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# A Review of Life Cycle Assessment of Solar Photovoltaic Electricity Generation Systems

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***Abstract***

*A popular system for calculating the environmental effects of energy systems from conception to death is life cycle assessment, or LCA. As a low-carbon generation technology, solar photovoltaic (PV) systems have fast spread throughout the world. The various PV technologies (monocrystalline, polycrystalline, thin-film), system scales (residential, commercial, utility), industrial locations, balance of system (BOS) configurations, and end-of-life (EoL) scenarios are all covered in this review of published LCA lessons on solar PV electricity generation. A thorough synthesis of published LCA studies on solar PV energy generation is given in this review. In addition to analyzing various system scales like residential rooftop installations, commercial applications, and large-scale utility plants, it covers a wide range of PV technologies, such as monocrystalline silicon, polycrystalline silicon, and thin-film modules. The evaluation also takes into account differences in EoL scenarios, such as recycling and disposal routes, BOS topologies, and manufacturing sites. Comparisons are made between major effect categories, borders, inventory assumptions, and average greenhouse gas (GHG) emissions per kWh. Common hotspots (module manufacturing and BOS), the impact of lifetime, capacity factor, and recycling, and methodological differences (allocation, system boundaries, data sources) that cause result heterogeneity are also highlighted in the review. Significant proposals are made for prospective study instructions, data transparency, and reliable LCA practice.*

**Keywords:** End-of-life (EoL), surrounding hotspots, greenhouse gas emissions, solar photoelectric, photovoltaic modules, life cycle assessment (LCA)

## INTRODUCTION

There has been a notable shift to renewable energy technology owing to the rapid expansion of the world's energy demand and the growing urgency of addressing climate change. Solar photovoltaic (PV) technology has developed into one of the most promising renewable energy sources for sustainable electricity generation. It has been broadly used in residential, profitable, and utility-scale submissions due to its assistance, which includes modularity, decreasing costs, low operating emissions, and appropriateness for a variety. A scientific framework for measuring the environmental properties of a system or product through the course of its life is provided by life cycle assessment, or LCA. LCA is widely recognized as a dependable tool for assisting initiatives, researchers, and politicians in achieving sustainable results. It is globally standardized under ISO 14040/44 [1–6]. When cast-off in combination with solar PV systems, life cycle calculation (LCA) provides answers to important concerns like: How much greenhouse gas (GHG) emissions are produced during the industrial period? Which elements are primarily responsible

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for environmental burdens? What effects do variable quantities such as permanence, geographic location, and module competence have on the overall environmental influence per kilowatt-hour of electricity? To evaluate the actual advantages of PV technology over traditional fossil fuel-based power generation, these issues must be addressed. of climatic locations. Although PV systems provide clean electricity while in use, their overall environmental performance is determined by the effects of the entire life cycle of the system, which includes raw material extraction, production, installation, operation, and end-of-life (EoL) treatment [7–13]. To comprehend the actual sustainability of photovoltaic systems, a thorough and uniform assessment procedure is required (Figure 1).

Many LCA studies on PV technology have been published globally in the last 20 years. Monocrystalline silicon, polycrystalline silicon, amorphous silicon, CdTe, and copper indium gallium selenide (CIGS) modules are a few of the many PV technologies covered by these studies. Even with this expanding body of research, the reported outcomes frequently differ greatly [14–20]. The differences are generated by system boundaries, functional units, manufacturing energy mixes, data sources, solar irradiation conditions, projected lives, and EoL management techniques. These organizational differences cast doubt on the comparison of results and highlight the requirement of an organized review that abridges recent research and identifies the main factors influencing environmental performance.

Additionally, periodic revaluation of environmental implications is required owing to the rapid technological evolution of PV manufacturing, including developments in cell productivity, fewer wafers, decreased material practice, and increased interest in bifacial and perovskite components. Provincial contemplations also have a wide impact: PV module lifespan effects are significantly affected by detergent network mixes, while industries in areas with coal-dominated electricity networks usually result in better embodied emissions. Furthermore, EoL campaigns, such as material recovery, recycling, and circular economy-focused projects, are becoming increasingly acknowledged as central elements for lowering long-term environmental impacts [21–22].

Thus, the goal of this study is to highlight the most recent developments, methodological strategies, and environmental hotspots while carefully synthesizing the body of LCA research on solar PV-based energy generation. To increase the dependability and policy relevance of upcoming PV LCA studies, the evaluation seeks to identify obstacles, opportunities for technological advancement, and research gaps that need to be filled.

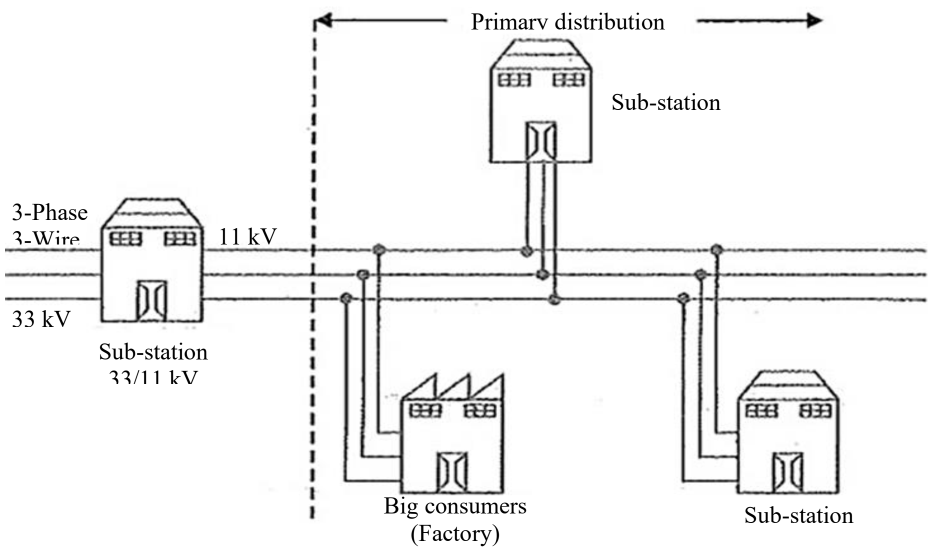


**Figure 1.** Single-line diagram of an 11 kV primary distribution system supplying substations and industrial loads.

 

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This assessment helps make well-informed decisions regarding the regional and global deployment of sustainable solar energy by providing a comprehensive understanding of lifetime consequences [23–25].

## OBJECTIVES

This review aims to use the LCA framework to provide a thorough and organized consideration of the environmental performance of solar photovoltaic (PV)-based energy assembly systems. Evaluating PV's dependable sustainability of solar PV beyond the zero-emission development phase is crucial as it aims to grow the world's energy markets comprehensively. Therefore, the goal of this approximation is to compile the results of preceding life cycle assessments and propose a clear, organized analysis of the full maturation implications of several PV technologies. Finding and complementing the environmental properties of the main phases of the PV lifecycle, such as raw material extraction, module and balance of system (BOS) industrial, transportation, installation, operation and conservation, and end-of-life (EoL) conduct, is one of the training's main goals. This review aims to categorize common environmental flashpoints and the particular elements that have an extreme impact on resource depletion, energy use, conservatory gas emissions, and other environmental pointers by analyzing several studies. Finding and complementing the environmental properties of the main phases of the PV lifecycle, such as raw material withdrawal, module and BOS industry, transportation, installation, process and maintenance, and EoL conduct, is one of the core goals of this study. This review aims to recognize common environmental hotspots and the precise elements that have an extreme impact on resource depletion, energy use, greenhouse gas production, and other environmental indicators by analyzing several trainings. Evaluating the differences in LCA results across technologies and geographical areas is another crucial goal. The efficiency, material composition, and manufacturing procedures of PV modules vary greatly, as do the irradiance levels and capacity factors at different installation sites. This review aims to compare these differences and comprehend how they affect the implications of total lifespan. To reflect both current industry norms and future directions, crystalline silicon, thin-film modules, and new technologies are emphasized. Additionally, this study aims to identify significant methodological differences in published LCA studies, such as differences in databases, functional units, system restrictions, effect evaluation methods, and recycling allocation policies. Understanding these variations is essential for improving comparability and ensuring consistency in further research.

## LCA METHODOLOGY

LCA is an organized and internationally standardized approach used to calculate the environmental impacts of a product or system throughout its complete life cycle. The methodology followed the procedures established by ISO 14040 and ISO 14044, confirming the transparency, scientific uniformity, and comparability of the results. In the setting of solar photovoltaic (PV) electricity generation systems, LCA helps evaluate environmental weights from the withdrawal of raw materials to module industrial, transport, installation, operation, conservation, and EoL discarding or recycling.

The LCA methodology comprises four major phases. The first phase is the Goal and Scope Definition, where the purpose of the study, system boundary, and functional unit are clearly stated. For PV systems, the predominantly used functional unit is 1 kWh of electricity generated, as it allows a contrast with other power generation technologies. The system boundary commonly follows a cradle-to-grave approach, although some studies may use cradle-to-gate or gate-to-gate limits, depending on data availability.

## VIRTUAL POWER PLANT SYSTEM ENGINEERING

A sophisticated energy management system called a virtual power plant (VPP) unifies different distributed energy resources (DERs) into a single, adaptable, and controlled power-producing entity. Solar PV systems, wind turbines, battery storage devices, diesel generators, electric cars, and demand response resources are examples of DERs. To provide dependable and market-ready power services, VPP system engineering focuses on planning, coordinating, and optimizing these components using digital platforms, communication networks, and intelligent control algorithms. The coordination and collection of dispersed resources is the basis of VPP system engineering. The VPP platform builds a unified portfolio that can operate like a traditional power plant in terms of scheduling, dispatch, and grid support, as opposed to handling each small generator as an isolated unit. Advanced technologies, including cloud computing, real-time monitoring tools, supervisory control and data acquisition (SCADA) systems, and the Internet of Things (IoT), are used to achieve this. Field campaigns and the central VPP controller can seamlessly interconnect data owing to these technologies.

## OPERATION OF VPP SYSTEM

To provide consistent, affordable, and grid-compliant power amenities, a VPP must organize, optimize, and control discrete energy resources (DERs) in real time. A VPP supervises a wide range of small-scale assets, including rooftop solar PV systems, battery energy storage, wind turbines, electric vehicles, and programmable loads, in contrast to conservative power plants, which are contingent on massive single-point generators. When these scattered resources function well, they operate as cohesive and dependable power generation entities.

Real-time monitoring and data collection are essential tasks for VPP operations. Data on generation output, battery state of charge (SOC), equipment condition, energy prices, and grid circumstances are continuously gathered by the VPP control center. Operators can make well-informed decisions on power dispatch and load management, thanks to the data collected by Internet of Things (IoT) devices, smart meters, and supervisory control and data acquisition (SCADA) systems.

### Trade

Trade within the sphere of influence (SoI) in the context of a VPP describes the economic activities that allow aggregated DERs to participate in electricity markets. To maximize financial gains and maintain grid stability, the VPP coordinates generation, storage, and flexible loads as a market-facing organization. The VPP combines them into a sizable and manageable portfolio that satisfies market participation requirements, in contrast to individual small-scale producers, who frequently lack the scale and technological capacity to participate in market transactions.

The main purpose of trade in a VPP is to optimize the sale and purchase of power. The VPP determines when to sell excess power to the grid, store energy in batteries, or buy electricity during periods of low pricing based on real-time estimates of demand, renewable generation, and market price. This procedure enables VPP to profit from price changes and lower expenses for system users.

### Balancing

To ensure a steady and dependable energy supply, the coordinated management of generating, storage, and demand-side resources is referred to as balancing within the SoI of a VPP. Due to the inherent variability and unpredictability of solar and wind generation, balancing is crucial in contemporary power systems with significant penetration of renewable energy sources. By cleverly combining several DERs and employing sophisticated control techniques to maintain supply and demand equilibrium, the VPP overcomes this difficulty. Demand response (DR) measures are also part of balancing. DR programs encourage users to modify or change their electricity usage in response to price signals or system constraints. The VPP can minimize the need for expensive peak power generation and greatly reduce grid stress by synchronizing these changes.

### Network Services

Technical support services that improve the stability, dependability, and efficiency of the electric grid are referred to as network services within the SoI of a VPP. VPPs provide ancillary services by coordinating the operation of DERs such as solar PV systems, battery storage units, electric cars, and controlled loads, whereas traditional power plants provide these services at a centralized level. A VPP can provide a variety of network services that improve the overall grid performance by wisely

 

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managing these resources. Frequency regulation is one of the main network services offered by a VPP. To maintain the necessary balance between generation and demand, the VPP modifies power production or consumption based on real-time grid frequency monitoring. Because battery energy storage devices respond quickly, they are useful for this service.

## CONCLUSIONS

This paper highlights the increasing significance of VPP systems in contemporary power networks by providing a thorough overview of their creation and functioning. VPPs offer a clever and practical way to manage distributed energy resourcesas (DERs) the mixing of renewable energy continues to grow worldwide. VPPs advance grid flexibility, dependability, and cost-effectiveness through sophisticated communication networks, prognostication tools, and optimization procedures. System engineering, market participation, balancing, and network services are just a few of the topics covered. Together, they show how VPPs allow decentralized resources to operate similarly to a coordinated utility-scale power plant.

The research shows that VPPs have many benefits, such as better use of renewable energy, higher demand-side participation, lower operating costs, and greater resistance to system disruptions. However, cybersecurity threats, communication infrastructure constraints, regulatory obstacles, and data integration difficulties are some of the issues that still exist. These problems must be resolved to guarantee the long-term scalability and dependability of VPP implementations. Future studies should focus on bolstering cybersecurity standards because VPPs heavily rely on digital connectivity. Cutting-edge methods, such as blockchain, edge computing, and secure IoT architectures, may greatly aid in increasing system robustness. The incorporation of electric vehicles (EVs) as adaptable and mobile storage assets in VPP systems is another crucial topic for future research. Vehicle-to-grid (V2G) technologies have the potential to significantly improve VPP capabilities, given the rapid growth in EV adoption.

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