

A Comprehensive Review of Solar Photovoltaic Systems: Technologies, Performance, Applications and Future Trends

HEMLTA PAREEK¹, DR. LALIT KUMAR YADAV², B. R. Nagaria³

^{1, 2}Department of Energy Technology, Gyanoday University, Neemuch, Madhya Pradesh, India

³HoD, Electrical Engineering, Gyanodaya University, Suwakheda, Neemuch

Corresponding Author: Hemlta Pareek

Abstract—Solar photovoltaic (PV) system is one of the most important renewable energy technologies. It is widely used because solar energy is clean, free and available in many parts of the world. The use of solar PV is increasing every year due to the high demand of electricity and environmental problems caused by fossil fuels. This review paper explains the basic working of solar PV system and different generations of solar cell technologies. The paper also discusses efficiency, cost, sustainability, service life and different applications of solar PV systems. Global development of solar PV and future technologies are also explained. Recent improvements in materials and manufacturing process have increased the performance of solar panels and reduced their cost. Although some challenges such as storage, recycling and weather conditions are still present, solar PV has become one of the best options for clean electricity generation. This review shows that solar PV technology will continue to grow in future and play an important role in sustainable energy development.

Keywords— solar photovoltaic, renewable energy, solar cell, solar energy, pv technology, efficiency, sustainability, applications.

I. INTRODUCTION

Energy is one of the basic requirements for human life and economic development. The demand for electricity is increasing every year because of population growth, industrial development and modern lifestyle. Most electricity is still produced from fossil fuels like coal, oil and natural gas. These energy sources produce greenhouse gases and increase global warming. Because of these environmental problems, many countries are focusing on renewable energy sources.

Renewable energy includes solar, wind, hydro, biomass and geothermal energy. Among these sources, solar energy has received more attention because sunlight is available in almost every country.

Solar energy is free, clean and does not produce harmful gases during electricity generation. It is one of the fastest growing renewable energy technologies in the world.

Solar photovoltaic (PV) technology converts sunlight directly into electricity by using semiconductor materials. When sunlight falls on the PV cell, electrical current is produced because of the photovoltaic effect. Many solar cells are connected together to make a module, and several modules form a solar PV array. The electricity generated from the PV system can be used in homes, industries, commercial buildings and agriculture.

During the last few years, solar PV technology has improved rapidly. The efficiency of solar cells has increased while the manufacturing cost has reduced. Government policies, financial support and technological improvements have also increased the installation of solar PV systems in many countries.

Many review papers are available on solar photovoltaic technology. Some papers explain only solar cell technologies, while others discuss applications or performance analysis. Very few studies explain all important aspects in one paper. Therefore, this review presents a detailed study of solar PV technologies, performance factors, applications, recent developments and future opportunities.

The main objective of this review paper is to provide complete information about solar photovoltaic systems. The paper explains different generations of solar cells, key performance factors, applications in different sectors, global development, future trends and major challenges. This review may help students, researchers and engineers to understand recent progress in solar PV technology.

Working Principle of Solar Photovoltaic System

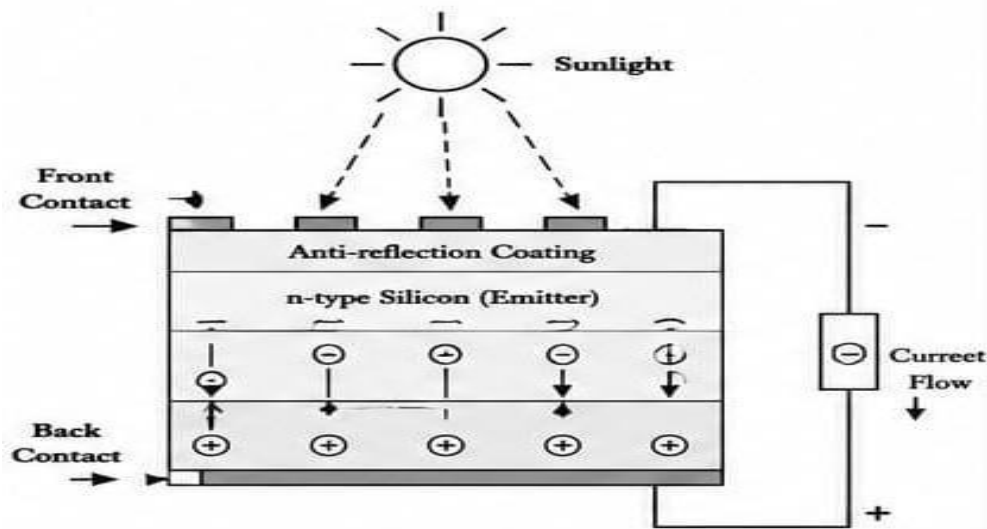


Figure 1. Working Principle of a Solar Photovoltaic Cell.

Solar photovoltaic (PV) system is a technology which converts sunlight directly into electrical energy. It is one of the clean and renewable energy sources. The working of PV system is based on the photovoltaic effect. This effect was discovered by Alexandre Edmond Becquerel in 1839. Today this technology is used in homes, industries, agriculture and many other sectors.

A solar PV system mainly consists of solar cells, solar modules, inverter, battery (optional), charge controller and electrical load. All these components work together to generate electricity from sunlight. When sunlight falls on the surface of a solar cell, photons from sunlight transfer energy to electrons present inside the semiconductor material. Due to this energy, electrons start moving and electric current is generated. This electricity is produced in the form of

direct current (DC). If alternating current (AC) is required, an inverter is used to convert DC into AC. A single solar cell produces only a small amount of electrical power. Therefore, many solar cells are connected together to form a solar module. Several modules are connected to make a solar array. A solar array can generate enough electricity for homes, commercial buildings and industries.

The output of a PV system depends on different factors such as solar radiation, temperature, panel orientation, dust accumulation and shading. Proper installation and regular maintenance improve the performance of the solar PV system.

2.1 Components of Solar PV System

The important components of a solar PV system are explained below.

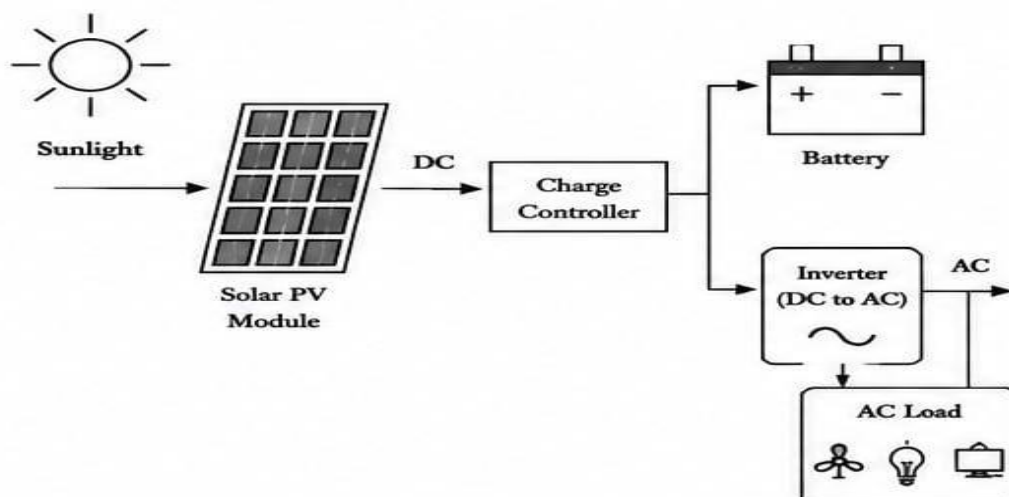


Figure 2. Basic Components of a Solar Photovoltaic (PV) System.

Solar Cell

Solar cell is the basic unit of a photovoltaic system. It converts sunlight into electrical energy. Most solar cells are made from silicon semiconductor material because silicon gives good performance and long service life.

Solar Module

A solar module is formed by connecting many solar cells together. The module is covered with protective glass to protect the cells from dust, rain and environmental conditions.

Solar Array

Many solar modules are connected together to form a solar array. Large solar arrays are used in commercial buildings and solar power plants where high power generation is required.

Charge Controller

The charge controller controls the charging and discharging of the battery. It protects the battery from overcharging and deep discharge.

Battery

The battery stores electrical energy generated during daytime. Stored energy can be used during night or when sunlight is not available.

Inverter

The inverter converts DC electricity produced by solar panels into AC electricity. Most household appliances operate on AC power, therefore the inverter is an important component in grid-connected and stand-alone systems.

III. CLASSIFICATION OF SOLAR PV TECHNOLOGIES

Solar photovoltaic technologies are generally divided into three generations based on manufacturing process, material used and performance.

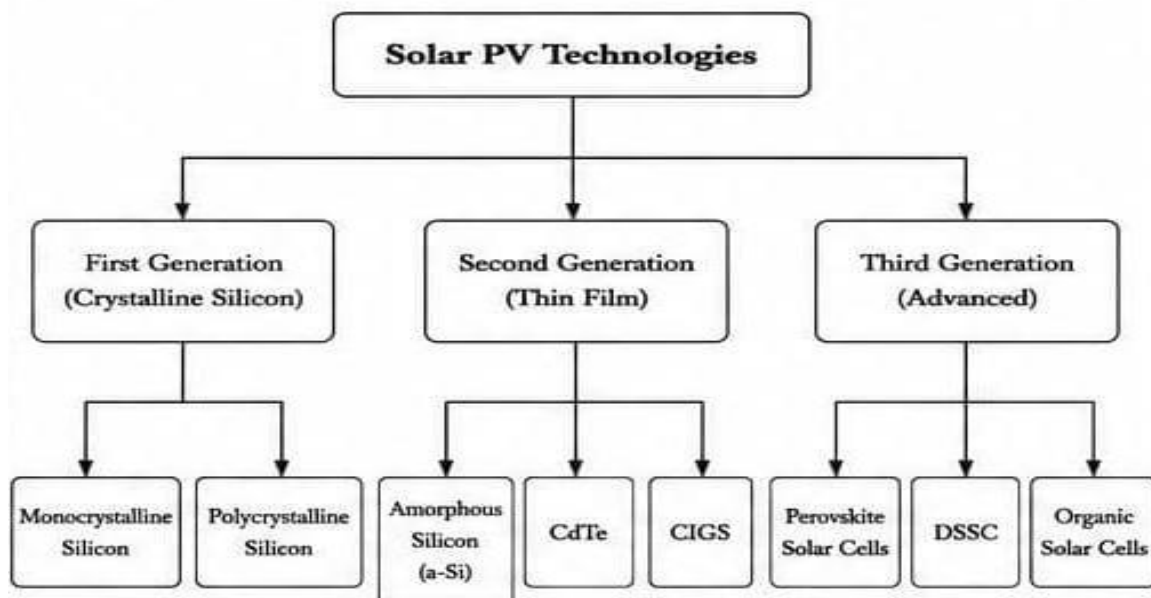


Figure 3. Classification of Solar Photovoltaic Technologies.

3.1 First Generation Solar Cells

First generation solar cells are made from crystalline silicon. These cells are the oldest and most commonly used solar cells in the world. They have good efficiency, long life and reliable performance.

There are two main types:

Monocrystalline Silicon Solar Cell

Polycrystalline Silicon Solar Cell

Monocrystalline solar cells are manufactured using a single silicon crystal. These cells provide high

efficiency and require less installation area. However, manufacturing cost is high.

Polycrystalline solar cells are manufactured using multiple silicon crystals. They are less expensive than monocrystalline cells but their efficiency is slightly lower.

Because of good performance and long lifetime, first generation solar cells are widely used in residential, commercial and industrial applications.

3.2 Second Generation Solar Cells

Second generation solar cells are also known as thin film solar cells. These cells are made by depositing a very thin layer of semiconductor material on glass, plastic or metal surface. Because the material used is very less, manufacturing cost is lower than crystalline silicon cells.

Different materials are used for making thin film solar cells. The most common materials are amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). Every material has its own advantages and limitations.

Thin film solar cells are light in weight and easy to transport. They can also be used on flexible surfaces. These cells perform better in cloudy weather and low light conditions than many conventional solar panels. Due to these properties, they are used in portable devices, building integrated photovoltaic systems and some commercial projects.

The efficiency of thin film solar cells is generally lower than first generation solar cells. Some materials used in these cells are costly or require special manufacturing processes. Even with these limitations, thin film technology has become an important option because it reduces material consumption and production cost.

3.3 Third Generation Solar Cells

Third generation solar cells are developed to improve efficiency and reduce manufacturing cost. These technologies are still under continuous research and many new materials are being tested.

One important technology is the perovskite solar cell. It has shown very high efficiency in laboratory studies. The manufacturing process is simple and the material cost is also lower. Researchers are working to improve its stability because long-term performance is still a challenge.

Another technology is the organic solar cell. These cells are made from carbon-based materials. They are flexible, light in weight and can be produced at low cost. However, their efficiency and lifetime are lower than silicon solar cells.

Dye-sensitized solar cells (DSSC) are also included in third generation technology. These cells use a special dye to absorb sunlight. They work well in low light conditions and are suitable for small electronic applications.

Researchers are also developing multi-junction solar cells. These cells use more than one semiconductor

layer to absorb different parts of sunlight. Because of this design, they can achieve very high efficiency. At present, these cells are mainly used in satellites and space applications because their manufacturing cost is high.

Third generation solar cells are expected to play an important role in future because they have the potential to provide higher efficiency, lower cost and better use of available solar energy.

IV. COMPARISON OF DIFFERENT SOLAR PV TECHNOLOGIES

Different generations of solar cells have different properties. First generation solar cells provide good efficiency and long service life, but manufacturing cost is comparatively high. Second generation cells reduce material use and production cost, but efficiency is moderate. Third generation technologies are still developing and have the potential to achieve better efficiency with lower production cost.

The selection of solar technology depends on application, available budget, installation area and required power output. Residential systems generally use crystalline silicon panels because of their reliability. Thin film panels are preferred where lightweight or flexible installation is needed. Advanced technologies like perovskite and multi-junction cells are expected to become more common in the future as research continues.

V. EFFICIENCY OF SOLAR PV SYSTEM

The efficiency of a solar photovoltaic (PV) system refers to its ability to convert sunlight into usable electrical energy. It is one of the most important factors that determine the overall performance of a solar power system. Modern solar panels have achieved significant improvements in efficiency due to continuous research and technological advancements.

Different types of solar panels provide different efficiency levels. Monocrystalline solar panels generally have the highest efficiency, ranging from 20% to 24%. Polycrystalline panels usually offer efficiencies between 15% and 18%, while thin-film panels have lower efficiencies, typically between 10% and 15%. The selection of a panel depends on available space, budget, and energy requirements.

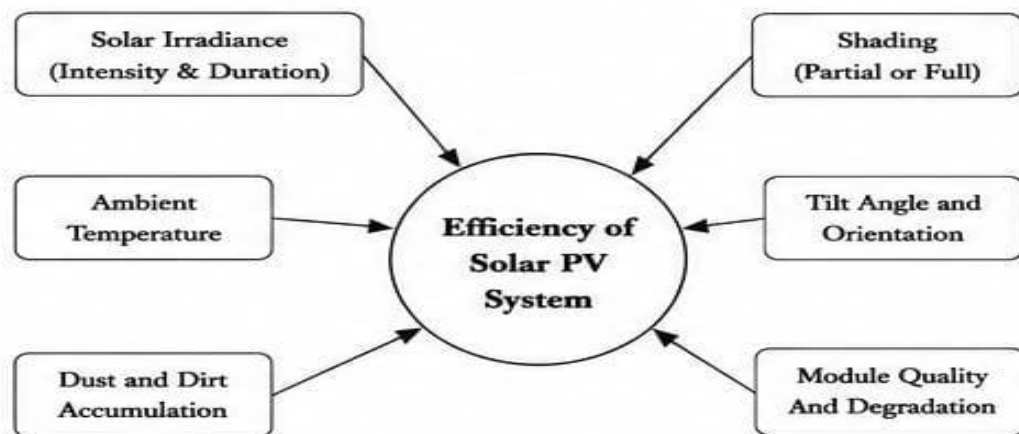
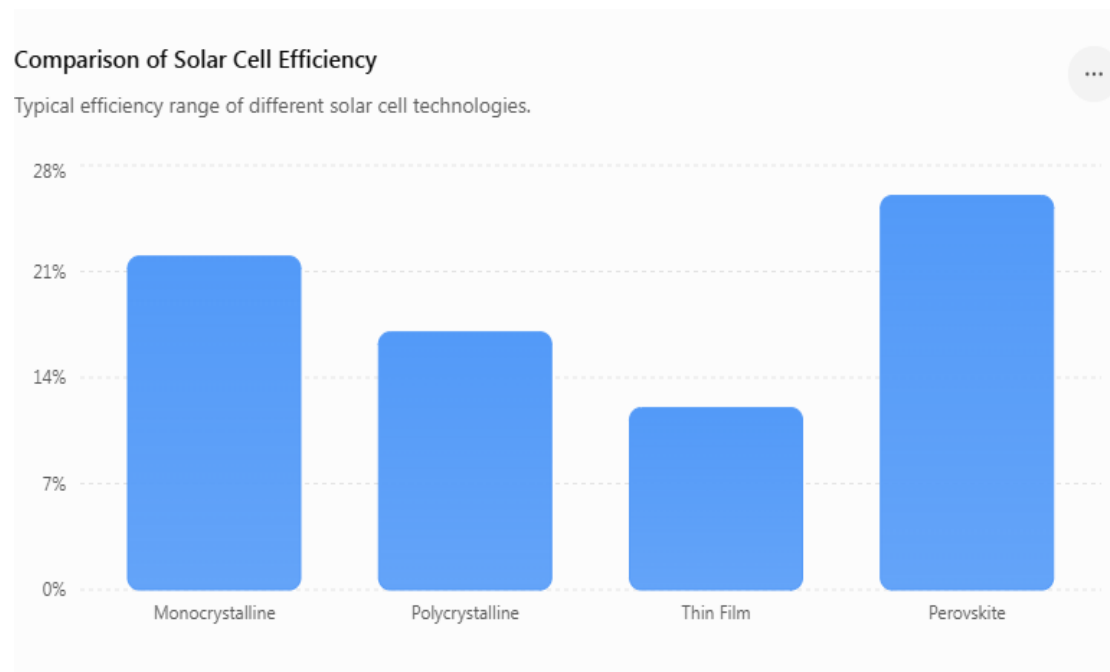


Figure 4. Factors Affecting the Efficiency of a Solar PV System.

Several environmental and technical factors influence the efficiency of a PV system. High temperatures reduce panel performance, while dust, dirt, and shading decrease the amount of sunlight reaching the solar cells. Proper installation angle, panel orientation, regular cleaning, and adequate ventilation help improve system efficiency. Modern technologies such as Maximum Power Point Tracking (MPPT), bifacial solar panels, and solar tracking systems further enhance energy production. Overall, improving efficiency not only increases electricity generation but also reduces the number of

panels required for a given power output, making solar PV systems more practical and economical.

VI. COST ANALYSIS OF SOLAR PV SYSTEM

The cost of a solar PV system includes the expenses associated with purchasing, installing, operating, and maintaining the system. Although the initial investment is relatively high compared to conventional electricity sources, the long-term financial benefits make solar energy an attractive option.

The total installation cost depends on system capacity, quality of solar panels, inverter type, battery storage (if used), mounting structures, wiring, and labor charges. Government subsidies, tax benefits, and financial assistance programs can significantly reduce the overall investment.

One of the major advantages of solar PV systems is their low operating and maintenance cost. Solar panels require only periodic cleaning and routine inspections to maintain good performance. Since sunlight is freely available, electricity generation does not involve fuel expenses. Most solar panels have a lifespan of 25 years or more, allowing users to recover the initial investment through reduced electricity bills.

The payback period generally ranges from 5 to 8 years, depending on electricity consumption, local solar radiation, and government incentives. After the payback period, the electricity generated is almost free, making solar PV systems a cost-effective and sustainable energy solution for residential, commercial, and industrial applications.

VII. CHALLENGES OF SOLAR PV SYSTEM

Although solar photovoltaic (PV) technology has become more reliable and affordable, several challenges still limit its large-scale adoption. One of

the major challenges is the intermittent nature of solar energy. Since electricity is generated only during daylight hours, energy production decreases on cloudy days and stops completely at night. Therefore, battery storage or backup power systems are often required, which increases the overall project cost.

Another challenge is the high initial investment required for purchasing solar panels, inverters, batteries, and installation equipment. Even though operating costs are low, many households and small businesses find the upfront cost difficult to afford.

The performance of solar panels is also affected by environmental conditions. Dust accumulation, shading from trees or buildings, high temperatures, and poor maintenance reduce the efficiency of the system. In addition, solar power plants require a large land area to generate significant amounts of electricity, which may not always be available.

The disposal and recycling of old solar panels is another emerging concern. As more PV systems reach the end of their service life, proper recycling methods will be essential to reduce environmental impacts. Addressing these challenges through technological improvements and supportive government policies will help increase the adoption of solar PV systems.

VIII. GLOBAL MARKET TRENDS OF SOLAR PV

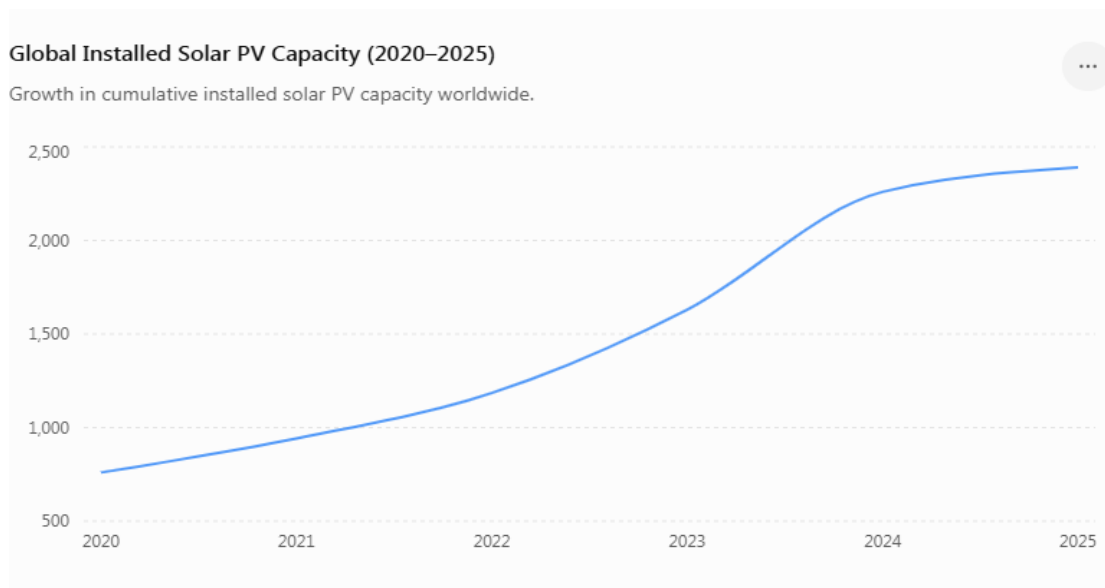


Figure 5. Global Installed Solar PV Capacity (2020–2025).
Source: IEA PVPS, *Trends in Photovoltaic Applications* (2025).

Table 1. Global Installed Solar PV Capacity

Year	Capacity (GW)
2020	760
2021	942
2022	1,185
2023	1,630
2024	2,260
2025	2,390

Table 2. India Installed Solar PV Capacity

Year	Capacity (GW)
2020	39
2021	49
2022	63
2023	73
2024	92
2025	108

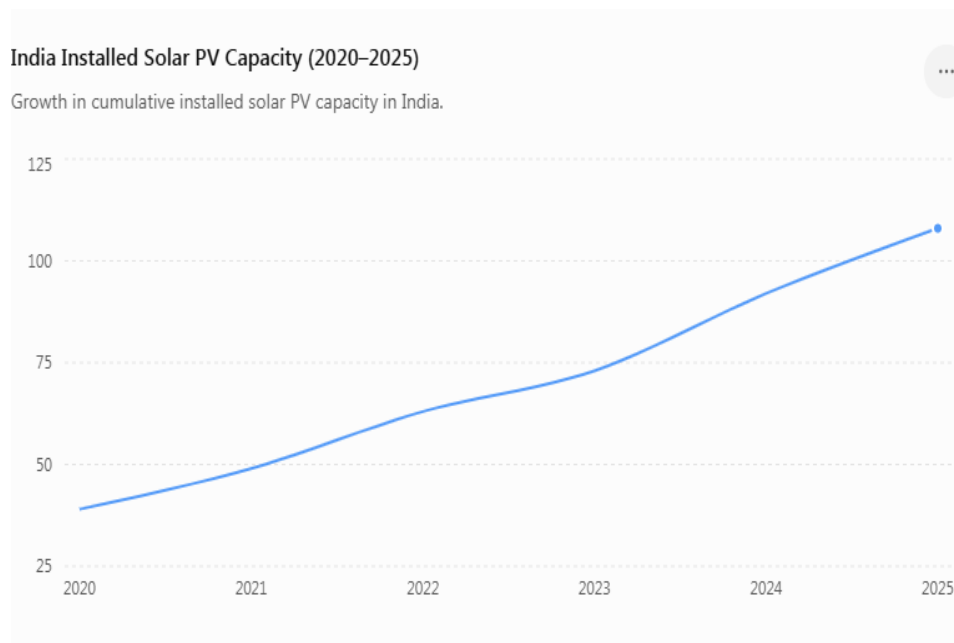


Figure 6. India Installed Solar PV Capacity (2020–2025).

Source: Ministry of New and Renewable Energy (MNRE), Government of India.

IX. FUTURE SCOPE

The future of solar photovoltaic technology is highly promising because of continuous research and technological advancements. Scientists are

developing high-efficiency solar cells, including perovskite and tandem solar cells, which are expected to produce more electricity than conventional silicon panels.

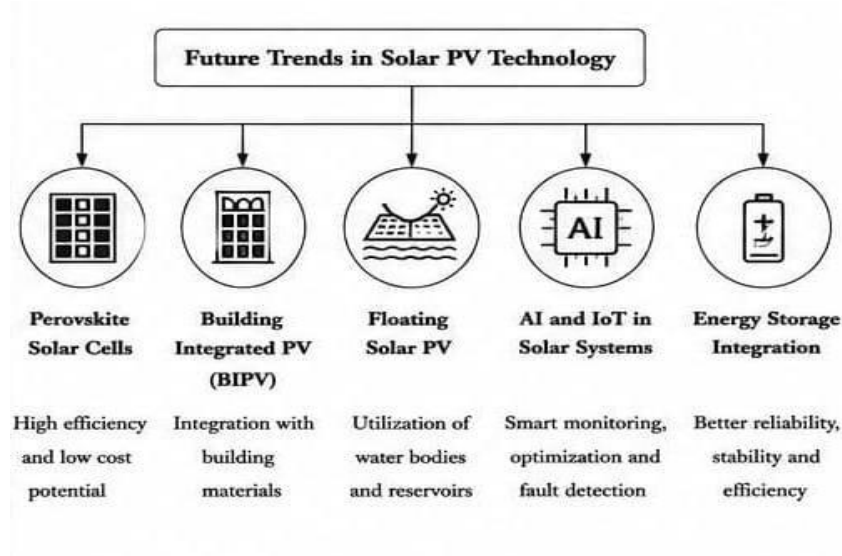


Figure 7. Future Trends in Solar Photovoltaic Technology

Battery energy storage systems are also improving rapidly, making solar power more reliable for use during the night and periods of low sunlight. The integration of solar PV with smart grids, artificial intelligence, and the Internet of Things (IoT) will improve energy management and system performance.

Emerging technologies such as floating solar power plants, building-integrated photovoltaic (BIPV), and agrivoltaics are creating new opportunities for efficient land use and sustainable energy generation. Government policies, financial incentives, and increasing public awareness are expected to accelerate the adoption of solar energy worldwide. With decreasing installation costs and increasing efficiency, solar PV systems are expected to become one of the most important sources of clean and renewable energy in the future.

10.2 Technical Details

Parameter	Details
Project Name	Welspun Solar MP Project
Location	Bhagwanpura, Near Diken, Neemuch (M.P.)
Installed Capacity	151 MW
Commissioned	February 2014
Land Area	305 hectares
Technology	Polycrystalline Solar PV
Module Rating	235 W
Inverter Rating	630 kW
Grid Voltage	132 kV
Project Life	25 Years

10.3 Electricity Generation

The Welspun Solar MP Project generates electricity by using solar photovoltaic (PV) technology. Solar panels absorb sunlight and convert it into direct current (DC). The DC power is then converted into alternating current (AC) by 630 kW inverters. After passing through transformers, the voltage is stepped up to 132 kV and the generated electricity is supplied to the regional electricity grid.

The plant has an installed capacity of 151 MW and operates under favourable solar radiation conditions available in the Neemuch region. It supplies electricity to about 6.24 lakh households and helps reduce approximately 216,372 tonnes of carbon dioxide emissions every year. This project demonstrates the practical use of large-scale solar PV

X. CASE STUDY: WELSPUN SOLAR MP PROJECT, BHAGWANPURA (NEAR DIKEN), NEEMUCH, M.P.

10.1 Introduction

To understand the practical application of solar photovoltaic technology, the Welspun Solar MP Project located near Diken, Neemuch has been selected as a case study. This project is one of the important grid-connected solar power plants in Madhya Pradesh. It was developed to produce electricity from solar energy and to increase the use of clean and renewable power.

The project started commercial operation in February 2014 with an installed capacity of 151 MW. It is spread over about 305 hectares (750 acres) of land. The plant uses polycrystalline solar photovoltaic modules for electricity generation. The expected operating life of the project is around 25 years.

technology for clean and sustainable electricity generation.

10.4 Cost Analysis

The initial investment in a solar photovoltaic power plant is comparatively high. However, the operation and maintenance cost is low, which makes the system economical over its lifetime. A simple method to estimate the electricity generation cost is given below.

Formula

Cost per Unit (₹/kWh) = Total Project Cost (₹) ÷ Total Energy Generated during Plant Life (kWh)

Sample Calculation

Project Cost = ₹1100 Crore

Installed Capacity = 151 MW

Average Peak Sun Hours = 5.5 hours/day

Estimated Daily Energy Generation
 $= 151 \times 5.5$
 $= 830.5 \text{ MWh/day}$
 Estimated Annual Energy Generation
 $= 830.5 \times 365$
 $= 303,132.5 \text{ MWh/year}$
 Estimated Lifetime Energy (25 years)
 $= 303,132.5 \times 25$
 $= 7,578,312.5 \text{ MWh}$
 Convert to kWh:
 $= 7,578,312,500 \text{ kWh}$
 Cost per Unit
 $= ₹1100 \text{ Crore} \div 7,578,312,500 \text{ kWh}$

$\approx ₹1.45 \text{ per kWh}$

Result

The above calculation shows that although the initial cost of a solar PV project is high, the average electricity generation cost becomes low over the complete life of the plant. This makes solar photovoltaic technology a cost-effective and sustainable option for long-term electricity generation.

Note: Note: *The above calculation is for academic illustration based on the installed capacity and average sunshine hours. Actual electricity generation and cost may vary with operating conditions.*

10.5 Site Visit



Figure 10.1: Site visit at Welspun Solar MP Project, Bhagwanpura (Near Diken), Neemuch, Madhya Pradesh.
 Source: Author's field visit.

XI. CONCLUSION

Solar photovoltaic technology has become one of the most effective renewable energy solutions for meeting the growing global demand for electricity. It converts sunlight directly into electrical energy without producing harmful emissions, making it an environmentally friendly alternative to conventional fossil fuels.

This review discussed the working principle, components, types, applications, efficiency, cost analysis, advantages, limitations, and challenges of solar PV systems. The study shows that continuous improvements in solar cell technology, energy

storage systems, and power electronics have significantly increased the performance and reliability of PV systems.

Although challenges such as high initial cost, weather dependency, and energy storage still exist, ongoing research and government support are helping to overcome these limitations. The declining cost of solar technology and increasing awareness of environmental protection are encouraging wider adoption across residential, commercial, industrial, and agricultural sectors.

In conclusion, solar PV systems offer a sustainable, clean, and economically beneficial solution for future

energy needs. Continued technological innovation and supportive policies will further strengthen the role of solar energy in achieving global energy security and sustainable development.

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