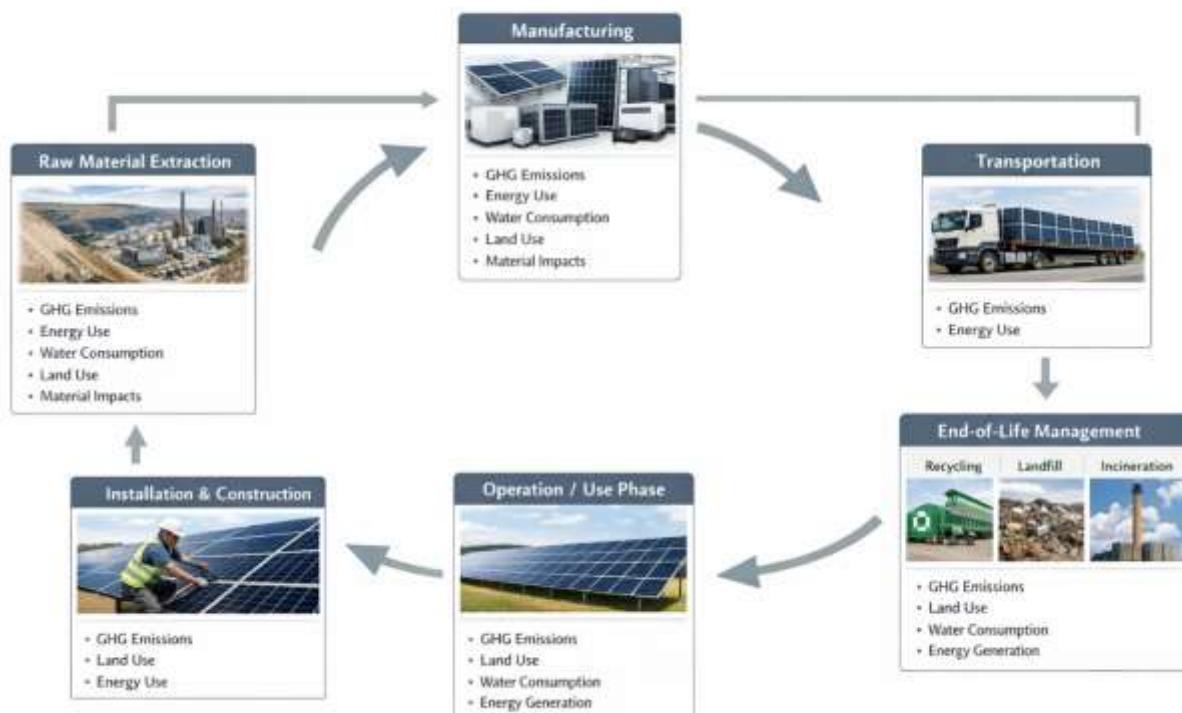


Figure 2. Life-Cycle Environmental Impact Pathways of Solar Photovoltaic Systems

This figure presents a life-cycle assessment schematic of solar photovoltaic systems, illustrating key environmental impact pathways across all stages, including raw material extraction, manufacturing, transportation, installation, operation, and end-of-life management. It highlights major impact categories such as greenhouse gas emissions, energy payback time, water use, land occupation, and material-related impacts, providing a comprehensive view of the environmental performance of solar energy systems over their full life cycle (Peng et al., 2013).

4. Sustainability Performance in Large Scale and Built Environment Applications

Commercial establishments like shopping malls and office buildings have high usage of electricity for operating systems such as lighting, heating, ventilation, escalators, and digital networks; therefore, they are suitable candidates for the application of solar PV systems in order to meet sustainability goals in the energy and construction industries. Additionally, integrating solar PV

systems into commercial environments provides many opportunities to significantly reduce greenhouse gas emissions and reduce operational energy costs while improving the overall environmental performance throughout the entire lifecycle of the building.

However, it is essential to conduct a complete sustainability evaluation in commercial environments for both operational impacts (i.e., energy consumption) and embodied impacts (i.e., energy used for producing, transporting and installing solar PV systems).

4.1 Role of Solar PV Systems in Large-Scale Commercial Establishments

Due to their extensive rooftop space, consistent daytime electricity loads, and long operational lifetimes, large commercial establishments and shopping malls are ideal candidates for the integration of solar PV systems. By installing solar PV systems on rooftops, commercial establishments and shopping malls can significantly reduce their reliance on the grid for electricity and thereby significantly reduce the amount of fossil fuels burned for electricity generation. Furthermore, in addition to utilizing available rooftop space for generating electricity, solar PV systems may also be installed on facades or integrated into car park systems in order to maximize the available surface area for generating electricity and thus increase on-site renewable energy production without increasing land use.

Solar PV systems contribute to significant reductions in the operational environmental impacts of electricity usage for commercial establishments. Due to their daytime operational characteristics, a large portion of the electricity generated by solar PV systems can be consumed by commercial establishments and therefore reduce transmission losses. In combination with energy-efficient design and the implementation of advanced energy management systems, solar PV systems can provide significant improvements to building energy performance indicators and sustainability ratings.

4.2 Operational Sustainability Impacts

Operational sustainability impacts represent the primary sustainability advantages of solar PV systems in the built environment (Raugei et al., 2017) During operation, solar PV systems generate electricity without emitting any pollutants, making them an attractive solution for urban environments where there are close links between energy consumption patterns and air quality/public health concerns (Zuo & Zhao, 2014) Long-term reductions in greenhouse gas emissions result from operational energy savings in large commercial establishments. The magnitude of these emission reductions increases when solar PV systems are designed to match the building's load profile and are implemented using smart control/demand management strategies and energy storage systems. Overall, the cumulative benefits of PV systems far exceed the negative environmental impacts of PV systems' manufacture/installation, reinforcing their positive sustainability impact.

4.3 Embodied Sustainability Impacts/Lifecycle Evaluation

While the operational sustainability impacts of solar PV systems are considerable, sustainability assessments of the built environment must also take into consideration the embodied sustainability impacts of solar PV systems, which comprise the energy and emissions generated during the production, extraction, manufacturing, transportation/installation of solar PV systems. For commercial developments, embodied impacts are generally limited to the construction phase and depend upon factors such as PV module type/system size/mounting structures/balance of system equipment (Wall et al., 2012).

Studies employing life cycle assessment methods consistently demonstrate that embodied impacts of solar PV systems are rapidly recovered through clean electricity generation and that energy payback times for commercial-scale PV systems are significantly less than system lifetimes, resulting in favorable net environmental sustainability performance (Fthenakis & Raugei, 2017) Furthermore, the adoption of increasingly efficient manufacturing processes, lighter PV module designs and increased PV recycling capabilities will continue to decrease embodied impacts and enhance sustainability outcomes (Kibert, 2016).

4.4 Urban Developments and Integrated Sustainability Strategies

Urban developments that integrate solar PV systems into buildings, parking garages, and other public spaces can realize numerous sustainability benefits by decentralizing energy generation and decreasing the strain on central power infrastructure (Hernandez et al., 2014) Urban developments that utilize solar PV systems in buildings, parking garages, and other public spaces can realize numerous sustainability benefits by decentralizing energy generation and decreasing the strain on central power infrastructure. Furthermore, the use of building-integrated photovoltaics enables the utilization of multiple functions for surfaces, supporting sustainable urban development by relating renewable energy generation to architecture and urban planning.

The deployment of solar PV systems in urban settings also supports other sustainability measures such as green building standards, energy-efficient building materials, and low-carbon construction practices. As part of a comprehensive sustainability strategy, solar PV systems can support reduced operational and lifecycle environmental impacts.

4.5 Comparing Sustainability Performance in the Built Environment

Comparative sustainability performance of solar PV systems in large-scale commercial establishments can be assessed based on various sustainability metrics, including operational energy savings and embodied energy impacts across varying commercial establishment types and system configurations. Table 1 illustrates several key sustainability metrics applicable to commercial establishments, shopping centers and urban developments.

Table 1. Sustainability Indicators for Solar PV Integration in the Built Environment

Sustainability Indicator	Commercial Buildings	Shopping malls	Urban Developments
Operational reduction	GHG	High	Very high
Energy payback time	Short	Short	Moderate
Embodied energy impact	Moderate	Moderate	Moderate
Land use efficiency	High	High	Very high
Integration flexibility	High	Very high	High

The table illustrates that shopping malls and large commercial facilities often achieve the strongest sustainability performance due to high electricity demand, large available surface areas, and favorable self-consumption patterns.

4.6 Long-Term Sustainability and Policy Alignment

Long term sustainability performance of a solar photovoltaic (PV) system within the built environment relies upon the longevity of the PV system, the maintenance practices adopted to ensure it continues to operate at optimal levels and the alignment of the PV system with applicable regulations. Increasingly, building codes, renewable energy incentives and sustainability certification programs are encouraging, if not requiring, the inclusion of on-site renewable energy generation systems in new developments. Developers and building owners may include on-site solar PV systems to comply with environmental regulations, enhance the value of an asset and optimize long term operation and maintenance.

For real estate developers, especially those involved in large scale commercial development, sustainability performance will become an increasing factor in competitive advantage and in meeting the expectations of investors. Solar PV systems provide measurable environmental benefits which can be quantified via life cycle assessment and sustainability reporting and support the transparency required in decision making and long term planning.

4.7 Overall Assessment of Sustainability Performance

In summary, the inclusion of solar PV systems in large-scale and built environment applications provides a high level of sustainability performance when measured using both operational and embodied perspectives. The operational reductions in greenhouse gas emissions, the relatively favorable energy payback periods and the efficient utilization of existing building surfaces all serve to offset the environmental impacts created during the production and installation phases of the PV systems. As technology evolves and circular economy practices develop, the sustainability performance of PV systems in commercial buildings and urban developments is expected to continue to increase, providing additional evidence of the critical role PV systems have in promoting sustainable construction and urban energy systems.

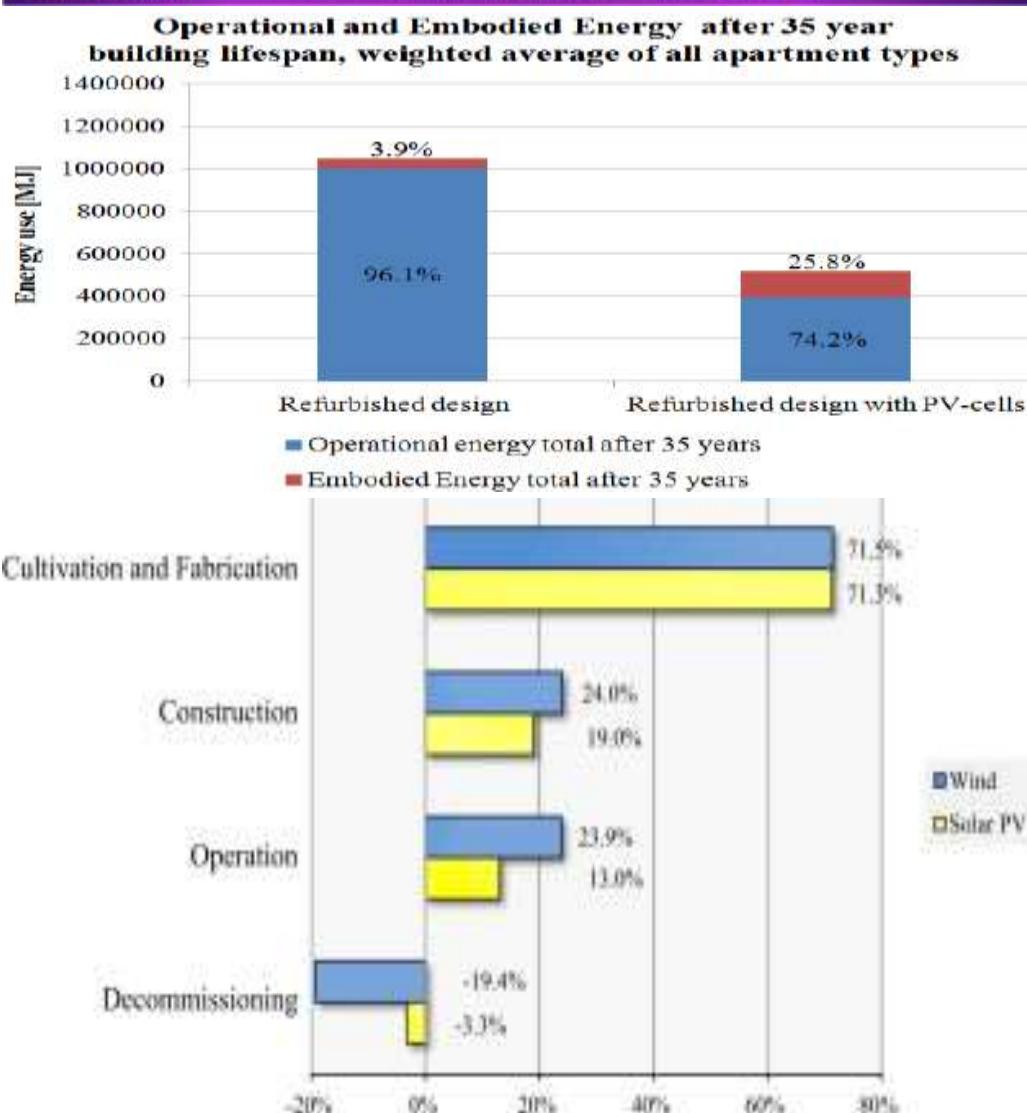
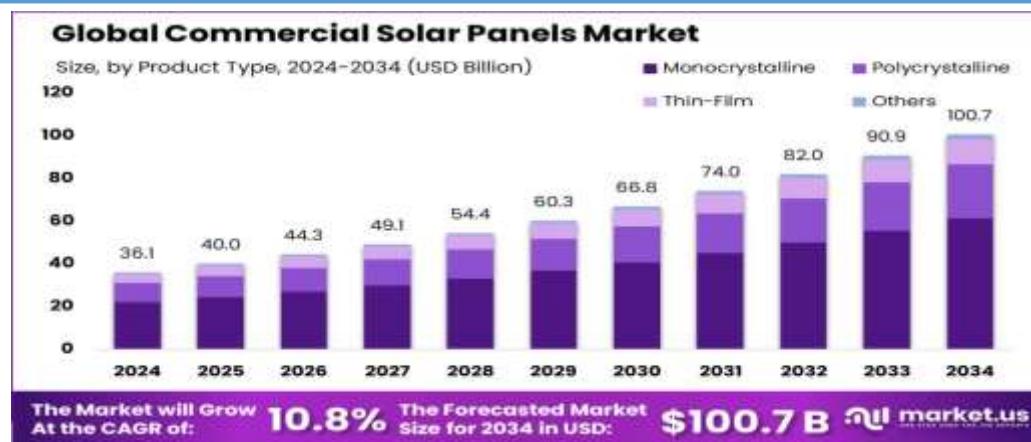


Figure 3. Sustainability Performance of Solar Photovoltaic Systems in the Built Environment

These three figures above compare the sustainability performance of solar photovoltaic integration in commercial buildings, shopping malls, and urban developments. It highlights differences in life-cycle greenhouse gas emission reductions by accounting for both operational energy savings and embodied environmental impacts. The results illustrate the strong sustainability benefits of solar PV in large commercial facilities, where high electricity demand and effective self-consumption enhance long-term environmental performance.

5. Comparative Assessment and Mitigation Strategies

A complete assessment of solar energy systems will involve comparing them to traditional ways of generating electricity and assessing how further reductions in environmental burdens may occur. The comparative assessments discussed here will serve to understand the relative sustainability performance of solar photovoltaics (PV) and assist in making decisions regarding energy planning, building design and policy development. An analysis of the life cycle impacts, operating characteristics and long-term sustainability implications of solar PV systems will highlight the benefits of solar energy systems and identify pathways for reducing remaining environmental burdens (Peng et al., 2013).

5.1 Comparison of Solar Energy Systems and Conventional Energy Sources

Historically, conventional energy generation has been based on fossil fuel-burning power plants, primarily those burning coal or natural gas, and have provided the majority of the world's electricity (Raugei et al., 2012) While fossil-fuel-based electric generation offers dispatchable power and well-established infrastructure, it comes at a cost of high greenhouse gas emissions, air pollution and high resource utilization over its lifetime. All of the life cycle assessment studies completed thus far clearly demonstrate that fossil fuel-based electric generation produces significantly greater amounts of carbon dioxide per unit of electricity generated as compared to solar photovoltaic systems.

The primary environmental aspects that distinguish solar PV systems from all conventional energy sources include the fact that, during operation, solar PV systems produce electricity through photovoltaic conversion of sunlight, producing virtually no direct emissions. If one considers the entire life cycle of solar PV systems, including the manufacture and installation phases, the greenhouse gas emissions from solar PV systems are still much less than those of conventional energy sources. Additionally, solar PV systems require little to no water during operation as opposed to thermal power plant systems which require large quantities of water for cooling purposes. The low water requirements of solar PV systems enhance the feasibility of solar energy in areas of the world where water is scarce and minimize competition for other water intensive uses.

In terms of resources, fossil fuel-based energy systems are dependent upon the continued extraction and consumption of limited resources. As a result, they create cumulative environmental harm and make consumers vulnerable to price fluctuations of fuels. Solar energy systems,

however, utilize an abundant renewable resource (Ferroni & Hopkirk, 2016) While material extraction is necessary for the production of solar PV modules, there is no requirement for ongoing fuel consumption, thereby providing better long-term resource utilization efficiencies. Overall, these distinctions demonstrate that solar PV systems are structurally more environmentally sustainable than conventional energy options; particularly if solar PV is used on a large-scale basis and is incorporated into long-term infrastructure such as commercial buildings and urban developments.

5.2 Performance Trade-Offs and System-Level Considerations

While the environmental benefits of solar energy systems are apparent, there are several performance trade-off considerations that must be addressed in the comparative assessment of solar energy systems. The most significant limitation of solar energy systems is the variability of solar energy production, which is dependent upon weather conditions and diurnal cycles. Traditional power plants offer continuous output and grid stabilization services, while solar PV requires additional measures such as energy storage, demand-side management and grid flexibility to provide similar reliability to solar PV systems.

However, advancements in power electronics, forecasting tools and energy storage technologies have dramatically reduced the limitations of solar energy systems. When evaluating solar energy systems at the system-level, integrated solar PV systems are capable of delivering reliable electricity supplies with a significantly smaller environmental footprint than conventional energy systems. In addition, the built environment is typically characterized by predictable electrical load patterns that correlate well with solar energy availability, thereby reducing the performance trade-offs inherent to solar PV systems and further increasing the comparative benefits of solar PV systems.

5.3 Design Strategies for Minimizing Environmental Impacts

Design oriented strategies for minimizing the environmental impacts of solar energy systems are crucial to realizing the full potential of solar energy systems. Integrating photovoltaic systems into building designs during the early stages of the design process allows designers to optimize the orientation, tilt angles and shading conditions of the solar panels to maximize energy yields and shorten energy payback times. Building Integrated Photovoltaics (BIPV) allow designers to integrate photovoltaic capabilities into building structural components, thereby reducing the amount of additional materials needed and minimizing land use impacts.

Additionally, the selection of materials for solar energy systems affects the environmental performance of solar energy systems. Selecting high-efficiency solar modules that have longer operational lifetimes will increase the total amount of energy that is generated versus the embodied impacts of the module. Lighter weight mounting structures and modular solar PV designs can reduce material usage and facilitate easier installation. Furthermore, designing standardized approaches to solar PV deployments for large commercial developments and utilizing modular

solar PV systems can improve the efficiency of deploying solar PV systems and ensure consistent performance across multiple solar PV deployments.

5.4 Technological Strategies for Impact Reduction

Environmental Impact Reduction through Technology

The driving force behind environmental impact reduction is technological innovation in solar energy systems. Efficiency improvements in manufacturing have resulted in decreased energy and emissions intensity in the production of solar modules.

Increasingly, manufacturers are utilizing renewable electricity in their manufacturing processes which further improves life-cycle sustainability of the solar modules.

Increased module durability and resistance to degradation extend the overall lifetime of the solar energy system providing additional environmental benefit.

Additionally, at the system level, integrating energy storage technologies (batteries) into solar energy systems provides stability to variable solar output and increases the value of the solar generated electricity.

Energy storage enables shifting of loads, peak demand reduction, and increased self-consumption, particularly in commercial buildings with high daytime energy demands.

Digital monitoring and predictive maintenance technologies provide operational loss reductions and increase system performance over time, improving long term sustainability of the solar energy system.

Designing solar modules with recyclable materials and designing modules for disassembly and recycling of materials, supports the principles of a circular economy and reduces the environmental impacts of waste from the disposal of used solar modules.

5.5 Policies and Regulatory Strategies

Policies that create an environmental cost for using environmentally damaging products or services, i.e., carbon pricing mechanisms and emissions standards, make solar energy a competitive choice in comparison to fossil fuels.

Government incentive programs for renewable energy deployment, energy efficient buildings, and on-site generation have accelerated the rate of adoption and encouraged the integration of solar energy into the built environment. Regulatory policies such as building codes and sustainability certification schemes are increasingly requiring the inclusion of solar energy systems in new commercial developments. These policies promote early stage adoption of solar energy systems allowing for optimized design and long term environmental benefits. Transparency in reporting and standardization of life-cycle assessments of solar energy systems will provide accountability and comparability among energy technologies.

5.6 Combination of Mitigation Strategies in Large-Scale Urban Applications

Combining design, technology and policy based mitigation strategies provide the most effective mitigation strategy in large scale and urban applications.

Solar energy systems that are part of energy efficient buildings, managed through smart energy management and provided with regulatory incentives will result in greater sustainability than stand-alone solar energy systems. This combination of design and technology provides maximum operational benefits, minimum life-cycle impacts, and maximum economic viability. Real Estate Developers and Building Owners Benefits Adopting integrated mitigation strategies also provides real estate developers and building owners with a means to provide asset resilience and long-term value to their assets (Kim et al., 2012).

Reduced operational energy costs, improved environmental performance, and compliance with changing sustainability standards provide real estate developers and building owners with a better position in the marketplace and risk mitigation.

5.7 Summary of Comparative Assessment and Mitigation Strategies

A comparative analysis indicates that solar energy systems produce less environmental damage throughout their life cycle than traditional energy sources. However, there continue to be challenges of variability and material impacts with solar energy systems. Mitigation strategies can be implemented in all three areas of design, technology, and policy to reduce the negative impacts of solar energy systems.

Implementing solar energy systems with energy efficient building designs, advance system technologies, and regulatory incentives will provide reliable electricity while minimizing the environmental footprint of solar energy systems.

These strategies support the implementation of solar photovoltaics as a key component of sustainable energy systems and provide a basis for the continued growth of solar energy in the built environment.

6. Future Perspectives and Research Needs

Life Cycle Assessment (LCA) has evolved to become an accepted tool for assessing the environmental performance of solar energy systems; however, new assessment tools are required to account for rapid advancements in technology, large-scale deployments of systems and changing regulatory requirements. In this context, it is essential that future LCA assessments develop more advanced and dynamic assessment methods that take into consideration the changing conditions that impact the systems' long-term environmental performance.

Therefore, future research and policy efforts must concentrate on developing enhanced sustainability metrics; developing improved circular economy solutions to integrate within the

design of solar energy systems and ultimately developing long-term sustainable solar energy systems (Raugei et al., 2012).

6.1 New Methods for Assessments of Sustainability

Typically, traditional life cycle assessments utilize static assumptions related to technology performance, manufacturing procedures and energy mix. To assess the evolving nature of solar technologies, future assessments must consider dynamic and scenario-based methods to reflect the changing environment over time (Zuo & Zhao, 2014) A dynamic life cycle assessment method considers temporal variations in electric power grids, technological learning and degradation of the system. This provides a better assessment of actual sustainability outcomes of the solar energy system.

Furthermore, the incorporation of environmental assessments with techno-economic and social assessment frameworks can provide a broader perspective of sustainability performance. Therefore, multi-criteria decision making and life cycle sustainability assessment approaches that consider the three dimensions of environmental, economic and social performance are expected to have a greater role in influencing energy planning and the development of energy infrastructure. The above-mentioned integrated assessment approaches will be particularly relevant for the assessment of large-scale commercial and urban solar energy applications where the sustainability decision-making process involves numerous trade-offs among various performance criteria.

6.2 Consideration of the Circular Economy in the Design of Solar Energy Systems

A transition toward a circular economy is considered to be an effective means to achieve increased sustainability of solar energy systems. As the global installed base of photovoltaic (PV) capacity increases, it is anticipated that significant quantities of PV modules at the end-of-life will be produced in the next few decades. The potential for designing PV systems with circularity in mind; specifically, modular design of PV systems, ease of disassembly and material recovery from existing PV systems can significantly reduce environmental burdens associated with disposal and extraction of raw materials (Ferroni & Hopkirk, 2016).

In addition to the consideration of the PV systems themselves, circular economy concepts may also apply to the manufacturing and supply chain aspects of solar energy systems. For example, through reduction of material usage, utilization of recycled inputs and elimination of hazardous materials in the manufacture of solar cells, material efficiency and the environmental impacts of upstream activities can be reduced (Hernandez et al., 2014) Additionally, research into alternative materials and the application of eco-design principles will be required to facilitate alignment of the production of solar PV cells with long-term sustainability objectives.

6.3 Recycling Technologies and End-of-Life PV Modules

Recycling and end-of-life management of solar energy systems is becoming increasingly important for achieving sustainability of deployed solar energy systems. Advancements in recycling

technologies can recover valuable materials such as glass, aluminum and semiconductor materials from decommissioned solar panels thereby reducing the reliance upon virgin material extraction. Nevertheless, recycling processes must be developed to ensure that the environmental benefits of recycling outweigh the energy and resources required to recycle the materials (Kibert, 2016).

Therefore, future research should focus on optimizing recycling efficiency, reducing recycling costs and establishing standardization of recycling processes that can be scaled with the expansion of PV installations. Furthermore, government policy and regulation, including extended producer responsibility schemes and recycling mandates, will be required to stimulate responsible end-of-life management and encourage the development of markets for recycled materials.

6.4 Future Research Directions for Improved Sustainability Performance

Research directions that will influence the long-term sustainability performance of solar energy systems include improving the long-term durability of modules and reducing degradation rates, especially in extreme environments. Improving thermal management and system resiliency will also result in increased energy yields and net environmental benefits over the system's lifetime.

In terms of system-level research, investigation into the integration of solar PV with energy storage systems, smart grid systems and demand response systems will be necessary to maximize sustainability outcomes of solar energy systems (de Wild-Scholten, 2013) Application of advanced digital monitoring, predictive analytics and data-driven optimization will improve the operational efficiency of solar energy systems and minimize environmental impacts resulting from maintenance activities. Ultimately, the collective research direction outlined above will be essential to facilitate continued advancement of solar energy systems as a key component of sustainable and resilient energy infrastructure.

6.5 Outlook for Sustainable Solar Energy Systems

Ultimately, the future sustainability of solar energy systems will be dependent on the coordination of research, technological innovation and policy initiatives. Through the advancement of dynamic assessment tools, adoption of circular economy concepts and development of recycling and end-of-life strategies for solar energy systems, the solar energy industry will be able to enhance its environmental performance. Future research and collaboration among stakeholders across industries will be required to ensure that solar photovoltaic systems provide sustained sustainability benefits and contribute effectively to global energy and climate goals.

Conclusion

This study presented a life-cycle assessment of the environmental and sustainability performance of solar photovoltaic systems, highlighting their growing role in the transition toward low-carbon and resource-efficient energy systems. By examining greenhouse gas emissions, energy payback time, resource consumption, land use, and material-related impacts across the photovoltaic life cycle, the analysis confirms that solar PV systems provide substantial environmental advantages

compared with conventional electricity generation technologies. Although manufacturing and raw material extraction introduce upstream environmental impacts, these are typically offset during the early operational years through clean electricity generation. The study further demonstrates the strong sustainability potential of large-scale and building-integrated photovoltaic installations in commercial buildings and shopping malls. Design factors such as high self-consumption rates, efficient use of available surfaces, and long system lifetimes significantly enhance net environmental benefits. Overall, the findings confirm that well-designed and technologically optimized solar PV systems can serve as a reliable and sustainable component of modern energy infrastructure.

Recommendations

To further enhance the sustainability performance of solar photovoltaic systems, continued improvements in sustainability assessment methodologies, circular economy practices, and photovoltaic recycling technologies are necessary (de Wild-Scholten, 2013) Policymakers should support regulatory frameworks that encourage environmentally responsible manufacturing, end-of-life management, and integration of renewable energy systems into commercial and urban developments. Developers and building owners should prioritize early-stage solar integration, optimize system design for self-consumption, and adopt digital monitoring technologies to improve long-term performance. Strengthening coordination between technological innovation, environmental assessment, and policy support will be essential for maximizing the contribution of solar energy systems to sustainable development and long-term climate goals.

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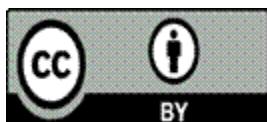
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