

A Review of Solar Photovoltaic (PV) Technologies and Their Applications to Improved Efficiency

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Abstract

Solar photovoltaic (PV) technology has emerged as a cornerstone of global renewable energy strategies due to its capacity to harness the sun's energy and convert it into electricity with minimal environmental impact. This review provides a comprehensive examination of existing and emerging PV technologies, with a focus on advancements aimed at improving efficiency. We explore traditional PV cell types—such as monocrystalline, polycrystalline, and thin-film technologies—alongside cutting-edge developments, including perovskite cells, tandem configurations, and concentrated photovoltaic (CPV) systems. The review highlights the factors that influence PV efficiency, including material properties, optical design, temperature effects, and electrical optimization. In addition, we analyze the practical applications of high-efficiency PV systems in utility-scale solar farms, building-integrated photovoltaics (BIPV), and space-based solar power solutions. While significant strides have been made in boosting efficiency and reducing costs, challenges such as durability, manufacturing scalability, and environmental impact remain. Finally, we discuss future prospects for further innovation, positioning PV technology as a pivotal solution in meeting global energy demands through improved efficiency and sustainability.

Keywords: *Polycrystalline, PV cell, Solar, farms.*

1. Introduction

The growing need for sustainable energy sources has propelled solar photovoltaic (PV) technology to the forefront of global energy discussions. Solar PV systems, which convert sunlight directly into electricity using semiconductor materials, offer a clean, renewable alternative to fossil fuels, contributing significantly to the reduction of carbon emissions and the fight against climate change. As the world

transitions toward low-carbon energy solutions, PV technology plays a critical role in meeting rising electricity demands, especially in regions with high solar insolation.

Over the past few decades, solar PV technology has evolved dramatically, both in terms of cost reduction and efficiency improvement. Early solar cells, primarily based on crystalline silicon, provided a foundation for the technology, but they were limited by high production costs and modest energy conversion efficiency. Recent advancements, however, have led to a variety of PV technologies that offer enhanced performance, including thin-film solar cells, tandem cells, and perovskite-based devices. These innovations have enabled the deployment of solar energy systems at both small and large scales, from residential rooftops to vast solar farms, further cementing solar energy's viability as a long-term energy solution.

This review aims to provide a comprehensive overview of the key solar PV technologies, their efficiency potential, and the applications where they have demonstrated notable improvements. By examining factors such as material selection, cell architecture, and system design, this paper will highlight current strategies for enhancing PV efficiency and discuss how these developments are shaping the future of solar energy. Additionally, the challenges and limitations faced by these technologies, including cost, scalability, and durability, will be addressed to provide a balanced perspective on their real-world applicability.

The integration of high-efficiency PV systems into energy grids worldwide will be critical to achieving energy sustainability. As such, this review will also explore the applications of these technologies across various sectors, including utility-scale solar farms, building-integrated photovoltaics (BIPV), and portable solar solutions. By evaluating the current state of PV

technologies and their path toward greater efficiency, this paper will provide insights into the future trajectory of solar energy as a major contributor to global renewable energy efforts.

2. Overview of Solar Photovoltaic Technology

Solar photovoltaic (PV) technology is one of the most promising renewable energy sources, capable of converting sunlight directly into electricity through the photovoltaic effect. The fundamental principle behind this technology involves the interaction of sunlight with semiconductor materials, which results in the generation of electrical current. This process offers a clean, reliable, and scalable way to produce energy, contributing significantly to global efforts in reducing dependence on fossil fuels.

2.1. Principle of PV system

The solar cell mostly consists of three layers of semi-conductors: An upper layer of an N-type semiconductor that has excess of electrons, a semiconductor band gap, and a lower layer of a P-type semi-conductor that has an excess of positively charged holes. When a photon is absorbed, it forms in the semi-conductor electrons (e-) and holes (h+), which are responsible for generating electricity. Figure 1 is a schematic that shows the structure of a PV solar cell and the mechanism of electricity generation [1].

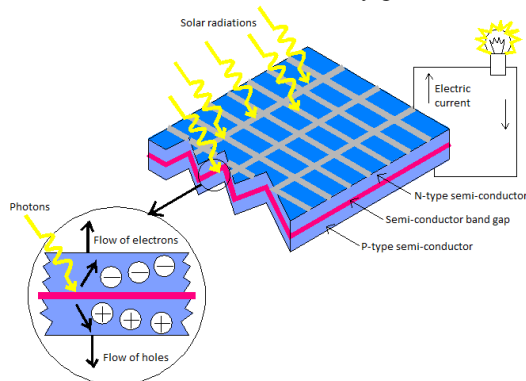


Figure 1 Solar photovoltaic cell [1].

Mundo-Hernández et al. [2] presented an overview of energy policies and the potential of solar photovoltaic energy in Germany, the world leader in producing photovoltaic technology, and Mexico, which has great potential of solar photovoltaics. The authors also reviewed the characteristics, advantages, and disadvantages of photovoltaic technology. Lin et al.

[3] performed a study to provide policy makers with evaluation agents to simulate concrete scenarios and optimal conditions that serve in progressing solar energy as an applicable renewable energy source in Taiwan. In [4], Paiano simulated the exponential growth in the installed photovoltaic system to evaluate the prospective waste emerging in Italy from utilizing end-of-life phases of these renewable energy systems in the coming years and their recycling or/and elimination. Moreover, Khan and Pervaiz presented a technological review on solar photovoltaic in Pakistan [5]. The optimum components and appropriate technology for producing energy in remote places within the country were identified

2.2. Components of PV systems

Photovoltaic systems consist mostly of three parts: PV module, power electronics and balance of system (BOS). The PV module is made up of solar cells, formed from semiconductor materials, and role is to convert light into electricity by collecting photons from sun light. When these photons hit the surface of the semiconductor materials they produce pairs of electrons and holes that diffuse in electric field, generating direct current (DC). When solar modules are connected together in series they form strings. Strings of modules are connected in parallel to form an array. Power electronics is important in PV installation, since the solar cell produces DC and all electrical applications found at home need alternating current (AC). Power electronics are mainly DC/AC inverters or regulators for the voltage. This is due to several factors such as meteorological and economic factors, in addition to the intrinsic parameters of the inverter. The remaining components to produce a complete PV system is called the “BOS”. It includes wiring, switches, a mounting system, a battery bank and battery charger and other installation components. Khatib et al. [6] presented a review including the present research on size optimization of PV systems and the size optimization techniques for the inverter in the photovoltaic systems. The authors concluded from the review that the optimization of PV system is significantly affected by the meteorological variables such as solar irradiance, ambient temperature and wind speed. In [7], Makki et al. presented a comprehensive review of different design and operating parameters that affect the cooling capacity of photovoltaic systems and hence their performance. Another review was done in [8] by Jordehi of the existent research works on photovoltaic cell parameter

evaluation problems in addition to some recommendations for future works.

2.3. Photovoltaic systems

Photovoltaic systems have two major types: Grid-connected and off-grid PV systems. Figure 2 presents schematics for grid-connected and off-grid PV systems [9]. A grid-connected system is a system that is connected to the local electricity network. This system is characterized by a bidirectional energy flow; electricity flows from the grid when the PV panels are not producing sufficient energy, and electricity is supplied to the grid when the panels are producing excess energy. Wong et al. [10] presented a review to study the voltage issues of grid-connected photovoltaic systems in Malaysia, where a 7.2 kW grid connected PV system had been installed.

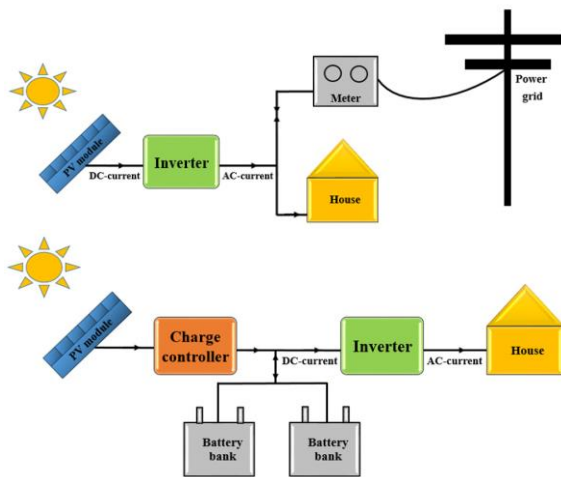


Figure 2 (a) Grid connected solar PV system; (b) Off-grid solar PV system [10].

An off-grid PV system or a stand-alone system refers to a system that is not connected to the local electricity network. Such a system is mainly composed of a number of photovoltaic panels that are connected to form a single array that supplies the desired output power, a charge controller, an inverter, and batteries. A charge controller is also known as a charge regulator. It is connected between the solar panel and the batteries and regulates the output from the solar array to prevent the overcharging or over discharging of the batteries. The inverter is utilized to transform the direct current (DC) from the solar array and batteries into an alternating current (AC) to power the AC main appliances. Furthermore, such systems need a backup battery to overcome the insufficient power production by the solar panels due to low irradiation or at night.

2.4. Photovoltaic technologies

In this work, PV technologies are classified according to their generation. Figure 3 illustrates the types of each generation of PV technology.

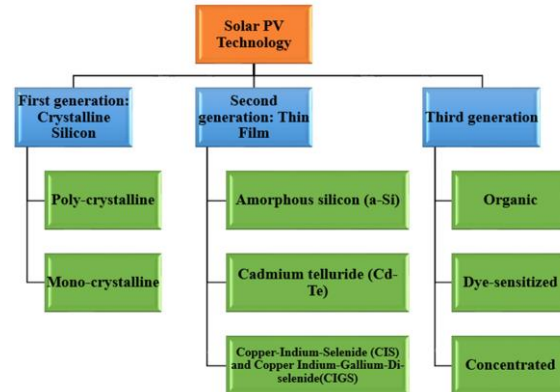


Figure 3. Solar photovoltaic technologies

The performance and overall efficiency vary greatly from one generation to another due to the difference in the type of semi-conductive materials utilized in each one. Contrary to the third generation, the first and the second generations are commercially mature.

3. Types of Solar PV Cells

Over the years, various types of solar PV cells have been developed, each with distinct material compositions, efficiency levels, and applications. The most widely used types of PV cells include:

- Monocrystalline Silicon (Mono-Si): These are the most established and efficient type of PV cells, made from a single continuous crystal structure. Monocrystalline cells offer high efficiency, typically ranging from 18% to 22%, due to their superior crystal quality and ability to convert a large portion of sunlight into electricity. They are widely used in residential and commercial solar installations due to their longevity and high power output per square meter.
- Polycrystalline Silicon (Poly-Si): Polycrystalline cells are made from multiple silicon crystals melted together, making them less expensive to produce than monocrystalline cells. While their efficiency is slightly lower, typically between 15% and 17%, polycrystalline panels offer a cost-effective solution for large-scale solar farms and residential systems.
- Thin-Film Solar Cells: Thin-film technology

involves depositing one or more layers of photovoltaic material on a substrate such as glass, plastic, or metal. The three main types of thin-film cells are cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si). Thin-film panels are lighter and more flexible than crystalline silicon panels, making them suitable for applications requiring lightweight or flexible materials. However, their efficiency is generally lower, around 10% to 12%.

- **Emerging PV Technologies:** Researchers are developing next-generation PV technologies that promise to significantly improve efficiency and reduce costs. These include:
- **Perovskite Solar Cells:** Offering rapid advances in efficiency (currently over 25%), perovskite solar cells are made from a class of materials with a crystal structure similar to that of calcium titanium oxide. They are attractive due to their low-cost fabrication methods and potential for high efficiency.
- **Tandem Solar Cells:** Tandem cells combine multiple layers of different semiconductor materials, each designed to capture different parts of the solar spectrum. This configuration allows for higher energy conversion efficiency, as more of the sunlight can be harnessed.
- **Organic PV Cells:** These cells are made from carbon-based materials and are known for their flexibility and potential for low-cost, large-scale manufacturing. However, their efficiency and stability currently lag behind other technologies.

4. Performance Metrics

Three key metrics are useful for understanding PV performance and reliability: availability, performance ratio (sometimes abbreviated as PR), and energy ratio.

- **Availability** is the actual measured hours of production divided by the modeled hours of production. An unavailable hour is easily identified by an output of zero, but values are often not exactly zero—an hour is therefore tallied as unavailable if the measured output is less than 5% of the model output.
- **Performance ratio** is the measured production divided by modeled production during time steps when the system is available.

- **Energy ratio** is the total measured production divided by total modeled production, and thus includes both the effects of availability (downtime) and performance ratio (inefficiency) in the same metric.

Availability and performance definitions may be found in International Electro-technical Commission (IEC) standards 63019 (2019) and 61724 (2017). Availability and performance ratio are reported separately because they affect management actions and life cycle cost in different ways as described in Walker et al. (2020b)—lower availability reduces operating hours and a lower performance ratio reduces power output. After presenting early reports to agency staff, we realized what staff are really interested in is the “bottom line”—how much energy was produced (in kWh or MWh) in each year—so we introduce an energy ratio metric as the ratio of measured energy delivery to model-prediction of energy delivery, thus including the effects of both availability and performance ratio. These three performance indicators were calculated for each system for which agencies provided data, and the data for each was anonymized and consolidated to provide distributions for these three performance indicators across the sample of 75 systems.

5. Applications of PV Technology

- **Remote locations**

PV systems can provide electricity to remote areas where power lines are not cost-effective or practical, such as rural homes, lighthouses, and offshore oil platforms.

- **Solar farms**

Large PV panel systems can generate megawatts or gigawatts of electricity to feed into regional or municipal power grids.

- **Stand-alone power**

PV systems can power devices and tools in remote or urban areas, such as parking meters, traffic signs, emergency phones, and water pumps.

- **Building-related needs**

PV panels can be mounted on roofs or the ground to supply electricity to buildings.

- **Power in space**

PV has been a primary power source for satellites orbiting Earth since the beginning.

- **Transportation**

PV can provide auxiliary power for vehicles like cars and boats.

- **Military uses**

Thin-film PV can be used in applications that require portability or ruggedness.

- **Floating solar farms**

Floating solar farms are a growing area of interest as they address the issue of excessive land use associated with traditional solar farms.

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