

Evaluation of Technological Advancement and Versatile Applications of Solar Panels

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ABSTRACT

The most common Renewable energies (RE) sources are solar, wind, and hydropower. RE are essential for guiding our energy system toward sustainability and supply security. Producing electricity, heat, or biofuels from renewable sources has gained high priority in national and international energy policies. To understand future RE development, it is vital to consider country- or region-specific factors, such as the potential of particular RE types and achievable near-term goals. This article explores global RE prospects, focusing on solar panels and covering technologies, production, maintenance, recycling, and applications. It also evaluates the practical deployment of these technologies and related challenges within applied energy policies. The development of solar power solutions has significantly changed how we utilize renewable energy. Flexible solar panels are leading this change, offering a more adaptable and efficient alternative to traditional rigid panels. Technological and material advancements have created new opportunities for solar applications where conventional panels previously struggled. The shift toward renewable energy has spurred innovation in photovoltaic (PV) systems, driving the rise of flexible, lightweight, ultra-thin solar modules. Flexible panels stand out for their innovative design and technology. This review article will discuss the technology, manufacturing process, advantages, applications, the future solar panel development and beyond.

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Introduction

Solar energy has become central to the global energy transition, with 2024 seeing record-breaking solar generation and capacity installations. Over the past three years, solar electricity production has doubled, contributing more growth than any other source. Meanwhile, overall electricity demand surged in 2024, outpacing growth in clean energy sources. This rise is partly driven by growing demand from technologies like AI, data centers, electric vehicles, and heat pumps. The main reason electricity demand rose more in 2024 than in 2023 was increased air-conditioning use during heatwaves [1]¹. This accounted for almost all of the small rise in fossil generation [2]². Renewable energy installations can be large or small and suit both urban and rural areas. For energy to be renewable, it must be an endless source [3]³. Renewable energy is frequently used alongside additional electrification. This approach offers several advantages: electricity efficiently transfers heat and powers vehicles, and it is clean where it is consumed [4]. Variable renewable energy sources like wind and solar power fluctuate, whereas controllable renewable sources such as dammed hydroelectricity, bioenergy, or geothermal power can be managed [5]. Renewable energy systems have significantly improved in efficiency and affordability over the past 40 years. Currently, most

new electricity capacity installed globally comes from renewable sources [6]. Renewable energy sources, like solar and wind, have dramatically decreased in cost over the last decade, increasing their competitiveness against traditional fossil fuels [7]. In certain geographic areas, photovoltaic solar or onshore wind represents the most affordable option for new electricity generation [8].

We know that, when sunlight strikes a solar panel, it transforms the light energy into electricity through the photovoltaic (PV) effect. This is why solar panels are also called photovoltaic panels, PV panels, or PV modules. The French physicist Edmond Becquerel first discovered that certain materials could generate an electrical charge when exposed to light in 1839 [9]. In 1881, American inventor Charles Fritts developed the first commercial solar cell, which he described as producing "continuous, constant, and considerable force not only from sunlight but also from dim, diffused daylight [10,11].". Finally, in 1939, Russell Ohl developed the solar cell design that is now used in many modern solar panels. He patented this design in 1941 [12]. However, Bell Labs first used this design to develop the world's first commercially viable silicon solar cell in 1954 [13]. A solar panel is a device that transforms sunlight into electricity through an array of solar modules made up of photovoltaic (PV) cells [14]. 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 power various devices or be stored in batteries [15]. Solar panels are also known as solar cells or electric panels [16]. Solar panels are typically grouped into arrays or systems. A photovoltaic setup includes one or more panels, an inverter that transforms direct current to alternating current when needed, and sometimes additional parts like charge controllers, meters, or solar trackers to optimize sunlight exposure. Historically, solar panels have harnessed renewable, clean energy sources, helping decrease greenhouse gas emissions compared to fossil fuels [17]. However, their effectiveness depends on sunlight availability and intensity, and they require regular cleaning along with high upfront costs. Solar panels are commonly used across sectors including residential, commercial, agricultural, transportation, and industrial applications, as well as in space, often combined with batteries.

Today the rising need for clean, sustainable, and cost-effective energy has elevated solar power from a niche technology to a key part of the global energy system. In the 21st century, as the world moves towards renewable sources, solar panels, especially monocrystalline types, are gaining popularity in the solar power market [18]. Their distinctive appearance, durability, user-friendly design, and high-quality components make them both attractive and valuable. These solar panels are crafted from a single silicon crystal, eliminating visible grain lines and providing a sleek, modern look. Monocrystalline panels, also called mono panels, are well-known for their uniform, elegant appearance and high efficiency. Their single-crystal construction gives them a seamless look without visible grain lines, setting them apart from polycrystalline panels. This manufacturing process involves growing a single crystal, which improves their ability to convert sunlight into electricity and makes them popular in renewable energy. Choosing between monocrystalline and polycrystalline panels usually depends on the trade-off between efficiency and cost; monocrystalline panels tend to be more efficient but cost more. Many users consider the long-term energy savings and aesthetic advantages worth the initial investment. Generally, monocrystalline panels outperform polycrystalline panels in efficiency and performance because their single, pure silicon crystal converts energy better, especially in low-light conditions. While polycrystalline panels are more affordable, they usually offer lower efficiency, a shorter lifespan, and greater temperature sensitivity. They also require more space for installation because of their size and efficiency limitations. A typical monocrystalline panel lasts about 25 to 30 years, though many continue to work well beyond that, with some efficiency loss.

The International Energy Agency (IEA, 2024) declared that, solar photovoltaic (PV) energy is now the quickest-growing source of electricity globally, representing a significant share of new renewable energy capacity installed annually [19]. Lower production costs, improved manufacturing efficiency, and supportive government policies have made photovoltaic systems financially competitive with traditional fossil fuel-based power generation [20]. For decades, photovoltaic electricity has relied primarily on rigid crystalline silicon modules with tempered glass, aluminum frames, and sturdy mounting systems. These traditional panels have proven highly efficient, durable, and reliable, often functioning effectively for over twenty-five years [21]. However, their weight, rigidity, and installation constraints limit their use on lightweight buildings, curved architectural designs, transportation infrastructure, portable devices, and other surfaces where conventional modules are unsafe to install. Flexible solar panels represent a major step forward in solar tech, offering portability, adaptability, and affordability [22]. Their distinctive features make

them suitable for a broader range of applications than traditional rigid panels. By learning about the various types, advantages, mounting options, and maintenance requirements, both businesses and consumers can optimize the value and efficiency of their solar investments. Collaborating with reputable manufacturers worldwide provides access to high-quality products supported by expertise and innovation. Flexible solar panels offer an attractive way to adopt sustainable energy in a changing, growing market. Today, the term "paper-like solar panel" is increasingly used in media and advertising because many of these modules are extremely thin and lightweight. Although no commercial photovoltaic module is truly made from paper, this description effectively illustrates their appearance and flexibility. Some modules are only a few millimeters thick and weigh less than a quarter of conventional glass modules, making transport and installation easier. Flexible photovoltaics expand the potential uses of solar energy beyond traditional rooftops, enabling integration into building facades, lightweight industrial roofs, recreational vehicles, boats, greenhouses, uncrewed aerial vehicles, tents, emergency shelters, consumer electronics, wearable devices, and aerospace systems. Modern systems include 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 offers distinct benefits and challenges related to efficiency, cost, flexibility, environmental impact, and durability. Perovskite photovoltaics, in particular, have gained notable attention because of rapid efficiency gains, reaching over 26% in labs—comparable to conventional crystalline silicon. Researchers are also creating tandem structures that combine silicon and perovskite layers to exceed single-junction cell output. Meanwhile, manufacturers are developing ultra-thin crystalline silicon modules that maintain high performance while reducing weight. These advances show that flexibility can be achieved without compromising electrical efficiency.

Unlike traditional crystalline silicon solar panels, which use rigid glass substrates and aluminum frames, flexible photovoltaic technologies incorporate lightweight polymers, thin semiconductor layers, and advanced encapsulation methods. This allows modules to bend, conform to curved surfaces, and integrate into buildings, vehicles, wearable electronics, and portable power sources. Recent advances in flexible crystalline silicon, perovskite, organic photovoltaic (OPV), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) technologies have broadened solar energy applications beyond conventional rooftop setups [23]. Global research institutions, universities, and photovoltaic manufacturers have invested substantially in developing flexible modules with higher conversion efficiencies, greater durability, lower manufacturing costs, and improved environmental sustainability. China has become the leading global producer of photovoltaic technology, playing a key role in advancing flexible silicon and perovskite modules through large-scale manufacturing, materials research, and process innovation [24]. Meanwhile, Europe, Japan, South Korea, and the United States are advancing specialized flexible photovoltaic technologies for sectors such as aerospace, transportation, architecture, and consumer electronics. This elaborate review article will explore the scientific principles, materials, manufacturing methods, performance features, applications, environmental impacts, market trends, and future outlooks of general and flexible PV solar panels with special emphasis on current technical challenges, ongoing research issues, and the significance of flexible photovoltaics in advancing global energy transition efforts.

Chronological Advancement of Solar Panel Technology

The photovoltaic effect is a physical phenomenon where a semiconductor produces electrical energy when exposed to light [25]. Photovoltaic (PV) modules consist of numerous solar cells and convert sunlight into electricity through the photovoltaic effect. Typically, they employ wafer-based crystalline silicon cells or thin-film technologies [26]. A module's structural member can be either the top or back layer. Cells must be safeguarded against mechanical damage and moisture. Typically, cells and modules are wired in series to boost voltage, then in parallel to increase current, forming the solar panel. While most panels are rigid, semi-flexible variants using thin-film cells are also available. A solar panel's wattage equals its voltage (in volts) multiplied by its current (in amperes), with actual output influenced by light

conditions and the electrical load connected [27]. Manufacturers specify solar panels based on standard test conditions, which often differ from the actual operating conditions at the installation site [28]. A PV junction box is mounted on the back of the solar panel and serves as its output connection point. Most photovoltaic modules utilize MC4 connectors for external system links [29]. A USB power interface can also be utilized. Solar panels often incorporate metal frames, racking components, brackets, reflector shapes, and troughs to provide enhanced support for the panel structure [30]. Solar cells connect via electrodes to form modules, with front electrodes slightly covering the solar cell surface. To improve efficiency, manufacturers increase the frontal surface area for sunlight and boost absorption by using various rear-electrode connection methods developed over time [31].

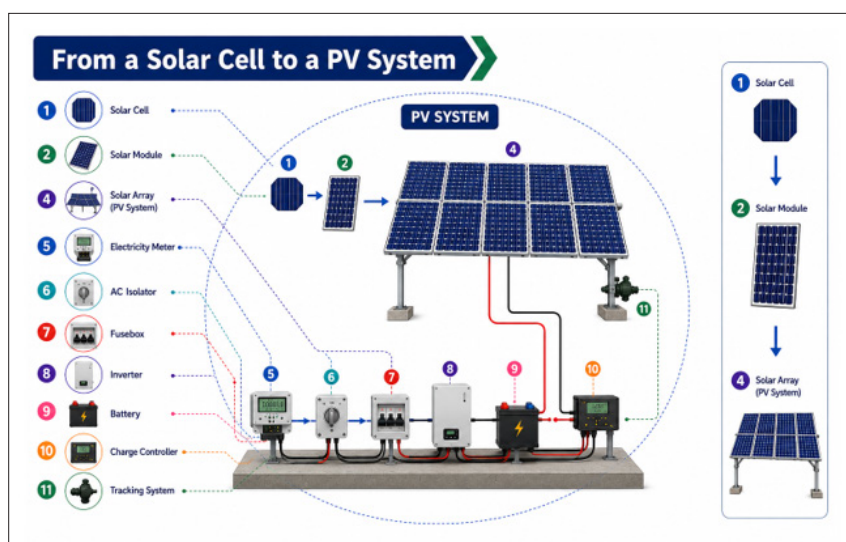


Figure 1: Solar Cell to Complete PV System

A single solar panel can generate only a limited amount of power; therefore, most setups include multiple panels that combine their voltages or currents. A photovoltaic system generally comprises an array of photovoltaic modules, an inverter, a battery pack for storing energy, a charge controller, interconnecting wiring, circuit breakers, fuses, disconnect switches, voltage meters, and sometimes a solar tracking mechanism [32]. Equipment is chosen meticulously to maximize energy output and storage, minimize power transmission losses, and often convert from direct current to alternating current [33]. Smart solar panels incorporate power electronics within the panel itself, unlike traditional panels that have power electronics attached to the frame or connected via a connector to the photovoltaic circuit [34]. Solar power electronics are used for maximum power point tracking, power optimization, and solar performance monitoring, supporting data collection and fault detection to improve safety [35]. Most solar modules today are made from crystalline silicon (c-Si) solar cells, which can be polycrystalline or monocrystalline. In 2021, crystalline silicon represented 95% of global PV production, while the remaining market primarily comprised thin-film technologies such as cadmium telluride (CdTe), copper indium gallium selenide, and amorphous silicon (a-Si) [36,37].

Bifacial cells generate power on both sides, boosting overall module output. This advantage depends on the environment's reflectivity and is enhanced by elevated structures, which allow more light to reach the back side [38]. The advantage of bifacial panels depends on the situation; they perform better with high-

albedo surroundings like snow, elevated structures, and overcast conditions. However, their benefits may be minimal when installed directly on surfaces with limited clearance, making them less cost-effective in such cases. The cost of bifacial cells has dropped to a level comparable with monofacial options. As a result, by 2024, bifacial panels are now the top choice for utility-scale PV projects. Furthermore, new third-generation solar technologies utilize advanced thin-film cells [39]. They offer relatively high efficiency at a lower cost compared to other solar technologies. Usually, densely packed rectangular multi-junction solar cells — which are expensive but highly efficient are used in spacecraft solar panels because they provide the highest power per kilogram for space launches [40]. Multi-junction cells are compound semiconductors made from gallium arsenide and other materials. They are also employed in a developing photovoltaic technology known as concentrator photovoltaics [41]. Thin-film solar cells are created by applying thin layers of photovoltaic material onto substrates such as glass, plastic, or metal. These cells are usually much thinner than the wafers found in traditional crystalline silicon solar panels [42]. These cells are commercially produced using various materials such as cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon (a-Si, TF-Si). The first-generation solar cells are typically made from single- or multicrystalline silicon [43].

This is the predominant technology currently used in most solar photovoltaic (PV) systems. Most thin-film solar cells are categorized as second generation, fabricated using thin layers of

materials such as amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or gallium arsenide (GaAs). Solar cells using newer, less established materials are classified as third-generation, or emerging, solar cells. This category includes innovative thin-film technologies such as perovskite, dye-sensitized, quantum dot, organic, and CZTS thin-film solar cells [44]. Thin-film cells offer several benefits compared to first-generation silicon solar cells, such as being lighter and more flexible because of their thin design. This allows them to be used in building-integrated photovoltaics and as semi-transparent photovoltaic glazing that can be laminated onto windows. Additionally, some commercial uses involve rigid thin-film solar panels installed in some of the world's largest photovoltaic power stations [45]. Thin-film solar cell materials are usually made through straightforward, scalable methods that are more cost-effective than those for first-generation cells, often resulting in reduced environmental impacts such as lower greenhouse gas emissions [46]. Thin-film cells generally perform better at producing electricity, especially because they tend to have lower impacts on human health and produce fewer heavy-metal emissions than other renewable and non-renewable sources. [47]

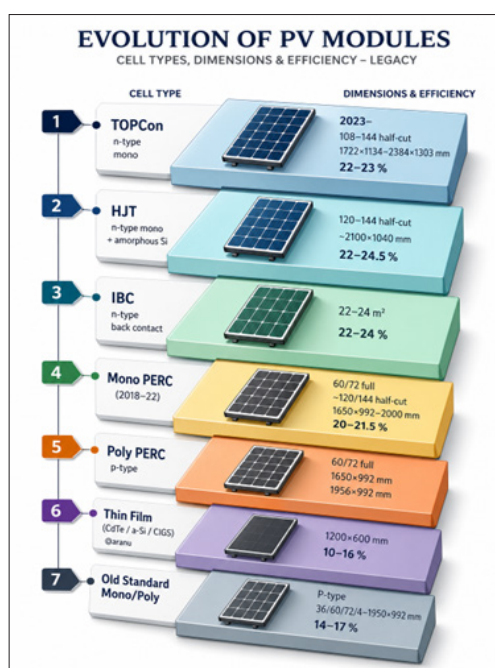


Figure 2: Evolution of Solar PV Modules: Dimension and Efficiency Legacy

Some PV companies in the U.S. are developing nearly transparent, glass-like plastic cells that significantly reduce the visual impact of PV arrays. These are not yet widely available in the UK. Only a few UK firms install transparent solar panels, but interest is growing, and they are expected to become more common. Innovative, paper-thin technologies could enable real-time electricity generation from windows and other discreet surfaces. Solar skins—thin, flexible, transparent materials—can generate electricity from sunlight, mainly as aesthetic overlays rather than high-efficiency power sources. Embedded with tiny "Quantum Dots," these materials excite when struck by photons, the primary component of sunlight. Depending on design and application, solar skins can retain about 90–99% of a panel's original output. As a recent innovation, they can be laid over existing solar panels to blend with roofs, making them attractive for those concerned about traditional panel appearance. Additionally, solar skins are designed

to improve fire safety by incorporating fire-protection features.

Traditional solar farms require land, which can be costly and needed for other purposes like agriculture or housing. As a solution, engineers have created floating solar power plants that can be positioned offshore. These systems involve installing solar panels on floating platforms in water bodies such as lakes, reservoirs, and sheltered coastal areas. Known as water-cooled floating photovoltaic (PV) systems, or photovoltaics, they often generate more energy than land-based panels because water helps cool the panels and reduce their temperature. Floating solar farms offer additional advantages: they decrease air circulation and shade the water surface, reducing evaporation. They can also inhibit certain algae growth, lowering water treatment costs. Moreover, the water underneath keeps the panels clean, minimizing energy loss. The growth of innovative energy storage solutions also influences solar technology adoption. Better storage lets excess energy from peak sunlight hours be saved for low-light periods or nighttime. Advances in lithium-ion and solid-state batteries show promise, though challenges remain before solid-state batteries become industry standards. As battery technology and smart energy management systems improve, households and businesses can use more solar power and rely less on grid energy.

Construction and Manufacture of Solar Panels

Today, solar panel technology is advancing rapidly, with increased efficiency and lower costs driven by soaring demand. Despite these technological breakthroughs, the fundamental design of solar panels has remained largely unchanged over recent years. Most panels consist of silicon crystalline cells placed between a front glass layer and a rear polymer back-sheet, all supported within an aluminum frame. Once installed, solar panels endure harsh conditions throughout their 25+ year lifespan. Extreme temperatures, humidity, wind, and UV radiation can put significant stress on them. Fortunately, most panels are engineered to withstand extreme weather, but some can fail in various ways, such as water ingress, cell micro-fractures, or potential induced degradation (PID) [72]. Today, solar panels are made using only the highest-quality components [73]. Solar panels use PV cells, typically made from crystalline silicon wafers similar to those used in computer processors. These wafers can be either polycrystalline or monocrystalline, produced through various manufacturing techniques. Monocrystalline wafers are the most efficient and are commonly made using the well-known Czochralski process. In the past, manufacturers produced polycrystalline wafers through several purification steps followed by a simpler casting method, making them more cost-effective but less efficient. This lower efficiency led to the phase-out of polycrystalline wafers in favor of the higher purity and better performance of monocrystalline wafers [74].

Manufacturing typical silicon-based solar cells begins with Quartzite, a type of quartz sandstone rock. Initially, Quartzite or silica sand is transformed into metallurgical-grade silicon by heating it with Carbon in an arc furnace [75]. This process occurs at very high temperatures, producing 99% pure silicon. The next step converts metallurgical-grade silicon into pure Polysilicon through either the Siemens chemical purification process or upgraded metallurgical-grade silicon (UMG-Si), which uses more cost-effective metallurgical methods [76]. Next, the polysilicon is doped with trace amounts of boron or phosphorus to produce P-type or N-type silicon [77]. At this stage, polycrystalline silicon can be melted, cast into large blocks, and sliced into wafers with a diamond wire method. To make more efficient monocrystalline

wafers or cells, the Czochralski process can transform doped silicon into a pure crystal ingot [78]. This process entails melting polycrystalline silicon at high pressure and temperature to grow a large monocrystalline ingot gradually. The steps for manufacturing monocrystalline solar PV cells are outlined below.

- 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 phosphorus (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 consist of six main components, assembled with high precision in advanced manufacturing facilities. This article mainly discusses panels made with crystalline silicon solar cells, as these are the most widespread and efficient solar technology currently available [79]. Other solar PV technologies, such as thin-film and screen-printed cells, exist but are not covered here because they have limited applications or are still in development. The six main components of a solar panel are listed below and illustrated in Figure 3.

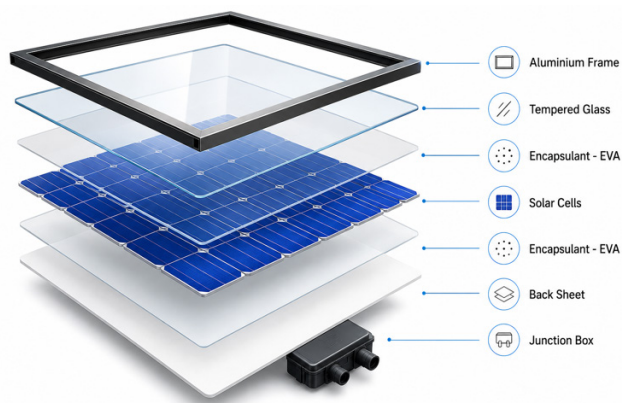


Figure 3: Major 6 Components Used in The Construction of a Solar Panel [80]

a. Solar PV Cells

The foundation of the photovoltaic (PV) cell is a very thin wafer, generally measuring 0.1 mm in thickness. It is fabricated from either positively-doped p-type silicon or negatively-doped n-type silicon [81]. Various cell sizes and configurations provide different efficiency and performance levels, such as half-cut or split cells, multi-busbar (MBB) cells, and more recently, shingled cells made from thin, overlapping wafer strips. The two primary types are monocrystalline and polycrystalline silicon [82]. Most residential solar panels have 60 full-size monocrystalline cells or 120 half-size cells connected in series by busbars, producing 30-40 volts depending on the cell type. Larger panels for commercial projects and utility-scale solar farms feature 72 full-size or 144 half-size cells and operate at higher voltages. The interconnecting electrical contacts, called busbars, enable current flow across all the cells in the circuit [83].

b. Toughened Glass

The front glass sheet shields the PV cells from weather and impacts like hail or debris. Usually made of high-strength tempered glass, measuring 3.0 to 4.0mm thick, it is built to withstand mechanical stress and temperature extremes. According to IEC standards, solar panels must withstand impacts from 1-inch (25 mm) hailstones traveling up to 60 mph (27 m/s). In severe impacts, tempered glass is safer than regular glass because it breaks into small, dull fragments instead of sharp shards, typically at a thickness of 3.2mm. To boost efficiency, many manufacturers use high-transparency glass with low iron content and an anti-reflective coating on the backside to minimize energy loss and enhance light transmission [84].

c. Extruded Aluminum Frame

The aluminum frame primarily shields the edge of the laminate section housing the cells and provides a robust structure for attaching the solar panel. The extruded aluminum components are designed to be lightweight, stiff, and able to withstand high stress and external forces from strong winds [85]. The aluminum frame comes in silver or anodized black. Corner sections can be screwed, pressed, or clamped, depending on the panel manufacturer, offering different strength and stiffness levels.

d. Encapsulation EVA Film

EVA, short for 'ethylene vinyl acetate', is a specially formulated polymer layer that is highly transparent and used to encapsulate solar cells, keeping them in place during manufacturing. This material must be exceptionally durable and resistant to extreme temperatures and humidity. Additionally, EVA plays a crucial role in long-term performance by preventing moisture and dirt from entering. The lamination on both sides of the PV cells offers some shock absorption, helping to shield the cells and interconnecting wires from vibrations, impacts, hailstones, and other objects [86]. A high-quality EVA film with a high level of 'cross-linking' can determine whether a panel lasts longer or fails prematurely due to water ingress. During manufacturing, the cells are initially encapsulated with EVA before being integrated with the glass and back sheet.

e. Polymer Rear Back-Sheet

The backsheet is the last layer of standard solar panels, serving as a moisture barrier and external cover that provides mechanical protection and electrical insulation. It is typically made from polymers such as PP, PET, and PVF, each offering varying degrees of protection, thermal stability, and UV resistance. Usually white, the backsheet can also be clear or black, depending on the manufacturer and module. For a comprehensive review of different backsheet materials, see the backsheet construction article from Taiyang News [87]. Certain panels, such as bifacial and frameless panels, utilize a rear glass panel instead of a polymer backsheet, and are classified as dual glass panels. Rear glass is more durable and has a longer lifespan than most backsheet materials. As a result, some manufacturers provide a 30-year performance warranty on dual glass panels.

f. Junction Box with Diodes and Connectors

The junction box is a small weatherproof enclosure on the rear of the panel that secures cables connecting the panels. It serves as the central interconnection point and must be protected from moisture and dirt. It also contains bypass

diodes, which prevent reverse currents when cells are shaded or dirty. Each 60-cell panel, divided into 3 groups of 20 PV cells, has a bypass diode per group. Bypass diodes can fail over time, especially under stress from shading caused by rooftop objects, and may need replacement [88]. Most contemporary solar panels feature more advanced, durable diodes and sealed junction boxes that require no maintenance [89].

Most solar panels are connected using weather-resistant MC4 connectors, which stand for multi-contact 4mm diameter connector. These connectors must withstand extreme weather and be robust, secure, and UV-resistant, while ensuring a good, low-resistance connection at both low and high voltages up to 1000V. They are designed for use with standard 4mm or 6mm double-insulated solar DC cables that have a tinned copper multi-strand core for better conductivity and durability [90]. To assemble the connectors properly, use a specialized crimping tool to attach the multi-strand cable to the inner terminal. Then insert and snap this terminal into the MC4 housing. Although several types of MC4 connectors may appear similar, they do not always fit securely. To minimize risks of water ingress or plug failure, always use the same type and make of connector, as mismatched connectors can cause arcing or even fire [91]. Again, next-generation MC4-EVO-2 connectors are manufactured by a few manufacturers and are the only dissimilar-looking connectors that are allowed to be used together.

Many reputable solar panel producers are vertically integrated, meaning they handle the supply and manufacturing of key components like silicon ingots and wafers used in solar PV cells. In contrast, some manufacturers assemble panels from externally sourced parts such as cells, polymer back sheets, and encapsulation EVA material. These firms have more flexibility in selecting components but must ensure they partner with high-quality suppliers to maintain product standards. Solar panels are assembled in high-tech factories employing automated robotic equipment and sensors for precise component placement. These facilities must be kept extremely clean to prevent contamination during assembly. Throughout production, panels and cells undergo thorough inspection with advanced optical and imaging sensors to confirm proper positioning and prevent damage to delicate wafers. Final testing—such as electroluminescent (EL) or flash tests—is routinely performed to detect defects that could cause failures when exposed to sunlight and high temperatures over time.

Photovoltaic panels are typically highly dependable because they contain no moving components and require minimal maintenance. Nonetheless, they may malfunction or perform below expectations over their anticipated 25-year lifespan due to various reasons. Cells typically gradually lose efficiency due to light-induced degradation (LID), which results in an average annual loss of about 0.5% [92]. This gradual degradation often goes unnoticed, with most solar panels retaining 80% or more of their initial rated capacity after 20 years, depending on the cell type. The manufacturer's performance warranty details the extent of degradation, as shown in Figure 4 below [93]. Unfortunately, solar panels can also face more serious problems, such as micro-cracks and accelerated degradation, due to various factors. High stresses from impacts, poor installation, or pedestrian traffic on rooftop panels can create tiny fractures in the cells. These problems are often hard to detect and, if ignored for years, may develop into hot spots, potentially leading to failures like arcing or fires. Fortunately, advances in panel design and manufacturing are helping reduce the risk of such failures, and most manufacturers are actively working to improve durability and longevity [94].

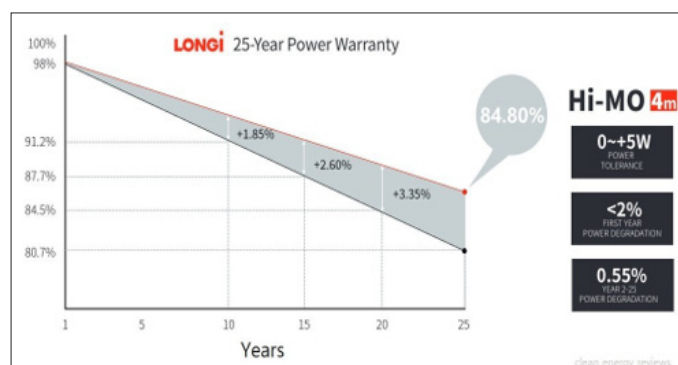


Figure 4: Solar Panel Performance Warranty Chart Showing Degradation Over 25 Years of Use - Image Credit Longi Solar [95]

Basic Types, Selecting, Caring, and Important Information of Flexible Solar Panels

Flexible solar panels are photovoltaic devices constructed on bendable substrates, enabling them to conform to curved surfaces and irregular shapes. Unlike traditional rigid panels made from glass and metal frames, flexible panels use thin-film or crystalline solar cells mounted on lightweight, pliable materials such as ETFE film. This design allows for diverse applications, including integration into vehicles, portable solar chargers, building surfaces, wearable solar devices, and other unconventional uses. They balance efficiency and adaptability, making them suitable for environments with space, weight, or shape constraints. The core technologies include thin-film solar cells, which are lighter and more flexible because they are deposited on flexible substrates, and crystalline silicon cells, which offer higher efficiency with slightly less flexibility [96]. These panels are often evaluated for performance, durability, and cost-effectiveness, helping users choose the best option for specific energy needs and installation contexts. Their lightweight and flexible design makes them ideal for portable chargers, camping gear, and vehicles.

Two main types of flexible solar panels exist: crystalline and thin-film. Crystalline flexible panels are constructed from very thin slices of silicon. They maintain high efficiency similar to rigid panels while offering some flexibility [97]. Today, manufacturers have improved the bending radius, allowing these panels to mount on slightly curved surfaces without compromising performance. They are well suited for applications that require a balance of power, flexibility, and adaptability. Manufacturers produce thin-film flexible solar panels by depositing photovoltaic materials onto pliable substrates such as plastic or metal foil. Examples include amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS) panels. These panels are generally more flexible and lighter; however, they typically have lower efficiency than crystalline variants. Their cost-effectiveness and straightforward manufacturing process establish them as a preferred choice for applications where flexibility and shape conformity are prioritized over maximum power output [98].

When choosing flexible solar panels, consider several key factors to ensure optimal performance and durability. Power output is crucial; evaluate the wattage and efficiency to suit your energy needs. Durability matters too, especially how well panels resist environmental factors like UV rays, moisture, and temperature changes. For instance, panels with ETFE coating provide better weather resistance and self-cleaning features. Solar cell technology also affects performance and suitability for different applications. Understanding the differences between crystalline and thin-film

solar cells helps businesses select the appropriate panel based on efficiency, weight, flexibility, and budget. Lastly, the installation method, whether using adhesive bonding or rack systems, impacts ease of setup and maintenance [99]. Finally, review the lifespan and warranty terms to protect your investment and ensure long-term reliability. Currently, adhesive mounting is favored for curved surfaces and portability, whereas rack mounting provides stability for permanent setups. The selection depends on specific application needs. Flexible solar panels, available from specialized manufacturers and suppliers worldwide, come in various thin designs tailored to diverse requirements needs.

Mounting flexible solar panels can be done mainly through two methods: rack mounting and adhesive mounting. Rack mounting involves attaching the panel to a frame or structure, offering stability especially for larger setups or if panel removal might be needed. While this method is durable, it can add weight and complexity. Adhesive mounting, known for its simplicity and minimal hardware, uses strong, weatherproof adhesives to bond the panel directly to surfaces like roofs, vehicles, or curved equipment. This method maintains the panel's flexibility and reduces wind resistance. Choosing adhesives compatible with the panel's backing and surface is crucial to prevent damage and ensure longevity. Proper surface prep and environmental factors improve adhesive bonding. To keep flexible solar panels efficient, regular cleaning and maintenance are necessary to remove dirt, dust, and debris. Gentle cleaning with soft cloths, mild detergents, and water helps avoid damaging the delicate surface or ETFE coating. Harsh chemicals or abrasive materials should be avoided to prevent harm to the solar cells or protective layers. Routine inspections for damage, loose connections, and wear help maintain performance. Since these panels are often used in tough environments, applying protective measures like UV-resistant coatings and weatherproof seals is beneficial [100]. Adhering to manufacturer maintenance guidelines helps extend lifespan and maximize energy output.

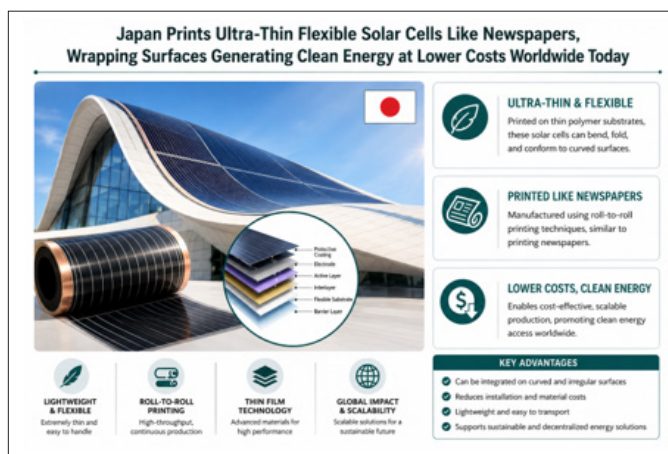


Figure 5: Ultra-Thin Flexible Solar Cells/Panel

Flexible solar panels offer several key advantages over traditional solar solutions. Their lightweight design and ability to bend make them suitable for curved and uneven surfaces, allowing for installations in places that were previously inaccessible. This flexibility is especially useful for mobile applications like RVs, boats, wearable tech, and emergency power sources. Moreover, flexible panels are typically cheaper to transport and install, lowering overall costs. They are also easier to install since they can be attached with adhesives or lightweight racks, removing the need for heavy frames or complex mounting systems [101]. The simple installation process reduces both deployment time and labor costs. Lightweight and impact-resistant, these panels

are highly portable, perfect for off-grid and remote power setups. Their flexibility enhances durability under mechanical stress compared to rigid panels, thereby extending their lifespan in dynamic environments. Although flexible solar panels typically have slightly lower efficiency than rigid crystalline panels, technological advancements have significantly narrowed this difference [102]. Efficiency varies from 10% to over 20%, depending on the technology. Many flexible solar panels feature protective coatings like ETFE that improve durability against UV rays, moisture, and temperature swings. Check the panel's specifications for environmental resistance. Japan is advancing flexible solar cell technology that allows clean energy panels to be mounted on surfaces unsuitable for heavy traditional solar panels. These lightweight solar sheets often incorporate perovskite materials, which are attracting attention due to their ability to be thinner, lighter, and potentially cheaper to produce than standard silicon panels, as shown in figure 5 above [103].

Working Principles and Materials Science of Flexible Solar Panels

Flexible solar panels operate through the photovoltaic effect, where semiconductor materials convert sunlight directly into electricity. When sunlight photons strike the photovoltaic surface, they transfer energy to electrons within the semiconductor lattice. If this energy surpasses the material's band gap, electrons are excited from the valence band to the conduction band, creating mobile electron-hole pairs. An electric field at the p-n junction then separates these charges: electrons move toward the negative electrode, and holes toward the positive. This charge separation generates an electric current that is collected via external circuits. Though the photovoltaic effect functions similarly in both rigid and flexible solar cells, their primary distinction lies in construction: conventional panels use thick crystalline silicon wafers with tempered glass, whereas flexible modules consist of thin semiconductor layers on lightweight substrates such as polyimide, PET, PEN, stainless steel foils, or ultra-thin silicon wafers [104]. These substrates' flexibility enables photovoltaic modules to bend without disrupting electron flow. Enhanced encapsulation materials shield the semiconductor layers from oxygen, moisture, UV radiation, and mechanical forces, boosting their operational lifespan. Recent advancements in nanostructured materials, interface engineering, and tandem architectures have significantly improved the efficiency of flexible solar cells while ensuring they remain mechanically durable. Researchers are actively refining charge transport layers, transparent conductive electrodes, and encapsulation methods to enhance electrical performance and ensure long-term stability.

Modern photovoltaic modules offer remarkable flexibility mainly due to advances in materials science rather than changes in basic electricity principles. Unlike traditional panels that use thick crystalline silicon wafers protected by tempered glass and framed with aluminum, flexible solar panels utilize lightweight materials that maintain electrical performance even under repeated bending. The choice of these materials impacts the module's flexibility, efficiency, durability, manufacturing cost, environmental footprint, and market potential. Currently, flexible panels are mostly made with thin-film photovoltaic technology, where one or more layers of photovoltaic material are deposited on a substrate. Common materials include amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS). This approach makes the panels lightweight, thin, and highly flexible [105]. Researchers have created various types of photovoltaic materials suited for flexible uses, each with distinct benefits and technical hurdles. These materials are constantly advancing as scientists aim to

enhance energy conversion efficiency, simplify production, and increase longevity.

a. Crystalline Silicon

Crystalline silicon continues to be the leading material in the global photovoltaic sector, constituting over 90% of the total installed solar capacity worldwide according to the International Energy Agency (IEA) in 2024. Historically, silicon cells were seen as unsuitable for flexible uses due to silicon's inherent brittleness and tendency to fracture under excessive bending. However, recent breakthroughs in wafer manufacturing have transformed this view. Current techniques allow for the production of ultra-thin crystalline silicon wafers, less than 100 micrometers thick, which are much more flexible without sacrificing electrical efficiency. Researchers have also improved flexibility by adding microscopic structural modifications that spread mechanical stress more evenly across the material. These advancements enable silicon-based modules to bend to moderate radii while still delivering excellent electrical performance [106]. As a result, flexible crystalline silicon modules merge the high efficiency of traditional photovoltaic technology with the practical benefits of lightweight, flexible systems. Thanks to the extensive existing manufacturing infrastructure for crystalline silicon worldwide, these flexible modules hold substantial commercial promise. Manufacturers can modify existing production lines instead of building new facilities, which lowers development expenses and speeds up market entry.

b. Thin-Film Silicon

Thin-film silicon was among the first successful methods for flexible photovoltaics. Instead of cutting thick wafers from silicon ingots, manufacturers apply very thin layers of amorphous or microcrystalline silicon onto flexible surfaces. This process greatly cuts down on material use and enables continuous roll-to-roll manufacturing. Although thin-film silicon modules usually have lower efficiency than crystalline silicon ones, they bring benefits like being lighter, more flexible, and produced at lower temperatures, which reduces transportation costs. Amorphous silicon works well in diffuse sunlight and high temperatures, making it ideal for environments with changing conditions. Despite newer photovoltaic options surpassing amorphous silicon in efficiency, it remains vital in niche markets that need lightweight, flexible energy sources.

c. Copper Indium Gallium Selenide (CIGS)

Copper indium gallium selenide (CIGS) is a leading thin-film photovoltaic material for flexible uses. It offers excellent light absorption and relatively high efficiencies, enabling the production of lightweight modules that rival traditional silicon panels. A key feature of CIGS is its very high optical absorption coefficient. Unlike crystalline silicon, which needs relatively thick layers to absorb sunlight, CIGS can absorb most solar radiation within layers only a few micrometers thick. This significantly reduces material needs and supports flexible module design. Flexible CIGS panels are used in various specialized fields, such as military gear, portable chargers, transportation, and aerospace. Their moderate efficiency, flexibility, and environmental durability make them ideal for lightweight renewable energy solutions [107]. However, CIGS manufacturing relies on relatively rare elements like indium and gallium, which might limit large-scale production if global demand rises significantly.

d. Cadmium Telluride (CdTe)

Cadmium telluride is another successful thin-film photovoltaic

technology used commercially. CdTe modules need less semiconductor material because cadmium telluride absorbs sunlight very efficiently. Its main benefits are lower manufacturing costs, strong performance at high temperatures, and established industrial production processes. Researchers have explored flexible CdTe modules for lightweight applications, though commercial use remains less widespread than silicon or CIGS technologies. Due to environmental concerns about cadmium toxicity, strict manufacturing controls and thorough recycling programs are essential [108]. Contemporary encapsulation methods prevent cadmium release during regular use, yet proper end-of-life disposal remains crucial to reduce environmental hazards.

e. Organic Photovoltaic Cells (OPVs)

Organic photovoltaic cells use carbon-based semiconducting molecules instead of traditional inorganic materials like silicon or metal compounds. Their distinct chemical properties enable manufacturing through printing methods akin to newspaper printing. A key benefit is production simplicity: large sheets can be printed continuously using roll-to-roll processes, drastically reducing costs and enabling high-volume manufacturing. Additionally, organic solar cells are highly flexible because their active layers are very thin and mechanically adaptable. Some prototypes can even endure repeated folding without major damage. However, despite these benefits, organic photovoltaics face notable limitations. Their conversion efficiencies remain lower than those of silicon and perovskite solar cells, and ensuring long-term stability against sunlight, moisture, and oxygen remains a significant engineering hurdle [109]. Therefore, OPVs are typically better suited for portable electronics, indoor energy harvesting, and disposable uses rather than long-term utility-scale power generation.

f. Perovskite Solar Cells

Perovskite solar cells have gained considerable scientific interest as a promising photovoltaic technology. The term "perovskite" refers to a particular crystal structure, not a specific chemical compound. These materials are renowned for their exceptional optoelectronic properties, enabling highly efficient conversion of sunlight into electricity. Since their emergence in solar research in 2009, perovskite photovoltaics have advanced rapidly, with laboratory efficiencies jumping from below 4% to over 26% in roughly fifteen years—a pace of progress noted by the National Renewable Energy Laboratory (NREL) in 2024. Their distinct features, including high optical absorption, long charge-carrier diffusion lengths, and low-temperature fabrication, make them particularly well-suited for flexible solar panel applications. Additional benefits include compatibility with flexible substrates, potentially low manufacturing costs, and excellent chemical tunability. Since perovskite layers can be deposited via printing, coating, or solution-processing techniques, they are highly compatible with roll-to-roll manufacturing processes [110]. Scientists imagine future manufacturing plants that produce photovoltaic films in a continuous process, similar to newspaper printing. Although significant advances have been made, stability issues still hinder commercialization. Moisture, oxygen, ultraviolet radiation, and high temperatures slowly break down many perovskite materials. Consequently, much research focuses on improving encapsulation techniques, creating more stable crystal structures, and extending operational lifetimes.

g. Tandem Solar Cells

Instead of replacing silicon entirely, many researchers now see the future of photovoltaics in tandem solar cells, which

integrate multiple semiconductor materials into one device. These architectures let each material absorb different parts of the solar spectrum: wide-bandgap materials like perovskites capture high-energy photons, while lower-energy photons pass through to silicon layers below. This setup enables more efficient use of sunlight. Theoretical studies indicate that tandem cells could reach efficiencies over 40%, greatly surpassing the limits of traditional single-junction silicon solar cells. One of the most active research areas in modern photovoltaic science is developing flexible tandem modules that combine ultra-thin silicon with perovskite materials [111].

Manufacturing Technologies and Quality Control

PV system production has adhered to a traditional learning curve, resulting in notable cost decreases as efficiency and output improve [112]. In 2019, PV module manufacturers saw over 100% year-over-year growth in PV system installations, prompting them to significantly boost shipments. They actively increased their capacity and established themselves as gigawatt-scale players [113]. Pulse Solar reports that five of the top ten PV module companies in 2019 boosted their solar panel production by at least 25% compared to that year [114]. Most solar panels use silicon cells. These silicon cells typically convert sunlight into electricity at 10–20% efficiency, with newer production models exceeding 22% [115]. In 2018, the world's top five solar module producers by shipped capacity were Jinko Solar, JA Solar, Trina Solar, Longi Solar, and Canadian Solar [116]. PV panel manufacturing uses toxic and reactive chemicals such as cadmium telluride, copper indium selenide, cadmium gallium (di)selenide, copper indium gallium (di)selenide, hexafluoroethane, lead, and polyvinyl fluoride. Silicon tetrachloride is also produced as a byproduct [117]. Silicon dust ("kerf") is produced when the silicon wafers are sawn [118]. The commercial viability of flexible solar panels depends not only on material performance but also on efficient manufacturing techniques that can produce high-quality photovoltaic modules at competitive prices. Contemporary manufacturing focuses on continuous production, automation, material conservation, and process scale-up.

a. Roll-to-Roll Manufacturing

Roll-to-roll manufacturing is a key innovation in flexible photovoltaics. Instead of assembling individual rigid panels, manufacturers use continuous rolls of flexible substrate, moving these through stages like coating, deposition, patterning, encapsulation, and quality control. This process is similar to high-speed newspaper printing or plastic film production. Its continuous nature brings many benefits, including lower manufacturing costs, faster production speeds, reduced labor needs, better material efficiency, easier automation, and increased scalability. This method is especially suitable for organic photovoltaics and perovskite solar cells, which use solution-processed materials that can be evenly deposited over large areas.

b. Vacuum Deposition

Some photovoltaic materials need strict vacuum conditions during production. Techniques like sputtering, evaporation, and chemical vapor deposition allow precise deposition of ultra-thin semiconductor layers at the atomic level. Vacuum deposition produces high-quality, uniform films that improve electrical performance and reliability. Nonetheless, this equipment tends to be costly, which raises manufacturing expenses compared to solution-based methods.

c. Printing Technologies

Printing technologies are increasingly vital in flexible photovoltaic manufacturing and use methods such as inkjet, screen printing, slot-die coating, gravure printing, and spray coating. These techniques enable precise deposition of semiconductor "inks" directly onto flexible substrates. Such printing-based approaches minimize material waste by applying compounds only where needed. Additionally, the relatively low production temperatures enable the use of affordable polymer substrates, which would otherwise deform under traditional semiconductor processing conditions.

d. Encapsulation

A major challenge for flexible photovoltaics is safeguarding fragile semiconductor materials from environmental damage. Encapsulation techniques involve sealing the photovoltaic layers with specialized protective films to block moisture, oxygen, dust, and ultraviolet rays. Modern systems usually include several polymer layers, adhesives, ultraviolet filters, and transparent coatings. Encapsulation success largely influences the lifespan of flexible solar modules. Inadequate encapsulation can cause a rapid performance decline, even if the photovoltaic material remains physically intact.

e. Quality Control

Because flexible photovoltaic modules often feature extremely thin active layers, their quality control relies on advanced inspection technologies. Manufacturers typically use methods such as Electroluminescence imaging, Infrared thermography, Laser scanning, Optical microscopy, Automated electrical testing, and Mechanical bending tests. These techniques detect microscopic defects that can impair module efficiency or reduce lifespan. Mechanical durability testing is particularly crucial for flexible photovoltaics, as modules undergo thousands of bending cycles to assess resistance to cracking, delamination, and electrical failures under real-world conditions. Ensuring solar module quality involves testing and evaluating solar cells and panels to meet specific standards. Because solar modules are expected to last 20 to 40 years, they must reliably generate and deliver power throughout their service life. Testing involves physical procedures, laboratory studies, and numerical analyses across various life cycle stages. Numerous companies, including Southern Research Energy & Environment, SGS, TÜV Rheinland, Sinovoltaics, CEA, CSA Solar, and Enertis, offer quality assurance services. Nonetheless, implementing consistent, traceable, and stable manufacturing processes is essential to maintain PV module quality. Certification follows standards such as ANSI/UL1703, IEC 17025, IEC 61215, IEC 61701, and IEC 61730-1/-2 [119-123].

Efficiency, Performance, and Maintenance of Solar Panels

Solar-cell efficiency refers to the percentage of sunlight energy a solar cell converts into electricity. Together with factors like latitude and weather, it influences a solar system's energy production. In 2024, the highest solar cell efficiency recorded was 47.6%, achieved in May 2022 by Fraunhofer ISE using a III-V four-junction concentrating photovoltaic (CPV) cell [124]. NREL holds the real-world record with triple-junction cells tested at 39.5% efficiency [125]. Commercial solar modules may exceed 24% efficiency [126]. As of 2025, the best reached 24.5% [127, 128]. Typically, their power density is lower than that of their cells when tested alone. The most efficient mass-produced solar modules achieve power densities of 175 W/m² (16.22 W/ft²) [129]. In 2026, Fraunhofer reached 34.4% efficiency using triple III-V germanium cells and shingled matrix technology for cell

interconnection. A key innovation was employing direct cell-to-cell contact, which removed the need for solder-coated copper ribbons and reduced shading on active cell areas [130]. Conversion efficiency depends on several factors, including reflectance, thermodynamic efficiency, charge carrier separation, charge carrier collection, and conduction efficiency [131]. Depending on their design, photovoltaic modules can generate electricity from various light frequencies. Generally, they cannot capture the full spectrum of solar radiation, including ultraviolet, visible, infrared, and low or diffused light. Consequently, they utilize only a small portion of the incident sunlight energy. In theory, sunlight could be divided into wavelength bands, each corresponding to a different color, and directed onto cells optimized for those ranges to improve conversion efficiency [132].

Researchers assess the performance of flexible solar panels using many of the same metrics as conventional photovoltaic modules. Additionally, they consider factors related to flexibility and mechanical durability. Key performance indicators include power conversion efficiency, specific power (W/kg), and power density (W/m²), which reflect energy output. They also evaluate mechanical flexibility, operational lifetime, temperature coefficient, and resistance to ultraviolet radiation, moisture, and mechanical fatigue. Modern flexible crystalline silicon modules can reach efficiencies over 20%, while laboratory-scale perovskite and tandem cells have exceeded 25%. Flexible CIGS modules typically achieve between 15% and 20%, and commercial organic photovoltaic modules generally range from 10% to 18%, depending on operating conditions and design. While efficiency remains crucial, flexibility offers additional benefits that electrical performance alone doesn't capture. Lighter modules reduce structural load, ease transportation, expand installation options, and lower labor costs, all enhancing the overall value of flexible photovoltaic systems.

Module performance is typically evaluated under standard test conditions: 1,000 W/m² irradiance, AM 1.5 solar spectrum, and a module temperature of 25 °C [133]. The module's voltage and current outputs fluctuate with changes in lighting, temperature, and load conditions, meaning it does not operate at a fixed voltage. Its performance depends on factors such as geographic location, time of day, season, solar irradiance, module orientation and tilt, cloud cover, shading, soiling, state of charge, and temperature [134]. You can assess a module's performance at various intervals using a direct current clamp meter or shunt, logging data that can be graphed or charted with a chart recorder or data logger. For best performance, a solar panel string should consist of similarly rated panels aligned in the same direction, perpendicular to the sunlight. Bypass diodes help maximize output by enabling current to flow continuously, bypassing shaded or broken panels [135]. Electrical characteristics encompass nominal power (W), open-circuit voltage (VOC), short-circuit current (ISC), maximum power point voltage (VMPP), maximum power point current (IMPP), peak power (Wp), and module efficiency (%). VOC is the highest voltage the module can generate when not connected to a load, indicating its maximum voltage capacity [136]. VOC can be measured by a voltmeter directly at an illuminated module's terminals or on its disconnected cable. The peak power rating (Wp) indicates the maximum output under standard test conditions, not the absolute maximum possible. Typical modules, roughly 1 by 2 meters (3 ft × 7 ft), are rated from about 75 W to 600 W, depending on their efficiency. During testing, modules are categorized based on their results. Manufacturers often rate their modules in 5 W increments, with tolerances of either +/- 3%, +/- 5%, or +3/-0% or +5/-0% [137, 138].

The durability of solar modules against rain, hail, heavy snow, and temperature changes depends on the manufacturer. However, most U.S. solar panels are UL listed, indicating they have been tested to endure hail [139]. S. Pingel and colleagues first coined the term "potential-induced degradation" (PID) in 2010 in a published study. It describes a degradation mode caused by the voltage potential between photovoltaic cells and ground [140]. PID refers to performance degradation in crystalline photovoltaic modules caused by stray currents induced by potential differences [141]. This effect can reduce power by as much as 30% [142]. A photovoltaic (PV) device's power output declines over time due to solar radiation and external influences. The degradation index, indicating the annual percentage decrease in output power, is essential for evaluating a photovoltaic plant's long-term performance. To estimate this degradation, we determine the percentage decrease for each electrical parameter. Degradation in a single solar panel can negatively affect the performance of the entire string [143]. Additionally, solar panels within the same installation do not all degrade at the same rate. Numerous studies examine power degradation in various photovoltaic technologies. A recent study highlights this variation, Crystalline silicon solar panels degrade at a steady rate of about 0.8% to 1.0% annually. Conversely, thin-film photovoltaic modules experience a swift initial decline over several months to two years, then enter a phase where degradation levels off and aligns with that of crystalline silicon [144, 145]. Solar panels made from amorphous silicon, micro-morphic silicon, or cadmium telluride can experience initial annual degradation rates of 3% to 4% [146].

Solar panel efficiency, usually around 20%, declines when dust, grime, pollen, and other particles, known as soiling, accumulate on the surface. Seamus Curran, a physics professor at the University of Houston and head of the Institute for Nano Energy, explains that in areas with high dust or pollen, or in deserts, a dirty panel can lose up to 30% of its power [147]. The average soiling loss worldwide in 2018 is estimated at least 3%–4% [148]. As of 2019, paying to have solar panels cleaned is a good investment in many regions [149]. In some areas, cleaning isn't cost-effective. For example, in California in 2013, the expenses of washing panels were rarely justified by the minimal losses caused by soiling. Typically, panels in California experienced a daily efficiency decline of just under 0.05% [150]. Installing and maintaining solar panels also involves occupational hazards. A UK study from 2015 to 2018 examined 80 fire incidents related to PV systems, with over 20 classified as "serious fires" directly linked to PV installation. These incidents affected 37 domestic buildings and 6 solar farms. In one-third of the cases, the root cause remained unidentified, while most others resulted from poor installation, defective products, or design flaws. The most common element responsible for fires was the direct current isolators [151]. A 2021 module reliability study revealed a rising trend in solar module failures, with 30% of manufacturers facing safety issues related to junction boxes (up from 20%) and 26% experiencing bill-of-materials failures (up from 20%) [152]. Cleaning methods for solar panels are categorized into five groups: manual tools, mechanized tools like tractor-mounted brushes, installed hydraulic systems such as sprinklers, installed robotic systems, and deployable robots. Manual tools are the most common, mainly due to their low initial cost. However, a 2014 study in Saudi Arabia discovered that "installed robotic systems, mechanized systems, and installed hydraulic systems are likely the three most promising technologies for cleaning solar panels." [153]. Innovative self-cleaning methods for solar panels are underway. For example, in 2019, nanowires created through wet-chemical etching combined with a hydrophobic coating allowed water droplets to remove up to 98% of dust particles,

making this approach particularly useful for desert environments [154]. In March 2022, MIT researchers revealed a waterless cleaning method for solar panels and mirrors to combat dust buildup, which can decrease solar efficiency by as much as 30% in a month. This technique uses electrostatic repulsion to remove dust particles from the surface, removing the necessity for water or brushes [155]. By removing the need for trucked-in water, preventing dust buildup that may contain corrosive substances, and reducing overall operational expenses [156].

Advantages of Flexible Solar Panels

Flexible solar panels have several benefits over traditional rigid photovoltaic modules, especially in scenarios where conventional systems aren't practical. The key advantage is their lightweight design. Replacing heavy tempered glass and aluminum frames with polymer substrates and thin semiconductor layers allows flexible modules to weigh 70–90% less than standard panels. This significant weight reduction decreases transportation costs, makes installation easier, and reduces structural stress on buildings. They also offer lower initial costs due to simpler installation and transport, cut material use and emissions, and provide long-term savings through their durability. Below are some main advantages and benefits.

a. Cost Reduction

Flexible solar panels offer a major economic benefit through cost savings. Their lightweight design means they need less structural support and can typically be installed without significant modifications or reinforcement [157]. This results in reduced installation costs compared to traditional rigid panels. Plus, their easy transportation and handling lower labor and logistics expenses, making these panels a cost-effective choice for large-scale industrial projects.

b. Versatility in Installation

Another key benefit is mechanical flexibility. These flexible modules can adapt to curved roofs, building façades, vehicle surfaces, boats, recreational vehicles, tents, and portable shelters without the need for elaborate support structures. This versatility enables solar energy generation in places where rigid panels are unsuitable.

c. Lightweight Nature

Their lightweight design lessens the structural burden on buildings, making it especially beneficial for older structures or those with particular weight restrictions.

d. Durability

These panels are typically more impact-resistant and better suited to withstand harsh environmental conditions compared to their rigid counterparts.

e. Environmental Impact

These panels have a smaller environmental footprint compared to traditional ones. Manufacturing flexible panels usually uses fewer raw materials and produces less waste. Additionally, by relying less on fossil fuels, they help lower greenhouse gas emissions and reduce other pollutants [158]. Their application across different industries facilitates the shift to cleaner, renewable energy sources, aiding in climate change mitigation and advancing environmental sustainability.

f. Longevity and Durability

Although these solar panels are lightweight and flexible, they are designed for durability and longevity. They can withstand

tough environmental challenges such as extreme temperatures, strong winds, and physical impacts. This robustness extends their lifespan, lowering the frequency of replacements and supporting long-term savings [159]. Their panels' capacity to perform reliably under tough conditions makes them a dependable energy choice for industrial uses.

g. Improve architectural aesthetics

Flexible photovoltaics enhance architectural aesthetics by seamlessly integrating into building elements. Building-integrated photovoltaic (BIPV) systems can be incorporated into roofs, walls, skylights, and curtain walls, enabling buildings to produce electricity while maintaining their visual appeal. This integration facilitates the creation of net-zero energy buildings and promotes sustainable urban infrastructure.

h. Easy to Installation

Installing flexible panels is much simpler. They can often be attached with adhesives, special mounting tapes, or lightweight fasteners, which lowers labor costs and shortens installation times. Since flexible panels need fewer structural parts, they are especially useful for retrofitting older buildings that cannot bear the weight of traditional solar systems [160].

Challenges of Solar Panels including Flexible Panels

Despite their numerous benefits, flexible solar panels face several technical and economic hurdles. Currently, many flexible technologies still have lower commercial efficiencies than high-end crystalline silicon modules. While laboratory-scale perovskite and tandem cells have reached impressive efficiencies, large-scale commercial versions often underperform compared to rigid panels. Durability is another issue: repeated bending, thermal expansion, UV radiation, moisture, and oxygen can gradually weaken the materials. Proper encapsulation is vital for long-term performance. Although many manufacturers target lifespans of 20–25 years, some new technologies—especially perovskites and organic photovoltaics—still need improvements in stability over time. Manufacturing costs remain relatively high due to specialized materials, advanced deposition equipment, and sophisticated encapsulation processes, but ongoing technological progress and economies of scale are expected to lower these costs. Environmental concerns are also important: some thin-film technologies use scarce or potentially hazardous elements like indium, gallium, cadmium, and tellurium. Developing sustainable recycling methods and responsible resource management will be crucial as flexible photovoltaic use grows worldwide. While flexible solar panels may have slightly lower efficiencies than traditional silicon rigid panels, advances in thin-film tech are narrowing this gap. The trade-off between efficiency and flexibility often makes these panels more suitable for specific industrial uses.

Solar panels generate clean energy, but both standard and flexible systems face notable challenges in performance and durability. Flexible panels are typically glued directly onto surfaces without an air gap, which causes them to become up to 40°C hotter than rigid panels, reducing voltage efficiency. Thermal expansion and bending induce internal stress, resulting in tiny cracks that can lower power output by 20% to 30% within just two years. Plastic laminates suffer from UV exposure, leading to yellowing, peeling, and water damage. Generally, flexible panels produce less energy per square foot than standard monocrystalline panels. Additionally, dust, debris, and shadows from trees or buildings can further decrease energy output. Batteries tend to be expensive and have limited storage capacity, often sufficient for only one or two days. Large frames and glass sheets may seem out of

place on some roofs. As rooftop PV systems expand, energy flow becomes two-way, with excess energy sent to the grid. This can cause issues like over-voltage, as traditional grids are not designed for bi-directional power transfer [161]. Solutions for managing overvoltage include regulating the PV inverter's power factor, deploying new voltage and energy control devices at the distributor level, re-conducting electricity lines, and implementing demand-side management. However, these methods often involve limitations and costs. Furthermore, to guarantee rooftop solar can provide enough backup power during a blackout, a battery is typically required [162].

For many households, the upfront cost can be a barrier—especially when considering other home improvement projects. However, the main challenge isn't just the price; it's determining whether the investment is financially viable for your household. By calculating the total system cost, projected savings, and payback period, you can better assess if solar panels are a worthwhile long-term solution for your home and finances. Aesthetics also influence many homeowners' decisions, as traditional panels can look bulky or clash with roofing materials like clay tiles or slate. It's important to remember that not every roof is suitable for solar; factors such as orientation, slope, and shading impact energy production. In colder regions like Europe or America, summer months yield high solar output with low heating needs, but winter months offer limited sunlight when energy demand peaks. This seasonal imbalance means conventional solar systems generate most energy when it's least needed and less when it's most needed. Without storage, many homeowners rely on the grid for much of the year, prompting them to seek energy independence [163]. To do this, it's crucial to store excess energy for later use, especially in the evenings or winter when generation drops and demand rises.

Applications of Common Solar Panel

Solar powered lights have become ubiquitous and can be seen everywhere from home landscaping and security lights to road signs and more. 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 [164]. Solar power is becoming more accessible as the cost of solar panels falls and more and more people are aware of the economic and environmental benefits of solar energy. Distributed solar photovoltaic systems are usually installed on the roof of a home or business. The electricity generated by these solar power systems can offset the owner's usage and send any excess production to the grid. Solar panels can be connected to your solar power system, enabling you to use solar power after the sun goes down, to power an electric vehicle overnight, or to provide backup power in an emergency [165]. 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 such as barns, monitoring, etc. or installed on the ground and then connected to the electricity meter with underground cables. In our connected world, where phones and tablets are always with us, there are frequent low battery situations [166]. 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 solves the problem of difficulty in using electricity outdoors, sunlight is everywhere [167]. Rural carrier telephone photovoltaic system, small communication machine, GPS power supply for soldiers, solar unattended microwave relay station, optical cable maintenance station, broadcasting/communication/paging power supply system, etc. The below mention 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 a cleaner world, let's do it together.

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 [168].

➤ **Energy Storage Integration:** Many households now complement solar panel systems with energy storage using lithium-ion batteries, such as Tesla Powerwall. 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 [169].

➤ **Bifacial Solar Panels:** Bifacial solar panels, capable of capturing sunlight from both sides (front and back), have become increasingly popular in residential installations. These panels can produce 10–30% more energy than traditional mono-facial solar panels [170].

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 [171].

➤ **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 [172].

➤ **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 those requiring high energy resilience are adopting off-grid systems equipped with energy storage [173].

➤ **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 Gigafactory, 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 [174].

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 function autonomously.

➤ **Solar-Powered Irrigation:** 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 and air pollution [175].

➤ **Sustainable Farming Applications:** Solar panels support sustainable farming by providing renewable energy for agricultural processing, such as 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 [176].

Portable and Remote

We can give few versatile portable and remote infrastructure solar panel applications as shown below [177].

➤ **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 [178].

➤ **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 [179].

➤ **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 [180].

Transportation Sector 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 range per day under sunny conditions [181].

➤ **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 [182].

Specialized Tech and Others We can give few versatile solar panel applications in specialized tech sector as shown below.

➤ **In Petroleum, marine and meteorological fields** as Oil pipeline and reservoir gate cathodic protection solar power system, marine detection equipment, life and emergency power supply of oil drilling platform, meteorological/hydrological observation equipment, etc [183].

➤ **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 [184].

➤ **Power in Space.** 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 [185]. 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. 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 [186].

Applications of Flexible Solar Panel

Flexible solar panels transform industrial and everyday energy use by offering adaptable, affordable, easy-to-use, and eco-friendly solutions. Their distinct features enable installation in a variety of settings, from warehouse rooftops to distant agricultural fields. These panels assist in enhancing energy efficiency and promoting sustainability across different industries. By broadening the environments suitable for photovoltaic technology, flexible solar panels have significantly increased their deployment options. Some common applications of flexible solar panels are outlined below.

a. Building Sector: In the building industry, flexible modules are used in curved roofs, façades, skylights, awnings, and membrane structures, allowing buildings to produce electricity without the need for heavy support systems. Building-integrated photovoltaics are increasingly featured in modern architectural designs to boost energy efficiency while preserving aesthetic appeal. Currently, flexible solar panels are especially suitable for manufacturing plants, transport sheds, industrial buildings, and warehouses, which often have large, irregular rooftops. These rooftops can be challenging for traditional rigid panels because of their weight and the need for structural reinforcement [187]. Flexible solar panels are lightweight and versatile, enabling installation on many surfaces without major modifications. This helps industrial facilities optimize roof space for energy generation, lowering electricity expenses and improving sustainability.

b. Transportation sector: In the transportation and logistics industry, flexible solar panels can be installed on the roofs of delivery vehicles, trucks, cars, taxis, and trailers [188]. This integration offers a mobile power source, lowering dependence on fossil fuels and cutting operational costs. For instance, delivery trucks fitted with flexible solar panels can harness solar energy to operate refrigeration units or supplementary systems, thereby decreasing fuel use and emissions [189]. These panels' flexibility allows them to follow curved vehicle surfaces while maintaining aerodynamic efficiency. As a result, in the transportation industry, flexible modules are used on electric vehicles, buses, trains, trucks, boats, yachts, and RVs. They supply auxiliary power for lighting,

ventilation, battery charging, and onboard electronics, decreasing reliance on external power sources.

c. Aerospace Industry: The aerospace sector has implemented lightweight, flexible photovoltaics in satellites, high-altitude unmanned aerial vehicles, and experimental solar-powered aircraft. Their high specific power (watts per kilogram) makes them especially valuable in applications where reducing weight is essential.

d. Agriculture Sector: Flexible photovoltaic systems are becoming more common in agriculture, being installed on greenhouses, irrigation equipment, livestock shelters, and portable structures. They enable farmers to generate renewable electricity without sacrificing valuable land. Flexible solar panels offer a reliable and adaptable energy source, especially in remote areas. They can be mounted on uneven surfaces, shaped structures such as greenhouses, or directly on the ground [190]. This flexibility is vital for operating irrigation systems, lighting, and other important equipment in regions lacking reliable access to the electrical grid. Using solar energy allows farmers to decrease reliance on diesel generators, cut operating expenses, and lessen environmental harm.

e. Oil, Gas, and Mining Industrial Sector: The oil, gas, and mining sectors frequently operate in remote and tough environments with limited or no access to the electrical grid. Flexible solar panels can be installed in these challenging areas, offering a sustainable power source for equipment, living spaces, and communication devices. Their robustness and capacity to endure harsh conditions make them an excellent option. Moreover, utilizing solar energy in these industries can decrease dependence on diesel generators, helping to cut operational costs and reduce carbon emissions.

f. Humanitarian assistance and disaster relief purposes

Flexible solar technology is vital for humanitarian aid, disaster relief, and emergency support. Portable photovoltaic systems supply electricity to emergency shelters, medical clinics, communication devices, and water purification units in areas impacted by natural disasters or without traditional electrical infrastructure.

g. Other sectors. Emerging consumer applications encompass wearable electronics, backpacks, tents, smart textiles, IoT sensors, and portable chargers. As the power needs of electronic devices decrease, flexible photovoltaics are likely to be more frequently incorporated into daily products [191].

The cause of global warming and climate change is the rise in greenhouse gases in our atmosphere. These gases are any gaseous substances that can absorb infrared radiation, trapping heat and increasing atmospheric temperature. This process, known as the greenhouse effect, is what leads to overall global warming [192]. Global warming is not a new scientific idea. Swedish physicist and chemist Svante Arrhenius first explored the fundamentals over a century ago, in 1896. His publication in the *Philosophical Magazine* and *Journal of Science* was the first to quantify how carbon dioxide contributes to the greenhouse effect known today [193]. The greenhouse effect happens because the sun sends large quantities of radiation to Earth, which enters the atmosphere as visible light, as well as ultraviolet (UV), infrared (IR), and other forms of radiation that cannot be seen by the human eye [194]. Ultraviolet (UV) radiation possesses a shorter wavelength and a higher energy level compared to visible light, whereas infrared

(IR) radiation has a longer wavelength and a lower energy level. Approximately 30% of the radiation incident on Earth is reflected back into space by clouds, ice, and other reflective surfaces. The remaining 70% is absorbed by the oceans, terrestrial surfaces, and the atmosphere, as reported by NASA's Earth Observatory [195].

As the Earth warms, the oceans, land, and atmosphere emit heat as IR thermal radiation, which escapes into space. This balance between incoming and outgoing radiation maintains Earth's habitability, resulting in an average temperature of approximately 150 °C, according to NASA [196]. Without this atmospheric balance, Earth would be either as cold and lifeless as the Moon, which has an almost nonexistent atmosphere and a temperature of about -1530 °C on its dark side, or as hot as Venus, with an atmosphere dense enough to trap solar radiation and maintain an average temperature around 462°C. The process of exchanging incoming and outgoing radiation that keeps Earth warm is known as the greenhouse effect, similar to how a greenhouse for plants functions. Greenhouse gases (GHGs), the atmosphere's radiation-absorbing gases, are mainly responsible for this effect, which is a major driver of global warming. According to the EPA, the key greenhouse gases are water vapor (H₂O), carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) [197]. Each of these gases can stay in the atmosphere for varying durations, from a few years up to thousands of years. They stay long enough to become well mixed, so their levels are roughly uniform worldwide, no matter the emission source. GHG emissions are commonly measured in terms of 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) [198]. GWP accounts for the fact that many gases warm Earth more effectively than CO₂ per unit mass.

Sunlight or solar energy is an abundant, renewable resource that will never run out. Unlike fossil fuels, which are limited and release greenhouse gases and particulates during extraction, processing, and burning, solar panels produce no emissions during operation. However, manufacturing solar panels involves using various materials that require different amounts of resources and energy. The energy invested in extracting raw materials and producing the product is called 'embodied energy.' The period needed for the product to generate enough energy to offset this initial investment is known as the total energy payback time (EPBT) [199]. A typical silicon crystalline solar panel usually produces enough energy to offset its embodied energy within 2 years of installation. As panel efficiency improves, this payback time has decreased to below 1.5 years in regions with abundant solar radiation. Modern, high-efficiency crystalline silicon panels can often repay their embodied energy within just a few years [200]. 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. Since a typical solar panel lasts 20+ years, it can repay its embodied energy multiple times and offset tons of emissions [201].

Solar Panels Waste Recycling and Environmental Sustainability

Despite widespread misinformation about solar panels being toxic, modern crystalline silicon solar panels are virtually free of harmful materials. The perception of toxicity mainly stems from outdated thin-film panels, like Cadmium telluride (CdTe), which contain trace amounts of cadmium and telluride. However, these panels typically do not pose a risk unless they are broken into fragments, as the trace cadmium is contained within the EVA layers and

cannot leach out. Additionally, current crystalline silicon panels contain only tiny amounts of lead in the solder used for connecting cells. Still, even solder is being phased out in favor of new busbar compression joining techniques and conductive paste materials [202]. Solder is used in hundreds of millions of electronic devices and appliances. Many consumer electronics, including mobile phones, computers, and TVs, contain even more toxic elements. This makes electronic waste, or E-waste, a major global concern. About 99% of the solar panels installed worldwide today are made of silicon crystalline and do not include cadmium or telluride. These solar panels are considered safe; even if damaged, they do not pose contamination risks because their cells are sealed within durable polymer layers and lack soluble materials [203]. Like all appliances, solar panels must be collected and recycled when they reach the end of their lifespan. However, because most solar panels installed in the last 20 years are still in use, the volume of solar waste remains relatively low [204]. However, over the next 10-20 years, many systems will reach end of life (EOL), and the volume of solar-related waste expected to be recycled will increase significantly [205]. Solar panel recycling is a growing industry. Many materials, including aluminum frames and mounting systems, are straightforward to recycle. Aiming for sustainability, most solar panel manufacturers have joined the non-profit PV Cycle organization [206].

PV waste totaled 30,000 tons in 2021, and Bloomberg NEF estimated it would rise to more than 1 million tons by 2035 and more than 10 million by 2050 [207]. For comparison, coal power produced 750 million tons of fly ash waste in 2022 [208]. In the United States, around 90% of decommissioned solar panels end up in landfills as of 2023 [209]. Most components of a solar module are recyclable, with up to 95% of some semiconductor materials or glass, plus significant quantities of ferrous and non-ferrous metals [210]. Some private companies and non-profit organizations collect and recycle end-of-life modules [211]. EU law mandates that manufacturers properly recycle their solar panels. Corresponding legislation is also being developed in Japan, India, and Australia [212]. A 2023 Australian report indicated a market for quality used panels and suggested strategies to promote reuse, but rules have not been implemented [213, 214]. Since 2010, an annual European conference has been held, gathering manufacturers, recyclers, and researchers to discuss the future of PV module recycling [215]. For silicon-based modules, aluminum frames and junction boxes are manually removed at the start. The module is then crushed in a mill, separating the different fractions—glass, plastics, and metals [206]. You can recover over 80% of the incoming weight [217]. Flat glass recyclers can handle this process because PV modules have a shape and composition similar to flat glass used in construction and automotive sectors.

The recovered glass is easily accepted by the glass foam and insulation industries. However, non-silicon-based modules need specialized recycling methods, like chemical baths, to separate the various semiconductor materials [218]. The recycling process for cadmium telluride modules starts with crushing the module, then separating the various fractions. This method aims to recover up to 90% of the glass and 95% of the semiconductor materials. Recently, some private companies have established commercial-scale recycling facilities [219]. Flexible solar panels play a vital role in advancing global sustainability by decreasing reliance on fossil fuels and reducing greenhouse gas emissions. During their lifespan, photovoltaic systems produce electricity without emitting carbon dioxide, air pollutants, or noise. Many flexible options use significantly less raw material than traditional crystalline silicon

panels, as their semiconductor layers are only a few micrometers thick. This reduction in material use decreases manufacturing energy and helps conserve natural resources. Nonetheless, sustainability also hinges on responsible manufacturing, recycling, and disposal practices. Scientists are working on recyclable encapsulation, eco-friendly semiconductor materials, and circular economy methods to recover valuable resources from end-of-life panels. As flexible solar technology becomes more widespread, ongoing improvements in recycling will be essential.

Global Market of Solar Energy and Panels

According to Solar Power Europe's most realistic forecast, solar installations are expected to rise by 10%, reaching 655 GW in 2025. Between 2027 and 2029, annual growth is projected to stay in the low double digits, ultimately reaching 930 GW by the end of this period. However, achieving the Global Solar Council's ambitious goal of 8 TW by 2030 will necessitate a much faster deployment pace, averaging about 1 TW of new installations annually [220]. 2025 will mark ten years since the formation of the Global Solar Council, which was established at COP21 in Paris. It was founded on the shared conviction that solar energy could speed up the global shift to renewable energy and fulfill the commitments of the Paris Agreement. Back then, the solar PV sector was rapidly growing but fragmented. The GSC was set up to unify the industry and provide it with a single, worldwide voice to advocate for more ambitious policies, increased investment, and quicker, fairer deployment [221]. With over 2 TW of installed solar capacity and costs reduced by more than 80% in many markets, solar power has demonstrated both its economic and environmental benefits. To stay aligned with the 1.5°C climate target and achieve the global aim of tripling renewable energy capacity by 2030, solar must expand to at least 8 TW. This expansion involves not just growth but a transformation to provide clean, reliable, and affordable energy to homes, schools, hospitals, and industries worldwide. It necessitates bold reforms: faster and cheaper financing, smart grids and storage systems capable of managing variable energy at scale, streamlined permitting processes, resilient supply chains, and a skilled workforce that represents diverse communities [222].

The uneven distribution of solar market growth remains a key concern. Most expansion has been in the Asia-Pacific region, primarily driven by China, leading to increasing regional disparities. In 2024, China's solar market grew by 30% to 329 GW, surpassing the combined total of the other top 10 markets and holding a 55% global market share. This rapid growth is a significant achievement for global decarbonization efforts, as China's extensive solar commitment has spurred worldwide development. However, it also highlights the world's heavy dependence on a single country. Following major changes to its solar market design this year, a temporary slowdown in global growth in 2026 seems likely. Meanwhile, other regions, especially the Middle East and Africa, installed less capacity than the previous year. Although 35 countries now have annual gigawatt-scale solar markets, this is below expectations. We anticipate this number will grow soon; our report offers a detailed analysis of these GW-scale markets, with insights from national solar and renewable energy associations [223].

Today, emerging solar markets are gaining momentum. India's comprehensive solar strategy, detailed in a dedicated chapter, is starting to show results. As the most populous country, India has become the third-largest solar market worldwide, more than doubling its annual installations in 2024, with continued strong growth expected. According to the GSC's policy suggestions,

maintaining global progress will involve tackling region-specific challenges. More developed markets should focus on improving grid flexibility, updating policies to suit variable renewables, prioritizing battery storage, and simplifying permitting and grid connection processes. Least developed countries need to address investment gaps. Across all regions, developing a skilled workforce and setting bold solar and storage targets are vital. During political uncertainty, low-cost solar power could be crucial to ensuring energy security and competitiveness worldwide. The upcoming years are pivotal for solar development, demanding foresight and dedication from policymakers and financial entities. In most growth scenarios, solar's influence in driving the global energy transition is expected to strengthen, reaching 7.1 TW by 2030 and contributing nearly two-thirds of the 11 TW renewable energy goal set at COP28. With suitable conditions, solar capacity could quadruple, surpassing 8 TW by the end of the decade [224]. The International Energy Agency (IEA) forecasts that solar PV will become the leading renewable energy source by 2029, contributing 80% of the growth in global renewable capacity from 2024 to 2030. AI integration is expected to be vital to reaching this goal by improving the efficiency and reliability of solar systems. In 2023, the global solar market was valued at USD 92.45 billion.

According to ‘Spherical Insights,’ the market is expanding at a compound annual growth rate (CAGR) of 11.95% from 2023 to 2033. By 2033, the global solar energy market is projected to reach USD 285.89 billion, as illustrated in Figure 6 [225]. Their forecast adopts a more analytical approach, considering all relevant factors when evaluating the global solar energy market. This includes the current global market size, share, and COVID-19 impact, as well as technological segments like Concentrated Solar Power Systems and Photovoltaic Systems. It also examines solar modules such as Monocrystalline, Polycrystalline, Cadmium Telluride, Amorphous Silicon Cells, among others. The analysis covers end-user categories—Residential, Commercial, and Industrial—and regions including North America, Europe, Asia-Pacific, Latin America, Middle East, and Africa. According to ‘Persistence-Market-Research,’ the global solar energy market is projected to reach US\$137.2 billion by 2025 and US\$313 billion by 2032, expanding at a CAGR of 12.5% during 2025-2032, as shown in Figure 7 below. This forecast is driven by growing environmental concerns, increased government-led renewable energy installations, and rapid technological advances that enhance efficiency and reduce costs [226].

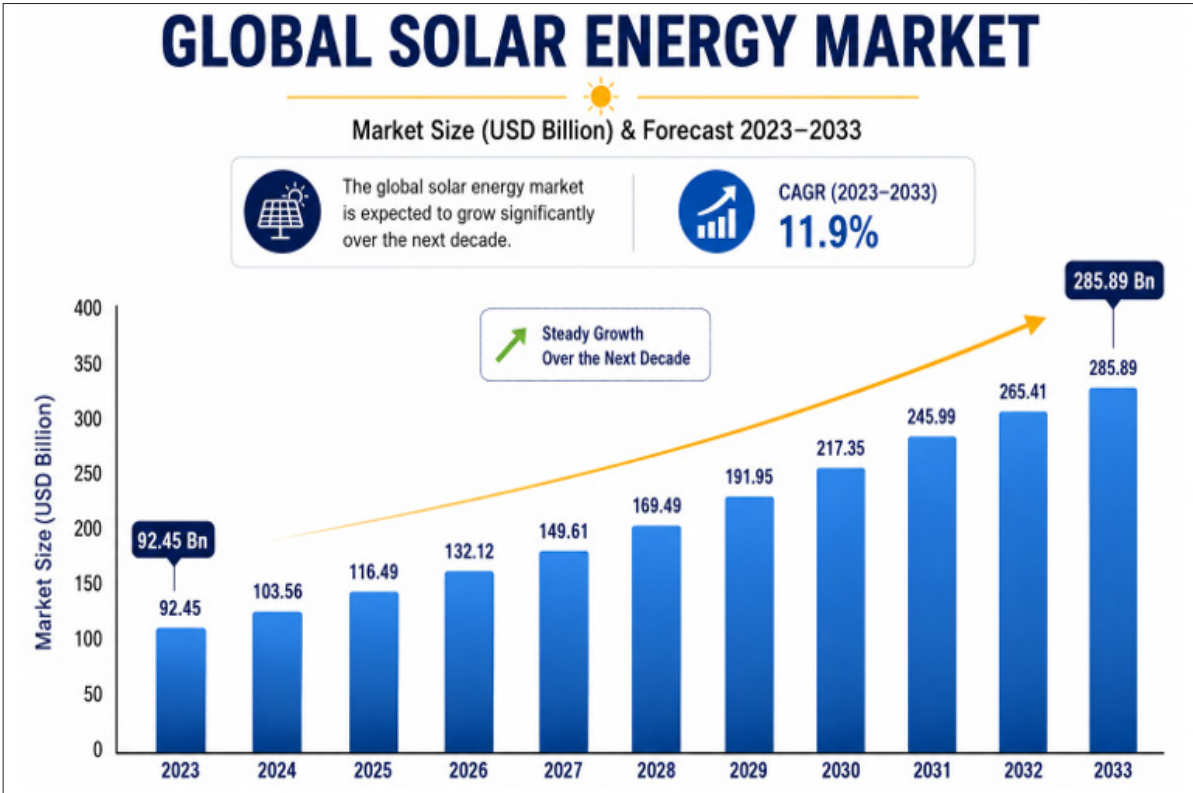


Figure 6: Prediction of Global Solar Energy Market Size (2023-2033) By Spherical Insights

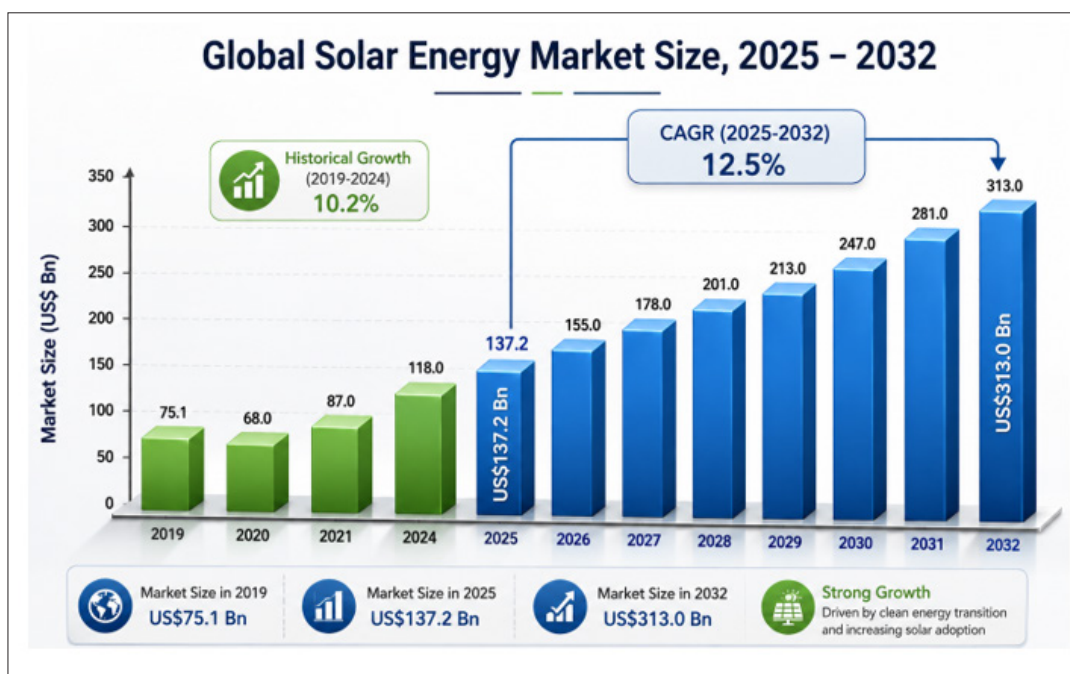


Figure 7: Prediction of Global Solar Energy Market Size (2025-2032) By Persistence-Market-Research

Conclusion

Today in global contest power generation is one industrial sector with a major contribution to Greenhouse Gas (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 [227]. 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 [228]. 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” approach fits and how techniques like machine learning, AI, 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 [229].

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Today, smart solar panels can respond to both direct sunlight and diffuse light reflected from particles in clouds and the atmosphere. They often generate some electricity even on cloudy days. Flexible solar panels are lightweight, malleable, and easy to attach to complex or irregular surfaces like curved machinery or vehicle roofs, making industrial solar deployment more practical and effective. They can be bonded to trucks, trailers, or other vehicles to power auxiliary systems, reducing fuel consumption and emissions while fitting aerodynamic shapes. Their design makes them suitable for use in agricultural, mining, oil, or gas sites with limited grid access. These panels are rugged, durable, and

reliable, well-suited for off-grid powering of essential equipment. One key economic benefit is their potential for cost savings: their lightweight design means they require less structural support and often need no extensive modifications, lowering installation costs. Ease of transport and handling further reduce labor and logistics expenses, making them an attractive option for large-scale industrial projects. Their ability to be installed on curved or uneven surfaces expands their applications where traditional rigid panels are less suitable. In transportation, lightweight modules improve energy efficiency by adding minimal mass to vehicles, ships, aircraft, and satellites. Portable flexible panels are also valuable for emergency response, humanitarian relief, military operations, and outdoor recreation, providing reliable power in remote locations.

Flexible paper-like solar panels are among the most notable advances in modern renewable energy technology. Their lightweight, flexible design combined with high efficiency broadens the scope of solar energy applications beyond traditional rooftops. Developments in crystalline silicon, thin-film semiconductors, organic photovoltaics, and perovskite materials have turned flexible solar tech from experimental prototypes into practical solutions for sectors like architecture, transportation, agriculture, aerospace, disaster relief, and consumer devices. While challenges such as durability, cost, and stability still exist, ongoing research suggests these issues will improve over time. As the global push for clean, sustainable, and decentralized energy grows, flexible solar panels are poised to become vital in shaping the future energy landscape. Continuous advancements in materials, manufacturing, and system integration further promise to speed up the world's shift to low-carbon, renewable electricity. Developing new solar power technologies is a key solution to meet the increasing global energy demand. Although the field is rapidly expanding, it faces technical challenges such as low solar cell efficiencies, subpar balance-of-systems (BOS) performance, economic issues like high initial costs and limited financing options, and institutional hurdles including inadequate infrastructure and a shortage of skilled workers. Solar energy technologies are now widely established and popular worldwide, supported by billions of dollars in investments, with more anticipated to address industry limitations.

Researchers and vehicle scientists have explored EV charging systems integrated with renewable energy, though future research could consider other clean energy options like fuel cells. Solar power has great potential for homeowners but presents practical and financial challenges. First-time buyers often find navigating subsidies, tax benefits, and permits confusing, especially as requirements vary across municipalities and may restrict heritage properties or areas with specific plans. Conversely, subsidies can greatly enhance home energy efficiency and independence. Choosing a reliable installer influences system performance and user experience significantly, yet there are wide differences in pricing, craftsmanship, and customer service, making trust difficult. Additionally, the one-size-fits-all approach in the flexible solar market causes systemic issues such as efficiency gaps, reduced lifespan, and mismatched application. However, as photovoltaic systems grow in popularity, the solar industry is expanding rapidly. Although the government ended Feed-in Tariff (FIT) payments in March 2019, demand for solar technology remains strong, driving down system prices. With yearly increases in grid electricity costs, now is an ideal time to invest in PV systems. The sector is expected to keep growing as technological efficiency improves and costs decline, attracting more investors who recognize the importance of renewable energy for the future. However, modern

solar panels can operate on cloudy days, though with reduced efficiency. Advances in solar technology make it a key part of the global shift toward sustainability. Solar power is now more dependable, thanks to energy storage options like lithium-ion and solid-state batteries that enable storing excess energy. Continued reductions in solar panel costs will make them more accessible to individuals and businesses. Additionally, ongoing improvements in solar cell materials and designs enhance panel efficiency, making solar energy increasingly competitive with fossil fuels and other renewables. Emerging technologies, for instance, perovskite solar panels, bifacial panels, and building-integrated photovoltaics (BIPV), are poised to further advance the industry.

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