

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

Dr Hossain K A^{1*}, Khandakar Anika Akhter², Khandakar Adiba Akhter³, Khandakar Shaffat Akhter⁴, Dr. Mohammad Khalilur Rahman⁵

¹Vice Chancellor, Bangladesh Maritime University, Dhaka, Bangladesh, ORCID ID:0009000708926069;

²Department of Accounting & Finance; North South University (NSU); Dhaka; Bangladesh

³Department of Accounting & Finance; North South University (NSU); Dhaka; Bangladesh

⁴Dept of Law, PrimeAsia University, Dhaka, Bangladesh;

⁵Scientist, Yokohama City, Tsuzuki ward, Hiradai, 10-7-403; Kanagawa, 224-0064, Japan

Corresponding Author: Dr Hossain K A

ABSTRACT: Solar power is a rapidly growing renewable energy source that converts sunlight into electricity using photovoltaic (PV) cells. Global solar capacity has grown exponentially over the past decade, driven by plummeting technology costs and aggressive government climate targets. China, the United States, and the European Union lead in total installed capacity. Continued efficiency improvements in perovskite solar cells and bifacial panels promise even higher energy yields. Solar is projected to become the largest source of global electricity generation in the coming decades. Intermittent generation requires heavy investment in battery storage and grid modernization. Supply chain bottlenecks for critical materials like polysilicon, silver, and silicon remain a concern. Beyond utility-scale solar farms, applications include building-integrated photovoltaics (BIPV), floating solar farms on reservoirs, and agrivoltaics (combining farming with solar panels). However, today flexible solar panels offer a revolutionary approach to overcoming structural hurdles. Unlike their rigid counterparts, flexible solar panels are lightweight and can be seamlessly integrated onto various surfaces, including curved and uneven ones. This adaptability allows industrial facilities to transform previously unusable spaces into productive energy-generating areas. Industrial facilities often struggle with space constraints and the logistical challenges of installing traditional solar panels. Roof structures, facades, and other surfaces may not support the weight and rigidity of conventional panels, leading to underutilization of potential solar energy resources. Flexible solar panels stand out from their rigid counterparts due to their unique construction and technology. This reviews paper will describe and evaluate the important information, materials, manufacturing process, technology, advantages, applications, market, and transformation of solar technology in general and flexible solar panel in particular to meet the global energy requirement as clean energy source to mitigate global warming and climate issues.

KEYWORDS: Renewable energy, PV, solar cells, solar panel, OPVs, CIGS, ETFE, CPV

1. INTRODUCTION

As we know, the most widely used renewable energy types are solar energy, wind power, and hydropower. However, bio-energy and geothermal power are also significant in some countries. Solar power has become the engine of the global energy transition, with both solar generation and capacity installations setting new records in 2024. Solar generation has maintained its high growth rate, doubling in the last three years, and adding more electricity than any other source over that period. At the same time, electricity demand saw a significant rise in 2024, outpacing the growth in clean electricity. Expanding technologies such as AI, data centers, electric vehicles and heat pumps are already contributing to the rise in global demand. However, the main reason why electricity demand growth was elevated in 2024 compared to 2023 was an increase in air conditioning use during heatwaves. This accounted for almost the entire small rise in fossil generation. Renewable energy installations can be large or small and are suited for both urban and rural areas. For any renewable energy, it need t be an endless source. Renewable energy is often deployed together with further electrification. This has several benefits: electricity can move heat and vehicles efficiently and is

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

clean at the point of consumption. Variable renewable energy sources are those that have a fluctuating nature, such as wind power and solar power. In contrast, controllable renewable energy sources include dammed hydroelectricity, bio-energy, or geothermal power. Renewable energy systems have rapidly become more efficient and cheaper over the past 40 years. A large majority of newly installed worldwide electricity capacity is now renewable. Renewable energy sources, such as solar and wind power, have seen significant cost reductions over the past decade, making them more competitive with traditional fossil fuels. In some geographic localities, photovoltaic solar or onshore wind is the cheapest new-build electricity.

When sunlight hits a solar panel, the light energy is converted into electricity and this process is known as the photovoltaic (PV) effect. That is why solar panels are also called photovoltaic panels, PV panels or PV modules. The ability of some materials to create an electrical charge from light exposure was first observed by the French physicist Edmond Becquerel in 1839. The American inventor Charles Fritts created the first commercial solar cell, which was reported by Fritts as "continuous, constant and of considerable force not only by exposure to sunlight but also to dim, diffused daylight" in 1881. Finally in 1939, Russell Ohl created the solar cell design that is used in many modern solar panels. He patented his design in 1941. However, this design was first used by Bell Labs to create the first commercially viable silicon solar cell in 1954. So, a solar panel is a device that converts sunlight into electricity by using multiple solar modules that consist of photovoltaic (PV) cells. PV cells are made of materials that produce excited electrons when exposed to light. These electrons flow through a circuit and produce direct current electricity, which can be used to power various devices or be stored in batteries. Solar panels can be known as solar cell/electric panels. Solar panels are usually arranged in groups called arrays or systems. A photovoltaic system consists of one or more solar panels, an inverter that converts direct current electricity to alternating current where it is necessary, and sometimes other components such as charge controllers, meters, or solar trackers to maximize direct sunlight. In recent past, solar panels use a renewable and clean source of energy, and reduce greenhouse gas emissions compared to hydrocarbon-sourced energy. Though, they depend on the availability and intensity of sunlight, require cleaning, and have high initial costs. Solar panels are widely used for residential, commercial, agricultural, transportation, and industrial purposes, as well as in space, often together with batteries.

The increasing demand for clean, sustainable, and affordable energy has transformed solar power from a niche technology into one of the most important components of the global energy system. In 21st century, as the world shifts towards renewable energy, solar panel or mono-crystalline panels are emerging as a favorite in the solar power market. Their distinctive uniform appearance, durability, user-friendly gesture and high-quality components make them a sight to behold and an asset to own. These solar panels are constructed from a single crystal of silicon, resulting in no visible grain lines and a sleek, modern aesthetic. Mono-crystalline solar panels, often referred to as mono panels, are distinctively known for their uniform, sleek appearance and high efficiency. These solar panels are constructed from a single crystal structure of silicon, which gives them their characteristic seamless look with no visible grain lines. This type of solar technology is unique in its construction process. Unlike other solar panels, such as poly solar panels, mono-crystalline panels are made by growing a single crystal. Because of their single crystal structure, these panels can more efficiently convert sunlight into electricity, making them a popular choice in the renewable energy market. The choice between mono-crystalline and polycrystalline solar panels often comes down to the balance between efficiency and cost, with mono-crystalline panels typically being more efficient but also more expensive. However, many find the long-term energy savings and aesthetic appeal of mono-crystalline solar panels worth the extra upfront cost. When comparing mono-crystalline vs. polycrystalline solar panels, mono-crystalline panels often come out ahead in efficiency and performance. They are made from a single, pure crystal of silicon, allowing for higher efficiency, especially in low-light conditions. Polycrystalline panels, while more cost-effective, typically have a lower efficiency and a shorter lifespan. It's disadvantages as a higher initial cost compared to polycrystalline panels and potentially lower performance in high-temperature environments. Moreover, they require a significant amount of space for installation due to their size and efficiency constraints. The life expectancy of a mono-crystalline solar panel is typically around 25 to 30 years. However, many panels continue to function effectively beyond this period, albeit at reduced efficiency.

According to the International Energy Agency (IEA, 2024), solar photovoltaic (PV) energy has become the fastest-growing source of electricity generation worldwide, accounting for a substantial proportion of newly installed renewable energy capacity each year. Declining production costs, improvements in manufacturing efficiency, and supportive governmental policies have enabled photovoltaic systems to become economically competitive with conventional fossil fuel-based electricity generation. For decades, photovoltaic electricity has relied primarily on rigid crystalline silicon modules constructed using tempered glass, aluminum frames, and heavy mounting structures. These conventional panels have demonstrated remarkable efficiency, durability, and reliability, often operating effectively for more than twenty-five years. However, their weight, rigidity, and installation requirements limit their application on lightweight buildings, curved architectural structures, transportation systems, portable

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

devices, and numerous other surfaces where traditional modules cannot be safely installed. Flexible solar panels represent a significant advancement in solar energy technology, combining portability, versatility, and cost efficiency. Their unique characteristics make them suitable for an expanding range of applications beyond the capabilities of traditional rigid panels. By understanding the different types, benefits, mounting methods, and maintenance needs, businesses and consumers can maximize the value and performance of their solar investments. Partnering with reputable manufacturers around the world ensures access to quality products backed by expertise and innovation. Flexible solar panels offer a compelling solution for sustainable energy adoption in a dynamic and evolving market.

The need for lightweight alternatives has stimulated extensive research into flexible photovoltaic technologies. Flexible solar panels represent a significant departure from conventional module design by replacing rigid glass substrates with thin polymer films, stainless steel foils, or ultra-thin flexible silicon wafers. These innovations reduce overall module weight while enabling the panels to bend, fold, or conform to irregular surfaces without compromising electrical performance. Today, the term paper-like solar panel has become increasingly popular in media reports and commercial advertising because many of these modules are extremely thin and lightweight. Although no commercially available photovoltaic module is literally made from paper, the description effectively communicates the appearance and flexibility of modern thin-film solar products. Some modules measure only a few millimeters in thickness and weigh less than one-quarter of conventional glass modules, making them easy to transport and install. Flexible photovoltaic extend the potential applications of solar energy far beyond traditional rooftops. They can be integrated into building facades, lightweight industrial roofs, recreational vehicles, boats, agricultural greenhouses, unmanned aerial vehicles, tents, emergency shelters, consumer electronics, wearable devices, and aerospace systems.

Their adaptability has led many researchers to consider flexible photovoltaic an essential technology for achieving universal access to clean energy while supporting innovations in sustainable architecture and smart infrastructure. The rapid development of flexible solar technology has been made possible through advances in materials science, semiconductor engineering, nanotechnology, and large-scale manufacturing. Modern flexible photovoltaic systems encompass several distinct technologies, including thin-film silicon, copper indium gallium selenide (CIGS), cadmium telluride (CdTe), organic photovoltaic cells (OPVs), dye-sensitized solar cells (DSSCs), and perovskite solar cells (PSCs). Each technology possesses unique advantages and limitations regarding efficiency, manufacturing cost, flexibility, environmental impact, and long-term durability. Among these technologies, perovskite photovoltaic have attracted exceptional attention because of their rapid improvement in conversion efficiency. Laboratory-scale perovskite cells have achieved efficiencies exceeding 26%, approaching those of conventional crystalline silicon. Researchers are also developing tandem architectures that combine silicon and perovskite materials to surpass the efficiency limits of single-junction photovoltaic cells. At the same time, manufacturers have refined ultra-thin crystalline silicon technologies that preserve the excellent performance of traditional silicon while significantly reducing module weight. These innovations demonstrate that flexibility does not necessarily require sacrificing electrical efficiency.

Renewable energies (RE) represent a cornerstone to steer our energy system in the direction of sustainability and supply security. Generating electricity, heat or bio-fuels from renewable energy sources has become a high priority in the energy policy strategies at national level as well as at a global scale. for a comprehensive investigation of the future RE development it is of crucial importance to provide a detailed investigation of the country or region specific situation like, with respect to the potential of the certain RE's in general as well as the part that can be realized in the near future. The prospects for RE in general and solar panels in particular with technologies, productions, maintenance, recycle, application, are presented in this article at a global level. Thus, the feasible deployment of these technologies and relevant issues has been discussed elaborately with the applied energy policies. The evolution of solar power solutions has dramatically transformed how we harness renewable energy. Among the innovations leading this transformation are flexible solar panels, a versatile and efficient alternative to traditional rigid panels. With advancements in technology and materials, flexible solar panels have opened new possibilities for solar power applications where conventional panels fall short. The transition toward renewable energy has accelerated technological innovation in photovoltaic PV systems, resulting in the emergence of flexible, lightweight, and ultra-thin solar modules.

Unlike conventional crystalline silicon solar panels that depend on rigid glass substrates and aluminum frames, flexible photovoltaic technologies employ lightweight polymers, thin semiconductor films, and advanced encapsulation techniques that allow the modules to bend, conform to curved surfaces, and integrate into buildings, vehicles, wearable electronics, and portable power systems. Recent developments in flexible crystalline silicon, perovskite, organic photovoltaic (OPV), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) technologies have expanded the possibilities for solar energy generation beyond traditional rooftop installations. Global research institutions, universities, and photovoltaic manufacturers have invested heavily in developing flexible modules with higher conversion efficiencies, improved durability, lower manufacturing costs, and enhanced environmental sustainability. China has emerged as the world's leading producer of photovoltaic technology, contributing

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

significantly to advances in flexible silicon and perovskite modules through large-scale manufacturing, materials research, and process innovation. Meanwhile, Europe, Japan, South Korea, and the United States continue to advance specialized flexible photovoltaic technologies for aerospace, transportation, architecture, and consumer electronics. This review article will explore and examine the scientific principles, materials, manufacturing methods, performance, characteristics, technology, applications, environmental implications, market trends, and future prospects of solar panel in general and flexible solar panels in specific. It also discusses current technical limitations, ongoing research challenges, and the role of flexible photovoltaic in supporting global energy transition goals. By synthesizing findings from scientific literature, international organizations, secondary resource materials, and industry reports, this analytical and informative paper will provides a comprehensive overview of one of the fastest-growing segments of renewable technology. This article will try to find out the answer of the following questions.

- a. What is the evolution of photovoltaic and flexible PV technology?
- b. How solar panels are constructed or manufactured?
- c. What are the types, selecting, caring and important information of flexible solar panels?
- d. What is the working principle and material science of flexible solar panels?
- e. What is manufacturing technologies and quality control of PV and solar panels?
- f. What is the efficiency, performance, and maintenance of solar panels?
- g. What are the advantages of flexible solar panels?
- h. What are the challenges of flexible solar panels?
- i. What are the applications of solar panel?
- j. What are the applications of flexible solar panel?
- k. What is the use and prospect of Electric Vehicle (EV) and smart EV charger?
- l. How solar panels waste can be recycled and environmental sustainability ensured?
- m. What is the future of solar energy and solar panel?

2. TECHNOLOGICAL DEVELOPMENT OF CONSTRUCTION OF SOLAR PANEL

The photovoltaic effect is a physical phenomenon in which a semiconductor material generates electric energy upon being exposed to light. Photovoltaic (PV) modules consist of a large number of solar cells and use light energy from the Sun to generate electricity through the photovoltaic effect. Most modules use wafer-based crystalline silicon cells or thin-film cells. The structural member of a module can be either the top layer or the back layer. Cells must be protected from mechanical damage and moisture. The cells and modules are usually connected electrically in series, one to another to increase the desired voltage output, and then in parallel to increase current output to create the solar panel. Most panels are rigid, but semi-flexible ones based on thin-film cells are also available. The power in watts of the solar panel is the voltage or volts multiplied by the current or amperes, and depends both on the amount of light and on the electrical load connected to the panel. The manufacturing specifications on solar panels are obtained under standard conditions, which are usually not the true operating conditions the solar panels are exposed to on the installation site. A PV junction box is attached to the back of the solar panel and functions as its output interface. External connections for most photovoltaic modules use MC4 connectors to facilitate easy weatherproof connections to the rest of the system. A USB power interface can also be used. Solar panels also use metal frames consisting of racking components, brackets, reflector shapes, and troughs to better support the panel structure. Solar cells need to be connected together by electrodes to form a module, with front electrodes blocking the solar cell front optical surface area slightly. To improve solar cell efficiency manufacturers, maximize frontal surface area available for sunlight and improve sunlight absorption using chronologically adopted, varying rear electrode solar cell connection techniques.

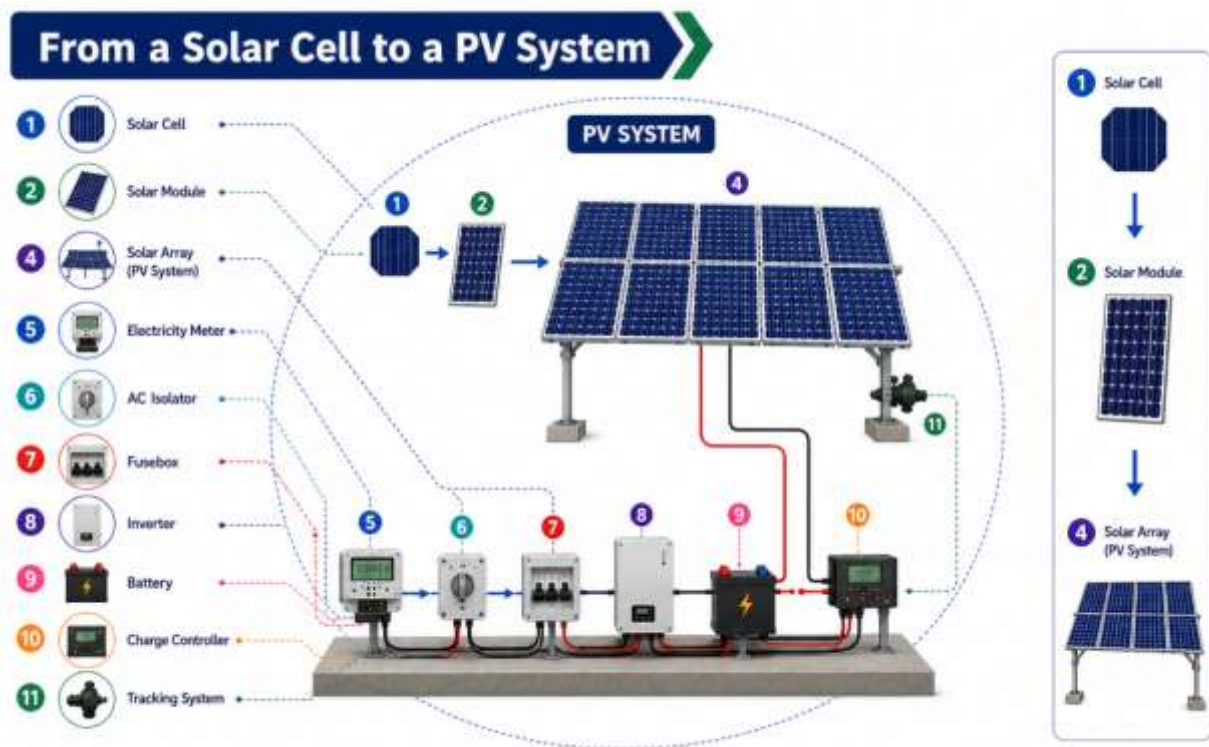


Figure 1: Solar cell, module and PV system

A single solar panel can produce only a limited amount of power; most installations contain multiple panels adding their voltages or currents. A photovoltaic system typically includes an array of photovoltaic modules, an inverter, a battery pack for energy storage, a charge controller, interconnection wiring, circuit breakers, fuses, disconnect switches, voltage meters, and optionally a solar tracking mechanism. Equipment is carefully selected to optimize energy output and storage, reduce power transmission losses, and many times convert from direct current to alternating current. However, smart solar panels have power electronics embedded in the panel and are different from traditional solar panels with power electronics attached to the frame or connected to the photovoltaic circuit through a connector. Solar power electronics can be used for maximum power point tracking power optimizers, solar performance monitors for data collection and fault detection for enhanced safety. Most solar modules are currently produced from crystalline silicon (c-Si) solar cells made of polycrystalline or monocrystalline silicon. In 2021, crystalline silicon accounted for 95% of worldwide PV production, while the rest of the overall market is made up of thin-film technologies using cadmium telluride (CdTe), copper indium gallium selenide and amorphous silicon (a-Si).

Bifacial cells produce energy on both sides which increases the total output of the module, this boost depends on the reflectivity of the surroundings and benefits from raised constructions since more light can reach the rear side. The gain is situational, the rear side benefits more from high-albedo surroundings such as snow, raised constructions and overcast weather but the gains might be minimal when the panels are installed directly on a surface with little clearance making it not cost-effective in those cases. The price of bifacial cells has dropped enough to be close to monofacial technologies, because of this as of 2024, bifacial panels are the leading choice for utility-scale PV installations. Emerging, third-generation solar technologies use advanced thin-film cells. They produce a relatively high-efficiency conversion for a lower cost compared with other solar technologies. Also, high-cost, high-efficiency, and close-packed rectangular multi-junction solar cells are usually used in solar panels on spacecraft, as they offer the highest ratio of generated power per kilogram lifted into space. However, multi-junction cells are compound semiconductors and made of gallium arsenide and other semiconductor materials. Another emerging PV technology using multi-junction cells is concentrator photovoltaics. Thin-film solar cells are made by depositing thin layers of photovoltaic material onto a glass, plastic or metal substrate. Those solar cells are typically much thinner than the wafers used in conventional crystalline silicon based solar cells.

Those cells are commercially made with one of several materials including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon (a-Si, TF-Si). The first-generation solar cells are made of single- or multi-crystalline silicon. This is the dominant technology currently used in most solar PV systems. Most types of thin-film solar cells are

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

classified as second generation, made using thin layers of materials like amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or gallium arsenide (GaAs). Solar cells made with newer, less established materials are classified as third-generation or emerging solar cells. This includes some innovative thin-film technologies, such as perovskite, dye-sensitized, quantum dot, organic, and CZTS thin-film solar cells. Thin-film cells have several advantages over first-generation silicon solar cells, including being lighter and more flexible due to their thin construction. This makes them suitable for use in building-integrated photovoltaics and as semi-transparent photovoltaic glazing material that can be laminated onto windows. Other commercial applications use rigid thin film solar panels in some of the world's largest photovoltaic power stations. The materials used in thin-film solar cells are typically produced using simple and scalable methods more cost-effective than first-generation cells, leading to lower environmental impacts like greenhouse gas (GHG) emissions in many cases. Thin-film cells also typically outperform renewable and non-renewable sources for electricity generation in terms of human toxicity and heavy-metal emissions. Despite initial challenges with efficient light conversion, especially among third-generation PV materials, as of 2023 some thin-film solar cells have reached efficiencies of up to 29.1% for single-junction thin-film GaAs cells, exceeding the maximum of 26.1% efficiency for standard single-junction first-generation solar cells. Multi-junction concentrator cells incorporating thin-film technologies have reached efficiencies of up to 47.6% as of 2023. Many thin-film technologies have been found to have shorter operational lifetimes and larger degradation rates than first-generation cells in accelerated life testing, which has contributed to their somewhat limited deployment. Globally, the PV market share of thin-film technologies remains around 5% as of 2023. However, thin-film technology has become considerably more popular in the United States, where CdTe cells alone accounted for 29% of new utility-scale deployment in 2021.

The global installed solar capacity in 2024 is estimated to be over 1,600 gigawatts or GW (or 1.6 terawatts), which is a substantial increase year-on-year. This is a huge increase if you compare this figure with Global PV installations for the year 2019 which reached about 121 GW. Global solar installations are expected to grow significantly in the next decade, with some projections calling for a nearly tripling of capacity. The Solar Energy Industries Association (SEIA) projects that total solar installations will increase by nearly 130% between 2022 and 2030. The International Energy Agency (IEA) forecasts that global renewable capacity will reach 7,300 GW by 2028, which is 2.5 times its current level. The global solar market has been growing due to several factors, including declining costs, supportive policies, technological improvements, and increased manufacturing capacity. In 2023, China led the world in solar capacity growth, installing well over half of the world's new solar capacity. In the first seven months of 2024, China added 28% more solar capacity than in the same period in 2023. In the first seven months of 2024, India installed 77% more solar capacity than in the same period in 2023. The United States is also experiencing growth in its solar market. In the first six months of 2024, the US installed 55% more solar capacity than in the same period in 2023. Europe's solar capacity has also grown significantly in the last decade, with the EU-27's solar PV capacity reaching 269 GW by the end of 2023 (and continuing to rise strongly through 2024). Other countries experiencing solar capacity growth include Brazil, Vietnam, and Poland.

3. EVOLUTION OF PHOTOVOLTAIC AND FLEXIBLE PV TECHNOLOGY

The history of photovoltaic technology dates back to the nineteenth century when Alexandre Edmond Becquerel discovered the photovoltaic effect in 1839. Though these initial solar cells were too inefficient for even simple electric devices, they were used as an instrument to measure light. The observation by Becquerel was not replicated again until 1873, when the English electrical engineer Willoughby Smith discovered that the charge could be caused by light hitting selenium. After this discovery, William Grylls Adams and Richard Evans Day published "The action of light on selenium" in 1876, describing the experiment they used to replicate Smith's results. In 1881, the American inventor Charles Fritts created the first commercial solar cell, which was reported by Fritts as "continuous, constant and of considerable force not only by exposure to sunlight but also to dim, diffused daylight". However, these solar cells were still very inefficient for practical power production, especially compared to coal-fired power plants. Actually, practical solar cells did not emerge until 1954, when researchers at Bell Laboratories developed the first modern silicon photovoltaic cell capable of converting sunlight into electricity with relatively high efficiency. For many decades, photovoltaic research focused primarily on improving crystalline silicon technology because silicon offered an excellent combination of abundance, stability, and electrical performance. Nevertheless, conventional silicon modules remained expensive and heavy, limiting widespread adoption.

The oil crises of the 1970s renewed international interest in alternative energy sources, encouraging governments and research institutions to invest in photovoltaic technologies. During this period, scientists began exploring thin-film semiconductors capable of reducing material consumption while lowering manufacturing costs. Since 2010, the cost of solar photovoltaic electricity has fallen 85%. Solar panel installers saw significant growth between 2008 and 2013. Due to that growth, many solar-roof installations were not "ideal" to work with - they had to find solutions to shaded roofs and orientation difficulties. This challenge was initially

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

addressed by the re-popularization of micro-inverters and later the invention of power optimizers. Solar panel manufacturers partnered with micro-inverter companies to create alternating current modules and power optimizer companies partnered with module manufacturers to create smart modules. In 2013 many solar panel manufacturers announced and began shipping their smart module solutions. Mono-crystalline panels are boasting high efficiency and are ideal for industries aiming for maximum energy capture with minimal spatial footprint. On the other hand, Semi-flexible panels are offering a robust alternative, able to withstand moderate physical stress, making them suitable for dynamic industrial environments. While they share the same photovoltaic principles as traditional panels, their uniqueness lies in their versatility. This allows flexible solar panel markets to cater to a diverse array of industrial needs with a touch of innovation.

Between 1992 and 2023, the worldwide usage of photovoltaic (PV) increased exponentially. During this period, it evolved from a niche market of small-scale applications to a mainstream electricity source. From 2016 to 2022, PV has seen an annual capacity and production growth rate of around 26%, doubling approximately every three years. The decreasing cost of solar panels is driving an increase in solar energy use in the Global South. Many countries in the Global South rely on expensive fossil fuel imports. Many homes and businesses are switching to solar energy to save money. About 99 percent of all European and 90 percent of all US solar power systems are connected to the electrical grid, while off-grid systems are somewhat more common in Australia and South Korea. PV systems rarely use battery storage. This may change, as government incentives for distributed energy storage are implemented and investments in storage solutions gradually become economically viable for small systems. A typical residential solar array is rack-mounted on the roof, rather than integrated into the roof or facade of the building, which is significantly more expensive. Utility-scale solar power stations are ground-mounted, with fixed tilted solar panels rather than using expensive tracking devices. Crystalline silicon is the predominant material used in 90% of worldwide produced solar modules, while its rival thin-film has lost market-share. About 70% of all solar cells and modules are produced in China and Taiwan, only 5% by European and US manufacturers. The installed capacity for both small rooftop systems and large solar power stations is growing rapidly and in equal parts, although there is a notable trend towards utility-scale systems, as the focus on new installations is shifting away from Europe to sunnier regions.

The newest solar panel technology has an expected lifespan of 25 to 35 years under standard performance warranties. TOPCon panels degrade at approximately 0.5% per year, meaning they retain about 87% to 90% of their original output at year 25. HJT panels degrade even more slowly at approximately 0.4% per year, guaranteeing 90% output at year 25 for top-tier models. Some HJT manufacturers are already offering 35-year performance warranties, reflecting their confidence in long-term durability. These degradation rates are a genuine improvement over the older PERC generation at 0.7% to 0.8% per year. AI will change solar panel systems for homes by enabling real-time monitoring that identifies underperforming panels, predicts maintenance needs before failures occur, and automatically adjusts system behavior to maximize production based on weather forecasts and usage patterns. According to SolarReviews, 52% of solar installers reported that monitoring, communication, and connectivity problems were among the most common post-installation issues they handled in 2024. AI-powered systems address this directly by providing homeowners with clear performance dashboards and by flagging issues automatically rather than requiring manual inspection. Smart inverters paired with AI monitoring are already available and will become standard features of new residential installations through 2030.

Flexible solar panels (thin-film or semi-flexible crystalline) and fixed (rigid crystalline PV modules) each have distinct trade-offs. Flexible amorphous silicon (a-Si) photovoltaic technology uses a non-crystalline silicon layer deposited onto lightweight, bendable substrates like plastic, metal, or flexible glass. One of the earliest flexible photovoltaic technologies involved amorphous silicon (a-Si), which could be deposited onto flexible substrates using plasma-enhanced chemical vapor deposition. Although amorphous silicon offered relatively low conversion efficiency compared with crystalline silicon, its flexibility demonstrated the feasibility of lightweight photovoltaic systems. It is a second-generation thin-film technology with a disordered atomic structure instead of a rigid crystal lattice. It has lower efficiency ratings (typically 6–14%) compared to conventional rigid crystalline silicon cells (20–25%). However, it maintains better performance during high-heat conditions and low-light or cloudy environments than traditional solar panels. One good thing is that, it contains no toxic heavy metals like cadmium or lead. Subsequent advances led to the commercialization of copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) thin-film technologies. These materials provided higher efficiencies while maintaining excellent flexibility, making them attractive for portable power systems, military applications, and specialized architectural installations.

In 21st century witnessed unprecedented advances in photovoltaic materials research. Nanotechnology enabled scientists to manipulate semiconductor structures at the molecular scale, leading to remarkable improvements in light absorption, charge transport, and energy conversion efficiency. Organic photovoltaic cells emerged as another promising technology due to their potential for low-cost printing using roll-to-roll manufacturing. Although OPVs generally exhibit lower efficiencies than silicon-

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

based technologies, they offer exceptional flexibility and lightweight characteristics suitable for consumer electronics and wearable devices. Perhaps the most significant breakthrough occurred with the discovery of hybrid organic-inorganic perovskite materials. Since their introduction into photovoltaic research in 2009, perovskite solar cells have experienced the fastest efficiency improvement in the history of photovoltaic technology. Researchers continue to investigate methods for enhancing their stability, moisture resistance, and commercial scalability. Parallel to these developments, improvements in wafer thinning technologies enabled manufacturers to produce ultra-thin crystalline silicon wafers capable of bending without fracture. This achievement challenged the long-held assumption that crystalline silicon must remain rigid and opened new opportunities for flexible silicon photovoltaics. Today, flexible solar technology represents one of the fastest-growing research fields in renewable energy science, supported by governments, universities, research laboratories, and private industry across the globe.

From early standard mono/poly panels to today's high-efficiency TOPCon, HJT, and IBC technologies, the solar industry has come a long way. In terms of technological advances, PV companies continue to make large strides, including the development of higher efficiency (22–24% commercial module efficiency, with some premium models exceeding this) PV cells and hybrid cells. These technologies are becoming increasingly accessible for the mass market. A new type of material for next-generation solar cells has been created which eliminates the need to use lead. This has been a major barrier to increasing the efficiency of this technology. Scientists have been working on incorporating the mineral perovskite in solar cells since the material was first shown to work in 2009. Solar cells that are created using this material are more efficient than current solar panels in laboratory conditions. Perovskite solar cells (PSCs) are a type of solar cell that uses a perovskite-structured material to harvest light. They are made from a hybrid organic-inorganic lead or tin halide-based material. Traditional solar panels capture 15% to 18% of the solar energy on average (modern mainstream panels are typically around 20–23% efficient), while perovskite solar cells have been found to be as much as 28% efficient in laboratory settings. Even higher efficiencies have been reached with some tandem cells up to an almost 34% efficiency rate (with laboratory tandem perovskite-silicon cells now exceeding 33–34% efficiency). A tandem solar cell is a solar panel made of multiple solar cells stacked on top of each other to convert more of the sun's energy into electricity. PSCs can be made with perovskite materials that are around 90% pure, as they are less sensitive to impurities, making them cheaper to produce. They are also lightweight and flexible and can be processed using coating techniques. PSCs also have the advantage of being able to generate power even indoors and in low-light conditions.



Figure 2: Evolution of solar PV modules: dimension and efficiency legacy

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

However, there are major obstacles to using these materials commercially because they are not stable and they contain water-soluble lead, which is a health hazard. PSCs are also not easy to mass produce and can deteriorate quickly although pilot-scale commercialization is now underway in some markets. "These structures are very exciting," Dou said. "The sandwich structures are like semiconductor quantum wells that are widely used today in many electronic and optoelectronic devices, but they are much easier to produce and more tolerant to defects," In a paper published in the Journal of the American Chemical Society the scientists had incorporated the material into an essential component of many electronic devices. Yao Gao, lead author of both research papers and a postdoctoral fellow in Dou's research group, said the new organic-inorganic hybrid perovskite materials are cheaper and perform better than a traditional inorganic semiconductor. Also, Gao said, the new material's design strategy could serve as a blueprint for many other functional hybrid materials. "Solar cells, as many people have demonstrated, can be highly efficient. With our new technology, we can make the hybrid perovskite materials intrinsically more stable. By replacing the toxic lead, these new materials are better for the environment and can also be safely used for bioelectronics sensors on the body." Some manufacturers are combining perovskite with silicon layers to create hybrid solar cells for better performance and stability. Researchers have also developed PSCs with a lifetime of about 30 years, which could open the way to commercialization although long-term real-world data is still being gathered. Evolution of solar PV modules in line of dimension and efficiency legacy has been shown in figure 2 below.

Some PV companies in the United States are developing near-transparent cells made from a glass-like plastic material, which greatly minimise the aesthetic impact of PV arrays, although at present these are not widely available in the UK. There are only a few companies in the UK that install transparent solar panels. However, transparent solar panels are gaining traction in the UK and are expected to become more common in the future. Transparent and paper-thin technology could allow electricity to be generated from windows and other discrete objects on the fly. Solar skins are a thin, flexible, transparent material that can be used to generate electricity from sunlight (primarily marketed as aesthetic overlays rather than standalone high-efficiency generation products). They are infused with tiny particles called "Quantum Dots" that become excited when exposed to photons, the main component of sunlight. Solar skins can preserve up to around 90–99% of a panel's original output depending on design and application. They are a relatively new invention that can be laid over solar panels, so they blend in with the roof of your home. So, for people who are concerned about the appearance of traditional panels, solar skins are a great incentive. They have also been designed to reduce the risk of fire by integrating fire protection products and systems.

Traditional solar farms can take up land, which is expensive and might be needed for other reasons like agriculture or house building. For this reason, engineers have developed floating solar power plants which can be placed offshore. Solar panels can be installed onto floating platforms in bodies of water such as lakes, reservoirs, and some sheltered coastal areas. These water-cooled floating photovoltaic (PV) systems or floatovoltaics can produce more energy than land-based ones due to the cooling effect of water reducing panel temperature. Floating solar farms have other benefits too. They limit air circulation and block sunlight from the surface of the water which reduces water loss through evaporation. They can also prevent certain types of algae from growing which can lower the cost of water treatment. On top of that the water below the floating solar farm helps to keep the solar panels clean and minimises energy waste. However, another factor influencing the popularity and take-up of solar energy technology is the rise of innovative power storage solutions. The more energy storage technology evolves the more solar power users can store excess energy generated during peak sunlight hours for use during periods of low sunlight or at night. Both lithium-ion and solid-state battery technologies are advancing, but there are still challenges to overcome before solid-state batteries can become the industry standard. Together with the advancements in battery technology, intelligent energy management systems will enable households and businesses to increase their solar energy usage and reduce their dependence on grid-supplied power.

4. CONSTRUCTION AND MANUFACTURE OF SOLAR PANELS

Today, solar panel technology is progressing rapidly with greater efficiency and lower prices, due to a huge increase in demand. However, despite the massive advancements in technology, basic solar panel construction hasn't changed much over the past years. Most solar panels are still made using a series of silicon crystalline cells sandwiched between a front glass plate and a rear polymer plastic back-sheet supported within an aluminium frame. Once installed; solar panels are subjected to severe conditions over the course of their 25+ year life. Extreme temperature, humidity, wind and UV radiation variations can put enormous stress on a solar panel. Luckily, most panels are well-engineered to withstand extreme weather. Though, some panels can fail in several ways, including water ingress, cell micro-fractures and potential induced degradation or PID. Today solar panels are manufactured using only the highest quality components. Solar panels use PV cells for short, made from silicon crystalline wafers similar to the wafers used to make computer processors. The silicon wafers can be either polycrystalline or monocrystalline and are produced using several different manufacturing methods. The most efficient type is monocrystalline, and which manufactured using the

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

well-known Czochralski process. In the past, Polycrystalline wafers were made using several purification processes, and which followed by a simpler casting method. It was much lower-cost. It was also less efficient, and which resulted in the phase-out of polycrystalline wafers in favour of the higher purity and higher performance monocrystalline wafers.

Manufacturing typical silicon-based solar cells requires a number of different processes, starting from a raw material called Quartzite, a form of quartz sandstone rock. First, Quartzite, or silica sand, is converted into metallurgical-grade silicon by combining Carbon and Quartzite in an arc furnace. This process occurs at very high temperatures, producing 99% pure silicon. The next step is to convert the metallurgical-grade silicon into pure Polysilicon using either a chemical purification process called the Siemens process or upgraded metallurgical-grade silicon (UMG-Si) using less costly metallurgical processes. Then, the polysilicon is doped with trace amounts of either boron or phosphorous to become either P-type or N-type silicon. At this stage, the polycrystalline silicon can be melted, cast into large rectangular blocks, and thinly sliced using a diamond wire cutting method to produce the polycrystalline or multicrystalline wafers. To manufacture the more efficient mono-crystalline wafer or cells, the doped silicon can be made into a pure solid crystal ingot using the Czochralski process. This process involves melting the polycrystalline silicon under high pressure and temperature to slowly grow a large monocrystalline crystal known as an ingot. Steps to manufacture mono-crystalline solar PV cells are as follows.

- Silica sand is purified in an arc furnace to create 99% pure silicon
- The 99% silicon is further refined close to 100% pure silicon
- The silicon is doped with boron or phosphorous (P-type or N-type)
- The doped silicon is melted and extracted into a crystalline ingot
- The round ingot is diamond wire-cut into thin square wafers
- The thin base wafer is coated with an ultra-thin layer of either P-type or N-type silicon to form the PN-junction.
- An anti-reflective layer and metallic fingers are added to the cell surface
- Flat ribbon busbars (as shown) or thin wire (MBB) busbars are added

Solar panels are made using the six major components described in detail below and assembled in advanced manufacturing facilities with extreme accuracy. This article will focus on panels made using crystalline silicon solar cells since these are by far the most common and best-performing solar technology available today. Other solar PV technologies are available, such as thin film and screen-printed cells, but we will not be discussing these as they have limited use or are still in development. Six Main components of a solar panel are as follows and shown in figure 3 below.

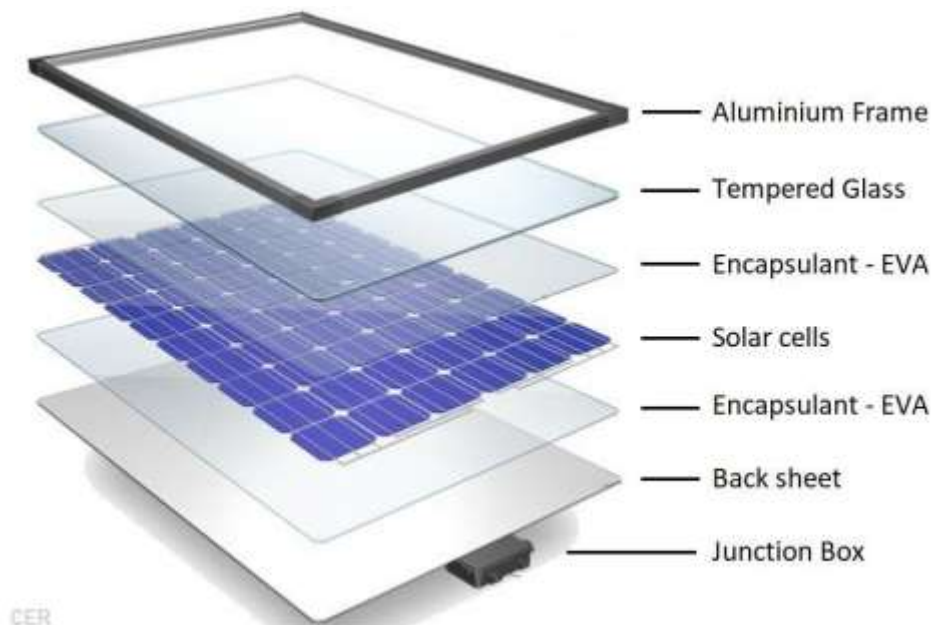


Figure 3: Major 6 components used in the construction of a solar panel

a. Solar PV cells. The base of the PV cell is a very thin wafer, typically 0.1mm thick, and is made from either positive p-type silicon or negative n-type silicon. There are many different cell sizes and configurations available that offer different levels of efficiency and performance, including half-cut or split cells, multi-busbar (MBB) cells, and, more recently, shingled cells using thin overlapping wafer strips. There are two main types being mono-crystalline and polycrystalline silicon. Most residential solar panels contain 60 full-size monocrystalline cells or 120 half-size cells linked together via busbars in series to generate a voltage between 30-40 volts, depending on the type of cell used. Larger solar panels used for commercial systems and utility-scale solar farms

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

contain 72 full-size or 144 half-size cells and, in turn, operate at a higher voltage. The electrical contacts that interconnect the cells are known as bus-bars and allow the current to flow through all the cells in a circuit.

b. Toughened Glass. The front glass sheet protects the PV cells from the weather and impact from hail or airborne debris. The glass is typically high strength tempered glass which is 3.0 to 4.0mm thick and is designed resist mechanical loads and extreme temperature changes. The IEC minimum standard impact test requires solar panels to withstand an impact of hail stones of 1 inch (25 mm) diameter traveling up to 60 mph (27 m/s). In the event of an accident or severe impact tempered glass is also much safer than standard glass as it shatters into tiny fragments rather than sharp jagged sections. The are typically 3.2mm thick. To improve efficiency and performance high trans-missive glass is used by most manufacturers which has a very low iron content and an anti-reflective coating on the rear side to reduce losses and improve light transmission.

c. Extruded Aluminium frame. The aluminium frame plays a significant role by both protecting the edge of the laminate section housing the cells and providing a solid structure to mount the solar panel in position. The extruded aluminium sections are designed to be extremely lightweight, stiff and able to withstand extreme stress and loading from high wind and external forces. The aluminium frame can be silver or anodised black and depending on the panel manufacturer the corner sections can either be screwed, pressed or clamped together providing different levels of strength and stiffness.

d. Encapsulation EVA film. EVA stands for 'ethylene vinyl acetate', which is a specially designed polymer highly transparent (plastic) layer used to encapsulate the cells and hold them in position during manufacture. The EVA material must be extremely durable and tolerant of extreme temperature and humidity. However, it plays an important part in the long-term performance by preventing moisture and dirt ingress. The lamination on either side of the PV cells provides some shock absorption and helps protect the cells and interconnecting wires from vibrations and sudden impact from hail stones and other objects. A high-quality EVA film with a high degree of 'cross-linking' can be the difference between a long life and a panel failure due to water ingress. During manufacture, the cells are first encapsulated with the EVA before being assembled within the glass and back sheet.

e. Polymer rear back-sheet. The backsheet is the rearmost layer of standard solar panels which acts as a moisture barrier and final external skin to provide both mechanical protection and electrical insulation. The backsheet material is made of various polymers or plastics including PP, PET and PVF which offer different levels of protection, thermal stability and long-term UV resistance. The backsheet layer is typically white in colour but is also available as clear or black, depending on the manufacturer and module. For a detailed analysis of the various backsheet materials used, refer to the backsheet construction article from Taiyang News. Some panels such as bifacial and frameless panels, use a rear glass panel instead of a polymer backsheet and those known as dual glass panels. The rear side glass is more durable and longer lasting than most backsheet materials and so some manufacturers offer a 30-year performance warranty on dual glass panels.

f. Junction box with diodes and connectors. The junction box is a small weatherproof enclosure located on the rear side of the panel. It is needed to securely attach the cables required to interconnect the panels. The junction box is important as it is the central point where the cell groups interconnect and must be protected from moisture and dirt. The junction box also houses the bypass diodes, which are needed to prevent reverse currents, which can occur when cells are shaded or dirty. Diodes only allow current to flow in one direction, and a typical 60-cell panel is divided into 3 groups of 20 PV cells, each with a bypass diode for preventing reverse current. However, bypass diodes can fail over time and may need to be replaced, especially if put under stress due to fixed rooftop objects causing permanent shading throughout the year. In most modern solar panels use more advanced, longer-lasting diodes and non-serviceable junction boxes.

On the other hand, almost all solar panels are connected using special weather-resistant plugs and sockets called MC4 connectors. The term MC4 stands for multi-contact 4mm diameter connector. Due to extreme weather conditions, the connectors must be very robust, secure, and UV resistant and maintain a good connection with minimal resistance at both low and high voltages up to 1000V. The connectors are designed to be used with the standard 4mm or 6mm double-insulated solar DC cable with a tinned copper multi-strand core for minimum resistance and increased durability. To correctly assemble the connectors, a special crimping tool is used to crimp the multi-strand cable to the inner terminal, which is then inserted and snapped into the MC4 housing. There are several different types of MC4 connectors that may look similar but do not always fit together securely. The same type and make of connector must always be used to reduce potential water ingress or plug failure which can result in arcing and even fire. Again, next-generation MC4-EVO-2 connectors are manufactured by few manufacturers and the only dissimilar looking connectors which are allowed to be used together.

Many well-known solar panel manufacturers are vertically integrated, meaning that one company supplies and manufactures all the main components, including the silicon ingots and wafers used to make the solar PV cells. However, many panel manufacturers assemble solar panels using externally sourced parts, including cells, polymer back sheet and encapsulation EVA material. These manufacturers can be more selective about which components they choose. Still, they do not always have control over the quality

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

of the products, so they should be sure they use the best suppliers available. Solar panels are assembled in advanced manufacturing facilities using automated robotic equipment and sensors to precisely position the components with extreme accuracy. The manufacturing plants must be extremely clean and controlled to prevent any contamination during assembly. Throughout the manufacturing process, the panels and cells are checked and inspected using advanced optical/imaging sensors to ensure all the components are located correctly and the cells wafers, which are very delicate, are not damaged or cracked during the assembly process. Depending on the manufacturer, the final panel assembly is thoroughly checked using a number of tests, including electroluminescent (EL) or flash testing, to identify any defects in the cells which could lead to failure once exposed to sunlight and high temperatures for many years.

Solar panels are generally very reliable as they have no moving parts and require minimal maintenance. However, they can fail or underperform over the expected 25-year life due to several different reasons. It is normal for the cells will slowly lose power due to what is known as light-induced degradation or LID, which results in an average of 0.5% loss per year. This slow degradation is often not noticeable, and most solar panels will still perform at 80% or higher of the original rated capacity after 20 years, depending on the type of cell used. The amount of degradation is specified in the manufacturer's performance warranty and an example has shown in figure 4 below. Unfortunately, solar panels can also suffer from more serious issues, such as micro-cracks and more severe degradation for several reasons. Any high stresses due to impacts, poor installation practices or people walking on rooftop panels can cause tiny fractures in the cell. These issues are often very difficult to detect and, if left for several years, can develop into hot spots and cause catastrophic failures such as arcing or fire. Fortunately, there are ways to reduce the likelihood of failure, and most manufacturers are improving both the panel design and manufacturing to minimize short and long-term issues.



Figure 4: Solar panel performance warranty chart showing degradation over 25 years of use

5. BASIC, TYPES, SELECTING, CARING AND IMPORTANT INFORMATION OF FLEXIBLE SOLAR PANELS

Flexible solar panels are photovoltaic devices designed with bendable and flexible substrates, which enabling them to adapt to curved surfaces and unusual shapes. Flexible panels utilize thin-film or crystalline solar cells mounted on lightweight, pliable materials such as ETFE film, rather than unlike traditional rigid solar panels made from glass and aluminum frames. This technology permits for a wide range of applications including integration into vehicles, portable solar chargers, building surfaces, wearable solar devices and many unusual uses. Flexible solar panels balance efficiency with adaptability, making them appropriate for environments where space, weight, or shape restrictions exist. The primary technologies behind flexible solar panels are thin-film solar cells and crystalline silicon cells. Where thin-film panels are typically lighter and more flexible due to their deposition on flexible substrates, while crystalline panels offer higher effectiveness but with a little reduced flexibility. These panels are often compared based on performance metrics, durability, and cost-effectiveness, providing users with choices tailored to specific energy needs and installation conditions. Their lightweight and bendable nature makes them ideal for portable chargers, camping gear, and vehicles.

There are two majortypes of flexible solar panels. Those are crystalline and thin-film. Crystalline flexible solar panels are made from ultra-thin slices of silicon. Those panels maintain high efficiency close to their rigid counterparts while offering some degree

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

of flexibility. Today, modern manufacturers have improved their bending radius, and allowing these panels to be mounted on little curved surfaces without forfeiting performance. These are ideal for applications requiring a balance of power output, flexibility, and panel adaptability. On the other hand, thin-film flexible solar panels are created by depositing photovoltaic materials onto flexible substrates like plastic or metal foil. Few examples include amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS) panels. Those panels usually offer greater flexibility and lighter weight. However, it may have lower efficiency rates compared to crystalline types. Their cost-effectiveness and ease of manufacturing make them a popular choice for applications, where flexibility and shape adaptability are more critical than maximum power output.

When selecting flexible solar panels, several critical factors must be evaluated to ensure optimal performance and longevity. Power output is paramount; buyers should assess the wattage and efficiency to meet their energy demands effectively. Durability is equally important, particularly resistance to environmental conditions such as UV exposure, moisture, and temperature fluctuations. Panels with ETFE coating, for example, offer enhanced weather resistance and self-cleaning properties. Solar cell technology impacts both performance and application suitability. Understanding the differences between crystalline and thin-film solar cells helps businesses choose the right panel based on efficiency, weight, flexibility, and budget. Installation preferences, including mounting options like adhesive bonding or rack systems, influence the ease of integration and maintenance. Lastly, the expected lifespan and warranty terms provided by manufacturers should be scrutinized to maximize return on investment and ensure long-term reliability. Today, adhesive mounting is popular for curved surfaces and portability, while rack mounting offers stability for fixed installations. The choice depends on the application requirements. Flexible solar panels are available through specialized manufacturers and suppliers around the world, and they offer a variety of thin solar panels tailored to different needs.

Mounting flexible solar panels can be achieved primarily through two methods: rack mounting and adhesive mounting. Rack mounting involves securing the panel to a frame or structure, providing a stable platform especially useful for larger installations or where panel removal may be necessary. This method offers robustness but can add weight and complexity to the setup. Adhesive mounting, favored for its simplicity and minimal hardware requirements, uses strong, weather-resistant adhesives to bond the panel directly to surfaces such as roofs, vehicles, or curved equipment. This technique preserves the panel's flexibility and reduces wind resistance. It is essential to select adhesives compatible with the panel's backing and mounting surface to prevent damage and ensure durability. Proper surface preparation and environmental considerations enhance the effectiveness of adhesive bonding. Maintaining the efficiency of flexible solar panels requires regular cleaning and care to prevent dirt, dust, and debris buildup. Gentle cleaning using soft cloths, mild detergents, and water is recommended to avoid damaging the delicate panel surface or ETFE coating. Avoid abrasive materials or harsh chemicals that could degrade the solar cells or protective layers. Regular inspections for physical damage, loose connections, and signs of wear also contribute to sustained performance. Since flexible solar panels are often deployed in challenging environments, protective measures such as UV-resistant coatings and weatherproof seals are beneficial. Following manufacturer guidelines for maintenance ensures longevity and optimal energy production.

Flexible solar panels provide several advantages that distinguish them from conventional solar solutions. Size and versatility are among the most notable benefits; their lightweight construction and ability to conform to curved and uneven surfaces enable installations in previously inaccessible locations. This versatility is valuable for mobile solar applications such as RVs, boats, wearable devices, and emergency power supplies. Additionally, flexible panels are often less expensive to transport and install, reducing overall project costs. Installation ease is another significant benefit. Flexible solar panels can be mounted using adhesives or lightweight racks, eliminating the need for heavy metal frames and extensive mounting hardware. This ease of installation shortens deployment times and reduces labor costs. Portability is enhanced by the panels' low weight and resilience to impact, making them ideal for off-grid and remote power solutions. Their flexibility also contributes to higher durability under mechanical stress compared to rigid panels, extending their lifespan in dynamic environments. However, flexible solar panels generally have slightly lower efficiency rates than rigid crystalline panels, but advancements in technology have narrowed this gap significantly. Depending on the technology used, efficiencies can range from 10% to over 20%. Again, many flexible solar panels are designed with protective coatings such as ETFE that enhance durability against UV radiation, moisture, and temperature extremes. It is important to verify the panel's specifications for environmental resistance. Japan is advancing flexible solar cell technology that could allow clean energy panels to be placed on surfaces where heavy traditional solar panels are not practical. These lightweight solar sheets are often linked to perovskite materials, which are attracting attention because they can be thinner, lighter, and potentially cheaper to manufacture than conventional silicon panels and shown in figure 5 below.



Figure 5: Ultra-thin flexible solar cells/panel

6. WORKING PRINCIPLES AND MATERIALS SCIENCE OF FLEXIBLE SOLAR PANELS

The operation of flexible solar panels is fundamentally based on the photovoltaic effect, a physical phenomenon in which semiconductor materials convert sunlight directly into electrical energy. When photons from sunlight strike the surface of a photovoltaic material, they transfer energy to electrons within the semiconductor lattice. If the absorbed energy exceeds the material's band gap, electrons are excited from the valence band into the conduction band, creating mobile electron-hole pairs. The internal electric field established at the p-n junction separates these charge carriers, directing electrons toward the negative electrode and holes toward the positive electrode. This separation generates an electric current that can be collected through external electrical circuits. Although the photovoltaic effect is identical in rigid and flexible solar cells, the primary distinction lies in the structural design of the module. Conventional solar panels utilize thick crystalline silicon wafers protected by tempered glass, whereas flexible photovoltaic modules employ thin semiconductor layers deposited onto lightweight substrates. These substrates may consist of polyimide films, polyethylene terephthalate (PET), polyethylene naphthalate (PEN), stainless steel foils, or ultra-thin silicon wafers. The flexibility of these substrates allows the photovoltaic module to bend without significantly affecting electron transport pathways. Advanced encapsulation materials further protect the semiconductor layers from oxygen, moisture, ultraviolet radiation, and mechanical stress, thereby extending operational lifetime. Recent innovations in nanostructured materials, interface engineering, and tandem cell architectures have substantially increased the efficiency of flexible photovoltaics while maintaining mechanical durability. Researchers continue to optimize charge transport layers, transparent conductive electrodes, and encapsulation strategies to improve both electrical performance and long-term reliability.

The remarkable flexibility of modern photovoltaic modules is primarily the result of advances in materials science rather than changes to the fundamental principles of electricity generation. Unlike conventional photovoltaic panels, which rely on thick crystalline silicon wafers protected by tempered glass and supported by aluminum frames, flexible solar panels employ lightweight materials capable of maintaining electrical performance while withstanding repeated mechanical deformation. The selection of these materials influences not only the flexibility of the module but also its efficiency, durability, manufacturing cost, environmental impact, and commercial viability. Today flexible panels are primarily made using thin-film photovoltaics, which involve depositing one or more layers of photovoltaic material onto a substrate. The materials commonly used include amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS). This technology allows the panels to be lightweight, thin, and, most importantly, flexible. Researchers have developed multiple classes of photovoltaic materials for flexible applications,

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

each offering unique advantages and presenting specific technical challenges. These materials continue to evolve as scientists seek to improve energy conversion efficiency while reducing manufacturing complexity and extending operational lifetimes.

a. Crystalline Silicon. Crystalline silicon remains the dominant material in the global photovoltaic industry, accounting for more than 90% of installed solar capacity worldwide by International Energy Agency (IEA) in 2024. Traditionally, silicon cells have been considered incompatible with flexible applications because silicon is inherently brittle and fractures when subjected to excessive bending. Advances in wafer manufacturing, however, have significantly altered this perception. Modern fabrication techniques enable manufacturers to produce ultra-thin crystalline silicon wafers with thicknesses below 100 micrometers. At these dimensions, silicon becomes considerably more flexible without substantial reductions in electrical efficiency. Researchers have further enhanced flexibility by introducing microscopic structural modifications that distribute mechanical stress more evenly throughout the material. These innovations allow silicon-based modules to bend to moderate radii while maintaining excellent electrical performance. Consequently, flexible crystalline silicon modules combine the high efficiencies associated with conventional photovoltaic technology with many of the practical advantages of lightweight flexible systems. Because crystalline silicon manufacturing infrastructure already exists on a massive global scale, flexible silicon modules possess significant commercial potential. Manufacturers can adapt existing production lines rather than constructing entirely new facilities, thereby reducing development costs and accelerating commercialization.

b. Thin-Film Silicon. Thin-film silicon represented one of the earliest successful approaches to flexible photovoltaics. Rather than slicing thick wafers from silicon ingots, manufacturers deposit extremely thin layers of amorphous or microcrystalline silicon directly onto flexible substrates. This manufacturing process dramatically reduces material consumption while allowing continuous roll-to-roll production. Thin-film silicon modules generally exhibit lower efficiencies than crystalline silicon, but they offer several compensating advantages, including reduced weight, improved flexibility, lower manufacturing temperatures, and decreased transportation costs. Amorphous silicon also performs relatively well under diffuse sunlight and elevated temperatures, making it suitable for applications where environmental conditions fluctuate significantly. Although newer photovoltaic technologies have surpassed amorphous silicon in efficiency, it continues to play an important role in niche markets requiring lightweight and flexible energy generation.

c. Copper Indium Gallium Selenide (CIGS). Copper indium gallium selenide (CIGS) has become one of the most successful thin-film photovoltaic materials for flexible applications. CIGS combines excellent light absorption with relatively high conversion efficiencies, allowing manufacturers to produce lightweight modules that perform competitively with conventional silicon technologies. One of the most important characteristics of CIGS is its exceptionally high optical absorption coefficient. Unlike crystalline silicon, which requires relatively thick semiconductor layers to absorb sunlight effectively, CIGS can capture most incoming solar radiation within layers only a few micrometers thick. This property substantially reduces material usage while facilitating flexible module construction. Flexible CIGS panels have been deployed in numerous specialized applications, including military equipment, portable charging systems, transportation infrastructure, and aerospace technology. Their combination of moderate efficiency, mechanical flexibility, and environmental resilience has made them attractive wherever lightweight renewable energy systems are required. Nevertheless, CIGS manufacturing involves relatively scarce elements such as indium and gallium, potentially constraining large-scale production if global demand increases substantially.

d. Cadmium Telluride (CdTe). Cadmium telluride represents another commercially successful thin-film photovoltaic technology. CdTe modules require minimal semiconductor material because cadmium telluride absorbs sunlight extremely efficiently. The principal advantages of CdTe include relatively low manufacturing costs, excellent performance under high temperatures, and well-established industrial production methods. Flexible CdTe modules have been investigated for numerous lightweight applications, although commercial deployment remains more limited than silicon or CIGS technologies. Environmental concerns surrounding cadmium toxicity require careful manufacturing controls and comprehensive recycling programs. Modern encapsulation techniques effectively prevent cadmium release during normal operation, but responsible end-of-life management remains essential to minimize environmental risks.

e. Organic Photovoltaic Cells (OPVs). Organic photovoltaic cells utilize carbon-based semiconducting molecules instead of inorganic materials such as silicon or metal compounds. Their unique chemical properties permit fabrication using printing technologies similar to newspaper production. One of the greatest advantages of organic photovoltaics is manufacturing simplicity. Large photovoltaic sheets can potentially be printed continuously using roll-to-roll techniques, substantially lowering production costs while enabling enormous manufacturing throughput. Organic solar cells also exhibit exceptional flexibility because their active layers are extremely thin and mechanically compliant. Some prototypes can even withstand repeated folding without catastrophic failure. Despite these advantages, organic photovoltaics currently face important limitations. Their conversion efficiencies remain lower than those of silicon and perovskite technologies, while long-term stability under sunlight, moisture, and

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

oxygen exposure continues to present significant engineering challenges. Consequently, OPVs are generally considered more suitable for portable electronics, indoor energy harvesting, and disposable applications than for long-term utility-scale electricity generation.

f. Perovskite Solar Cells. Among all emerging photovoltaic technologies, perovskite solar cells have generated perhaps the greatest scientific excitement. The term "perovskite" refers to a specific crystal structure rather than a single chemical compound. These materials possess exceptional optoelectronic properties that enable highly efficient conversion of sunlight into electricity. Perovskite photovoltaic have experienced unprecedented progress since their introduction into solar research in 2009. Laboratory efficiencies have increased from less than 4% to more than 26% within approximately fifteen years, representing the fastest improvement ever recorded in photovoltaic technology by National Renewable Energy Laboratory (NREL) in 2024. Several characteristics make perovskites particularly attractive for flexible solar panels are high optical absorption, long charge-carrier diffusion lengths, Low-temperature manufacturing, Compatibility with flexible substrates, potentially low production costs, Excellent tunability through chemical engineering. Because perovskite layers can be deposited using printing, coating, or solution-processing techniques, they are especially well suited to roll-to-roll manufacturing. Scientists envision future production facilities capable of manufacturing photovoltaic films continuously in a manner analogous to newspaper printing. Despite extraordinary progress, commercialization remains limited by stability concerns. Moisture, oxygen, ultraviolet radiation, and elevated temperatures gradually degrade many perovskite materials. Extensive research is therefore focused on improving encapsulation methods, developing more stable crystal compositions, and increasing operational lifetimes.

g. Tandem Solar Cells. Rather than replacing silicon entirely, many researchers now believe that the future of photovoltaic lies in tandem solar cells, which combine multiple semiconductor materials within a single device. In tandem architectures, each material absorbs different portions of the solar spectrum. High-energy photons are captured by wide-bandgap materials such as perovskites, while lower-energy photons continue into silicon layers beneath. This arrangement enables much more complete utilization of incoming sunlight. Theoretical analyses suggest that tandem cells could achieve efficiencies exceeding 40%, substantially surpassing the practical limits of conventional single-junction silicon photovoltaics. Flexible tandem modules combining ultra-thin silicon with perovskite materials represent one of the most active research areas in modern photovoltaic science.

7. MANUFACTURING TECHNOLOGIES AND QUALITY CONTROL

The production of PV systems has followed a classic learning curve effect, with significant cost reduction occurring alongside large rises in efficiency and production output. With over 100% year-on-year growth in PV system installation, PV module makers dramatically increased their shipments of solar modules in 2019. They actively expanded their capacity and turned themselves into Gigawatt GW players. According to Pulse Solar, five of the top ten PV module companies in 2019 have experienced a rise in solar panel production by at least 25% compared to 2019. The basis of producing most solar panels is mostly on the use of silicon cells. These silicon cells are typically 10–20% efficient at converting sunlight into electricity, with newer production models exceeding 22%. In 2018, the world's top five solar module producers in terms of shipped capacity during the calendar year of 2018 were Jinko Solar, JA Solar, Trina Solar, Longi solar, and Canadian Solar. However, the manufacture of PV panels depends on the use of toxic and reactive chemicals. These include cadmium telluride, copper indium selenide, cadmium gallium (di) selenide, copper indium gallium (di)selenide, hexa-fluoroethane, lead, and polyvinyl fluoride. Byproducts include silicon tetrachloride. Silicon dust ("kerf") is produced when the silicon wafers are sawn. The commercial success of flexible solar panels depends not only on material performance but also on efficient manufacturing processes capable of producing high-quality photovoltaic modules at competitive costs. Modern manufacturing emphasizes continuous production, automation, material conservation, and scalability.

a. Roll-to-Roll Manufacturing. Roll-to-roll manufacturing represents one of the defining innovations of flexible photovoltaics. Instead of assembling individual rigid panels, manufacturers process continuous rolls of flexible substrate through sequential coating, deposition, patterning, encapsulation, and quality-control stations. This approach resembles high-speed newspaper printing or plastic film manufacturing. Continuous production offers several advantages like, Reduced manufacturing costs, Higher production speeds, Lower labor requirements, Improved material utilization, Easier automation, Greater scalability, etc. Roll-to-roll manufacturing is particularly compatible with organic photovoltaics and perovskite solar cells because these technologies employ solution-processable materials that can be deposited uniformly over large areas.

b. Vacuum Deposition. Certain photovoltaic materials require highly controlled vacuum environments during fabrication. Processes such as sputtering, evaporation, and chemical vapor deposition enable manufacturers to deposit extremely thin semiconductor layers with atomic-scale precision. Vacuum deposition provides exceptional film quality and uniformity,

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

contributing to improved electrical performance and reliability. However, the equipment required is relatively expensive, increasing manufacturing costs compared with solution-based production methods.

c. Printing Technologies. Printing technologies have become increasingly important in flexible photovoltaic manufacturing. Here numerous methods are employed like, Inkjet printing, Screen printing, Slot-die coating, Gravure printing, and Spray coating. These techniques allow semiconductor "inks" to be deposited directly onto flexible substrates with high precision. Printing-based manufacturing reduces material waste because photovoltaic compounds are placed only where required. Furthermore, production temperatures remain relatively low, allowing the use of inexpensive polymer substrates that would deform under conventional semiconductor processing conditions.

d. Encapsulation. One of the greatest challenges facing flexible photovoltaics is protecting delicate semiconductor materials from environmental degradation. Encapsulation involves sealing the photovoltaic layers within specialized protective films that prevent moisture, oxygen, dust, and ultraviolet radiation from reaching sensitive components. Modern encapsulation systems typically consist of multiple polymer layers, adhesive barriers, ultraviolet filters, and transparent protective coatings. The effectiveness of encapsulation largely determines the operational lifetime of flexible solar modules. Poor encapsulation can lead to rapid performance degradation even when the photovoltaic material itself remains structurally intact.

e. Quality Control. Because flexible photovoltaic modules often contain extremely thin active layers, quality control requires sophisticated inspection technologies. Manufacturers routinely employ: Electroluminescence imaging, Infrared thermography, Laser scanning, Optical microscopy, Automated electrical testing, Mechanical bending tests, etc. These techniques identify microscopic defects that could reduce module efficiency or shorten operational lifetime. Mechanical durability testing is especially important for flexible photovoltaics. Modules undergo thousands of repeated bending cycles to evaluate resistance to cracking, delamination, and electrical degradation under realistic operating conditions. Solar module quality assurance involves testing and evaluating solar cells and Solar Panels to ensure the quality requirements of them are met. Solar modules (or panels) are expected to have a long service life between 20 and 40 years. They should continually and reliably convey and deliver the power anticipated. Solar modules can be tested through a combination of physical tests, laboratory studies, and numerical analyses. Furthermore, solar modules need to be assessed throughout the different stages of their life cycle. Various companies such as Southern Research Energy & Environment, SGS Consumer Testing Services, TÜV Rheinland, Sinovoltaics, Clean Energy Associates (CEA), CSA Solar International and Enertis provide services in solar module quality assurance. However, the implementation of consistent traceable and stable manufacturing processes becomes mandatory to safeguard and ensure the quality of the PV Modules. Certification is carried out according to standards ANSI/UL1703, IEC 17025, IEC 61215, IEC 61701, and IEC 61730-1/-2.

8. EFFICIENCY, PERFORMANCE, AND MAINTENANCE OF SOLAR PANELS

Solar-cell efficiency is the portion of energy in sunlight that is transformed into electricity by a solar cell. So, efficiency is the combination with latitude and weather, determine the energy output of a solar system. As of 2024, the record for solar cell efficiency was 47.6%, set in May 2022 by Fraunhofer ISE, with a III-V four-junction concentrating photovoltaic (CPV) cell. The record in real-world conditions is held by NREL, which developed triple junction cells with a tested efficiency of 39.5%. Commercial solar modules may exceed 24% efficiency. As of 2025, the best reached 24.5%, typically lower than their cells in isolation. The most efficient mass-produced solar modules have power density values of 175 W/m^2 (16.22 W/ft^2). In 2026 using triple III-V germanium cells and shingled matrix technology to interconnect cells, Fraunhofer achieved efficiency of 34.4%. An important innovation was the use of direct cell-to-cell contact, eliminating traditional solder-coated copper ribbons and the resulting shading of active cell areas. Several factors affect conversion efficiency, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values. Depending on construction, photovoltaic modules can produce electricity from a range of frequencies of light, but usually cannot cover the entire solar radiation range (specifically, ultraviolet, visible, infrared and low or diffused light). Hence, much of the incident sunlight energy is not processed by solar modules. Theoretically, sunlight could be split into wavelength bands (each a different color), each directed onto cells tuned to those ranges that would convert that band more efficiently.

The performance of flexible solar panels is evaluated using many of the same metrics applied to conventional photovoltaic modules. However, additional criteria relating to flexibility and mechanical durability are also considered. The most important performance indicators include **Power conversion efficiency, Specific power (W/kg), Power density (W/m²)**, indicating energy **Mechanical flexibility, Operational lifetime, Temperature coefficient, Resistance to ultraviolet radiation, moisture, and mechanical fatigue**. Modern flexible crystalline silicon modules can achieve efficiencies exceeding 20%, while laboratory-scale perovskite and tandem cells have surpassed 25%. Meanwhile, flexible CIGS modules generally achieve efficiencies between 15% and 20%, and commercial organic photovoltaic modules typically range from 10% to 18%, depending on operating conditions and

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

device architecture. Although efficiency remains an important metric, flexibility introduces additional performance advantages that cannot be measured solely through electrical output. Lightweight modules reduce structural loading, simplify transportation, expand installation options, and lower labor requirements, all of which contribute to the overall value proposition of flexible photovoltaic systems.

Module performance is generally rated under standard test conditions: irradiance of $1,000 \text{ W/m}^2$, solar spectrum of AM 1.5 and module temperature at 25°C . The actual voltage and current output of the module changes as lighting, temperature and load conditions change, so there is never one specific voltage at which the module operates. Performance varies depending on geographic location, time of day, the day of the year, amount of solar irradiance, direction and tilt of modules, cloud cover, shading, soiling, state of charge, and temperature. Performance of a module or panel can be measured at different time intervals with a direct current clamp meter or shunt and logged, graphed, or charted with a chart recorder or data logger. For optimum performance, a solar panel string needs to be made of similar electrical voltage solar panels oriented in the same direction perpendicular to direct sunlight. Bypass diodes are used to optimize output by allowing continuous current flow by circumventing broken or shaded panels. Electrical characteristics include nominal power measured in W, open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum power voltage (V_{MPP}), maximum power current (I_{MPP}), peak power (W_p), and module efficiency (%). Open-circuit voltage or V_{oc} is the maximum voltage the module can produce when not connected to an electrical circuit or system. V_{oc} can be measured with a voltmeter directly on an illuminated module's terminals or on its disconnected cable. The peak power rating, W_p , is the maximum output under standard test conditions (not the maximum possible output). Typical modules, which could measure approximately 1 by 2 metres (3 ft $\times$ 7 ft), will be rated from as low as 75 W to as high as 600 W, depending on their efficiency. At the time of testing, the test modules are binned according to their test results, and a typical manufacturer might rate their modules in 5 W increments, and either rate them at $\pm 3\%$, $\pm 5\%$, $+3/-0\%$ or $+5/-0\%$.

The ability of solar modules to withstand damage by rain, hail, heavy snow load, and cycles of heat and cold varies by manufacturer, although most solar panels on the U.S. market are UL listed, meaning they have gone through testing to withstand hail. The term "potential-induced degradation" (PID) was first introduced in the English language in a published study by S. Pingel and coworkers in 2010. It was introduced as a degradation mode resulting from voltage potential between the cells in the photovoltaic module and ground. PID is a potential-induced performance degradation in crystalline photovoltaic modules, caused by so-called stray currents. This effect may cause power loss of up to 30%. The power output of a photovoltaic (PV) device decreases over time due to exposure to solar radiation as well as other external conditions. The degradation index, defined as the annual percentage of output power loss, is a key factor in determining the long-term production of a photovoltaic plant. To estimate this degradation, the percentage of decrease associated with each of the electrical parameters is calculated. Individual degradation of a solar panel can negatively influence the performance of a complete string. Furthermore, not all solar panels in the same installation decrease their performance at exactly the same rate. There are several studies dealing with the power degradation analysis of solar panels based on different photovoltaic technologies available in the literature. According to a recent study, the degradation of crystalline silicon solar panels is linear, between 0.8% and 1.0% per year. On the other hand, if we analyze the performance of thin-film photovoltaic modules, an initial period of strong degradation is observed (which can last several months and even up to 2 years), followed by a later stage in which the degradation stabilizes, being then comparable to that of crystalline silicon. Solar panels of amorphous silicon, micro-morphic silicon or cadmium telluride, can have annual degradation rates for the first years of between 3% and 4%.

Solar panel conversion efficiency, typically in the 20% range, is reduced by the accumulation of dust, grime, pollen, and other particulates on the solar panels, collectively referred to as soiling. "A dirty solar panel can reduce its power capabilities by up to 30% in high dust/pollen or desert areas", says Seamus Curran, associate professor of physics at the University of Houston and director of the Institute for NanoEnergy, which specializes in the design, engineering, and assembly of nanostructures. The average soiling loss in the world in 2018 is estimated to be at least 3% – 4%. Paying to have solar panels cleaned is a good investment in many regions, as of 2019. However, in some regions, cleaning is not cost-effective. In California as of 2013 soiling-induced financial losses were rarely enough to warrant the cost of washing the panels. On average, panels in California lost a little less than 0.05% of their overall efficiency per day. There are also occupational hazards with solar panel installation and maintenance. A 2015–2018 study in the UK investigated 80 PV-related incidents of fire, with over 20 "serious fires" directly caused by PV installation, including 37 domestic buildings and 6 solar farms. In $\frac{1}{3}$ of the incidents a root cause was not established and in a majority of others was caused by poor installation, faulty product or design issues. The most frequent single element causing fires was the direct current isolators. A 2021 module reliability study found an increasing trend in solar module failure rates with 30% of manufacturers experiencing safety failures related to junction boxes (growth from 20%) and 26% bill-of-materials failures (growth from 20%).

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

Cleaning methods for solar panels can be divided into 5 groups: manual tools, mechanized tools (such as tractor mounted brushes), installed hydraulic systems (such as sprinklers), installed robotic systems, and deployable robots. Manual cleaning tools are by far the most prevalent method of cleaning, most likely because of the low purchase cost. However, in a Saudi Arabian study done in 2014, it was found that "installed robotic systems, mechanized systems, and installed hydraulic systems are likely the three most promising technologies for use in cleaning solar panels". Novel self-cleaning mechanisms for solar panels are being developed. For instance, in 2019 via wet-chemically etched nanowires and a hydrophobic coating on the surface water droplets could remove 98% of dust particles, which may be especially relevant for applications in the desert. In March 2022, MIT researchers announced the development of a waterless cleaning system for solar panels and mirrors to address the issue of dust accumulation, which can reduce solar output by up to 30% in one month. This system utilizes electrostatic repulsion to detach dust particles from the panel's surface, eliminating the need for water or brushes. We can improve the performance of the solar panel by eliminating the dependency on trucked-in water, by eliminating the buildup of dust that can contain corrosive compounds, and by lowering the overall operational costs.

9. ADVANTAGES OF FLEXIBLE SOLAR PANELS

Flexible solar panels offer several advantages over conventional rigid photovoltaic modules, making them suitable for applications where traditional systems are impractical. Their most significant benefit is their lightweight construction. By replacing tempered glass and aluminum frames with polymer substrates and thin semiconductor layers, flexible modules can weigh up to 70–90% less than conventional panels. This reduced weight lowers transportation costs, simplifies installation, and decreases structural loading on buildings. They lower upfront costs via simplified installation and transport; they reduce material usage and emissions; and their durability ensures long-term energy and financial savings. Few core advantages/benefits have been described below.

a. Cost Reduction. One of the most significant economic advantages of flexible solar panels is their potential for cost reduction. Due to their lightweight nature, flexible panels require less structural support and can often be installed without the need for extensive modifications or reinforcement. This translates into lower installation costs compared to traditional rigid panels. Additionally, the ease of transport and handling reduces labor costs and logistics expenses, making them panels a financially attractive option for large-scale industrial projects.

b. Versatility in Installation. Another major advantage is mechanical flexibility. Flexible modules can conform to curved roofs, building façades, vehicle surfaces, boats, recreational vehicles, tents, and portable shelters without requiring extensive support structures. This versatility allows solar energy generation in locations where rigid panels cannot be installed.

c. Lightweight Nature. Their lightweight nature reduces the structural load on buildings, which is particularly advantageous for older structures or those with specific weight limitations.

d. Durability. These panels are generally more resistant to impacts and can withstand harsh environmental conditions better than their rigid counterparts.

e. Environmental Impact. These panels have a smaller environmental footprint than traditional panels. The manufacturing process for flexible panels typically requires fewer raw materials and generates less waste. By reducing dependence on fossil fuels, these panels contribute to a decrease in greenhouse gas emissions and other pollutants. Their use in various industries supports the transition towards cleaner, renewable energy sources, helping to mitigate climate change and promote environmental sustainability.

f. Longevity and Durability. Despite their lightweight and flexible design, these solar panels are built to be durable and long-lasting. They are capable of withstanding harsh environmental conditions, including extreme temperatures, heavy winds, and physical impacts. This durability ensures a longer lifespan, reducing the need for frequent replacements and contributing to long-term cost savings. The ability to maintain performance under challenging conditions makes them panels a reliable energy solution for industrial applications.

g. Improve architectural aesthetics. Flexible photovoltaics also improve architectural aesthetics. Building-integrated photovoltaic (BIPV) systems can blend into roofs, walls, skylights, and curtain walls, allowing buildings to generate electricity without altering their appearance significantly. Such integration supports the development of net-zero energy buildings and sustainable urban infrastructure.

h. Easy to Installation. Flexible panel installation is also considerably easier. Many flexible modules can be attached using adhesives, specialized mounting tapes, or lightweight fastening systems, reducing labor costs and installation time. Because they require fewer structural components, flexible panels are particularly valuable for retrofitting older buildings that cannot support the weight of conventional solar systems.

10. CHALLENGES OF SOLAR PANELS INCLUDING FLEXIBLE PANELS

Despite their numerous advantages, flexible solar panels continue to face several technical and economic challenges. today, many flexible technologies still exhibit lower commercial efficiencies than premium crystalline silicon modules. Although laboratory-scale perovskite and tandem cells have achieved impressive efficiencies, large-scale commercial products often perform below their rigid counterparts. Durability remains another concern. Repeated bending, thermal expansion, ultraviolet radiation, moisture, and oxygen exposure can gradually degrade flexible photovoltaic materials. Effective encapsulation is therefore essential to maintain long-term performance. While many manufacturers project operational lifetimes of 20–25 years, some emerging technologies—particularly perovskites and organic photovoltaics—still require further improvements in long-term stability. Manufacturing costs also remain relatively high for certain flexible technologies because specialized materials, advanced deposition equipment, and sophisticated encapsulation processes increase production expenses. However, continued technological progress and economies of scale are expected to reduce costs over time. Environmental considerations must also be addressed. Some thin-film technologies use scarce or potentially hazardous elements, including indium, gallium, cadmium, and tellurium. Sustainable recycling systems and responsible resource management will therefore be essential as flexible photovoltaic deployment expands globally. Flexible solar panels may have slightly lower efficiency rates compared to traditional silicon-based rigid panels, advancements in thin-film technology are continually closing this gap. The trade-off between efficiency and flexibility often makes these panels a more suitable choice for certain industrial applications.

Solar panels provide clean energy, but standard systems and flexible panels face major performance and durability challenges. Flexible panels are often glued directly onto surfaces without an air gap, making them run up to 40°C hotter than rigid panels and reducing voltage efficiency. Thermal expansion and physical bending create internal stress, causing tiny cracks that can cut power output by 20% to 30% in just two years. Plastic laminates break down under ultraviolet (UV) light, leading to yellowing, peeling, and water damage. Most flexible panels harvest less energy per square foot compared to standard rigid mono-crystalline options. However, dust, debris, and shadows from trees or buildings lower total energy output. Batteries are expensive and store limited energy, typically enough for only one to two days. Bulky frames and glass sheets can look out of place on some roofs. With the increasing levels of rooftop photovoltaic systems, the energy flow becomes 2-way. When there is more local generation than consumption, electricity is exported to the grid. However, an electricity network traditionally is not designed to deal with the 2-way energy transfer. Therefore, some technical issues may occur. An over-voltage issue may result as the electricity flows from PV households back to the network. There are solutions to manage the over voltage issue, such as regulating PV inverter power factor, new voltage and energy control equipment at the electricity distributor level, re-conducting the electricity wires, demand side management, etc. There are often limitations and costs related to these solutions. For rooftop solar to be able to provide enough backup power during a power cut a battery is often also required.

For many households, the upfront cost can feel like a barrier – especially when weighed against other home improvement projects. But the real challenge isn't just the price itself; it's understanding whether the investment makes financial sense for your household. So, by calculating the system's total cost, expected savings, and payback period, we can better evaluate whether solar panels are a strong long-term choice for your home and budget. For many homeowners, aesthetics plays a big role in the decision to add solar panels. Conventional panels can sometimes appear bulky or stand out against traditional roof materials such as clay tiles or slate. We need to remember, not every roof is ideal for solar panels. The orientation, slope, and shading can all affect energy production. For cold reason like Europe or America, Summer months bring high solar production and low household heating needs. Winter months, however, bring limited sunlight, precisely when energy demand is highest. This seasonal imbalance means that traditional solar systems produce most of their energy when you need it least, and least when you need it most. Without a storage solution, we remain dependent on the grid for a large part of the year. The desire to become energy-independent is a key motivation for many homeowners. To achieve that, it's essential to store surplus energy for later use, particularly in the evenings or winter months when production is low and consumption is high.

11. APPLICATIONS OF COMMON SOLAR PANEL

Solar powered lights have become ever-present and can be seen everywhere from home landscaping and security lights to road signs and further. These solar lighting technologies for homes are inexpensive and range from basic to high-end designs. These are also daily powers that use solar panels to charge the battery during the day and maintain the battery at night. Such as black lights, tapping lights, fishing lights, garden lights, mountaineering lights, street lights, portable lights, camping lights, energy-saving lamps, etc. Today, solar power is becoming more reachable as the cost of solar panels falling continuously with innovation and more and more people are conscious of the economic and environmental benefits of solar energy. Again, distributed solar photovoltaic systems are usually installed on the roof of a home or business. The electricity generated by these solar power

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

systems can offset the owner's usage and send any surplus production to the national grid. Solar panels can be connected to our solar power system, enabling us to use solar power after the sun goes down, to power an electric vehicle overnight, or to provide backup power in an emergency in any place. Moreover, some homeowners may choose to go completely off the grid with a solar and battery system or a solar and generator system. In some cases, solar photovoltaics may be installed on adjacent structures like barns, monitoring, etc. or installed on the ground and then connected to the electricity meter with underground cables. In 21st century, in the highly connected world, where phones and tablets are always with us, there are frequent low battery situations. Portable solar photovoltaic chargers can keep our electronic devices charged on the go. Like the solar power bank, the surface is made of solar panels, and the bottom is connected to the battery. In the daytime, the solar panel is used to charge the battery, and the solar panel can also be used to charge the mobile phone directly. There are also convenient solar panels, which are generally used with energy storage, which can solve the problem of difficulty in using electricity outdoors, sunlight is everywhere. Those application may includes rural carrier telephone photovoltaic system, small communication machine, GPS power supply for soldiers, solar unattended microwave relay station, optical cable maintenance station, broadcasting or communication or paging power supply system, etc. The list has been mention below is only a part; there are many applications in our daily life. Renewable energy has also become a more familiar part of our lives, and innovation will continue to drive new applications of solar technology to improve our daily lives and help power with a cleaner world, we need to work together for this development.

Residential Applications. We can give few versatile residential solar panel applications like: rooftop arrays power household appliances and lighting, Hybrid storage systems run refrigerators and Wi-Fi during outages and plug-in mini panels offset apartment electricity bills.

- Energy Storage Integration. today, many households now complement solar panel systems with energy storage using lithium-ion batteries, like Tesla Powerwall, BYD, etc. These systems allow homes to store energy generated during the day for use at night or during cloudy weather, enhancing energy resilience and cost efficiency.
- Bifacial solar panels. Those are capable of capturing sunlight from both sides (front and back), and that have become increasingly popular in residential installations. These panels can produce 10–30% more energy than traditional mono-facial solar panels.

Commercial and Industrial Use. Today, office complexes lower daytime operational costs and peak grid demand. Factories run large machinery and assembly lines sustainably. Warehouses utilize expansive roofs for high-volume energy output.

- Adoption in Office Buildings. Over the past decade, commercial buildings, particularly office towers, have increasingly adopted solar panels as part of sustainability initiatives and energy cost-saving measures.
- On-Grid and Off-Grid Systems. Many commercial buildings now choose on-grid systems that connect solar panels to the public electricity grid [20]. This allows companies to send excess energy back to the grid and receive financial incentives. Meanwhile, buildings in remote areas or that requiring high energy resilience are adopting off-grid systems equipped with energy storage.
- Utilization in Manufacturing Facilities. Large industries are transitioning to solar energy to reduce electricity costs and their carbon footprint. For example, Tesla uses solar panels at its factories, particularly at the Giga-factory, to meet a significant portion of its energy needs. In India, companies like Tata Steel and Adani Group have implemented solar energy systems in their production facilities.

Agriculture and Remote Infrastructure. We can give few versatile agriculture and remote infrastructure solar panel applications like: water pumps operate off-grid for crop irrigation, cold storage units reduce post-harvest crop spoilage, streetlights, parking meters, and telecom towers and those can function autonomously without human touch. They need some maintenance only.

- Solar-Powered Irrigation. Now, solar technology has been widely used to power water pumps in irrigation systems, particularly in remote areas or regions without access to electricity grids. In India, more than 300,000 solar-powered pumps have been installed for agricultural irrigation, reducing dependence on expensive diesel fuel or other fossil energy sources and reduce air pollution. Even in Bangladesh, such system is becoming popular slowly.
- Sustainable Farming Applications. Nowadays solar panels support sustainable farming by providing renewable energy for agricultural processing, like grain drying and milk processing. Flexible solar technologies, like solar-powered cold storage, help preserve the freshness of produce and reduce post-harvest losses in rural areas.

Portable and Remote. Today, portable solar power finds many noteworthy applications in the research field. Researchers can deploy these systems to power scientific instrumentation in remote areas without the need for permanent infrastructure. We can give few versatile portable and remote infrastructure solar panel applications as shown below.

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- **Stand-Alone Power.** In urban or remote areas, PV can power stand-alone devices, tools, and meters. PV can meet the need for electricity for parking meters, temporary traffic signs, emergency phones, radio transmitters, water irrigation pumps, stream-flow gauges, remote guard posts, lighting for roadways, and more.
- **Remote Locations.** It is not always cost-effective, convenient, or even possible to extend power lines to locations where electricity is needed. PV can be the solution—for rural homes, villages in developing nations, lighthouses, offshore oil platforms, desalination plants, and remote health clinics. It is necessary to monitor for pollution levels and other information in remote areas like island, forests and mountain regions, where human activity is less widespread. By using solar power, researchers can collect vital information or data without harming the environment.
- **Solar Farms.** Many acres of PV panels can provide utility-scale power—from tens of megawatts to more than a Gigawatt of electricity. These large systems, using fixed or sun-tracking panels, feed power into municipal or regional grids.

Transportation Sector. Global energy demand in the transportation sector has increasingly increased over the last few decade due to rapid population expansion and economic development. in spite of adopting strategies aimed at reducing GHGs across all industries, emissions from the transportation sector are projected to increase to 60 % by 2050, mainly due to its excessive reliance on fossil fuels. So, transitioning to electric vehicles (EVs) can significantly reduce GHG emissions, diminish reliance on non-renewable resources, and mitigate the adverse environmental impacts of traditional fossil fuel usage. Here solar energy is the best option for EV. We can give few versatile solar panel applications in transport sector as shown below.

- **Solar-Powered Electric Vehicles:** Solar-powered electric vehicles have rapidly advanced over the past decade. Companies like Lightyear One and Sono Motors have launched electric cars equipped with solar panels to extend their driving range by utilizing solar energy directly. For instance, Lightyear One can add up to 12 km orange per day under sunny conditions.
- **Solar Charging Stations:** In countries like Japan and Australia, solar-powered charging stations for electric vehicles have been introduced. These stations are equipped with solar panels to generate clean energy for charging electric vehicles.

Specialized Tech and Others. Today, Micro-grids and portable solar generators provide reliable electricity at remote camps, cutting diesel fuel consumption and reducing the need for dangerous supply convoys. We can give few versatile solar panel applications in specialized tech sector as shown below.

- **Petroleum, marine and meteorological fields.** For example oil pipeline and reservoir gate cathodic protection solar power system, marine detection equipment, life and emergency power supply of oil drilling platform, meteorological or hydrological observation equipment, etc.
- **Military use.** Lightweight, flexible thin-film PV can serve applications in which portability or ruggedness are critical. Soldiers can carry lightweight PV for charging electronic equipment in the field or at remote bases. Today, solar-powered Unmanned Aerial Vehicles (UAVs) represent a transformative advancement in defense and military operations, offering extended endurance, reduced operational costs, and enhanced sustainability. Contrasting manned aircraft, UAVs offer cost-effective and risk-free alternatives for intelligence gathering, border monitoring, and electronic warfare. Their ability to operate autonomously in hostile environments makes them invaluable in both strategic and tactical missions.

Power in Space. In space, power generation and source innovating, designing and developing new technologies is just the beginning. Ensuring they are reliable, durable, affordable, and manufacturable is also important for success. With deep expertise in characterizing space power materials, researchers can help build longer-lasting, higher-performing devices. They also study the manufacturing processes and supply chains that underpin the space power industry to ensure that new advancements can be widely adopted. From the beginning, PV has been a primary power source for Earth-orbiting satellites. High-efficiency PV has supplied power for ventures such as the International Space Station and surface rovers on the moon and Mars, and its applications in space will continue to grow. For almost 50 years, the National Laboratory of the Rockies (NLR) has developed solar cells to power satellites and spacecraft. Today, NLR is working to improve the durability, performance, and affordability of several PV materials for space and power beaming applications. The lab works closely with partners to ensure this research can be quickly and widely adopted. Silicon was traditionally used as the PV material for space applications until it was supplanted by more radiation-tolerant III-V cells. However, as launch costs decrease and mission lifetimes shorten for large satellite constellations, silicon has regained interest for space applications because of its lower cost, higher manufacturability, and improved efficiency coupled with radiation hardness. The lab is working to reduce the degradation of silicon in high-radiation and extreme thermal environments. Though silicon is the most- studied PV material, there is more to learn about radiation-induced defects in silicon infused with gallium and antimony and their ability to self-heal under certain conditions. NLR scientists are using an in-house proton beam accelerator and silicon processing tools to study the role of hydrogen in the healing process. The team is also developing methods to fabricate thin (30-micrometer) silicon PV cells at scale.

12. APPLICATIONS OF FLEXIBLE SOLAR PANEL

Flexible solar panels revolutionize industrial and day-to-day applications by providing adaptable, cost-effective, user-friendly, and sustainable energy solutions. Their unique properties allow them to be utilized in diverse environments, from the rooftops of warehouses to the remote fields of agricultural operations. Those panels are ensuring and performing their potential to drive energy efficiency and sustainability across various sectors. Flexible solar panels have greatly expanded the range of environments in which photovoltaic technology can be deployed. Few common uses of flexible solar panel have described below.

a. building sector. In the **building sector**, flexible modules are integrated into curved roofs, façades, skylights, awnings, and membrane structures, enabling buildings to generate electricity without requiring heavy support systems. Building-integrated photovoltaics are increasingly incorporated into modern architectural designs to improve energy efficiency while maintaining aesthetic appeal. Again, today flexible solar panels are well-suited for manufacturing plants, transport shed, industrial building, and warehouses, which often feature large, irregular rooftops. These rooftops can pose challenges for traditional rigid panels due to their weight and they need for structural reinforcement. Flexible solar panels, being lightweight and adaptable, can be installed on a variety of surfaces without extensive modifications. This allows industrial facilities to maximize their roof space for energy production, reducing electricity costs and enhancing sustainability.

b. Transportation sector. In the transportation and logistics sector, flexible solar panels can be integrated into the roofs of delivery vehicles, trucks, car, taxi, and trailers. This integration provides a mobile power source, reducing reliance on fossil fuels and decreasing operational costs. For example, delivery trucks equipped with flexible solar panels can use solar energy to power refrigeration units or auxiliary systems, reducing fuel consumption and emissions. The flexibility of these panels also ensures they can conform to the curved surfaces of vehicles without compromising aerodynamic performance. So, in the **transportation sector**, flexible modules are installed on electric vehicles, buses, trains, trucks, boats, yachts, and recreational vehicles. These systems provide auxiliary electricity for lighting, ventilation, battery charging, and onboard electronics, reducing dependence on external power sources.

c. Aerospace industry. The **aerospace industry** has adopted lightweight flexible photovoltaics for satellites, high-altitude unmanned aerial vehicles, and experimental solar-powered aircraft. Their high specific power (watts per kilogram) makes them particularly suitable where minimizing weight is critical.

d. Agriculture sector. In **agriculture**, flexible photovoltaic systems are being installed on greenhouses, irrigation equipment, livestock shelters, and portable agricultural structures. These applications enable farmers to generate renewable electricity while preserving productive land. Flexible solar panels offer a versatile and reliable energy solution for agricultural operations, especially those located in remote areas. They can be placed on irregularly shaped buildings, greenhouses, or even directly on the ground. This adaptability is crucial for powering irrigation systems, lighting, and other essential equipment in areas where access to the electrical grid is limited or non-existent. Farmers can reduce their dependence on diesel generators by harnessing solar energy, lowering operational costs and minimizing environmental impact.

e. Oil, Gas, and Mining Industrial sector. The oil, gas, and mining industries often operate in remote and harsh environments where access to the electrical grid is either limited or unavailable. Flexible solar panels can be deployed in these challenging locations, providing a sustainable power source for machinery, living quarters, and communication systems. Their durability and ability to withstand extreme conditions make them an ideal choice for such applications. Additionally, using solar energy in these industries can reduce reliance on diesel generators, lowering operational costs and carbon emissions.

f. Humanitarian assistance and disaster relief purpose. Flexible solar technology also plays an important role in **humanitarian assistance, disaster relief and emergency catastrophic human support**. Portable photovoltaic systems provide electricity for emergency shelters, medical clinics, communication equipment, and water purification systems in areas affected by natural disasters or lacking conventional electrical infrastructure.

g. Other sectors. Emerging consumer applications include wearable electronics, backpacks, tents, smart textiles, Internet of Things (IoT) sensors, and portable charging devices. As power requirements for electronic devices continue to decrease, flexible photovoltaics are expected to become increasingly integrated into everyday products.

Behind the phenomena of global warming and climate change lies the increase in greenhouse gases in our atmosphere. A greenhouse gas is any gaseous compound in the atmosphere that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere. By increasing the heat in the atmosphere, greenhouse gases are responsible for the greenhouse effect, which ultimately leads to global warming. Global warming isn't a recent scientific concept. The basics of the phenomenon were worked out well over a century ago by Swedish physicist and chemist Svante Arrhenius, in 1896. His paper, published in the Philosophical Magazine and Journal of Science, was the first to quantify the contribution of carbon dioxide to what scientists now call the greenhouse effect. The greenhouse effect occurs because the sun bombards Earth with enormous amounts of

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

radiation that strike Earth's atmosphere in the form of visible light, plus ultraviolet (UV), infrared (IR) and other types of radiation that are invisible to the human eye. UV radiation has a shorter wavelength and a higher energy level than visible light, while IR radiation has a longer wavelength and a weaker energy level. About 30% of the radiation that strikes Earth is reflected back out to space by clouds, ice and other reflective surfaces. The remaining 70% is absorbed by the oceans, the land and the atmosphere, according to NASA's Earth Observatory.

As they heat up, the oceans, land and atmosphere release heat in the form of IR thermal radiation, which passes out of the atmosphere and into space. It's this equilibrium of incoming and outgoing radiation that makes the Earth habitable, with an average temperature of about 15^o Celsius, according to NASA. Without this atmospheric equilibrium, Earth would be as cold and lifeless as its moon, or as blazing hot as Venus. The moon, which has almost no atmosphere, is about minus 153^o C on its dark side. Venus, on the other hand, has a very dense atmosphere that traps solar radiation; the average temperature on Venus is about 462^o C. The exchange of incoming and outgoing radiation that warms the Earth is often referred to as the greenhouse effect because an agricultural greenhouse works in much the same way. The gases in the atmosphere that absorb radiation are known as greenhouse gases (GHG), because they are largely responsible for the greenhouse effect. The greenhouse effect, in turn, is one of the leading causes of global warming. The most significant greenhouse gases, according to the Environmental Protection Agency (EPA), are: water vapor (H₂O), carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Each of these gases can remain in the atmosphere for different amounts of time, ranging from a few years to thousands of years. All these gases remain in the atmosphere long enough to become well mixed, meaning that the amount that is measured in the atmosphere is roughly the same all over the world, regardless of the source of the emissions. GHG emissions are often measured in carbon dioxide (CO₂) equivalent. To convert emissions of a gas into CO₂ equivalent, its emissions are multiplied by the gas's Global Warming Potential (GWP). The GWP takes into account the fact that many gases are more effective at warming Earth than CO₂, per unit mass.

Sunlight or solar energy is a free source of renewable energy that will never be depleted. Fossil fuels, on the other hand, are finite resources that emit greenhouse gases and other particulates during extraction, processing and combustion. In comparison, solar panels do not produce emissions while in use, but they are made from several different materials that require different levels of resources and energy. The energy used to extract the raw materials and manufacture a product is known as the 'embodied energy'. The time it takes for a product to repay the embodied energy is measured in years. This is known as the total energy payback time (EPBT). A typical silicon crystalline solar panel will generate enough energy to repay the embodied energy within 2 years of installation. Yet, as panel efficiency has increased, the payback time has been reduced to less than 1.5 years in many areas with high average solar radiation. However, modern, efficient crystalline silicon solar panels generate enough energy to repay the embodied energy within couple of years. Multiple detailed studies and life-cycle analyses support this. Though, many studies are outdated as solar PV cell efficiency has increased from 15% to 22% over the last few years, and payback time is estimated to be as low as one year. Considering that a typical solar panel will last 20+ years, it will easily repay the embodied energy multiple times and offset tons of emissions.

13. PROSPECT OF ELECTRIC VEHICLE (EV), SMART EV CHARGER AND USE SOLAR ENERGY

EVs are attractive alternative for current conventional cars consuming fossil fuels like gasoline in order to mitigate emissions of greenhouse gases. The renewable energy systems with ability of power generation can be off-grid or grid connected depending on the requirements, design constraints etc. The generated power by the means of renewable energy technologies can be supplied to the grid or be used independently from the grid for some purposes such as hydrogen production. There are some opportunities and challenges in development of renewable energy systems for supplying power of EV charging. Development of renewable energy systems for supplying the needed power of EV charging systems can influence different stakeholders including consumers, energy providers and policymakers. For the consumers, use of the renewable energy electricity cannot be economically attractive particularly in the countries with high subsidies for the electricity generated from the power plants using fossil fuels. Smart charging is an approach to optimize the process of charging on the basis of constraints of distribution grid, local renewable energy sources availability and preferences of the costumers.

Between 1990 and 2022, emissions in the transport sector increased at yearly mean rate of 1.7 %, which is faster than other end-use sector except industry. In order to achieve the target of Net Zero Emissions (NZE) by 2050 Scenario, it is necessary to have more than 3 % reduction per annum in transport sector CO₂ emission by 2030. Road transport has a significant share in total fossil fuel consumption and emissions in the transport sector and it is necessary to have some amendment in this part of transport sector to reduce the emissions. Energy transition to a cleaner transport sector needs significant change in the structure and nature of this sector. The important technologies towards toad transport decarbonization, which is responsible for more than 15 % of global emissions related to energy, are Electric Vehicles (EVs). Aside from the benefits of development of EVs in term of

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

environment, it will contribute to the supply security by incrementing the transport fuel diversity. There has been exponential increment in the sale of EVs. Along with the increment in the numbers of EVs, supply of required power for charging them must be taken into account. In assessment of the EVs' ecological value, electricity consumption is the core consideration. In this regard, charging process, the required electricity and its supply are the key factors that should be considered in policy making.

Technological progress in electric vehicle batteries, electric traction motors and automotive electronics (particularly electronic control units) has made electric cars more feasible and. However, in some cases, more cost-efficient than conventional ICE vehicles during the 21st century, with market penetration in some countries like China reaching nearly half of all new vehicles sold. As a means of reducing tailpipe emissions of greenhouse gases and other air pollutants, and to reduce the dependency on fossil fuels, government incentives are also available in many areas to promote the adoption of electric vehicles. As of 2026, the electric vehicle industry in China produces more than the rest of the world combined. Recent advancements in battery technology and charging infrastructure have addressed many of the earlier barriers to EV adoption, making electric vehicles a more viable option for a wider range of consumers. China is the world's leading EV producer, accounting for more than 70% of global production and 67% of global sales of electric vehicles in 2024. EVs can be made less polluting overall by modifying the source of electricity. In some areas, individuals can ask utilities to provide their electricity from renewable energy. Therefore, it gives the greatest degree of energy resilience.

Most battery-electric vehicles also include a separate low-voltage auxiliary battery, commonly a 12-volt system, which powers accessories and control electronics. This auxiliary battery is typically recharged from the high-voltage traction battery through a DC/DC converter. Since their first commercial release in 1991, lithium-ion batteries have become an important technology for achieving low-carbon transportation systems. Most electric vehicles use lithium-ion batteries (Li-Ions or LIBs). Lithium-ion batteries have a higher energy density, longer life span, and higher power density than most other practical batteries. Complicating factors include safety, durability, thermal breakdown, environmental impact, and cost. Li-ion batteries should be used within safe temperature and voltage ranges to operate safely and efficiently. Increasing the battery's lifespan decreases effective costs and environmental impact. One technique is to operate a subset of the battery cells at a time and switching these subsets. The prices of lithium-ion batteries have declined dramatically over the past decade, contributing to a reduction in price for electric vehicles, but an increase in the price of critical minerals such as lithium from 2021 to the end of 2022 has put pressure on historical battery price decreases.

EV charging methods and technologies has evolved over time to meet the increasing demand for convenient and efficient charging solutions. These developments have widely varied the classifications of EV charging infrastructures based on many factors such as: locations, available power sources (RES, EES, conventional sources), Charging speed, Power transfer method, purpose, and so on. Smart EV charging or intelligent charging refers to a system where an electric vehicle and a charging device share a data connection, and the charging device shares a data connection with a charging operator. As opposed to traditional (or dumb) charging devices that aren't connected to the cloud, smart charging allows the charging station owner to monitor, manage, and restrict the use of their devices remotely to optimise energy consumption. Chargers are becoming more sophisticated as manufacturers seek to make EV charging easier and more cost-effective for homes and businesses. Electric cars connected to the grid with smart charging create a symbiosis with the power grid and they support each other. This connection wouldn't exist without smart charging, and electric vehicles (EVs) could burden the grid. Smart EV chargers allow automatic charging to occur when electricity prices are low or when solar power is being generated. Regular home chargers can draw a lot of power, so intelligent monitoring and controls help prevent overloading the grid supply. In addition to helping optimize EV charging, most smart chargers now have Wifi and Bluetooth as standard to enable easy setup and monitoring using a mobile app. Smart EV charging service can be modified: adding and removing features and creating a system that suits our need is effortless.

Smart electric car chargers are powered by an intelligent back-end solution that brings real-time data from connected charging devices and charging events to the charging station owner's fingertips. As stations and charging sessions are connected to the cloud, they can be managed based on various signals, such as fickle energy production, local electricity consumption, the amount of other vehicles being charged, or electrical devices being used on a nearby premise. To create a more sustainable energy system based on renewable energy sources, EV charging has to be smart. Today, EV charging using solar energy relies on PV panels to convert sunlight into clean electricity for vehicle batteries. Here basic principle is Sunlight hits the PV panels, generating direct current (DC) electricity. A solar inverter converts the DC power into alternating current (AC) for standard use, or a DC-to-DC boost converter manages power flow directly into storage or vehicle chargers. Today production based on renewable energy like solar and wind energy, the excess energy can be stored in storage units. In this way, continuity of energy can be ensured and interruption of charging services of electric vehicles can be prevented. Or EV can use solar energy directly during underway in some percentage by solar panel fixed on top-roof. So, developing countries that are dependent on energy imports have certain

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

strategic national needs like, supporting national sustainability goals, reducing energy dependence, managing electricity demand, and developing the electric vehicle ecosystem, among other things. As a result, considering national needs, EV charging systems that utilize solar and wind energy from renewable energy sources in a coordinated manner are essential.

The majority of the vehicles in the world consuming fossil fuels that causes emissions of harmful greenhouse gases. In order to mitigate the emissions regarding the transport sector, EVs have attracted attentions. One of the main concerns in the development of EVs is supply of required power for the charging stations. Renewable energy systems would be clean and attractive options for supply of required power of charging stations. In recent years, several studies have investigated applications of renewable energy systems for charging stations of EV and analyzed different aspects of these technologies. Charging stations and the related problems and issues are among the hot topics related to the EVs that have attracted attentions of researchers in recent years. If we look to the reviewed works, significant potential of renewable energy systems mainly solar and wind for supply of charging stations can be resolved. Different factors like the applied technology and components, meteorological data of the installation site and operating condition influence the performance of these systems. Additionally, it can be resolved that control design system can influence various aspects of EV charging technologies powered by renewable energy systems like share of renewables in the grid-connected configurations and performance reliability.

Renewable energy systems can be applied for power generation and the generated electricity can be used for variety of purposes such as cooling and heating, desalination, etc., The generated electricity by the renewable energy systems would be applicable for charging EVs. By combining the EVs, that are emission-free, with the low carbon power generation systems such as solar photovoltaic (PV), the issues related to the harmful gases owing to the internal combustion engines could be decreased. The performance of these systems is influenced by several factors that must be taken into account to have reliable and efficient systems. Regarding the demand for electricity, it is obvious that there are some environmentally-unfavorable impacts in use of EVs. Furthermore, by increase in number of EVs in near future, the required power by these systems can negatively affect the grids due to their substantial need for electricity. In order to eliminate or reduce these effects, it is crucial to find a way to supply electricity with lower emissions. Employment of renewable and clean energy technologies for electricity generation to be supplied in charging station is a practical way to reduce emissions and make the EVs more environmentally-friendly systems. Charging of EVs can be a challenging issue in near future regarding increase in use of these systems and appropriate electrification systems must be designed and applied. Employment of renewable energy technologies would be a practical way to supply power of EV chargers in a clean and sustainable way.

14. SOLAR PANELS WASTE RECYCLING AND ENVIRONMENTAL SUSTAINABILITY

Despite the large amount of information circulating about solar panels being toxic, modern crystalline silicon solar panels contain virtually no toxic materials. The claims of toxic solar panels come from the mostly obsolete thin-film (Cadmium telluride - CdTe) solar panels containing trace amounts of cadmium and telluride. However, unless these (relatively rare) panels are broken up into fragments, the trace amount of cadmium is contained within the EVA layers and cannot leach out. Modern crystalline silicon solar panels contain only traces of lead in the solder used for the cell interconnections. Though, the use of solder is also being phased out with the new busbar compression joining techniques and conductive paste materials. It's worth noting solder is used in hundreds of millions of electrical devices and appliances. There are far more toxic elements used in consumer electronic devices, mobile phones, computers, and TVs. That is why electronic waste or E-waste is a significant global problem. Roughly 99% of the solar panels installed worldwide today are silicon crystalline and do not contain cadmium or telluride. Solar panels are benign, and even when damaged, they do not cause any contamination, as the cells are encapsulated within very durable polymer layers and contain no readily soluble materials. However, like all appliances, solar panels need to be collected and recycled at the end of life. Since most solar panels installed over the last 20 years are still in use, there is not a great volume of solar waste. However, over the next 10-20 years, many systems will reach the end of life (EOL), and there is expected to be a very large increase in the volume of solar-related waste that will need to be recycled. Solar panel recycling is an emerging industry. Most of the materials, such as aluminium frames and mounting systems, are relatively easy to recycle. Most solar panel manufacturers are pushing to be more sustainable and are now part of the not-for-profit PV Cycle organization.

There were 30 thousand tons of PV waste in 2021, and the annual amount was estimated by Bloomberg NEF to rise to more than 1 million tons by 2035 and more than 10 million by 2050. For comparison, 750 million tons of fly ash waste was produced by coal power in 2022. In the United States, around 90% of decommissioned solar panels end up in landfills as of 2023. Most parts of a solar module can be recycled including up to 95% of certain semiconductor materials or the glass as well as large amounts of ferrous and non-ferrous metals. Some private companies and non-profit organizations take-back and recycle end-of-life modules. EU law requires manufacturers to ensure their solar panels are recycled properly. Similar legislation is underway in Japan, India,

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

and Australia. A 2023 Australian report said that there is a market for quality used panels and made recommendations for increasing reuse, but rules have not been implemented. Since 2010, there is an annual European conference bringing together manufacturers, recyclers and researchers to look at the future of PV module recycling. For Silicon based modules, aluminum frames and junction boxes are dismantled manually at the beginning of the process. The module is then crushed in a mill and the different fractions are separated – glass, plastics and metals. It is possible to recover more than 80% of the incoming weight. This process can be performed by flat glass recyclers, since the shape and composition of a PV module is similar to flat glass used in the building and automotive industry. The recovered glass, for example, is readily accepted by the glass foam and glass insulation industry. On the other hand, non-silicon-based modules: they require specific recycling technologies such as the use of chemical baths in order to separate the different semiconductor materials. For cadmium telluride modules, the recycling process begins by crushing the module and subsequently separating the different fractions. This recycling process is designed to recover up to 90% of the glass and 95% of the semiconductor materials contained. Some commercial-scale recycling facilities have been created in recent years by private companies.

Flexible solar panels contribute significantly to global sustainability by reducing dependence on fossil fuels and lowering greenhouse gas emissions. Throughout their operational lifetimes, photovoltaic systems generate electricity without producing direct carbon dioxide emissions, air pollution, or noise. Many flexible technologies also require substantially less raw material than conventional crystalline silicon modules because their semiconductor layers are only a few micrometers thick. Reduced material consumption lowers manufacturing energy requirements and conserves valuable natural resources. However, sustainability depends not only on electricity generation but also on responsible manufacturing, recycling, and disposal. Researchers are developing recyclable encapsulation materials, environmentally friendly semiconductor compositions, and circular economy strategies that recover valuable materials from end-of-life photovoltaic modules. Continued advances in recycling technology will play an increasingly important role as flexible photovoltaic deployment expands worldwide.

15. GLOBAL MARKET SOLAR ENERGY AND PANELS

In the most realistic scenario, the Solar-Power-Europe anticipate a 10% increase in installations to 655 GW in 2025, with annual growth rates remaining in the low double digits between 2027-2029, reaching 930 GW by the end of this outlook period. Though, meeting the Global Solar Council's (GSC) aspirational target of 8 TW by 2030 will require a significantly accelerated pace of deployment roughly 1 TW of new installations per year on average. However, 2025 marks ten years since the Global Solar Council was launched at COP21 in Paris and born from the collective belief that solar power could accelerate the global energy transition and help deliver on the promises of the Paris Agreement. At that time, solar PV was a fast-growing but fragmented sector. GSC was created to unite it and giving the industry a single, global voice to push for more ambitious policy, greater investment, and faster, fairer deployment. With over 2 TW installed and costs down by more than 80% in many markets, solar has proven its economic and climate value. Now, to stay on track for 1.5°C and meet the global goal of tripling renewables by 2030, solar must scale to at least 8 TW. That means powering not just growth, but transformation and delivering clean, reliable, and affordable energy to homes, schools, hospitals, and industries across every region. It requires bold reforms: finance that flows faster and cheaper, smart grids and storage systems that can handle variable energy at scale, permitting processes that move faster, supply chains that are resilient, and a skilled workforce that reflects every community it serves.

A key issue is the uneven distribution of solar market growth. Most expansion has been concentrated in the Asia-Pacific region, led by China, creating widening disparities between regions. In 2024, China's solar market grew by 30% to 329 GW, more than the combined total of the other top 10 markets, with a 55% global market share. China's growth is a major achievement from a global decarbonization perspective and its comprehensive solar commitment has enabled the technology's rapid global development, but it also underscores the world's heavy reliance on a single country. With China implementing major changes to its solar market design this year, a temporary dip in global growth in 2026 appears very likely. Meanwhile, other regions are falling behind, particularly the Middle East and Africa, which installed less capacity than in the previous year. Although the number of countries with annual Gigawatt-scale solar markets has increased to 35, this is fewer than anticipated. We do expect this to change in the near future; our report provides a detailed analysis of these GW-scale markets, with insights from national solar and renewable energy associations.

There are also rising solar stars today. India's comprehensive solar strategy and covered in a dedicated chapter is beginning to bear fruit. The most populous nation on Earth has emerged as the world's third-largest solar market after more than doubling its annual installations in 2024. Continued strong growth is expected. As outlined in the GSC's policy recommendations, sustaining global momentum will require addressing a range of region-specific challenges. More advanced markets must focus on enhancing grid flexibility, adapting policy frameworks to the needs of variable renewables, prioritizing battery storage, and streamlining

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

permitting and grid-connection processes. For least developed countries, the key lies in bridging investment gaps. Across all regions, developing a skilled workforce and setting ambitious solar and storage targets are essential tasks. In these times of political uncertainty, low-cost solar power could turn into the key tool to provide energy security and competitiveness to nations across the world. The years ahead are crucial for solar development and will require foresight and commitment from policy leaders and financial institutions. In most likely or medium growth scenario, there is an expectation of solar's role in the driver seat of the global energy transition to become even stronger, reaching a total installed capacity of 7.1 TW by 2030 and delivering nearly two-thirds of the 11 TW renewable energy target set at COP28. With the right enabling conditions, solar capacity could even quadruple its capacity and exceed 8 TW by the end of the decade.

the International Energy Agency (IEA) projects that solar PV will become the largest renewable energy source by 2029, accounting for 80% of the growth in global renewable capacity between 2024 and 2030. The adoption of AI technologies is expected to play a crucial role in achieving this milestone by improving the efficiency and reliability of solar energy systems. The global solar energy market size was valued at USD 92.45 billion in 2023. As per 'Spherical Insights', the solar market is growing at a CAGR of 11.95% from 2023 to 2033. The worldwide solar energy market size is expected to reach USD 285.89 billion by 2033 and that has been shown in figure 6 below. Their forecast found more analytical. They have considered all elements during evaluating the global solar energy market. Such as: Present Global Solar Energy Market Size, Share, and COVID-19 Impact Analysis; Technology like Concentrated Solar Power Systems, Photovoltaic Systems; Solar Module like Monocrystalline, Polycrystalline, Cadmium Telluride, Amorphous Silicon Cells, Others; End User like Residential, Commercial, Industrial, etc; and Region like North America, Europe, Asia-Pacific, Latin America, Middle East, and Africa; etc. On the other hand, as per 'Persistence-Market-Research' the global solar energy market size is likely to be valued at US\$ 137.2 Billion in 2025 and is estimated to reach US\$ 313.0 Billion by 2032, growing at a CAGR of 12.5% during the forecast period 2025-2032 and their survey and forecast have driven by rising environmental concerns and increasing installation of renewable energy systems by governments, alongside rapid technological advancements that improve efficiency and reducing costs of solar power. They give emphasis on the market trend and that has been shown in figure 7 below.. On the other hand, as per 'market.us' the global photovoltaic solar panel market size is expected to be worth around USD 452.3 billion by 2034, from USD 201.9 billion in 2024, growing at a CAGR of 8.4% during the forecast period from 2025 to 2034 and that has been shown in figure 8 below. Their forecast was more optimistic. The PV solar panel industry in India has experienced significant growth, driven by supportive government policies, technological advancements, and increasing demand for clean energy. As of April 2025, India's total installed solar power capacity reached approximately 107.94 GW, comprising 82.39 GW from ground-mounted plants and 17.69 GW from grid-connected rooftop systems.

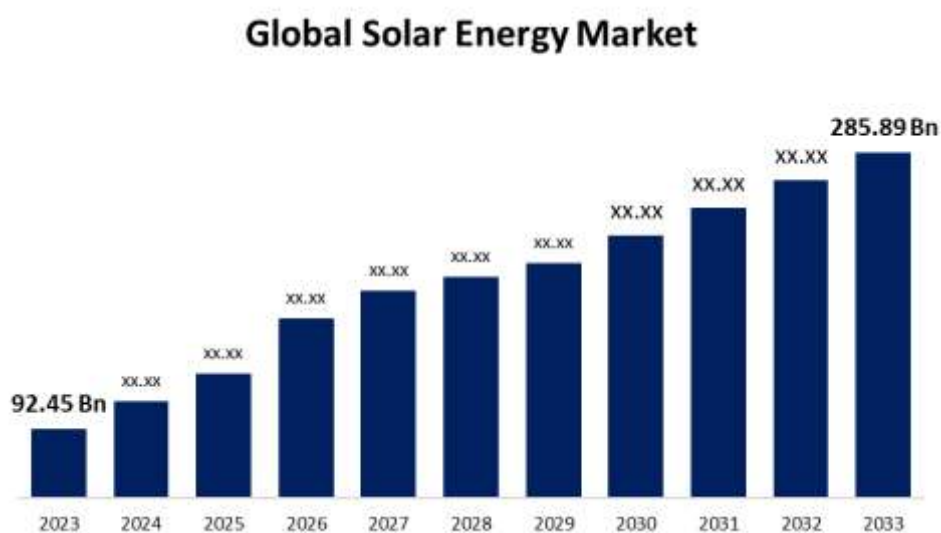


Figure 6: Prediction of global solar energy market size (2023-2033) by Spherical Insights

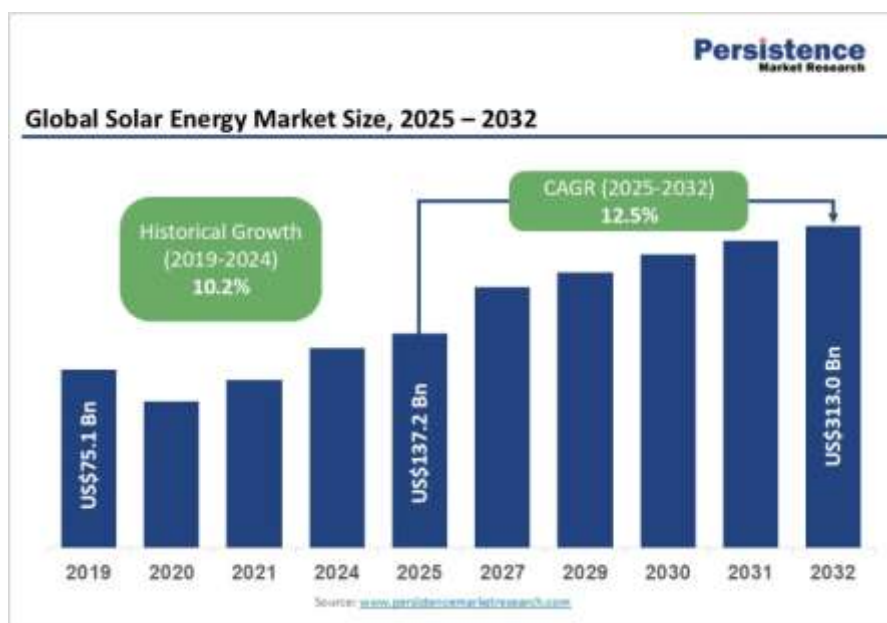


Figure 7: Prediction of global solar energy market size (2025-2032) by Persistence-Market-Research

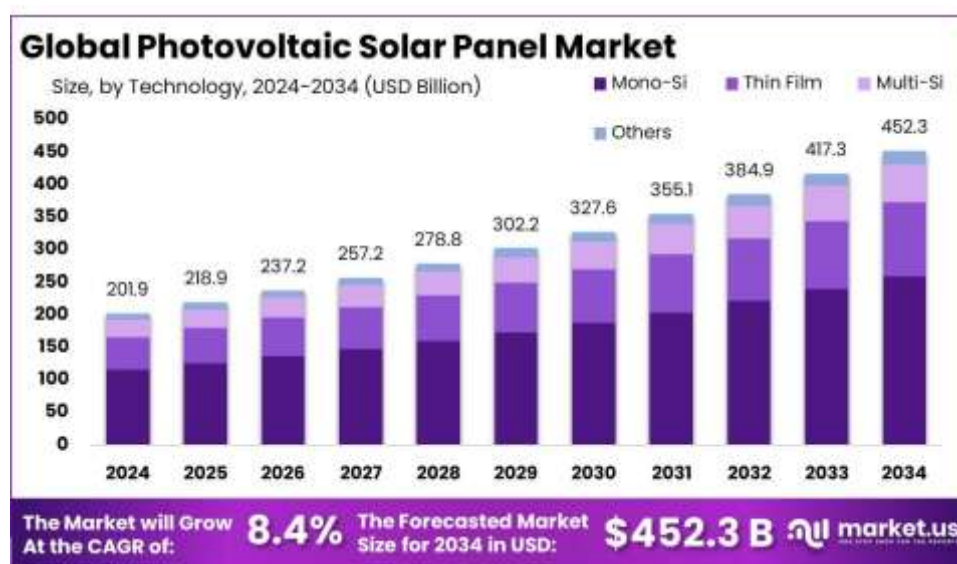


Figure 8: Prediction of global solar panels market size (2024-2034) by market.us

16. FUTURE PROSPECTS OF SOLAR ENERGY, SOLAR PANELS TECHNOLOGY

Scientists have pushed efficiency past the 30% mark by combining traditional silicon with revolutionary perovskite layers to capture multiple light wavelengths. The future of solar panel technology is advancing faster than most homeowners realize. Today's best panels already hit 24% to 26% efficiency in commercial production, compared to just 15% in 2010. Perovskite-silicon tandem cells have already broken 34% efficiency in certified lab conditions. Solar panels that generate power from both sides are shipping at scale. Transparent solar windows that generate electricity from ordinary glass are moving from research labs into real buildings. And AI-powered monitoring is making solar systems smarter by the year. The newest solar panel technology widely available to homeowners right now is TOPCon, which stands for Tunnel Oxide Passivated Contact. According to SolarTech research, TOPCon now dominates approximately 75% of new solar panel production globally and accounts for roughly 50% of all panel shipments in 2025 and 2026. It is a direct upgrade from the older PERC technology that dominated for most of the last decade. TOPCon panels achieve 24% to 26% efficiency in commercial production, compared to 20% to 22% for standard PERC panels, and they degrade more slowly over time. Right behind TOPCon in the market is Heterojunction Technology, commonly called HJT. Those panels deliver 24% to 26% efficiency as well, but they handle heat better. According to A1 SolarStore, HJT panels have a temperature coefficient of just -0.24% per degree Celsius, meaning they lose less performance on hot days compared to standard

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

panels at -0.35% per degree. For homeowners in South Florida, where panels sit in intense heat and humidity for most of the year, that difference is meaningful.

New panels are becoming ultra-thin (thinner than paper), flexible, and anti-dust to prevent energy loss in harsh environments. Transparent solar windows and solar roof shingles turn ordinary building surfaces into active power generators. The latest solar panel technology on its way to homes is perovskite-silicon tandem panels, which have already crossed the threshold from research into limited commercial production. In April 2025, LONGi achieved a certified efficiency record of 34.85% on a perovskite-silicon tandem cell, verified by the U.S. National Renewable Energy Laboratory (NREL). Oxford PV shipped its first commercial perovskite-silicon tandem modules to a U.S. utility-scale project in September 2024, with 24.5% module efficiency. Hanwha Qcells achieved 28.6% efficiency on production-scale cells and has commercial production planned for 2026 and mass production by early 2027. For residential buyers, mainstream perovskite tandem panels with full 25-year warranties are realistically expected between 2027 and 2030, according to SurgePV analysis. Most homeowners shopping for solar today will still find traditional silicon-based panels, specifically TOPCon and HJT. Those are the right choice for 2026 installations. Waiting for perovskite means waiting several more years for technology that, even when it arrives at scale, will come at a premium price before manufacturing catches up to demand. Perovskite-silicon tandem solar panels are already more efficient than standard silicon panels in both lab records and early commercial modules. Standard monocrystalline silicon panels available to homeowners today deliver 20% to 24% efficiency. Oxford PV's first commercial tandem modules achieve 24.5% module efficiency, with 26% targeted in 2026. LONGi's NREL-certified lab record stands at 34.85%. In practical terms, a tandem panel producing 30%+ efficiency in real-world conditions would generate the same electricity as today's best panels while using significantly less roof space, which matters for homes where roof area is limited. For reference, the average solar panel efficiency has already improved from about 15% in 2010 to over 22% in commercial production by 2025, according to Lawrence Berkeley National Laboratory. That is a 47% improvement in roughly 15 years. The shift to tandem technology in the late 2020s is likely to produce gains that are just as large in a much shorter window. Agin, Bifacial solar panels are panels that generate electricity from both the front and the back surface instead of just the front. The front side captures direct sunlight the same way any standard panel does. The back side captures reflected light bouncing off the ground, water, white roofing surfaces, or any nearby reflective material. According to the International Energy Agency (IEA), bifacial panels now account for 35% of global solar installations and are projected to reach 60% by 2030. The bifacial solar market, valued at over \$19.2 billion in 2024, is growing at 16.8% annually through 2030, according to PS Market Research.

The additional output from the rear side adds 5% to 30% more energy compared to a standard single-sided panel, depending on installation conditions. Solar farms with highly reflective ground surfaces see the largest gains, typically 20% to 30%. Residential rooftop installations see more modest gains of 5% to 10%, but that is still meaningful over a 25-year system lifespan. In South Florida, white or light-colored roofing materials are common, which increases the rear-side reflectivity and makes bifacial panels a strong fit for residential installations. Bifacial solar panels are worth it for most home installations, particularly when the roof surface is light-colored or the panels are installed at an elevated angle where the back side can capture reflected light. HJT panels are naturally bifacial by design, giving homeowners who choose HJT technology the dual benefit of strong heat performance and built-in bifacial energy capture. The future of flexible solar technology appears highly promising. Ongoing research focuses on improving conversion efficiency, enhancing durability, reducing manufacturing costs, and developing environmentally sustainable materials. Perovskite-silicon tandem cells are expected to surpass the efficiency limits of conventional silicon modules, while advances in roll-to-roll manufacturing may enable large-scale, low-cost production. Artificial intelligence (AI), machine learning, and advanced materials modeling are accelerating the discovery of new photovoltaic materials with improved stability and performance. Nanotechnology continues to enhance light absorption, charge transport, and protective coatings, further increasing device reliability.

Flexible photovoltaics are expected to play an important role in smart cities, net-zero energy buildings, electric transportation, wearable electronics, portable power systems, and space exploration. Rather than replacing conventional solar panels entirely, flexible modules will complement existing technologies by expanding solar energy generation into applications previously considered unsuitable for photovoltaics. The future of solar panels for home use includes higher efficiency in smaller footprints, smarter AI-powered monitoring, solar panels built directly into building materials, and eventually transparent solar windows that generate electricity while you look through them. According to the IEA's Renewables 2025 report, global renewable power capacity is projected to increase by nearly 4,600 Gigawatts between 2025 and 2030, with solar accounting for approximately 80% of that growth. Distributed solar applications, meaning residential and commercial rooftop systems, will represent 42% of all new solar installations through 2030. The future is residential as much as it is utility-scale. Again, for homeowners, the most practical near-term advances are threefold. First, higher efficiency panels like TOPCon and HJT mean you need fewer panels to achieve the same output, reducing roof space requirements. Second, falling panel costs continue. According to IEA data, global solar module

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

manufacturing capacity surpassed 1,100 Gigawatts by 2024, well above projected demand, which keeps driving prices down. Third, pairing solar with battery storage is becoming the standard installation model rather than an upgrade. According to SolarReviews, 92% of residential solar installers offered energy storage as part of their installation packages in 2024.

There are new solar panel concepts that can generate electricity at night, though they are still in research and early prototype stages rather than available for home installation. Researchers at UC Davis published a concept paper in ACS Photonics describing thermos-radiative cells that work by radiating heat into the night sky rather than absorbing light from the sun. Under ideal conditions, such a device could theoretically generate up to 50 watts of power per square meter at night, roughly one quarter of what a conventional solar panel produces during daytime. Separately, researchers at Korea University developed a transparent solar window system that generates electricity from indoor lighting at night in addition to sunlight during the day. The system combines a distributed Bragg reflector with bifacial silicon solar cells and can generate power continuously around the clock. These technologies remain in the research phase for now. The practical solution available today for overnight power is a solar battery backup system that stores excess daytime production and releases it during evening hours when panels are not producing. Transparent solar windows are glass panels that generate electricity while still allowing visible light to pass through, functioning as both a window and a solar panel simultaneously. Several real installations already exist. Copenhagen International School in Denmark is covered in 12,000 semi-transparent solar panels that serve as building windows while generating power. A Netherlands-based company called Physee has installed its Smart Windows in office buildings across Europe, with the technology projected to cut building energy costs by up to 30%. Research teams at MIT, Korea University, and Nanjing University are all advancing different approaches to transparent solar coatings.

MIT's version transmits more than 70% of visible light, within the range of tinted glass used in commercial buildings today. In September 2025, Nanjing University researchers published a prototype of a clear coating that can be applied to any standard window to redirect sunlight to the window's edges, where photovoltaic cells convert it to electricity without affecting the window's clarity. The technology remains a few years from residential scale, but it represents a genuine coming shift in how buildings generate power. Solar panel efficiency has improved dramatically over time, nearly doubling in practical commercial terms over the past 15 years. The average panel efficiency sat around 10% to 15% in the early 2000s. By 2010, most residential panels were near 15%. By 2025, commercial mono-crystalline panels routinely deliver 22% to 25% efficiency, with premium HJT models reaching 26%. According to Lawrence Berkeley National Laboratory data cited by SolarTech, the average panel efficiency improved by approximately 33% from 2010 to 2025. Combined with a 70% reduction in panel costs over the same period, the economics of solar have transformed entirely. The future of solar panels' efficiency points toward 30% to 35% commercial module efficiency by the late 2020s to early 2030s, driven by perovskite-silicon tandem technology reaching mass production scale. According to SolarTech projections, perovskite-silicon tandem cells are on a path to achieve 35% to 40% efficiency by 2028 to 2030 in laboratory conditions, with commercial modules trailing lab records by roughly 5 to 7 percentage points. Silicon-only cells are fundamentally capped near 29% by physics, making tandem architecture the only viable route past that barrier for the foreseeable future. Even within silicon technology, improvements continue.

TOPCon cells have already surpassed 25% in laboratory settings, and mass production modules routinely achieve 22.5% or better. The practical ceiling for silicon-based panels is getting closer, which makes the development timeline for perovskite tandem technology genuinely important for the next decade of solar. Solar technology will change for homeowners by 2030 in four specific ways. Panels will produce more power in less space as tandem cells transition from limited commercial products to mainstream availability. Battery storage will become a standard part of nearly every residential installation rather than an add-on, driven by the erosion of net metering programs across states and the growing demand for backup power resilience. AI-integrated monitoring will make solar systems self-diagnosing, alerting homeowners and installers to underperforming panels before they cause months of hidden production losses. And building-integrated photovoltaics, meaning solar built directly into roofing materials, siding, and eventually windows, will give homeowners options beyond traditional rooftop panel arrays. The IEA projects global solar capacity will grow by 2.6 times its 2022 level by 2030, with distributed residential and commercial applications accounting for 42% of all new solar added through the end of this decade. South Florida's year-round sun and high electricity rates position it as one of the strongest residential solar markets in the country for the years ahead. Homeowners who install solar energy systems now with modern TOPCon or HJT panels will have systems built on the strongest technology available today while perovskite tandem options mature toward mass availability.

Modern solar panels do work on cloudy days, though at reduced output. According to Couleenergy, solar panels generate approximately 10% to 25% of their rated power under heavy cloud cover and 50% to 80% under light cloud cover. TOPCon panels perform well in diffused light due to their advanced passivation layer. HJT panels are especially effective in low-light conditions. Germany, one of the cloudiest countries in Europe, generates substantial solar power because modern panel technology is

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

sensitive enough to operate on ambient daylight, not just direct sunshine. The most efficient solar panel technology for home use in 2026 is HJT, which delivers 24% to 26% commercial module efficiency and the best temperature performance of any mainstream panel type. TOPCon is a close second at 22.5% to 25% efficiency and offers broader availability at a lower price point. For most homeowners, TOPCon is the practical choice because it delivers near-HJT efficiency at a lower cost. HJT is the right choice for homes with limited roof space where maximum power per square foot is the priority, or for South Florida installations where heat tolerance during long summer months is critical.

Installing solar now with TOPCon or HJT panels is a better financial decision than waiting for perovskite tandem technology for most homeowners. The federal residential solar tax credit expired at the end of 2025 for homeowner-owned systems, making 2026 installations more expensive than they would have been a year ago. Every year of delay is a year of full-rate utility bills that a solar system could be offsetting. By the time perovskite panels reach mainstream residential availability with full warranties around 2027 to 2030, today's TOPCon or HJT system will already have delivered three to five years of energy savings and begun its payback period in earnest. The future of solar panel technology is genuinely exciting. Perovskite-silicon tandem cells are breaking efficiency records that silicon alone could never reach. Bifacial panels are already generating power from both sides of the module. Transparent solar windows are moving from research labs into real buildings. AI-powered monitoring is making systems smarter and more reliable. And the global solar industry, which the IEA projects will account for 80% of all new renewable energy capacity added through 2030, is only accelerating. For homeowners today, the right technology is already in the market. TOPCon and HJT panels deliver efficiency, durability, and heat performance that makes sense for demanding climate. Pairing them with battery storage makes a system that works around the clock, not just when the sun is up."

17. CONCLUSION

Today power generation in industrial sector has become a major contributor to GHG emissions, mainly CO₂. For climate change mitigation, special attention is given to the reduction of CO₂ emissions by applying carbon capture and storage (CCS) techniques. CCS technologies refer to a broad range of methods to allow CO₂ emissions to be captured and then transported to safe geological storage, rather than being emitted into the atmosphere. CCS technologies are expected to play a significant role in the future for curbing greenhouse gas emissions and for sustainable development. Power or electricity generation is the process of generating electric power from sources of primary energy such as heat (thermal), wind, solar, and chemical energy. We need to capture, store, contextualize, and visualize time-series information and make it available to the right people at the right time to enable the right decisions. Many operators in the power generation industry are increasingly looking to move toward a data-driven and technology-enabled way of working. Often this is called the Manufacturing 4.0 or Plant 4.0. household energy storage policies in major countries around the world. Today, organizations face many challenges of scale and performance, data quality, data silos, integration, and cybersecurity. There is also an increasing number of confusing and conflicting messages within the industry about how best to support digital operations to enable further automation and advanced Big-data predictive analysis. Most companies are trying to evaluate how the new digital and smart approach fits and how techniques like Artificial Intelligent (AI), Machine Learning (ML), Deep Learning (DL), Internet of Things, (IoT), and advanced statistics can improve the performance of plants and operation supply chains. With this degree of digitization, operators can develop data-driven models that combine physics, statistics, and best practice engineering principles in order to gain greater insight into what is going on in the plant, and how they can improve performance of the total asset lifecycle. However, net-zero is a pivotal concept in the global effort to combat climate change, and this balance is essential for stabilizing global temperatures and mitigating the adverse effects of climate change.

Now, smart solar panels respond to both direct sunlights coming straight from the sun and diffuse sunlight reflected from particles in clouds and the atmosphere. Solar panels are usually able to generate some electricity even on a cloudy day. Flexible solar panels are lightweight, malleable, and easy to fit onto complex or irregular surfaces like curved machinery or vehicle roofs, making industrial solar deployment more feasible and effective. They can be bonded to delivery trucks, trailers, or vehicles to power auxiliary systems, cutting fuel usage and emissions while conforming to aerodynamic contours. Their design enables use in agricultural, mining, oil, or gas sites with limited grid access. They are rugged, durable, and reliable, ideal for powering essential equipment off-grid. One of the most significant economic advantages of flexible solar panels is their potential for cost reduction. Due to their lightweight nature, flexible panels require less structural support and can often be installed without the need for extensive modifications or reinforcement. This translates into lower installation costs compared to traditional rigid panels. Additionally, the ease of transport and handling reduces labor costs and logistics expenses, making them panels a financially attractive option for large-scale industrial projects. Flexible panels can be installed on curved or uneven surfaces, making them ideal for various industrial applications where traditional rigid panels might not fit. For transportation applications, lightweight

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

modules improve energy efficiency because they add minimal mass to vehicles, ships, aircraft, and satellites. Portable flexible panels are similarly valuable for emergency response, humanitarian relief, military operations, and outdoor recreation, where reliable electricity is needed in remote locations.

Flexible paper-like solar panels represent one of the most significant technological advances in modern renewable energy systems. By combining lightweight construction, mechanical flexibility, and increasingly high conversion efficiencies, these innovative photovoltaic technologies have expanded the potential applications of solar energy far beyond conventional rooftop installations. Advances in crystalline silicon, thin-film semiconductors, organic photovoltaics, and perovskite materials have transformed flexible photovoltaics from laboratory concepts into commercially viable products serving architecture, transportation, agriculture, aerospace, disaster relief, and consumer electronics. Although challenges related to durability, manufacturing cost, and long-term stability remain, continuous scientific progress suggests that these limitations will gradually diminish. As global demand for clean, sustainable, and decentralized energy continues to grow, flexible photovoltaic technology is expected to become an essential component of the future energy landscape. Through ongoing innovation in materials science, manufacturing processes, and system integration, flexible solar panels have the potential to significantly accelerate the worldwide transition toward low-carbon and renewable electricity generation.

The development of novel solar power technologies is considered to be one of many key solutions toward fulfilling a worldwide increasing demand for energy. Rapid growth within the field of solar technologies is nonetheless facing various technical barriers, such as low solar cell efficiencies, low performing balance-of-systems (BOS), economic hindrances like, high upfront costs and a lack of financing mechanisms, and institutional obstacles like, inadequate infrastructure and a shortage of skilled manpower. Solar energy technologies have become well-established and popular technologies throughout the world. To achieve this, billions of US dollars have been invested and much more are expected to be invested in the near future to overcome the current limitations in the solar industry. Today some scholars and vehicle scientists have investigated the performance of EV charging systems integrated with renewable energy technologies; however, some ideas can be considered for the future works. For instance, employment of other clean energy technologies such as fuel cell could be useful. Solar power offers enormous potential for homeowners, but it also comes with practical and financial challenges. For first-time solar buyers, navigating the rules around subsidies, tax benefits, and building permits can be confusing. Requirements often vary between municipalities and can include restrictions for heritage properties or areas with specific local plans. On the other hand, subsidies can provide significant benefits when improving the energy-efficiency and self-sufficiency of our home. Selecting the right installer can significantly impact both the performance of our system and our overall experience. There are large variations in pricing, craftsmanship, and customer service, making it difficult to know who to trust. On the other hand, the flexible solar market's one-size-fits-all approach creates systematic problems: efficiency gaps, short life-spans, and application mismatches.

With more and more people choosing to install photovoltaic systems, the solar technology industry is growing rapidly. Despite the government ending the FIT (Feed-in Tariff) payments in March 2019, solar technology continues to be popular causing the price of systems to fall. With grid electricity prices going up year on year it remain a good time to invest in PV technology. The solar industry is expected to continue to grow as the technology becomes more efficient and affordable. Many more investors are being attracted to the sector recognizing the importance of renewable energy for our future. The solar industry has seen remarkable technological advancements which makes it a crucial component in the global shift towards renewable technology. Today, solar power is now more reliable than ever as users can store excess energy for later use due to the development of energy storage technologies such as lithium-ion and solid-state batteries. Again, the cost of solar panels is expected to continue to fall making them more accessible for individuals and businesses. On the other hand, because improvements are being made in solar cells and materials, solar panels are becoming more efficient at converting sunlight into electricity. So, in future, solar energy is expected to become more competitive with fossil power and other renewable energy sources. Moreover, new technologies like perovskite solar panels, bifacial solar panels, and building-integrated photovoltaics (BIPV) are expected to develop and grow further.

REFERENCES

- 1) Bellini, E. (2020). *Flexible solar panel for BIPV from Sunport*. PV Magazine, accessed on 01 Aug 2026
- 2) <https://ember-energy.org/latest-insights/global-electricity-review-2025/>, accessed on 01 Aug 2026
- 3) <https://www.un.org/en/climatechange/what-is-renewable-energy>, accessed on 01 Aug 2026
- 4) [Armaroli, Nicola; Balzani, Vincenzo](#) (2011). "Towards an electricity-powered world". [Energy and Environmental Science](#). 4 (9): 3193–3222, [doi:10.1039/c1ee01249e](#), accessed on 01 Aug 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 5) Armaroli, Nicola; Balzani, Vincenzo (2016). "Solar Electricity and Solar Fuels: Status and Perspectives in the Context of the Energy Transition". [Chemistry – A European Journal](#). 22 (1): 32–57, [doi:10.1002/chem.201503580](#), accessed on 01 Aug 2026
- 6) <https://www.irena.org/news/pressreleases/2019/Apr/Renewable-Energy-Now-Accounts-for-a-Third-of-Global-Power-Capacity>, accessed on 01 Aug 2026
- 7) <https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/>, accessed on 01 Aug 2026
- 8) IEA (2020). [Renewables 2020 Analysis and forecast to 2025](#) (Report). p. 12. [Archived](#) from the original on 26 April 2021, accessed on 01 Aug 2026
- 9) <https://www.aps.org/apsnews/2009/04/bell-labs-silicon-solar-cell>, accessed on 01 Aug 2026
- 10) Meyers, Glenn (31 December 2014). ["Photovoltaic Dreaming 1875--1905: First Attempts At Commercializing PV"](#). cleantechnica.com. Sustainable Enterprises Media Inc. CleanTechnica, accessed on 01 Aug 2026
- 11) Adams, William Grylls; Day, R. E. (1 January 1877). "IX. The action of light on selenium". *Philosophical Transactions of the Royal Society of London*. 167 (167): 313–316. [doi:10.1098/rstl.1877.0009](#). [ISSN 0261-0523](#), accessed on 01 Aug 2026
- 12) <https://patents.google.com/patent/US2402662>, accessed on 01 Aug 2026
- 13) <https://cleantechnica.com/2014/12/31/photovoltaic-dreaming-first-attempts-commercializing-pv/>, accessed on 01 Aug 2026
- 14) Green, Martin A. (1998). *Solar cells: operating principles, technology and system applications* (Repr. [der Ausg.] Englewood Cliffs, NJ 1982 ed.). Kensington, NSW: Univ. of New South Wales. [ISBN 978-0-85823-580-9](#), accessed on 01 Aug 2026
- 15) Palz, Wolfgang (2013). [Solar Power for the World: What You Wanted to Know about Photovoltaics](#). CRC Press. pp. 131–. [ISBN 978-981-4411-87-5](#), accessed on 01 Aug 2026
- 16) Shubbak, Mahmood H. (2019). ["The technological system of production and innovation: The case of photovoltaic technology in China"](#). *Research Policy*. 48 (4): 993–1015. [doi:10.1016/j.respol.2018.10.003](#), accessed on 01 Aug 2026
- 17) <https://ourworldindata.org/emissions-by-sector>, accessed on 01 Aug 2026
- 18) Dodman, David (April 2009). ["Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories"](#). *Environment and Urbanization*. 21 (1): 185–201, [doi:10.1177/0956247809103016](#), accessed on 01 Aug 2026
- 19) International Energy Agency. (2024). *Renewables 2024: Analysis and forecast to 2030*. <https://www.iea.org>,
- 20) Fraunhofer Institute for Solar Energy Systems. (2024). *Photovoltaics report*,
- 21) Powalla, M., et al. (2022). Advances in CIGS thin-film solar cells. *Advanced Energy Materials*, 12(5), 2102344, accessed on 01 Aug 2026
- 22) International Renewable Energy Agency. (2023). *Renewable capacity statistics 2023*. <https://www.irena.org>,
- 23) Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Hao, X. (2024). Solar cell efficiency tables (Version 64). *Progress in Photovoltaics: Research and Applications*, 32(7), 573–589,
- 24) <https://www.wired.com/story/african-imports-of-chinese-solar-panels-increase/>, accessed on 01 Aug 2026
- 25) <https://www.chemistryexplained.com/Ru-Sp/Solar-Cells.html>, accessed on 01 Aug 2026
- 26) Feldman, David; Dummit, Krysta; Jarett, Zuboy; Margolis, Robert (July 12, 2022). ["Summer 2022 Solar Industry Update"](#) (PDF). [National Renewable Energy Laboratory](#), accessed on 01 Aug 2026
- 27) Glisson, Tildon H. (2011). [Introduction to Circuit Analysis and Design](#). USA: Springer. pp. 114–116. [ISBN 978-9048194421](#), accessed on 01 Aug 2026
- 28) <https://www.energy.gov.au/solar/get-know-solar-technology/solar-panels>, accessed on 01 Aug 2026
- 29) <https://www.electricalknowledge.com/electricians-tools/junction-box/>, accessed on 01 Aug 2026
- 30) <https://www.energy.gov/sites/default/files/2024-12/Solar%2520Energy%2520Supply%2520Chain%2520Report%2520-%2520Final%5B1%5D.pdf>, accessed on 01 Aug 2026
- 31) <https://www.pv-magazine.com/2025/08/01/non-stop-solar-innovation-despite-module-oversupply/>, accessed on 01 Aug 2026
- 32) Li, Wei; Garg, Akhil; Xiao, Mi; Peng, Xiongbai; Le Phung, My Loan; Tran, Van Man; Gao, Liang (2020-10-10). ["Intelligent optimization methodology of battery pack for electric vehicles: A multidisciplinary perspective"](#). *International Journal of Energy Research*. 44 (12): 9686–9706, accessed on 01 Aug 2026
- 33) N. N. Bhargava & D. C. Kulshreshtha (1983). [Basic Electronics & Linear Circuits](#). Tata McGraw-Hill Education. p. 90. [ISBN 978-0-07-451965-3](#), accessed on 01 Aug 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 34) <https://www.woodmac.com/market-insights/power-and-renewables/discover-global-power-and-renewables-insights/>, accessed on 01 Aug 2026
- 35) https://alumni.media.mit.edu/~nate/AES/PV_Theory_II.pdf, accessed on 01 Aug 2026
- 36) Teixeira, Bernardo; Centeno Brito, Miguel; Mateus, Antonio (2024). ["Raw materials for the Portuguese decarbonization roadmap: The case of solar photovoltaics and wind energy"](#). Resources Policy. 90 (104839) 104839, doi:10.1016/j.resourpol.2024.104839, accessed on 01 Aug 2026
- 37) Patrick (15 August 2024). ["Bifacial tracking systems dominate utility-scale PV market"](#). pv magazine International, accessed on 01 Aug 2026
- 38) Grau-Luque, Enric; Antonanzas-Torres, Fernando; Escobar, Rodrigo (15 October 2018). ["Effect of soiling in bifacial PV modules and cleaning schedule optimization"](#). Energy Conversion and Management. 174: 615–625, doi:10.1016/j.enconman.2018.08.065, accessed on 03 Aug 2026
- 39) Green, M. A. (2001). "Third generation photovoltaics: Ultra-high conversion efficiency at low cost". Progress in Photovoltaics: Research and Applications. 9 (2): 123–135. doi:10.1002/pip.360, accessed on 03 Aug 2026
- 40) Martí, A.; Luque, A. (1 September 2003). [Next Generation Photovoltaics: High Efficiency through Full Spectrum Utilization](#). CRC Press. ISBN 978-1-4200-3386-1, accessed on 03 Aug 2026
- 41) López, Antonio Luque; Andreev, Viacheslav M. (2007). [Past Experiences and New Challenges of PV Concentrators](#), G Sala and A Luque, Springer Series in Optical Sciences 130, 1, (2007). Vol. 130. doi:10.1007/978-3-540-68798-6. ISBN 978-3-540-68796-2, accessed on 03 Aug 2026
- 42) Henini, M (December 1999). ["Properties of Lattice-matched and Strained Indium Gallium Arsenide by P. Bhattacharya \(Ed.\). London: INSPEC, the Institution of Electrical Engineers, ISBN 0-85296-865-5; Properties of Indium Phosphide, London: INSPEC, the Institution of Electrical Engineers, ISBN 0-85296-491-9; Properties of Aluminium Gallium Arsenide by S. Adachi \(Ed.\). London: INSPEC, the Institution of Electrical Engineers, ISBN 0-85296-558-3"](#). Microelectronics Journal. 30 (12): 1273–1274. doi:10.1016/s0026-2692(99)00043-9, accessed on 03 Aug 2026
- 43) Chapin, D. M.; Fuller, C. S.; Pearson, G. L. (1954). "A New Silicon p–n Junction Photocell for Converting Solar Radiation into Electrical Power". Journal of Applied Physics. 25 (5): 676–677, doi:10.1063/1.1721711, accessed on 03 Aug 2026
- 44) Joern Hoppmann; Jonas Volland; Tobias S. Schmidt; Volker H. Hoffmann (July 2014). ["The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model"](#). Renewable and Sustainable Energy Reviews. 39: 1101–1118, accessed on 03 Aug 2026
- 45) <https://www.bernreuter.com/files/data/polysilicon/industry-reports/Solar-Silicon-Report-Info.pdf>, accessed on 03 Aug 2026
- 46) Milman, Oliver (2024-04-06). ["Scientists confirm record highs for three most important heat-trapping gases"](#). The Guardian. ISSN 0261-3077, accessed on 03 Aug 2026
- 47) <https://www.renewableenergyworld.com/rea/blog/post/2010/04/the-worst-metric-in-renewables-the-payback-period>, accessed on 03 Aug 2026
- 48) https://web.archive.org/web/20141001012612/http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf, accessed on 03 Aug 2026
- 49) [file:///C:/Users/Lenovo/Downloads/Photovoltaics-Report%20\(1\).pdf](file:///C:/Users/Lenovo/Downloads/Photovoltaics-Report%20(1).pdf), accessed on 03 Aug 2026
- 50) Feldman, David; Dummit, Krysta; Jarett, Zuboy; Margolis, Robert (12 July 2022). ["Summer 2022 Solar Industry Update"](#) (PDF). National Renewable Energy Laboratory, accessed on 03 Aug 2026
- 51) <https://seia.org/research-resources/us-solar-market-insight/>, accessed on 03 Aug 2026
- 52) <https://www.iea.org/reports/renewables-2023/executive-summary/>, accessed on 03 Aug 2026
- 53) <https://www.energymatters.com.au/panels-modules/>, accessed on 03 Aug 2026
- 54) ["April 25, 1954: Bell Labs Demonstrates the First Practical Silicon Solar Cell"](#). APS News. 18 (4). American Physical Society. April 2009, accessed on 03 Aug 2026
- 55) Meyers, Glenn (December 31, 2014). ["Photovoltaic Dreaming 1875-1905: First Attempts At Commercializing PV"](#). CleanTechnica. Archived from [the original](#) on June 9, 2018, accessed on 03 Aug 2026
- 56) Cropper, Maureen; Cui, Ryna; Guttikunda, Sarath; Hultman, Nate; Jawahar, Puja; Park, Yongjoon; Yao, Xinlu; Song, Xiao-Peng (2 February 2021). ["The mortality impacts of current and planned coal-fired power plants in India"](#). Proceedings of the National Academy of Sciences. 118 (5) e2017936118, accessed on 03 Aug 2026
- 57) <https://www.wri.org/insights/growth-renewable-energy-sector-explained>, accessed on 03 Aug 2026
- 58) <https://web.archive.org/web/20170806162250/https://www.seia.org/research-resources/solar-industry-data>,

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 59) <https://web.archive.org/web/20131213194550/https://www.energy.ca.gov/2007publications/CEC-500-2007-048/CEC-500-2007-048.PDF>, accessed on 03 Aug 2026
- 60) https://backwoodssolar.com/catalog/Spec_Sheets/SolarWorld_245_Spec.pdf, accessed on 03 Aug 2026
- 61) <https://web.archive.org/web/20250615183248/https://www.greentechmedia.com/articles/read/Solar-Module-OEMs-Seeking-Advantage-with-Inverter-Electronics>, accessed on 03 Aug 2026
- 62) <https://web.archive.org/web/20120812095050/https://www.tigoenergy.com/press-releases/leading-solar-module-oems-display-next-generation-tigo-energy-technology-during-pv>, accessed on 03 Aug 2026
- 63) <https://evoenergy.co.uk/news-updates/a-comprehensive-guide-to-monocrystalline-solar-panels-construction-efficiency-and-performance/>, accessed on 03 Aug 2026
- 64) <https://evoenergy.co.uk/news-updates/the-advantages-of-flexible-solar-panels-for-industrial-applications/>, accessed on 03 Aug 2026
- 65) https://iea-pvps.org/wp-content/uploads/2023/04/IEA_PVPS_Snapshot_2023.pdf,
- 66) Jaeger, Joel (20 September 2021). ["Explaining the Exponential Growth of Renewable Energy"](#), accessed on 03 Aug 2026
- 67) <https://www.theatlantic.com/science/archive/2024/10/solar-power-energy-revolution-global-south/680351/>, accessed on 03 Aug 2026
- 68) https://web.archive.org/web/20140625154728/http://www.epia.org/fileadmin/user_upload/Publications/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf, accessed on 03 Aug 2026
- 69) Joern Hoppmann; Jonas Volland; Tobias S. Schmidt; Volker H. Hoffmann (July 2014). ["The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model"](#). Renewable and Sustainable Energy Reviews. 39: 1101–1118, accessed on 03 Aug 2026
- 70) <http://helioscsp.com/concentrated-solar-power-had-a-global-total-installed-capacity-of-6451-mw-in-2019/>, accessed on 03 Aug 2026
- 71) <https://www.iea.org/reports/solar-pv-global-supply-chains>, accessed on 03 Aug 2026
- 72) <https://www.quora.com/What-are-the-advantages-and-disadvantages-of-flexible-solar-panels-compared-to-fixed-solar-panels>, accessed on 03 Aug 2026
- 73) <https://nexioprojects.com/what-is-net-zero/>, accessed on 26 Aug 2026
- 74) https://www.linkedin.com/posts/haribhagat-singh-bais-3b2959227_evolution-of-solar-pv-modules-from-early-activity-7364303314634661888-TXcb, accessed on 03 Aug 2026
- 75) <https://www.renewableenergyhub.co.uk/main/solar-panels/the-future-of-solar-panel-technology>, accessed on 03 Aug 2026
- 76) <https://www.cleanenergyreviews.info/solar-panel-failure-degradation>, accessed on 03 Aug 2026
- 77) <https://www.cleanenergyreviews.info/blog/best-quality-solar-panels-manufacturers>, accessed on 03 Aug 2026
- 78) Karl W. Boer (6 December 2012). [Advances in Solar Energy: An Annual Review of Research and Development, Volume 1 · 1982](#). Springer Science & Business Media. pp. 153–. ISBN 978-1-4684-8992-7, accessed on 03 Aug 2026
- 79) Zulehner, Werner; Neuer, Bernd; Rau, Gerhard. "Silicon". [Ullmann's Encyclopedia of Industrial Chemistry](#). Weinheim: Wiley-VCH. doi:10.1002/14356007.a23_721. ISBN 978-3-527-30673-2, accessed on 03 Aug 2026
- 80) Lv, Qinghui; Yuan, Xingping; Guo, Lijie; Zhao, Dan; Ma, Wenhui; Xie, Gang; Hou, Yanqing; Shen, Jinglei; Yang, Ni (May 2025). "Advances in production and optimization of electronic-grade polysilicon: A review of modified Siemens and silane methods". Solar Energy Materials and Solar Cells. 283 113446, doi:10.1016/j.solmat.2025.113446, accessed on 03 Aug 2026
- 81) Stuart Dowell. ["Scientist who laid the foundations for Silicon Valley honoured at long last"](#). thefirstnews.com. Archived from [the original](#) on 13 July 2023, accessed on 03 Aug 2026
- 82) Nishinaga, Tatau (2015). Handbook of Crystal Growth: Fundamentals (Second ed.). Amsterdam, the Netherlands: Elsevier B.V. p. 21. ISBN 978-0-444-56369-9, accessed on 03 Aug 2026
- 83) Vesselinka Petrova-Koch (2009). [High-Efficient Low-Cost Photovoltaics: Recent Developments](#). Springer Science & Business Media. pp. 47–. ISBN 978-3-540-79358-8, accessed on 03 Aug 2026
- 84) http://www.appropedia.org/LCA_of_silicon_PV_panels, accessed on 03 Aug 2026
- 85) <https://www.pveducation.org/pvcdrom/pn-junctions/formation-of-a-pn-junction>, accessed on 03 Aug 2026
- 86) <https://www.cleanenergyreviews.info/blog/latest-solar-panel-cell-technology>, accessed on 03 Aug 2026
- 87) <https://www.bernreuter.com/polysilicon/production-processes/>, accessed on 03 Aug 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 88) <https://web.archive.org/web/20150102020609/http://www.nyecospaces.com/2007/09/photovoltaics-getting-cheaper.html>, accessed on 03 Aug 2026
- 89) <https://news.metal.com/newscontent/101647120-photovoltaic-demand-drives-the-highest-price-of-trichlorosilane-to-reach-40000-per-ton-of-supply-shortage-support-contin>, accessed on 03 Aug 2026
- 90) <https://www.wsj.com/articles/SB114624912379938991>, accessed on 03 Aug 2026
- 91) <https://taiyangnews.info/technology/so-many-backsheet-structure>, accessed on 03 Aug 2026
- 92) <https://www.cleanenergyreviews.info/blog/solar-panel-shading-problems-bypass-diodes-optimisers>, accessed on 03 Aug 2026
- 93) <https://www.positronicsolar.com.au/2019/08/02/panels-shade-and-diodes/>, accessed on 03 Aug 2026
- 94) <https://www.cityu.edu.hk/phy/appkchu/AP6120/2.PDF>, accessed on 03 Aug 2026
- 95) www.electrical4u.com, accessed on 03 Aug 2026
- 96) <https://www.cleanenergyreviews.info/solar-panel-failure-degradation>, accessed on 03 Aug 2026
- 97) <https://www.cleanenergyreviews.info/solar-panel-warranty>, accessed on 03 Aug 2026
- 98) <https://www.cleanenergyreviews.info/solar-panel-failure-degradation>, accessed on 07 Aug 2026
- 99) Ibid
- 100) Horowitz, Kurt; Woodhouse, Michael (1 October 2015). ["Current Status of Concentrator Photovoltaic \(CPV\) Technology"](#) (PDF). National Renewable Energy Laboratory, accessed on 07 Aug 2026
- 101) <https://www.newscientist.com/article/2076599-space-solar-the-global-race-to-tap-the-suns-energy-from-orbit/>, accessed on 07 Aug 2026
- 102) <https://www.sfedssolar.com/news/Explore-the-Advantages-of-Flexible-Solar-Panels.html>, accessed on 07 Aug 2026
- 103) Rajinder Sharma (July 2019). "Effect of obliquity of incident light on the performance of silicon solar cells". Heliyon. 5 (7) e01965, [doi:10.1016/j.heliyon.2019.e01965](https://doi.org/10.1016/j.heliyon.2019.e01965), accessed on 07 Aug 2026
- 104) Janakeeraman, Suryanarayana Vasantha (May 2013). [Angle of Incidence And Power Degradation Analysis of Photovoltaic Modules](#) (PDF) (MSt). Arizona State University, accessed on 07 Aug 2026
- 105) https://www.ul.com/sites/default/files/2019-05/AlternativeEnergy_EquipmentandSystemsMarking_AG_2016.pdf, accessed on 07 Aug 2026
- 106) <https://www.solarpaneltilt.com/>, accessed on 07 Aug 2026
- 107) <https://www.facebook.com/engineeringexploration/posts/japan-is-advancing-flexible-solar-cell-technology-that-could-allow-clean-energy-/1039439018629679/>, accessed on 07 Aug 2026
- 108) <https://www.cleanenergyreviews.info/solar-panels/how-solar-panels-work>, accessed on 07 Aug 2026
- 109) <https://evoenergy.co.uk/news-updates/the-advantages-of-flexible-solar-panels-for-industrial-applications/>, accessed on 07 Aug 2026
- 110) ye, Gøran; Ceccaroli, Bruno (November 2014). "Solar grade silicon: Technology status and industrial trends". Solar Energy Materials and Solar Cells. 130: 634–646, [doi:10.1016/j.solmat.2014.06.019](https://doi.org/10.1016/j.solmat.2014.06.019), accessed on 07 Aug 2026
- 111) Feldman, David; Dummit, Krysta; Jarett, Zuboy; Margolis, Robert (July 12, 2022). ["Summer 2022 Solar Industry Update"](#) (PDF). [National Renewable Energy Laboratory](#), accessed on 07 Aug 2026
- 112) Bauhuis, G. J.; Mulder, P.; Schermer, J. J.; Haverkamp, E. J.; Deelen, J. van; Larsen, P. K. (2005). ["High Efficiency Thin Film GaAs Solar Cells With Improved Radiation Hardness"](#). 20th European Photovoltaic Solar Energy Conference: 468–471, accessed on 07 Aug 2026
- 113) <https://news.mit.edu/2016/ultrathin-flexible-solar-cells-0226>, accessed on 07 Aug 2026
- 114) Kangsabanik, Jiban; Svendsen, Mark Kamper; Taghizadeh, Alireza; Crovetto, Andrea; Thygesen, Kristian S. (November 2, 2022). ["Indirect Band Gap Semiconductors for Thin-Film Photovoltaics: High-Throughput Calculation of Phonon-Assisted Absorption"](#). Journal of the American Chemical Society. 144 (43): 19872–19883, [doi:10.1021/jacs.2c07567](https://doi.org/10.1021/jacs.2c07567), accessed on 07 Aug 2026
- 115) Fthenakis, Vasilis M. (2004). ["Life cycle impact analysis of cadmium in CdTe PV production"](#) (PDF). Renewable and Sustainable Energy Reviews. 8 (4): 303–334. [Bibcode:2004RSERv...8..303F](#). [doi:10.1016/j.rser.2003.12.001](https://doi.org/10.1016/j.rser.2003.12.001)
- 116) <https://www.bbc.com/news/business-49344595>, accessed on 07 Aug 2026
- 117) <https://web.archive.org/web/20190806121659/https://www.helicalpower.com/>, accessed on 07 Aug 2026
- 118) <https://web.archive.org/web/20210305031224/https://pulsesolar.com.au/longi-who-are-they-and-why-do-we-use-them>, accessed on 07 Aug 2026
- 119) <https://www.engineeringchallenges.org/cms/8996/9082.aspx>, accessed on 07 Aug 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 120) <https://web.archive.org/web/20151002211024/http://www.solarcity.com/newsroom/press/solarcity-unveils-world%E2%80%99s-most-efficient-rooftop-solar-panel-be-made-america>, accessed on 07 Aug 2026
- 121) <https://www.pv-tech.org/editors-blog/top-10-solar-module-suppliers-in-2018>, accessed on 07 Aug 2026
- 122) David, Nguyen (5 January 2020). "[Solar Panels Produce Tons of Toxic Waste—Literally](#)". American Experiment, accessed on 07 Aug 2026
- 123) https://www.ijstm.com/images/short_pdf/1415296203_P25-31.pdf, accessed on 07 Aug 2026
- 124) Dickie, P.M. (1999). [Regional Workshop on Solar Power Generation Using Photovoltaic Technology](#). DIANE publishing. p. 120. [ISBN 978-0-7881-8264-8](#), accessed on 07 Aug 2026
- 125) Hough, T.P. (2006). [Trends in solar energy research](#). Nova. p. 98. [ISBN 978-1-59454-866-6](#), accessed on 07 Aug 2026
- 126) Parra, Vicente; Gómez, Ruperto (September 2018). "[Implementing risk mitigation strategies through module factory and production inspections](#)". PV Tech. 16: 25–28, accessed on 07 Aug 2026
- 127) <https://www.intertek.com/building/standards/ul-1703/>, accessed on 07 Aug 2026
- 128) <https://webstore.iec.ch/en/publication/62135>, accessed on 07 Aug 2026
- 129) <https://webstore.iec.ch/en/publication/75156>, accessed on 19 Aug 2026
- 130) <https://webstore.iec.ch/en/publication/59588>, accessed on 19 Aug 2026
- 131) <https://webstore.iec.ch/en/publication/59803>, accessed on 19 Aug 2026
- 132) Helmers, Henning; Höhn, Oliver; Lackner, David; Schygulla, Patrick; Klitzke, Malte; Schön, Jonas; Pellegrino, Carmine; Oliva, Eduard; Schachtner, Michael; Beutel, Paul; Heckelmann, Stefan; Predan, Felix; Ohlmann, Jens; Siefer, Gerald; Dimroth, Frank (8 March 2024). "[Advancing solar energy conversion efficiency to 47.6% and exploring the spectral versatility of III-V photonic power converters](#)". In Freundlich, Alexandre; Hinzer, Karin; Collin, Stéphane; Sellers, Ian R. (eds.). Physics, Simulation, and Photonic Engineering of Photovoltaic Devices XIII. SPIE Proceedings. Vol. 12881. p. 1288103, accessed on 19 Aug 2026
- 133) France, Ryan M.; Geisz, John F.; Song, Tao; Olavarria, Waldo; Young, Michelle; Kibbler, Alan; Steiner, Myles A. (18 May 2022). "Triple-junction solar cells with 39.5% terrestrial and 34.2% space efficiency enabled by thick quantum well superlattices". Joule. 6 (5): 1121–1135, [doi:10.1016/j.joule.2022.04.024](#), accessed on 19 Aug 2026
- 134) Ulanoff, Lance (2 October 2015). "[Elon Musk and SolarCity unveil 'world's most efficient' solar panel](#)". [Mashable](#), accessed on 19 Aug 2026
- 135) National Renewable Energy Laboratory (12 April 2024). "[Photovoltaic Module Efficiency Records](#)". National Renewable Energy Laboratory, accessed on 19 Aug 2026
- 136) <https://web.archive.org/web/20140701144231/http://us.sunpower.com/homes/products-services/solar-panels/e-series/>, accessed on 19 Aug 2026
- 137) https://www.panasonic.com/business/pesna/includes/pdf/eco-construction-solution/HIT_Power_220A_Datasheet.pdf, accessed on 19 Aug 2026
- 138) Shahan, Zachary (13 June 2026). "[Most Efficient Solar Module in the World — New Record](#)". CleanTechnica, accessed on 19 Aug 2026
- 139) Kumar, Ankush (3 January 2017). "Predicting efficiency of solar cells based on transparent conducting electrodes". Journal of Applied Physics. 121 (1): 014502, [doi:10.1063/1.4973117](#). [ISSN 0021-8979](#), accessed on 19 Aug 2026
- 140) Orcutt, Mike. "[Managing Light To Increase Solar Efficiency](#)". MIT Technology Review. Archived from [the original](#) on 20 February 2016, accessed on 19 Aug 2026
- 141) Dunlop, James P. (2012). Photovoltaic systems. National Joint Apprenticeship and Training Committee for the Electrical Industry (3rd ed.). Orland Park, IL: American Technical Publishers, Inc. [ISBN 978-1-935941-05-7](#), accessed on 19 Aug 2026
- 142) Michael Boxwell, Solar Electricity Handbook: A Simple, Practical Guide to Solar Energy (2012), pp. 41–42, accessed on 19 Aug 2026
- 143) <https://www.pveducation.org/pvcdrom/modules-and-arrays/bypass-diodes>, accessed on 19 Aug 2026
- 144) <https://electricalschool.org/open-circuitvoltagebattery/>, accessed on 19 Aug 2026
- 145) https://web.archive.org/web/20131029200512/http://www.trinasolar.com/images/PDF/datasheets/us/TSM-PA14_US.pdf, accessed on 19 Aug 2026
- 146) <https://web.archive.org/web/20190109155544/https://www.lubisolar.com/wp-content/uploads/2018/03/Poly-260-275W.pdf>, accessed on 19 Aug 2026
- 147) <https://energyinformative.org/>, accessed on 19 Aug 2026
- 148) Proceedings of the 35th IEEE PVSC 20–25 June 2010 pp. 2817–2822, accessed on 19 Aug 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 149) <https://www.solarplaza.com/resource/11674/potential-induced-degradation-combatting-phantom-menace/>, accessed on 19 Aug 2026
- 150) https://web.archive.org/web/20150414054132/http://www2.jpl.nasa.gov/adv_tech/photovol/ppr_81-85/Pred%20Electrochem%20Breakdown%20-%20PVSC1984.pdf, accessed on 19 Aug 2026
- 151) Jordan, Dirk C.; Kurtz, Sarah R. (1 November 2012). ["Photovoltaic Degradation Rates — An Analytical Review"](#) (PDF). National Renewable Energy Laboratory, accessed on 19 Aug 2026
- 152) Piliouguine, M.; Oukaja, A.; Sánchez-Friera, P.; Petrone, G.; Sánchez-Pacheco, J.F.; Spagnuolo, G.; Sidrach-de-Cardona, M. (2021). "Analysis of the degradation of single-crystalline silicon modules after 21 years of operation". *Progress in Photovoltaics: Research and Applications*. 29 (8). *Progress in Photovoltaics*: 907–919. doi:10.1002/pip.3409, accessed on 19 Aug 2026
- 153) Piliouguine, M.; Oukaja, A.; Sidrach-de-Cardona, M.; Spagnuolo, G. (2022). "Analysis of the degradation of amorphous silicon-based modules after 11 years of exposure by means of IEC60891:2021 procedure 3". *Progress in Photovoltaics: Research and Applications*. 30 (10). *Progress in Photovoltaics*: 1176–1187. doi:10.1002/pip.3567, accessed on 19 Aug 2026
- 154) Piliouguine, M.; Sánchez-Friera, P.; Petrone, G.; Sánchez-Pacheco, J.F.; Spagnuolo, G.; Sidrach-de-Cardona, M. (2022). "New model to study the outdoor degradation of thin-film photovoltaic modules". *Renewable Energy*. 193: 857–869, doi:10.1016/j.renene.2022.05.063, accessed on 22 Aug 2026
- 155) Crawford, Mike (October 2012). ["Self-Cleaning Solar Panels Maximize Efficiency"](#). The American Society of Mechanical Engineers. ASME, accessed on 22 Aug 2026
- 156) Ilse K, Micheli L, Figgis BW, Lange K, Dassler D, Hanifi H, Wolfertstetter F, Naumann V, Hagendorf C, Gottschalg R, Bagdahn J (2019). ["Techno-Economic Assessment of Soiling Losses and Mitigation Strategies for Solar Power Generation"](#). *Joule*. 3 (10): 2303–2321. Bibcode:2019Joule...3.2303I. doi:10.1016/j.joule.2019.08.019, accessed on 22 Aug 2026
- 157) Crawford, Mike (October 2012). ["Self-Cleaning Solar Panels Maximize Efficiency"](#). The American Society of Mechanical Engineers. ASME. Retrieved 15 September 2014, accessed on 22 Aug 2026
- 158) Patringenaru, Ioana (August 2013). ["Cleaning Solar Panels Often Not Worth the Cost, Engineers at UC San Diego Find"](#). UC San Diego News Center. Retrieved 31 May 2015, accessed on 22 Aug 2026
- 159) <https://www.gov.uk/government/publications/fire-incidents-involving-solar-panels>, accessed on 22 Aug 2026
- 160) <https://www.pv-tech.org/solar-module-failure-rates-continue-to-rise-as-record-number-of-manufacturers-recognised-in-pvel-module-reliability-scorecard/>, accessed on 22 Aug 2026
- 161) Alshehri, Ali; Parrott, Brian; Outa, Ali; Amer, Ayman; Abdellatif, Fadl; Trigui, Hassane; Carrasco, Pablo; Patel, Sahejad; Taie, Ihsan (December 2014). "Dust mitigation in the desert: Cleaning mechanisms for solar panels in arid regions". 2014 Saudi Arabia Smart Grid Conference (SASG). pp. 1–6. doi:10.1109/SASG.2014.7274289, accessed on 22 Aug 2026
- 162) American Associates, Ben-Gurion University of the Negev (9 December 2019). ["Researchers develop new method to remove dust on solar panels"](#). *Ben-Gurion University of the Negev*, accessed on 22 Aug 2026
- 163) Heckenthaler, Tabea; Sadhujan, Sumesh; Morgenstern, Yakov; Natarajan, Prakash; Bashouti, Muhammad; Kaufman, Yair (3 December 2019). "Self-Cleaning Mechanism: Why Nanotexture and Hydrophobicity Matter". *Langmuir*. 35 (48): 15526–15534. doi:10.1021/acs.langmuir.9b01874, accessed on 22 Aug 2026
- 164) <https://news.mit.edu/2022/solar-panels-dust-magnets-0311>, accessed on 22 Aug 2026
- 165) Kaltenbrunner, M., et al. (2015). Ultrathin and lightweight organic solar cells with high flexibility. *Nature Communications*, 6, 7702, accessed on 22 Aug 2026
- 166) Zhao, Y., & Zhu, K. (2016). Organic–inorganic hybrid lead halide perovskites for optoelectronic applications. *Chemical Society Reviews*, 45(3), 655–689, accessed on 22 Aug 2026
- 167) <https://www.ecoflow.com/us/blog/what-are-the-most-efficient-solar-panels>, accessed on 22 Aug 2026
- 168) International Technology Roadmap for Photovoltaics. (2024). *ITRPV Report 2024*. <https://itrpv.vdma.org>,
- 169) <https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2025-2029/detail>, accessed on 22 Aug 2026
- 170) Correa-Baena, J. P., Saliba, M., Buonassisi, T., Grätzel, M., Abate, A., Tress, W., & Hagfeldt, A. (2017). Promises and challenges of perovskite solar cells. *Science*, 358(6364), 739–744, accessed on 22 Aug 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 171) Miller, Wendy; Liu, Aaron; Amin, Zakaria; Wagner, Andreas (2018). ["Power Quality and Rooftop-Photovoltaic Households: An Examination of Measured Data at Point of Customer Connection"](#). Sustainability. 10 (4): 1224, doi:10.3390/su10041224, accessed on 22 Aug 2026
- 172) Paulos, Bentham; Barbose, Galen; Gorman, Will (28 September 2022). ["Could solar and batteries power your home when the electricity grid goes out?"](#). The Conversation, accessed on 22 Aug 2026
- 173) <https://www.photoncycle.com/en/news/7-common-challenges-when-investing-in-solar-panels/>, accessed on 28 Aug 2026
- 174) Cui, F. Research on Future Development and Challenges of New Energy. Adv. Econ. Manag. Polit. Sci. 2025, 162, 66–72, accessed on 28 Aug 2026
- 175) Barasa Kabeyi, M.J.; Olanrewaju, O.A. Solar Energy as a Sustainable Energy for Power Generation. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Melbourne, Australia, 14–16 November 2023; IEOM Society International: Southfield, MI, USA, 2023, accessed on 28 Aug 2026
- 176) Arvizu, D.; Balaya, P.; Cabeza, L.F.; Hollands, K.G.T.; Jäger-Waldau, A.; Kondo, M.; Konseibo, C.; Meleshko, V.; Stein, W.; Tamaura, Y.; et al. Direct Solar Energy. In Renewable Energy Sources and Climate Change Mitigation; Cambridge University Press: Cambridge, UK, 2011; pp. 333–400, accessed on 28 Aug 2026
- 177) <https://www.inverter.com/what-are-the-applications-of-solar-panels>, accessed on 28 Aug 2026
- 178) https://www.researchgate.net/publication/395081826_Utilization_of_Solar_Panels_in_Various_Applications_A_Systematic_Literature_Review, accessed on 28 Aug 2026
- 179) Jairam, Y.; Kumar, U.V.; Rajesh, Y.; Surya, K.S.; Simhadri, M.K. A REVIEW OF Solar Panel Efficiency: The Influence of Installation Angles and Design. Int. J. Sci. Res. Eng. Manag. 2024, 8, 1–7, accessed on 28 Aug 2026
- 180) Badran, G.; Dhimish, M. A comparative study of bifacial versus monofacial PV systems at the UK's largest solar plant. Clean Energy 2024, 8, 248–260, accessed on 28 Aug 2026
- 181) Akinyemi, T.O.; Ramonu, O.J. Mitigation of CO₂ Emissions in Transportation and Industrial Processes using Renewable Energy Technologies. Eur. J. Eng. Technol. Res. 2019, 4, 58–66, accessed on 28 Aug 2026
- 182) <https://www.mdpi.com/2673-4591/107/1/33>, accessed on 28 Aug 2026
- 183) Shukir, S.S. (On-Grid) Solar System Designing with a Capacity of 10kw. J. Altern. Renew. Energy Sources 2022, 8, 9–12, accessed on 28 Aug 2026
- 184) Barasa Kabeyi, M.J.; Olanrewaju, O.A. Solar Energy as a Sustainable Energy for Power Generation. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Melbourne, Australia, 14–16 November 2023; IEOM Society International: Southfield, MI, USA, 2023, accessed on 28 Aug 2026
- 185) Barrera, N.A.G.; González, D.C.P.; Mesa, F.; Aristizábal, A.J. Procedure for the practical and economic integration of solar PV energy in the city of Bogotá. Energy Rep. 2021, 7, 163–180, accessed on 28 Aug 2026
- 186) Minak, G.; Lukovic, M.; Maglio, S.; Kojic, S. Toward a sustainable mobility: A solar vehicle for a new quality of life. IOP Conf. Ser. Mater. Sci. Eng. 2019, 659, 01207, accessed on 28 Aug 2026
- 187) <https://www.nlr.gov/pv/applications>, accessed on 05 Sep 2026
- 188) Arieffadillah, M.F.; Kumara, I.N.S.; Divayana, Y. The Development of Solar PV Car to Reduce Carbon Emissions from Transport Sector. J. Electr. Electron. Inform. 2021, 5, 10, accessed on 05 Sep 2026
- 189) Owolabi, O.F.; Ogundipe, D.S.; Makinde, P. Integration of renewable energy-powered cold storage solutions for reducing post-harvest food waste in rural agricultural areas. World J. Adv. Res. Rev. 2024, 24, 1829–183, accessed on 05 Sep 2026
- 190) <https://www.bluettipower.com/blogs/news/portable-solar-power-for-remote-research-energy-solutions-for-field-work>, accessed on 05 Sep 2026
- 191) Taboada, H.; Xiong, Z.; Jin, T.; Jimenez, J. Exploring a solar photovoltaic-based energy solution for green manufacturing industry. In Proceedings of the 2012 IEEE International Conference on Automation Science and Engineering (CASE), Seoul, Republic of Korea, 20–24 August 2012; pp. 40–45, accessed on 05 Sep 2026
- 192) <https://www.sciencedirect.com/science/article/pii/S2667113125000221>, accessed on 05 Sep 2026
- 193) Kishore, A.; Shah, T.; Tewari, N.P. Solar irrigation pumps: Farmers' experience and state policy in Rajasthan. Econ. Polit. Wkly. 2014, 49, 55–62, accessed on 05 Sep 2026
- 194) https://www.researchgate.net/publication/395081826_Utilization_of_Solar_Panels_in_Various_Applications_A_Systematic_Literature_Review, accessed on 05 Sep 2026
- 195) <https://www.sciencedirect.com/science/article/abs/pii/S0927024825006762>, accessed on 05 Sep 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 196) Balode, L.; Dolge, K.; Blumberga, D. Sector-Specific Pathways to Sustainability: Unravelling the Most Promising RenewableEnergy Options. Sustainability 2023, 15, 1263, accessed on 05 Sep 2026
- 197) Balode, L.; Dolge, K.; Blumberga, D. Sector-Specific Pathways to Sustainability: Unravelling the Most Promising RenewableEnergy Options. Sustainability 2023, 15, 12636, accessed on 05 Sep 2026
- 198) <https://www.sciencedirect.com/science/article/abs/pii/S0927024825006762>, accessed on 05 Sep 2026
- 199) Almoghira, G.; Hussein, A.A. A Review of Solar Energy Applications in Transportation Sector. In Proceedings of the 2024 6thInternational Symposium on Advanced Electrical and Communication Technologies (ISAECT), Alkhobar, Saudi Arabia, 3–5December 2024; pp. 1–5, accessed on 05 Sep 2026
- 200) <https://docs.nlr.gov/docs/fy26osti/99933.pdf>, accessed on 05 Sep 2026
- 201) <https://evoenergy.co.uk/sectors/factories-manufacturing-facilities/>, accessed on 22 Aug 2026
- 202) <https://sono-solar.com>, accessed on 22 Aug 2026
- 203) <https://evoenergy.co.uk/sectors/transport-and-logistics/>, accessed on 22 Aug 2026
- 204) National Renewable Energy Laboratory. (2024). *Best research-cell efficiency chart*. <https://www.nrel.gov/pv/cell-efficiency.html>, accessed on 22 Aug 2026
- 205) ¹ Joern Hoppmann; Jonas Volland; Tobias S. Schmidt; Volker H. Hoffmann (July 2014). "[The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model](#)". Renewable and Sustainable Energy Reviews. 39: 1101–1118, accessed on 22 Aug 2026
- 206) <https://www.livescience.com/37821-greenhouse-gases.html>, accessed on 22 Aug 2026
- 207) https://www.rsc.org/images/Arrhenius1896_tcm18-173546.pdf, accessed on 22 Aug 2026
- 208) <https://www.space.com/17683-earth-atmosphere.html>, accessed on 22 Aug 2026
- 209) <https://science.nasa.gov/earth/earth-observatory/global-warming/>, accessed on 22 Aug 2026
- 210) <https://www.livescience.com/tag/nasa>, accessed on 22 Aug 2026
- 211) <https://www.epa.gov/ghgemissions/overview-greenhouse-gases>, accessed on 22 Aug 2026
- 212) <https://www.epa.gov/ghgemissions/understanding-global-warming-potential/>, accessed on 22 Aug 2026
- 213) ¹ <https://www.sciencedirect.com/topics/engineering/energy-payback-time>, accessed on 22 Aug 2026
- 214) S.M. Parsa, A. Rahbar, M.H. Kolehini, S. Aberoumand, M. Afrand, M. Amidpour, (2020), A renewable energy-driven thermoelectric-utilized solar still with external condenser loaded by silver/nanofluid for simultaneously water disinfection and desalination, Desalination, 480 (2020), Article 114354, accessed on 22 Aug 2026
- 215) <https://www.sciencedirect.com/science/article/pii/S1364032123005208>, accessed on 29 Aug 2026
- 216) <https://www.sciencedirect.com/science/article/pii/S2352484721004066>, accessed on 29 Aug 2026
- 217) <https://www.sciencedirect.com/science/article/abs/pii/S0360544224007746>, accessed on 29 Aug 2026
- 218) <https://www.sciencedirect.com/science/article/pii/S2666386423000462>, accessed on 29 Aug 2026
- 219) <https://www.sciencedirect.com/science/article/abs/pii/S2590116820300333>, accessed on 29 Aug 2026
- 220) <https://www.sciencedirect.com/science/article/abs/pii/S136655451830485X>, accessed on 29 Aug 2026
- 221) P. Barman et al., (2023), [Renewable energy integration with electric vehicle technology: a review of the existing smart charging approaches](#), Renew Sustain Energy Rev, accessed on 29 Aug 2026
- 222) <https://www.sciencedirect.com/science/chapter/monograph/pii/B9780128158012000034>, accessed on 29 Aug 2026
- 223) <https://www.sciencedirect.com/science/article/pii/S0306261917318287>, accessed on 29 Aug 2026
- 224) <https://www.sciencedirect.com/science/article/abs/pii/S0306261921013180>, accessed on 29 Aug 2026
- 225) <https://www.sciencedirect.com/science/article/pii/S136403212100931X>, accessed on 29 Aug 2026
- 226) <https://www.sciencedirect.com/science/chapter/edited-volume/abs/pii/B9780128030219000082>, accessed on 29 Aug 2026
- 227) <https://www.sciencedirect.com/science/article/abs/pii/S0959652619319304>, accessed on 29 Aug 2026
- 228) <https://www.sciencedirect.com/science/article/abs/pii/S2352152X22001700>, accessed on 29 Aug 2026
- 229) <https://www.sciencedirect.com/science/article/abs/pii/S1364032121009291>, accessed on 29 Aug 2026
- 230) Dressler, R. A.; Dahn, J. R. (March 2024). "[Investigation of The Failure Mechanisms of Li-Ion Pouch Cells with Si/Graphite Composite Negative Electrodes and Single Wall Carbon Nanotube Conducting Additive](#)". Journal of the Electrochemical Society. 171 (3): 030532, doi:10.1149/1945-7111/ad3398, accessed on 04 Sep 2026
- 231) Randall, Chris (14 October 2025). "[1.6 million NEVs: China records unprecedented electric car sales in September](#)". Electrive, accessed on 04 Sep 2026

- 232) Scott, D'Errah (15 July 2025), ["Why India's e-truck incentive scheme can be a gamechanger for the economy and the environment"](#). International Council on Clean Transportation, accessed on 04 Sep 2026
- 233) Slinger, Dan (15 September 2025). ["Airports and the Advancement of Net-Zero Aviation Innovation"](#). RMI,
- 234) <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-markets-2>, accessed on 04 Sep 2026
- 235) Balcioglu, Yavuz Selim; Sezen, Bülent; İşler, Ali Ulvi (2 September 2024). "Evolving preferences in sustainable transportation: a comparative analysis of consumer segments for electric vehicles across Europe". Social Responsibility Journal. 20 (9): 1664–1696. [doi:10.1108/SRJ-12-2023-0713](#), accessed on 09 Sep 2026
- 236) <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-the-electric-car-industry-3>, accessed on 09 Sep 2026
- 237) <https://web.archive.org/web/20140825064622/http://www.american.com/archive/2008/july-august-magazine-contents/our-electric-future/>, accessed on 09 Sep 2026
- 238) <https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work>, accessed on 09 Sep 2026
- 239) Chagas, Luciana Gomes; Jeong, Sangsik; Hasa, Ivana; Passerini, Stefano (26 June 2019). "Ionic Liquid-Based Electrolytes for Sodium-Ion Batteries: Tuning Properties To Enhance the Electrochemical Performance of Manganese-Based Layered Oxide Cathode". ACS Applied Materials & Interfaces. 11 (25): 22278–22289, [doi:10.1021/acsami.9b03813](#), accessed on 09 Sep 2026
- 240) Armand, Michel; Axmann, Peter; Bresser, Dominic; Copley, Mark; Edström, Kristina; Ekberg, Christian; Guyomard, Dominique; Lestriez, Bernard; Novák, Petr; Petranikova, Martina; Porcher, Willy; Trabesinger, Sigita; Wohlfahrt-Mehrens, Margret; Zhang, Heng (15 December 2020). "Lithium-ion batteries – Current state of the art and anticipated developments". Journal of Power Sources. 479 228708, [doi:10.1016/j.jpowsour.2020.228708](#), accessed on 04 Sep 2026
- 241) Lu, L.; Han, X.; Li, J.; Hua, J.; Ouyang, M. (2013). "A review on the key issues for lithium-ion battery management in electric vehicles". Journal of Power Sources. 226: 272–288, [doi:10.1016/j.jpowsour.2012.10.060](#), accessed on 04 Sep 2026
- 242) Adany, Ron (June 2013). "Switching algorithms for extending battery life in Electric Vehicles". Journal of Power Sources. 231: 50–59. [doi:10.1016/j.jpowsour.2012.12.075](#). [ISSN 0378-7753](#), accessed on 09 Sep 2026
- 243) <https://www.iea.org/data-and-statistics/data-product/global-ev-outlook-2023>, accessed on 09 Sep 2026
- 244) <https://insideevs.com/bloomberg-predicts-rapidly-falling-battery-prices/>, accessed on 09 Sep 2026
- 245) <https://www.sciencedirect.com/science/article/abs/pii/S2352467720303064>, accessed on 09 Sep 2026
- 246) <https://www.sciencedirect.com/science/article/abs/pii/S0360544220307878>, accessed on 09 Sep 2026
- 247) I.A. Nienhueser et al., (2016), [Economic and environmental impacts of providing renewable energy for electric vehicle charging – a choice experiment study](#), Appl Energy, accessed on 09 Sep 2026
- 248) <https://www.sciencedirect.com/science/article/abs/pii/S1364032112006557>, accessed on 09 Sep 2026
- 249) <https://www.virta.global/smart-ev-charging>, accessed on 09 Sep 2026
- 250) <https://www.virta.global/guides/overview-virta-hub-cpms>, accessed on 09 Sep 2026
- 251) <https://www.virta.global/blog/what-is-smart-charging>, accessed on 09 Sep 2026
- 252) <https://www.sciencedirect.com/science/article/abs/pii/S1364032114001920>, accessed on 09 Sep 2026
- 253) https://www.researchgate.net/publication/406141936_Renewable_Energy_Supported_Electric_Vehicle_Charging_Systems, accessed on 09 Sep 2026
- 254) <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/fossil-fuel>, accessed on 09 Sep 2026
- 255) <https://www.sciencedirect.com/topics/engineering/renewable-energy-system>, accessed on 09 Sep 2026
- 256) A.K. Karmaker et al., (2018), Feasibility assessment & design of hybrid renewable energy based electric vehicle charging station in Bangladesh, Sustain Cities Soc, accessed on 09 Sep 2026
- 257) <https://www.sciencedirect.com/science/article/abs/pii/S004579062400329X>, accessed on 10 Sep 2026
- 258) M.U. Mutarraf et al., (2022), [Electric cars, ships, and their charging infrastructure – a comprehensive review](#), Sustain Energy Technol Assess, accessed on 10 Sep 2026
- 259) S. Mateen et al., (2023), [Ultra-fast charging of electric vehicles: a review of power electronics converter, grid stability and optimal battery consideration in multi-energy systems](#), Sustain Energy Grids Netw, accessed on 10 Sep 2026
- 260) Y. Wang et al., (2020), [Electrical and thermal analyses of solar PV module by considering realistic working conditions](#), J Therm Anal Calorim, accessed on 10 Sep 2026
- 261) D.S. Ayoub et al., (2021), [Small-scale renewable polygeneration system for off-grid applications: desalination, power generation and space cooling](#), Appl Therm Eng, accessed on 10 Sep 2026
- 262) J.K. Szinai et al., (2020), [Reduced grid operating costs and renewable energy curtailment with electric vehicle charge management](#), Energy Policy, accessed on 10 Sep 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 263) M. Alhuyi-Nazari et al., (2024), [Applications of geothermal sources for absorption chillers as efficient and clean cooling technologies for buildings: a comprehensive review](#), J Build Eng, accessed on 10 Sep 2026
- 264) <https://www.sciencedirect.com/science/article/pii/S0306261916300988>, accessed on 10 Sep 2026
- 265) <https://www.sciencedirect.com/science/article/abs/pii/S1364032119308639>, accessed on 10 Sep 2026
- 266) <https://ieeexplore.ieee.org/document/10649555>, accessed on 10 Sep 2026
- 267) <https://www.pv-magazine.com/2019/10/26/the-weekend-read-a-lead-free-future-for-solar-pv/>, accessed on 10 Sep 2026
- 268) <https://pv-manufacturing.org/silicon-production/cz-monocrystalline-silicon-production/>, accessed on 10 Sep 2026
- 269) https://www.researchgate.net/publication/264672000_Life_Cycle_Analysis_LCA_of_photovoltaic_panels_A_review, accessed on 11 Sep 2026
- 270) <https://sinovoltaics.com/solar-basics/solar-cell-production-from-silicon-wafer-to-cell/>, accessed on 11 Sep 2026
- 271) <https://pvcycle.org/homepage>, accessed on 11 Sep 2026
- 272) Holger, Dieter (5 May 2022). ["The Solar Boom Will Create Millions of Tons of Junk Panels". The Wall Street Journal. ISSN 0099-9660](#), accessed on 11 Sep 2026
- 273) <https://www.sciencedaily.com/releases/2023/03/230328145425.htm>, accessed on 11 Sep 2026
- 274) <https://e360.yale.edu/features/solar-energy-panels-recycling>, accessed on 11 Sep 2026
- 275) Krueger, Lisa. ["Overview of First Solar's Module Collection and Recycling Program"](#) (PDF). [Brookhaven National Laboratory](#). p. 23, accessed on 11 Sep 2026
- 276) Stone, Maddie (22 August 2020). ["Solar Panels Are Starting to Die, Leaving Behind Toxic Trash"](#). Wired,
- 277) <https://www.wired.com/story/solar-panels-are-starting-to-die-leaving-behind-toxic-trash/>, accessed on 11 Sep 2026
- 278) https://www.circularpv.com.au/_files/ugd/10e921_d7a4fbb30adb4fd585b5d4784ccdc24b.pdf, accessed on 11 Sep 2026
- 279) Mathur, Deepika; Gregory, Robin (15 June 2025). ["A solar panel recycling scheme would help reduce waste, but please repair and reuse first". The Conversation](#), accessed on 11 Sep 2026
- 280) <https://web.archive.org/web/20130512230542/http://www.unendlich-viel-energie.de/en/details/browse/11/article/253/first-breakthrough-in-solar-photovoltaic-module-recycling-experts-say.html>, accessed on 11 Sep 2026
- 281) Cynthia, Latunussa (9 October 2015). ["Solar Panels can be recycled – BetterWorldSolutions – The Netherlands"](#). BetterWorldSolutions – The Netherlands. Archived from [the original](#) on 29 April 2018, accessed on 11 Sep 2026
- 282) Latunussa, Cynthia E.L.; Ardente, Fulvio; Blengini, Gian Andrea; Mancini, Lucia (2016). ["Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels"](#). Solar Energy Materials and Solar Cells. 156: 101–11, doi:10.1016/j.solmat.2016.03.020, accessed on 11 Sep 2026
- 283) <https://web.archive.org/web/20121210042052/http://www.pvcycle.org/3rd-international-conference-on-pv-module-recycling/>, accessed on 11 Sep 2026
- 284) Wambach, K. (2017), ["A Voluntary Take Back Scheme and Industrial Recycling of Photovoltaic Modules"](#) (PDF). [Brookhaven National Laboratory](#). p. 37, accessed on 11 Sep 2026
- 285) <https://www.e-solar.co.jp/en/column/post1664>, accessed on 11 Sep 2026
- 286) <https://www.globalsolarcouncil.org/our-work/possiblewithsolar/>, accessed on 11 Sep 2026
- 287) Ibid
- 288) <https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2025-2029/detail>, accessed on 11 Sep 2026
- 289) Ibid
- 290) <https://www.sphericalinsights.com/reports/solar-energy-market>, accessed on 11 Sep 2026
- 291) <https://www.persistencemarketresearch.com/market-research/solar-energy-market.asp>, accessed on 11 Sep 2026
- 292) <https://market.us/report/global-photovoltaic-solar-panel-market/>, accessed on 11 Sep 2026
- 293) Ibid
- 294) <https://www.aspsuperhome.com/blog/future-of-solar-panel-technology>, accessed on 11 Sep 2026
- 295) World Bank. (2023). *Tracking SDG7: The energy progress report*. <https://www.worldbank.org>, accessed on 11 Sep 2026
- 296) <https://www.solarreviews.com/solar-companies>, accessed on 11 Sep 2026
- 297) <https://www.aspsuperhome.com/solar-battery-backup/doral-south-florida>, accessed on 11 Sep 2026

Study on Development, Prospects, Challenge, and Applications of Solar Panel: Global and Local Perspective

- 298) <https://solarbazaar.io/comparisons/solar-basics/topcon-vs-hjt>, accessed on 11 Sep 2026
- 299) <https://www.aspsuperhome.com>, accessed on 11 Sep 2026
- 300) <https://www.sciencedirect.com/science/article/abs/pii/S0957417419301022>, accessed on 11 Sep 2026
- 301) <https://escholarship.org/content/qt06b4h95q/qt06b4h95q.pdf>, accessed on 11 Sep 2026
- 302) M. Hu, and Z.H. Zhang, (2023), What is the relationship between energy consumption and economic development? New evidence from a rapidly growing economic development region, *Environment, Development and Sustainability*, ISSN: 1387585X Volume: 25, Issue: 4, Pages: 3601 – 3626, DOI: 10.1007/s10668-022-02196-8, accessed on 23 Aug 2026
- 303) <https://www.smartpropel.com/electric-vehicles-and-energy-storage-lithium-batteries-market-development-analysis/>, accessed on 23 Aug 2026
- 304) Youssra Riahi, and Ismail Badraoui, (2021), Artificial intelligence applications in supply chain: A descriptive bibliometric analysis and future research directions, 2021, *Expert Systems with Applications*, accessed on 23 Aug 2026
- 305) <https://www.sciencedirect.com/topics/engineering/power-engineering>, accessed on 11 Sep 2026



There is an Open Access article, distributed under the term of the Creative Commons Attribution – Non-Commercial 4.0 International (CC BY-NC 4.0) (<https://creativecommons.org/licenses/by-nc/4.0/>), which permits remixing, adapting and building upon the work for non-commercial use, provided the original work is properly cited.