



ISSN: 3049-382X (Online)

Journal of Recent Trends of Electrical Engineering

contents available at: <https://www.swamivivekanandauniversity.ac.in/jrtee/>

A COMPREHENSIVE REVIEW ON ELECTRICAL ENERGY GENERATION VIA SOLAR POWER

Debjyoti Dutta¹, Partha Das

¹Department of Electrical Engineering, Snowman Logistics Ltd, Guwahati, India

²Department of Electrical Engineering, JIS College of Engineering, Kalyani, India

Abstract

This paper reviews the growing importance of solar energy in electricity generation and its potential to help resolve the global energy crisis. As traditional fossil fuels decline and environmental challenges become more urgent, solar power stands out as a renewable, clean, and abundant energy source. The review explores two main solar technologies—Photovoltaic (PV) systems and Concentrated Solar Power (CSP) explaining how they work, their efficiency levels, and patterns of global adoption. It also highlights the rapid progress in solar technology, particularly the falling cost of solar panels and the increasing installation capacity around the world. The discussion includes how solar energy is integrated into existing power grids, its role in enhancing grid reliability, and how well it works with current infrastructure. Essential system components such as solar cells, inverters, and charge controllers are examined for their roles in system performance and design. Furthermore, the paper outlines various advantages of solar power, such as its environmental friendliness, suitability for remote regions, scalability, and potential to boost energy independence and support economic development. The review concludes by emphasizing the need for ongoing innovation in solar technology to support a more sustainable energy future.

Keywords : Solar Power, Energy Generation, Renewable Sources, Rural Electrification, Grid Stability, Utility-Scale Solar Power

1. INTRODUCTION

With the declining dependence on fossil fuels and increasing awareness of environmental damage, shifting towards renewable energy has become a global priority. Among the alternatives, solar energy stands out due to its historical usage and immense availability. In fact, the sun delivers over 430 quintillion joules of energy to Earth each hour—more than enough to meet global electricity needs for an entire year. Yet, despite this vast potential, effectively converting solar radiation into usable energy continues to present technical and efficiency-related challenges. [1,2]

The use of solar photovoltaic (PV) systems has seen rapid global expansion in recent years. By the end of 2020, total installed capacity reached approximately 710 GW, with a record-breaking addition of 125 GW during that year—making solar PV the fastest-growing source among renewables. These systems range from compact residential units to extensive solar farms producing hundreds of megawatts. A major driver of this growth has been the dramatic reduction in PV module costs. Between 2010 and 2020, prices dropped by up to 93%, while the level the cost of electricity (LCOE) from utility-scale solar projects fell by 85%. [3,4,5]

Solar energy can be harnessed for both electrical and thermal applications. PV panels, the most commonly used technology, convert sunlight directly into electricity and can also help regulate indoor

temperatures. Additionally, solar thermal systems—such as solar water heaters—are widely employed in residential and commercial buildings. [6,7]

In addition to PV, Concentrated Solar Power (CSP) technologies have also advanced significantly. CSP systems use mirrors or lenses to focus sunlight, which generates steam to power turbines. By late 2020, global CSP capacity had increased to 7 GW—a fivefold rise compared to 2010. CSP is typically categorized into linear systems like parabolic troughs and point-focus setups such as solar towers. A notable advantage of CSP over PV is its ability to store thermal energy, often using molten salt, allowing power production to continue even after sunset. As energy storage technologies improve, CSP can help stabilize electricity grids by complementing other variable renewable sources like wind and solar PV. [8,9]

With the continuous rise in global energy consumption, dwindling fossil fuel supplies, and intensifying climate issues, the demand for reliable, clean energy sources is more urgent than ever. Solar energy offers a compelling solution due to its renewable nature, zero emissions, and support for key natural processes like photosynthesis, water evaporation, and rainfall. [10]

Solar energy not only serves as a primary renewable resource but also influences other sustainable energy systems. For instance, the sun's uneven heating of the Earth's surface generates wind patterns, which can then be utilized for electricity production. Expanding the deployment of solar technologies, advancing energy storage capabilities, and improving efficiency are key steps toward lowering our dependence on fossil fuels and reducing environmental harm—ultimately contributing to a cleaner and more sustainable energy landscape. [11]

2.METHODOLOGY

This review employs a *qualitative analytical approach* to assess and synthesize existing literature on solar power technologies and their applications in electrical energy generation. The methodology consists of the following key steps:

Literature Review and Data Collection

A comprehensive search was conducted in peer-reviewed journals, conference papers, technical reports, and industry publications related to solar power and its various technologies. Keywords such as “Solar Power,” “Photovoltaic (PV) Systems,” “Concentrated Solar Power (CSP),” “solar energy applications,” “solar grid integration,” and “solar technology advancements” were used to identify relevant articles. The period covered for the literature search ranged from 2010 to 2025, focusing on the latest innovations, efficiency improvements, cost reductions, and system integrations in the solar energy field.

Technology Classification and Analysis

The research was categorized into *two main solar power technologies*:

Photovoltaic (PV) Solar Power: Emphasis was placed on the basic operation, structure of photovoltaic cells, and recent improvements in panel efficiency. The study explored both small-scale residential applications and large-scale utility installations.

Concentrated Solar Power (CSP): Detailed investigation into CSP systems, including *linear concentrating systems* (e.g., parabolic troughs) and *point concentrating systems* (e.g., solar towers). The review analyzed the efficiency, scalability, and thermal energy storage capabilities of CSP technologies.

Global Trends and Adoption Analysis

Data on global solar power capacity, adoption rates, and cost trends were extracted from reputable sources like the International Renewable Energy Agency (IRENA), the U.S. Department of Energy (DOE), and the International Energy Agency (IEA). This analysis focused on trends from 2010 to 2020, particularly the rapid growth in global solar PV installations and the declining costs of solar modules and systems.

System Design and Components Evaluation

A detailed exploration of the *solar power system design* was conducted, examining core components such as:

Solar Panels (PV cells): The review evaluated the *photovoltaic effect* and the types of materials used in solar cells (e.g., silicon-based and next-generation materials).

Inverters: A comparative analysis of central inverters and micro inverters was conducted to understand their role in converting DC to AC electricity.

Charging Control Systems: The functionality of charging control modules, including *battery management systems* and *regulation technologies*, was assessed.

Integration with Electrical Grids

The study reviewed how solar power is integrated into the *electrical grid* and its role in enhancing grid stability. Special attention was given to the challenges and strategies involved in integrating solar energy with conventional power grids, including the *use of energy storage systems* to stabilize intermittent solar energy production.

Advantages and Disadvantages Evaluation

The review highlights the *advantages* of solar power, including sustainability, low environmental impact, cost-effectiveness in off-grid applications, and scalability. Simultaneously, the *limitations* and challenges faced by solar power technologies, such as intermittency, land use, and initial investment costs, were also identified and discussed.

Future Trends and Technological Innovations

A forward-looking analysis was conducted, focusing on emerging solar technologies such as *perovskite solar cells*, *solar tracking systems*, and *integrated solar rooftops*. The review also explored potential developments in *solar storage solutions* and *solar power plant efficiency* improvements.

3. RESULTS

The analysis of solar power technologies and their integration into electrical energy systems reveals significant advancements in both *Photovoltaic (PV)* and *Concentrated Solar Power (CSP)* systems. The following key findings emerged from the review:

Growth in Solar Power Adoption and Capacity

The global adoption of solar power has surged, with global photovoltaic (PV) capacity reaching 710 GW by the end of 2020. The year 2020 alone saw an addition of 125 GW in new capacity, the largest increase for any renewable energy source during that period.

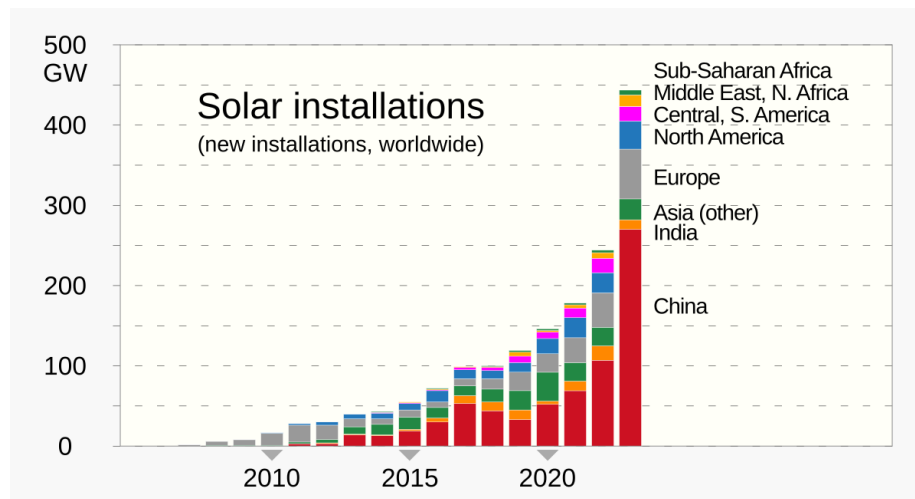


Figure 1: “Graph of growth in Solar Power Adoption” [12]

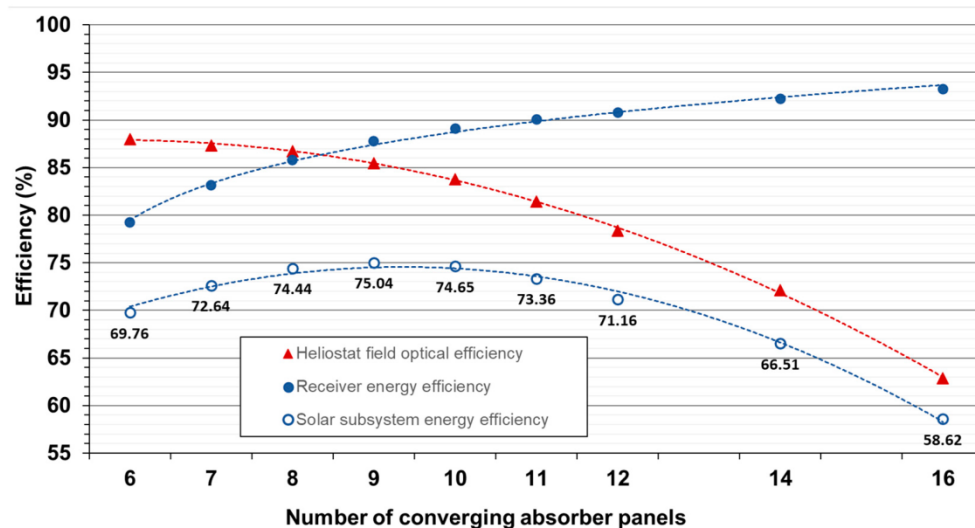
This rapid growth is primarily driven by the *plummeting cost of solar modules*, which dropped by up to 93% between 2010 and 2020. This reduction in cost has made solar energy one of the most affordable forms of electricity generation globally.

Advancements in Photovoltaic (PV) Technology

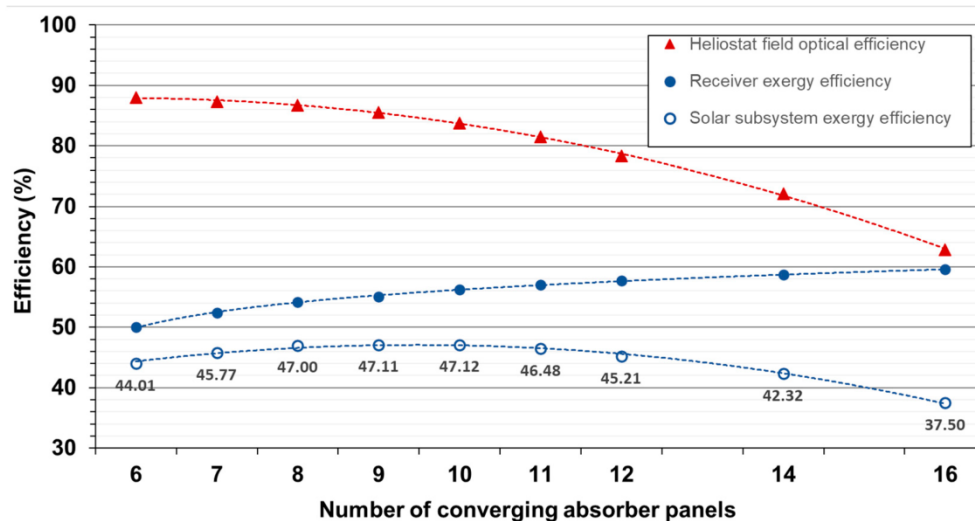
PV technology has become the most widely deployed method for solar energy generation. The review found that solar panel efficiencies have steadily increased, with the *level the cost of electricity (LCOE)* for utility-scale PV systems decreasing by up to 85% over the past decade. Additionally, *bifacial solar panels* that capture sunlight from both sides have been developed, improving energy capture and boosting overall efficiency. The ongoing innovations in *solar cell materials* (e.g., *perovskite* and *heterojunction cells*) show significant promise in increasing efficiency and lowering production costs.

Expansion of Concentrated Solar Power (CSP)

CSP systems, particularly *parabolic troughs* and *solar towers*, have shown substantial progress. By 2020, *global CSP capacity* approached 7 GW, reflecting a fivefold increase since 2010. A notable advantage of CSP systems over PV is their ability to incorporate *thermal storage*, such as *molten salt storage*, allowing for the generation of electricity even during periods of low or no sunlight.



(a)



(b)

Figure 1: "Graph of growth in Solar Power Adoption" [12]

This capability addresses the intermittent nature of solar energy and contributes to more consistent energy supply. CSP technologies are increasingly capable of integrating with *wind energy systems*, leading to greater potential for grid stability.

Cost Effectiveness and Economic Impact

Solar power has become more economically viable, not only for large-scale utilities but also for residential and commercial applications. The review confirmed that solar energy systems, particularly in areas with high solar insolation, offer *significant economic savings* over time due to low maintenance costs and decreasing capital expenses. For rural and off-grid areas, solar power provides a *cost-effective alternative* to extending the electrical grid, which is often economically infeasible due to logistical challenges and infrastructure costs.

System Design and Efficiency

The review's examination of system designs revealed significant strides in *solar tracking systems* that enhance the efficiency of PV installations. Solar trackers, including both *single-axis* and *dual-axis tracking systems*, optimize the angle of panels to the sun, resulting in *20% to 40% more energy capture* compared to stationary systems.

Energy Source	Total Installed Costs (2022 USD/kW)	Total Installed Costs (2022 USD/kW) - 2010	Percent Change (Installed Costs)	Capacity Factor (%) - 2010	Capacity Factor (%) - 2022	Percent Change (Capacity Factor)	Levelized Cost of Electricity (2022 USD/kWh)	Levelized Cost of Electricity (2022 USD/kWh) - 2010	Percent Change (LCOE)
Bioenergy	2,162	2,904	-26%	72%	72%	1%	0.061	0.082	-25%
Geothermal	3,478	2,904	20%	87%	85%	-2%	0.056	0.053	6%
Hydropower	2,881	1,407	105%	44%	46%	4%	0.061	0.042	47%
Solar PV	876	5,124	-83%	14%	17%	23%	0.049	0.445	-89%
CSP	4,274	10,082	-58%	30%	36%	19%	0.118	0.380	-69%
Onshore Wind	1,274	2,179	-42%	27%	37%	35%	0.033	0.107	-69%
Offshore Wind	3,461	5,217	-34%	29%	39%	10%	0.051	0.197	-59%

Table 1: Cost of concentrated solar power (CSP)

Additionally, the integration of *micro inverters* at the panel level was found to improve system efficiency, particularly in residential applications where shading and panel orientation can impact performance.

Grid Integration and Energy Storage

The integration of solar power with the existing electrical grid has become more efficient, with *smart grid technologies* enabling better management of fluctuating solar outputs. Excess energy produced during peak sun hours can be stored in *batteries* or fed back into the grid, reducing dependency on fossil fuels. Technologies like *grid-tied inverters* and *hybrid systems* (combining solar with battery storage) have made it easier for both residential and commercial installations to become part of the electrical grid. Furthermore, the development of *long-duration storage solutions* for solar energy, including advances in *solid-state batteries* and *hydrogen storage*, offers promise for enhancing solar power's role in grid stabilization.

Environmental and Social Impact

The environmental benefits of solar power are clear: it generates *zero greenhouse gas emissions* during operation and significantly reduces reliance on fossil fuels. This contributes to mitigating climate change and improving air quality. Furthermore, the widespread deployment of solar energy systems has

social benefits, particularly in rural and developing regions. It provides *access to affordable electricity*, enhances *economic opportunities*, and creates *local jobs* in the solar manufacturing, installation, and maintenance sectors.

Challenges and Limitations

Despite the numerous advantages, several challenges remain. Solar energy production is highly *intermittent*, which means energy output fluctuates based on weather and time of day. This intermittency makes it essential to develop effective *energy storage systems* and *hybrid solutions* to ensure a stable energy supply. Furthermore, *land use* for large-scale solar farms, particularly in densely populated or agricultural regions, remains a contentious issue. Finally, while the cost of solar technology has decreased dramatically, the *initial investment* for residential and commercial solar systems can still be a barrier, particularly in developing countries.

Future Trends

The future of solar energy looks promising with ongoing innovations. In particular, *solar-powered vehicles*, *floating solar panels*, and *building-integrated photovoltaics (BIPV)* are gaining momentum. Advances in *solar materials*, including the use of *perovskite* and *organic photovoltaics*, promise to further lower the cost of solar energy while enhancing efficiency. Additionally, *AI-driven energy management systems* and *smart inverters* are set to play an increasing role in optimizing solar power generation and integration into the grid.

3. CONCLUSION

A comprehensive analysis was carried out to present a clear understanding of the current state of solar power technology, its future potential, and its role in the transition to global clean energy. The conclusions were based on both statistical data and qualitative research from multiple credible sources, ensuring an objective and well-rounded evaluation.

The approach used in this study is designed to offer a detailed and updated overview of solar energy systems, including their structure, uses, and future development opportunities. Through a structured review and integration of existing literature, this work contributes to the broader understanding of solar energy as a reliable and sustainable power solution.

In summary, solar technology has experienced substantial progress in terms of innovation and global usage. The combination of reduced costs, better efficiency, and environmental advantages makes it one of the most promising renewable energy options. With continued advancements and successful integration into today's energy infrastructure, solar power is positioned to become a key pillar in the move toward a cleaner and more sustainable global energy system.

2. REFERENCES

1. A. Kassem , M. Hamad , “A Microcontroller-Based MultiFunction Solar Tracking System”, IEEE 2011.
2. A.K.Saxena, V. Dutta, “A versatile microprocessor- based controller for solar tracking”, IEEE 1990.
3. “ *Electrical Machines*” by Nagrath & Gopal
4. B. Koyuncu, K. Balasubramanian, “A microprocessor controlled automatic sun tracker”, IEEE 1991.
5. Ministry of Non-conventional Energy Sources (MNES)

6. M. F. Khan, R. L. Ali, "*Automatic sun tracking system*", IEEE2005.
7. O. Bingol, A. Altinta, Y. Oner, "*Microcontroller based solar tracking system and its implementation*", IEEE 2006.
8. Md. Tanvir Arafat Khan, S.M. Shahrear Tanzil, Rifat Rahman, S M Shafiul Alam, "*Design and Construction of an Automatic Solar Tracking System*", *6th International Conference on Electrical and Computer Engineering ICECE ,IEEE 2010. NWTC Wind Resource Information.htm*"
9. "*Renewable energy*" from Wikipedia, the free encyclopedia
10. "*Power Generation Programmes*" at a Glance.htm
11. "*Theory of Machines*" by Parker& Smith
12. www.wikipedia.com