International Journal of Innovative Research in Engineering and Management (IJIREM)
ISSN (Online): 2350-0557, Volume 13, Issue 4, August 2026
DOI: https://doi.org/10.55524/ijirem.2026.13.4.8
Article ID IJIR3226, Pages 58-74
www.ijirem.org

A Review of Photovoltaic Cell Generations, Materials, and Emerging Bifacial PV Technology

Monaem Elmnifi[1,2], Yasser F. Nassar[1], Ibrahim Imbayah[3], *Asiye Aslan[4,*] and Ali Osman Büyükköse[5]

[1]Mechanical & Renewable Energy Eng. Department., Eng. Faculty, Wadi Alshatti University, Brack, Libya
[2]Department of Mechanical Engineering Technology, Belgorod Technological University named after V.G. Shukhov Belgorod, Kostyukova Str., Russia
[3]Department of Energy Engineering, College of Renewable Energy, Tajoura, Libya
[4]Department of Electricity and Energy, Gönen Vocational School, Bandırma Onyedi Eylül University, Balıkesir, Türkiye
[5]Enerjisa Enerji Uretim Inc., Istanbul Türkiye

Correspondence should be addressed to Asiye Aslan; aaslan@bandirma.edu.tr

Received: 24 July 2026; Revised: 7 August 2026; Accepted: 21 August 2026

ABSTRACT- The generation of electricity from solar radiation is now one of the most promising technologies in sustainable energy generation because it is able to directly transform the radiation from the sun into electricity. Photovoltaic (PV) materials and PV cell architectures have been continuously advanced to further increase conversion efficiency, decrease manufacturing costs, and increase the number of practical use cases for solar energy systems. The review provides an overview on the major generations of PV cells (crystalline silicon PV, thin film PV, third generation PV cells: organic solar cells, dye-sensitized solar cells, quantum dot solar cells, perovskite solar cells and black silicon solar cells).The working principles, material properties, strengths and weaknesses, and technological problems are reviewed for each generation of PV technology. New PV technology also receives special attention: bifacial PV modules, which can capture electricity from the front and back surfaces of the PV module. Several design and environmental factors affect the performance of bifacial modules such as the irradiance on the back surface, ground albedo, module height, tilt angle, row spacing, shading etc. Thus, bifacial PV technology has great potential in the field of improving energy yield particularly in high irradiance, high reflectance environments like desert and semi-arid regions.In short, it has been a review of the development related to PV materials and technologies and future research lines on improving the efficiency, stability, lowering costs, recycling, and the broader application of advanced PV systems.

KEYWORDS- Photovoltaic Cells, Bifacial pv Modules, Generations, Types, Performance, Efficiency, Production, Use, Innovation

I. INTRODUCTION

As global demand for energy continues to grow, so has the need for clean, reliable and sustainable energy sources, particularly as environmental effects of the consumption of fossil fuels is a growing concern [1]. Solar PV has been heavily discussed as one of the renewable energy technologies due to its ability to transform sunlight into electricity with minimal operating emissions, modular design, and its versatility in residential, commercial and industrial applications [2].The photovoltaic effect is the basis for photovoltaic technology, in which photons incident on semiconductors are absorbed and create electron-hole pairs. If these charge carriers are separated by an internal electric field in a p-n junction or other device structure, an electric current will flow [3]. Thus, the characteristics of the absorber material, band gap, the mobility of carriers, recombination loss, surface passivation, structure of the solar cell, and manufacturing quality are all significant factors that influence the performance of a solar cell [4].In the history of PV, there have been several generations of crystalline silicon solar cells since they first emerged. Most of the PV cells in the global market are the first-generation cells, which are essentially based on silicon (Si), and these are mainly monocrystalline and polycrystalline silicon. The first-generation PV cells are mainly based on silicon (Si), are presently the most prevalent in the global market due to their high stability, long life, and developed manufacturing processes. To minimize material usage and manufacturing costs, 2nd generation thin-film technologies like amorphous silicon, cadmium telluride and copper indium gallium selenide have been developed. In recent years, third-generation solar cells, such as dye-sensitized solar cells, black silicon solar cells, perovskite solar cells, quantum dot solar cells and organic solar cells have shown great promise in terms of the potential for increased efficiencies, flexible fabrication, low cost and new applications [5]. Besides material development, contemporary PV research also aims at enhancing the energy yields of the PV modules and the PV system. Bifacial PV modules are one of the most promising emerging technologies, as they are able to produce electricity from both the front and rear of the module. The use of direct sunlight on the front surface and reflected and diffuse sunlight on the back surface of bifacial PV systems can enhance overall PV energy production as compared to

traditional monofacial PV. The performance is dependent on the following factors: ground albedo, module height, row spacing, and tilt angle, tracking configuration, rear shading and environmental conditions [6].
The goal of this review is to give an overview of the photovoltaic (PV) cell generations, materials, operation principles, benefits, drawbacks and future trends of development. It also emphasizes the potential of bifacial PV as another area of improvement needed for PV harvesting, especially in areas of high irradiance and high reflectance, like desert and semi-arid climates. The review aims to help researchers and engineers to gain insight into the latest developments in PV technologies and the remaining challenges for efficiency gain, reduction in costs and sustainable deployment.

II. PHOTOVOLTAIC CELL OPERATING PRINCIPLE

Photovoltaic (PV) cells are semiconductor devices that use the photovoltaic effect to directly transform the radiant energy of the Sun into electrical energy [7]. Figure 1 shows the workings of a conventional photovoltaic cell, an n-type negative layer of silicon and a p-type positive layer. When photons from the sun strike the cell, electron-hole pairs are generated, and charges move through the external circuit to generate an electric current. This is the process in which the semiconductor material and the electrons absorb photons from sunlight and holes are created. The photon energy is sufficient to match or exceed the energy band gap of the semiconductor and causes electrons to be excited from the valence band to the conduction band, resulting in the formation of holes in the valence band. PV cells use silicon as the semiconductor material because it has a desirable band gap, it is abundant, it is stable, and manufacturing technology is well developed [8]. Covalent bond is formed between silicon atoms and neighbouring atoms, resulting in a stable crystal structure in crystalline silicon. The silicon material absorbs sunlight resulting in generation of charge carriers within the cell material. They need to be separated and picked up before they can recombine. Pn junction is the elementary structure which is associated with the charge separation in a conventional solar cell. It is created by combining p-type silicon (with an abundance of holes) with n-type silicon (with an abundance of electrons). The junction forms an electric field inside. The photogenerated electrons are attracted to the n-type region and the holes to the p-type region by this electric field [9].

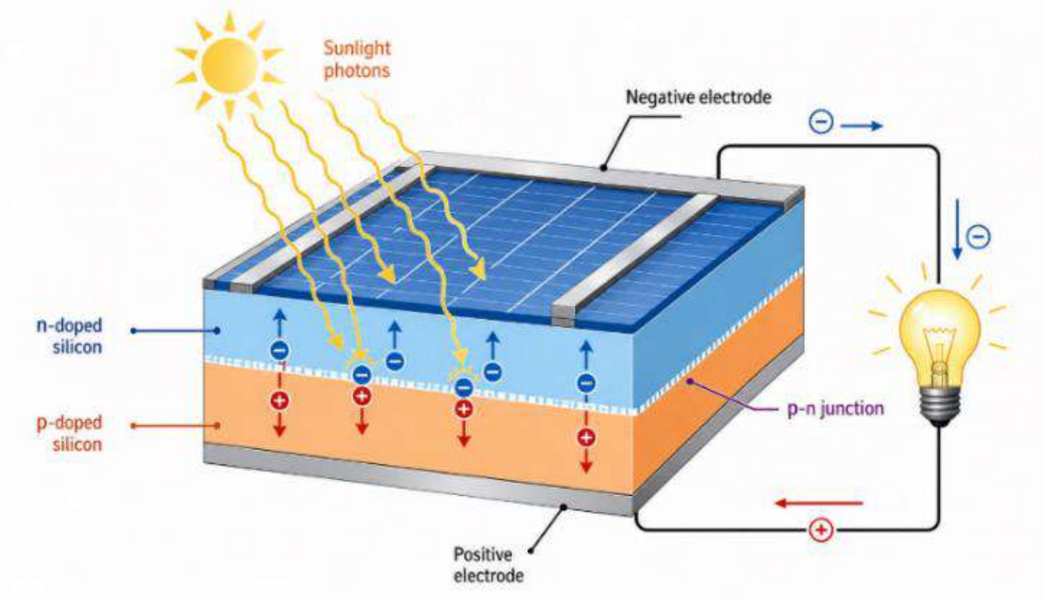


Figure 1: Photovoltaic cell with p-type and n-type layers

III. DIFFERENT TYPES OF PHOTOVOLTAIC

Photovoltaic (PV) cells have been developed through different generations over the course of technological advancement, with each generation exhibiting distinct characteristics in terms of the materials used, cell design, efficiency, advantages, and limitations [10][11].

A. First-Generation PV Cells (Conventional Crystalline Silicon)

- **Monocrystalline Silicon (Mono c-Si)**
  Monocrystalline silicon cells are created from single crystal silicon wafers that are cut from cylindrical silicon ingots. These cells have the highest efficiency of all commercially available silicon technologies, with best module efficiencies of up to 20%. Monocrystalline cells are stable, with a long life of 25-30 years, and a performance that does not change according to temperature. However, the purification and cutting of wafers to obtain the production process is energy consuming and the loss of material is large [12].
- **Polycrystalline silicon (Poly c-Si / mc-Si)**
  The molecular structure of silicon consists of several tiny groups or crystalline grains separated by barriers. They are more economical and efficient to produce than monocrystalline elements. The efficiency of solar cells is lower than that of monocrystalline silicon. Unlike monocrystalline silicon, it is cast into blocks. When the crystals are cemented, they form crystalline formations of different sizes with defects on the faces. These defects reduce efficiency; laboratory efficiency

ranges from 8 to 23%, and production efficiency ranges from 14 to 17% [13][14].

B. Second-Generation PV Cells (Thin-Film Technology)

- **Amorphous Silicon (a-Si) and Microcrystalline Silicon (μc-Si)**
  Thin-film silicon cells use very thin layers of semiconductor material deposited on substrates like glass, metal, or polymer. Amorphous silicon modules have lower efficiency (4–12%) but offer lower production cost and flexibility for integration in building facades or curved surfaces [7]. Microcrystalline silicon can be combined in multi-junction cells to increase red and near-infrared light absorption, slightly improving efficiency [15][16].
- **Cadmium telluride (CdTe) Cells**
  The CdTe solar cells are a proven thin film technology based on compounds of cadmium and tellurium. CdTe modules are lightweight, low cost and capable of large substrate area. The efficiency is around 16% for the usual cases, and a bit higher in laboratory conditions [17]. Cadmium toxicity, thermal sensitivity, and limited availability of raw materials are challenges.
- **Copper Indium Gallium Selenide (CIGS) Cells**
  The CIGS cells are made of a thin film of the elements copper, indium, gallium, and selenium. The modules have a high absorption value; they are very flexible and can reach absorption efficiency of 7% to 20% (lab/commercial production) [18]. While material availability and temperature sensitivity are concerns, CIGS cells can be used in flat roofs and integrated applications.

C. Third-Generation PV Cells (Emerging High-Performance Technologies)

- **Organic PV Cells**
  Organic solar cells are made of polymer or organic materials. Despite their low cost, they are not particularly effective. Commercial organic photovoltaic modules have a conversion efficiency of 4 to 5%, and laboratory organic photovoltaic modules have a conversion efficiency of 6 to 8%. When creating organic elements, roll production is used at high speeds and low temperatures, as well as conventional printing technologies. Organic solar cells have been able to compete with other photovoltaic technologies in some applications due to lower production costs [19]. As in the printing industry, organic elements can be applied to plastic sheets. In other words, organic solar cells are lightweight and flexible, making them ideal for mobile applications and uneven surfaces. This is especially useful for portable devices such as cell phones, computers, radios, flashlights, toys, and virtually any other battery-powered gadget [20]. Figure 2 illustrates the electronic principle of a polymer/organic solar cell through the HOMO and LUMO energy levels. When light is absorbed, electronic excitations are generated, and then electrons and holes move towards the electrodes to form an electric current.

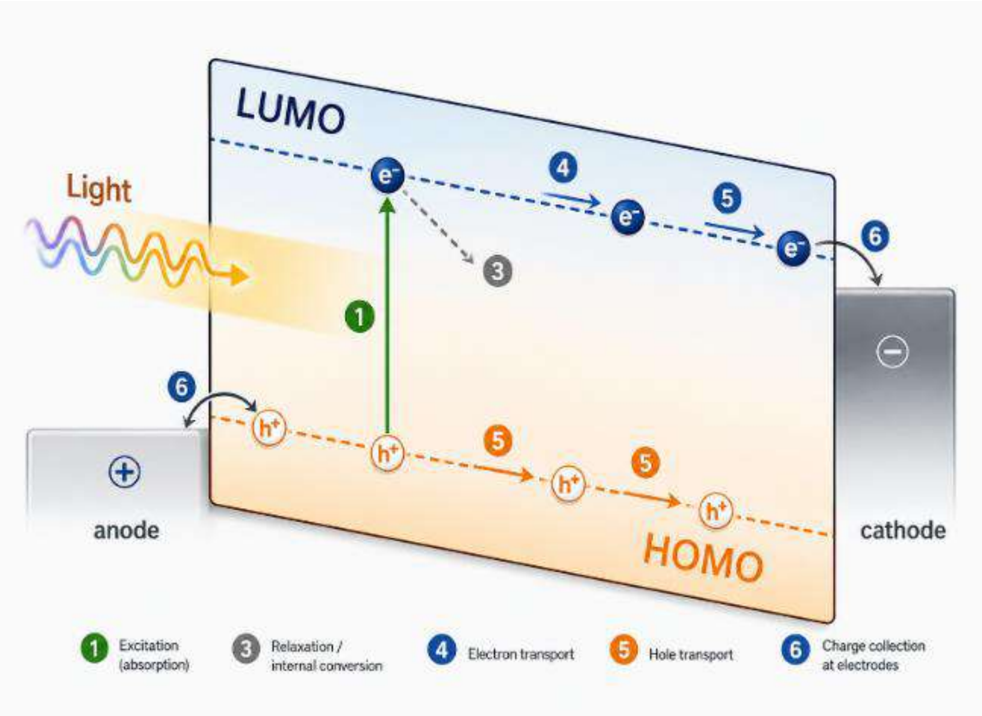


Figure 2: The solar cell based on the polymer principle.

- **Dye-Sensitized Solar Cells (DSSC)**
  The dye-sensitized solar cells (DSSCs) use oxide semiconductors with a large band gap along with the photosensitizing dye that absorbs electromagnetic radiation in the visible-light range. A chlorophyll-sensitized solar cell using the electrode of zinc oxide (ZnO) was invented in 1972. Later, in 1976, Carlson and Wronski fabricated the first PV cell made with amorphous silicon, with a conversion efficiency of ~2.4% [21]. These early advances helped to redouble the scientific interest in new PV technologies, such as DSSCs.One of the major drawbacks of the early dye-

sensitized systems was the low percentage of incident solar radiation absorbed by a single molecular layer of dye on the semiconductor surface. The ability of such a monolayer to absorb only around 1% of the incident sunlight restricts the performance and future development of these cells; it was reported. In 1991, a significant improvement in the efficiency of DSSC was reported with the conversion efficiency up to 7.1% . Moreover, about 80% of the absorbed photons were converted into electrical current [22].The DSSC's simple design coupled with low manufacturing costs has inspired a large amount of research seeking to achieve the conversion efficiency and stability necessary for commercial use. The mechanism of operation of a DSSC is sometimes likened to natural photosynthesis as the process involves light absorption and charge transfer is triggered by a light-sensitive dye [23]. When light strikes the dye molecules, they absorb the light and are electronically excited, as shown in Figure 3. The excited electrons then enter the conduction band of the semiconductor, TiO_2, and are carried through the semiconductor to the external electrical circuit. The electrons pass through the external load, then back to the cell via the counter electrode; the electrolyte re-reduces the dye molecules to their oxidized form and returns them to their original state. The set of continuous light absorption, electron injection, and charge transport and dye regeneration transforms the solar radiation into electrical energy.

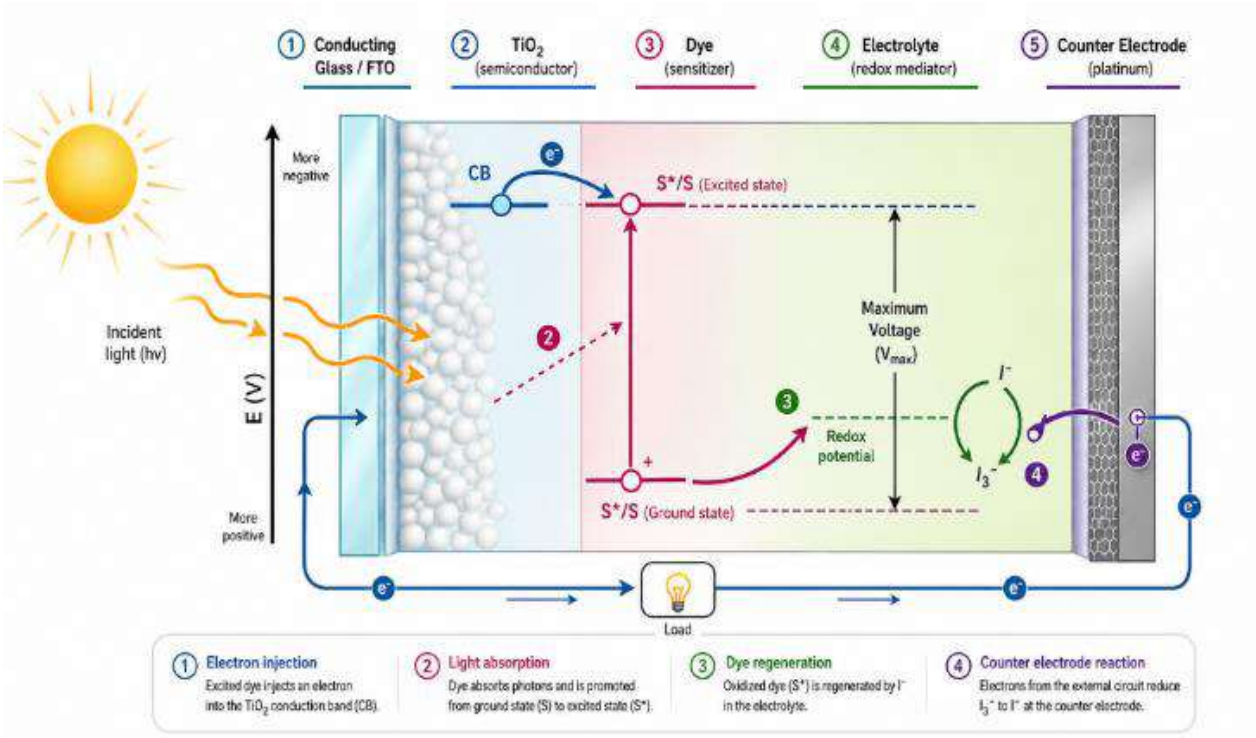


Figure 3: Dye-sensitized solar cells

- **Quantum Dot‹ Sensitized Solar Cells (QDSSC)**
  With the progress of the research on dye-sensitized solar cells (DSSCs), as an alternative to the conventional organic dyes, quantum dots (QDs) were proposed as the sensitizing materials, which resulted in quantum dot-sensitized solar cells (QDSSCs). The nanometer-scale semiconductor particles, also called quantum dots, have size-dependant band gaps allowing them to absorb light over a wide range of the visible spectrum. After being photoexcited, the electrons formed inside the QDs can be injected into a conduction band of a mesoporous titanium dioxide (TiO_2) layer on which the quantum dots are deposited.During the 1960s, the idea of using a narrow band-gap light absorbing material to sensitize a wide-band-gap semiconductor started to gain scientific interest [24]. The first use of quantum dots as a sensitizer for wide-band-gap semiconductors dates from 1986. Later, the development of these sensitization techniques was successfully achieved to lead to the development of the DSSCs, and then to the replacement of molecular dyes with semiconductor quantum dots. This is done according to a configuration of porous TiO_2 photoelectrode, as introduced by O'Regan and Grätzel [25]. Since then; there has been a significant amount of research that has focused on the improvement of the PV performance of the QDSSC. The reported literature shows that about 9% conversion efficiency has been reported. The inorganic quantum dots have several benefits over the traditional organic dyes. They are also more easily synthesized, more chemically and photo-stable and have a longer operational lifetime. Furthermore, they are capable of fine-tuning the optical band gaps by varying particle size and composition and optimizing their absorption for better utilization of the solar spectrum. A second important property of quantum dots is the ability to create more than one electron–hole pair per high-energy photon (multiple exciton generation). This effect is called impact ionization in nanoscale

semiconductor materials and can result in higher generation of photocurrent [26]. In addition, the quantum dots have very high optical extinction coefficients, which makes it possible to absorb light from a relatively small amount of material. This property can enhance the light harvesting efficiency, and help diminish recombination losses and dark current, under proper device design. Considering multiple exciton generation and carrier transport; the theoretical conversion efficiency of a QDSSC is estimated to be ~44.4% [24]. The tunable optical properties, high absorption coefficients, and capability of generating multiple charge carriers make QDSSCs a promising photovoltaic technology for future high efficiency solar-energy applications; although no practical, efficiencies are currently as high as this theoretical limit.

- **Perovskite solar cell**

The main drawbacks of dye-sensitized solar cells (DSSCs) are the difficulty in dye synthesis, durability, and chemical stability of the dyes. To overcome these limitations, alternative light absorbing materials such as quantum dots (QDs) and perovskites have been proposed as alternative to molecular dyes. The materials have shown significant promise for high photovoltaic efficiencies: up to 20% has been achieved in small area devices. Among example, relatively inexpensive fabrication cost, high optical absorption and high power-conversion efficiency of OIHC solar cells catch big attention as the next-generation PV technologies. In 2009, the first perovskite-SSCs with a power-conversion efficiency of about 3.81% was reported [25]. Further improvements in materials composition and in interfaces and device structures led to a further rapid improvement in performance. PSCs have also been claimed to outperform many of the organic thin film photovoltaics (OTFTs) that are in use now, with efficiencies surpassing 21%. The advantage of using lead-based methylammonium halide perovskites was due to their favorable optical and electronic properties, that yielded some of the highest efficiencies. In general, the chemical formula of perovskite materials is ABX_3, with A and B being cations, and X being an anion, typically a halide like iodide, bromide or chloride. The crystal structure consists of BX_6 octahedra, with the B-site cation located in the center of each octahedron and the X-site anions surrounding it. The A-site cation is located in the interstitial sites between the BX_6 octahedra. Organic–inorganic lead-halide perovskites typically have an organic cation in the A site, a metal ion in the B site, and a halide anion in the X site. The size of the A-site cation must have an appropriate size such that it can stabilize the perovskite framework, but not be too large to fit into the cavities between the adjacent BX_6 octahedra. The Goldschmidt tolerance factor is a commonly used criterion for the structural stability and geometric compatibility of the constituent ions. The light absorption of lead-halide perovskites is high over a wide range of the visible light spectrum. For instance, the band gap of methylammonium lead iodide (MAPbI3) is around 1.5–1.6 eV [27] and it can absorb light at wavelengths up to almost 800 nm [28]. This broad absorption range further helps capture a significant portion of the incident solar radiation in the perovskite layer and thus enhances the photocurrent generation and photovoltaic performance.In general, perovskite solar cells are made in either planar or mesoporous device architecture. When it comes to the planar structure, the perovskite absorber layer is sandwiched between compact charge-selective transport layers. In the mesoporous configuration, the perovskite material fills a porous titanium dioxide (TiO_2) scaffold that is placed on top of a dense TiO_2 layer. This thin compact TiO_2 film is usually a hole blocking electron transport layer that is deposited on a transparent conductive oxide substrate. Typically, this thin film is about tens of nanometres thick, as observed in some devices. Absorbed photons in the perovskite layer create electron–hole pairs. The excited electrons in the perovskite enter the electron-transporting layer, TiO_2, while the holes move through a hole transporting material to the back electrode. The reported energy levels aid this charge separation process, as electrons are injected into the TiO_2 at about −4.0 eV, with the holes then being transferred through a hole-transport pathway to the counter electrode [28]. The separation and extraction of these charge carriers are effective, creating a photocurrent for the device.

Figure 4 shows two prototypical PV structures based on PVSCs: a single-junction thin film perovskite solar cell and a perovskite–silicon tandem PV cell. The key functional layers are shown: transparent and metallic electrodes, perovskite absorber, electron- and hole-selective transport layers. The tandem configuration is a combination of perovskite top cell with silicon bottom cell, where the different region of the solar spectrum could be absorbed more efficiently and thus maximize the possibility of conversion efficiencies higher than both cells separately.

- **Black silicon solar cell**

Black silicon (b-Si) is a nanostructured form of crystalline silicon characterized by its extremely low reflectance and outstanding light-trapping capability over a broad range of the solar spectrum. Owing to these unique optical properties, b-Si has attracted significant attention as a promising material for high-efficiency photovoltaic applications. The exceptional light-management characteristics of b-Si enable enhanced solar energy absorption, leading to improved photovoltaic performance. In addition to increasing conversion efficiency, the use of b-Si can lower manufacturing costs by eliminating the need for a separate anti-reflective coating. Despite these advantages, the practical implementation of b-Si solar cells is still challenged by increased surface recombination caused by the large surface area of their nanostructures. This problem becomes more severe in conventional front-contact solar cells, where heavily doped nanostructured regions are susceptible to Auger recombination. Consequently, a substantial portion of the photogenerated electron–hole pairs recombines within the nanostructures before reaching the electrical contacts, resulting in reduced device efficiency.

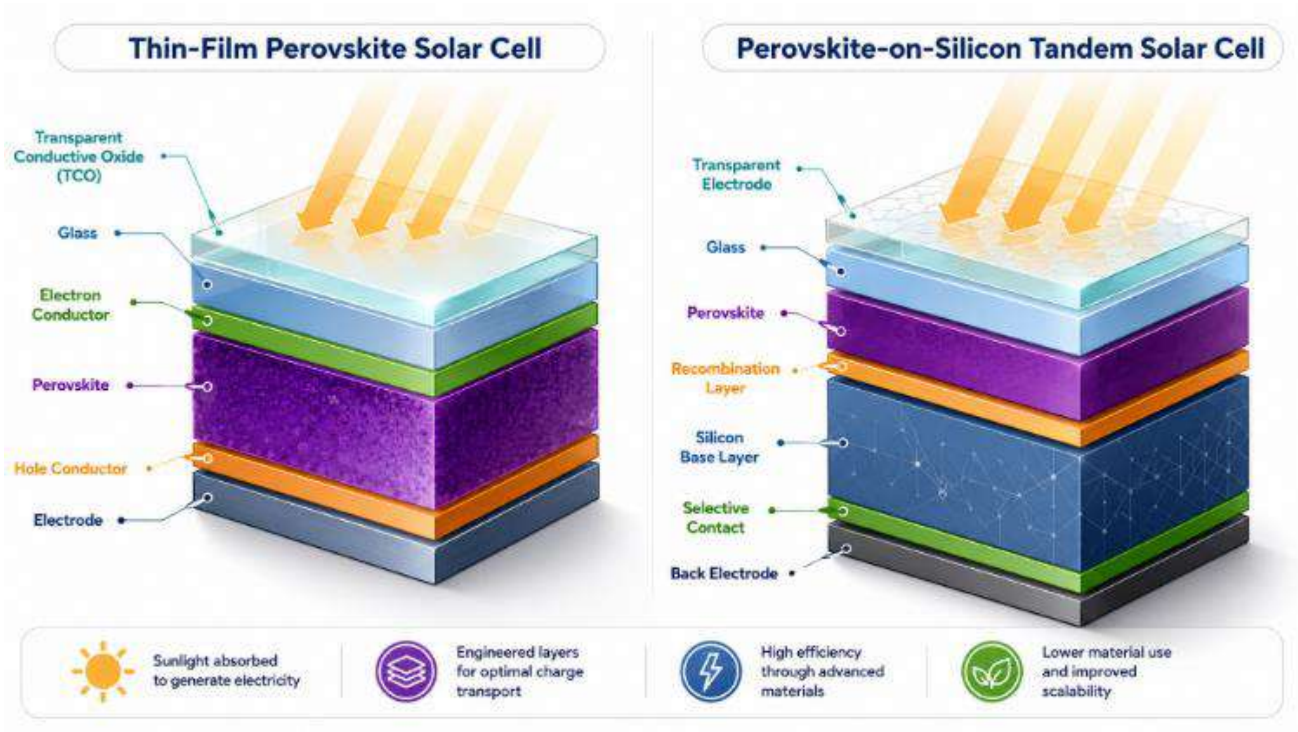


Figure 4: Perovskite solar cells

A promising strategy to alleviate Auger recombination is the use of an interdigitated back-contact (IBC) solar cell architecture, in which both the p–n junction and the electrical contacts are positioned on the rear side of the device. By relocating these components away from the illuminated front surface, the IBC configuration suppresses front-surface recombination losses and enables more efficient collection of photogenerated charge carriers, thereby improving the overall performance of black silicon solar cells [29].

D. Fourth generation

Fourth-generation (4G) solar cells represent an emerging photovoltaic approach based on the integration of organic and inorganic materials. These hybrid structures typically incorporate polymers and nanoscale materials within the photoactive architecture, combining the flexibility and processability of conductive polymers with the structural stability and favorable optoelectronic properties of inorganic nanomaterials. Such material combinations provide opportunities for fabricating thin and potentially cost-effective photovoltaic devices while improving light-harvesting capability [30]. Another approach to improving photovoltaic conversion efficiency involves utilizing different regions of the solar spectrum more effectively. In tandem solar cells, materials with different bandgaps are arranged in stacked subcells so that different portions of the incident spectrum can be absorbed. For example, a GaAs-based upper cell can absorb higher-energy photons, while a Si-based lower cell utilizes part of the radiation transmitted through the upper cell. The subcells are electrically interconnected through an intermediate layer, enabling the photogenerated charge carriers to contribute to the overall photocurrent of the tandem device [31]. In 4G photovoltaic concepts, the complementary properties of organic and inorganic components are exploited to enhance device performance while maintaining the potential for economical fabrication. Transparent indium tin oxide (ITO) is commonly employed as a transparent conductive electrode; however, alternative electrode materials and architectures, including graphene, metallic nanowires, and metal grids, are increasingly being investigated. In addition, nanoscale architectures provide considerable flexibility in material design by allowing conductive polymers and other functional materials to be incorporated within or around nanostructured components. Consequently, the integration of organic and inorganic materials offers the potential to improve light harvesting and photovoltaic conversion performance while supporting lower-cost and flexible manufacturing strategies [32].

E. Fifth Generation

Maxeon Solar Technologies introduced the SunPower Performance 5 series as an advanced generation of bifacial photovoltaic modules developed primarily for utility-scale solar power plants. The Performance 5 modules incorporate bifacial monocrystalline Passivated Emitter and Rear Cell (PERC) technology based on large-format G12 silicon wafers [33]. This configuration combines large-area crystalline silicon cells with a bifacial architecture to improve solar energy utilization and increase energy yield under suitable operating conditions [33][34]. PERC technology enhances photovoltaic performance through rear-surface passivation, which reduces charge-carrier recombination losses and improves internal light reflection. In bifacial configurations, solar radiation can be utilized from both the front and rear surfaces of the cell, allowing reflected irradiance from the surrounding environment to contribute to electricity generation. Consequently, bifacial PERC modules can provide higher energy yields than conventional monofacial modules, particularly under favorable albedo conditions [34]. The Performance 5 series employs large-format G12 silicon wafers, with dimensions of approximately 210 ×

210 mm. The use of larger wafers enables higher cell and module power ratings and represents an important development in utility-scale crystalline silicon PV technology [35]. Together with bifacial operation and PERC architecture, these technological developments have contributed to improving the performance and energy-yield potential of large-scale photovoltaic systems [34].
First generation crystalline silicon solar cells have a high level of stability, relatively high conversion efficiency and have a mature manufacturing system. Their manufacture, however, consumes a lot of energy, especially during the purification of the silicon, the growth of crystals, the processing of the wafers, and the production of the cells, Figure 5. In contrast, later generations in PV are typically thinner active layers, lower-temperature processing, and less complex manufacturing. These properties can help decrease the embodied energy and production costs. The price of the technology, whether in manufacture or in purchase, is not the sole criterion for assessing the economic viability of a photovoltaic technology. Other factors such as conversion efficiency, degradation rate, service life, maintenance needs and overall energy output also affect the cost of electricity produced over the life of the system. PV technologies (both 1st and 2nd generation) offer good operational stability and long service life. Many third and fourth generation technologies however still struggle with long term exposure to the sun, moisture, oxygen and high temperatures. The active materials and interfaces can degrade due to exposure to the environment, including the effects of UV radiation, and device performance can decrease over time. In real terms, the organic photovoltaic cells (OPVs) have not yet become a common product in the real market for electricity generation in the field of conventional utility applications due to degradation, short lifetime and environmental instability concerns. Today, their applications are growing

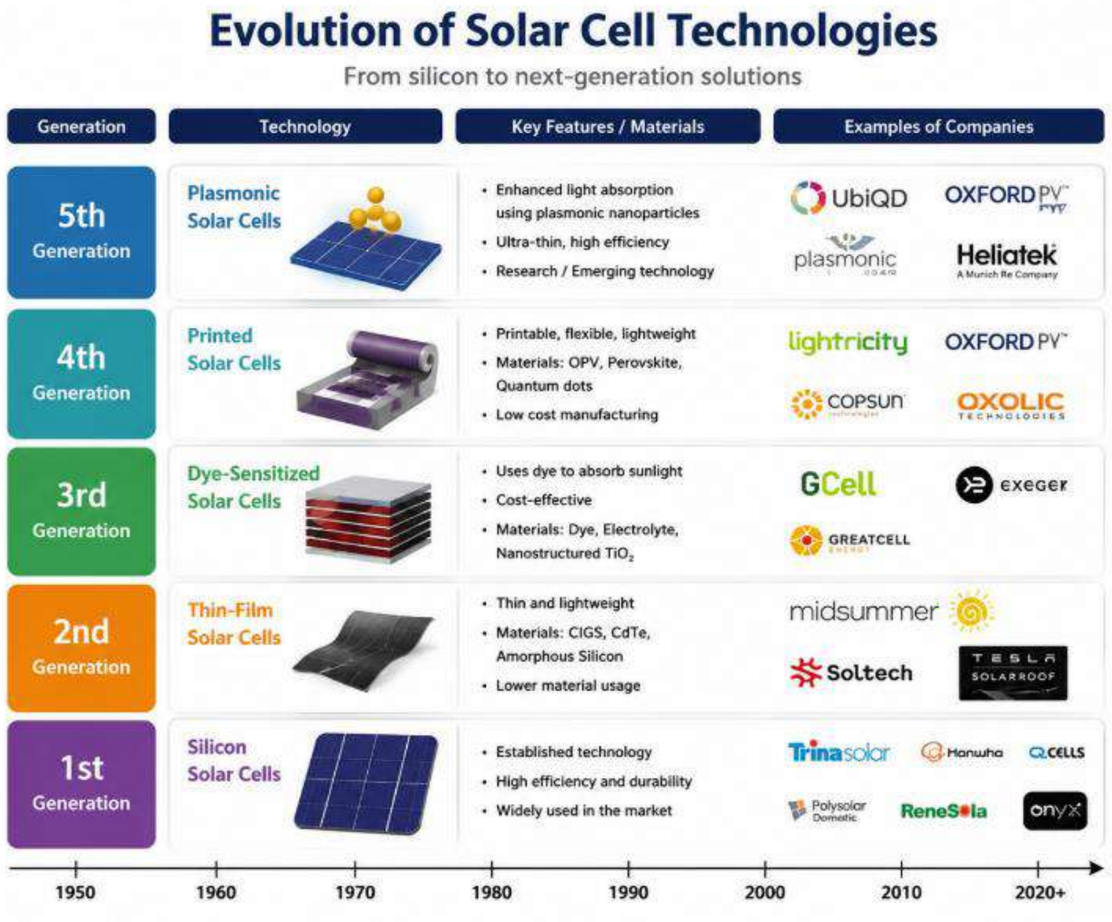


Figure 5: Generations of solar cell technology

more towards low-power energy-harvesting systems, flexible electronics, wearable electronics, wireless sensors and indoor photovoltaic applications. For these applications, the following properties are more critical than the highest possible outdoor conversion efficiency: lightweight construction, mechanical flexibility, low-temperature fabrication and compatibility with different surfaces. Other PV technologies (typically of the third and fourth generation) could also show favorable performance when significantly more diffuse and low intensity light is available.

Table 1 provides a comprehensive comparison of the five different generations of solar cells, including the evolution of photovoltaic cell technologies from the first silicon-based generation to the potential fifth generation, plasmonic cells. It summarizes the characteristics, efficiency, advantages, and disadvantages of each generation. The aim is to provide readers with a clear overview of technological advancements, performance improvements, and material innovations, along with the costs and compromises associated with each generation. In this context, this comparison is valuable for researchers, engineers, and practitioners evaluating the feasibility of different types of solar cells for diverse applications, from large-scale solar power plants to flexible, building-integrated photovoltaic systems.

Table 1: Comparison of Solar Cell Generations.

Generation	Key Features	Efficiency	Advantages	Disadvantages
1st – Silicon	Established technology, high efficiency and durability, widely used in the market	28.1% (crystalline Si) [36]	High stability, long lifespan, reliable performance	High material cost, temperature sensitivity, rigid structure
2nd – Thin-Film	Thin and lightweight, uses less semiconductor material, flexible options, lower production cost	23.4% (CIGS), 21.0% (CdTe) [36]	Lower material usage, lightweight, flexible options	Lower efficiency than crystalline Si for some technologies, technology-dependent stability
3rd – DSSC / Organic	Dye-sensitized and organic solar cells, low-cost potential, operation under low-light conditions, flexible designs	11.9% (DSSC) [36], >21% (Organic PV) [37]	Low-cost potential, good performance under diffuse light, flexibility	Limited long-term stability, relatively short operational lifetime, scalability challenges
4th – Printed / Perovskite	Printable and lightweight, incorporating perovskite, quantum-dot, and other emerging materials, with low-cost manufacturing potential	28.0% (Perovskite) [36]	Printable, flexible, low material usage, high efficiency potential	Stability issues, moisture sensitivity, commercialization challenges
5th – Plasmonic	Enhanced light absorption using plasmonic nanoparticles, ultra-thin structures, emerging research technology	No standardized efficiency value; performance depends on the underlying PV technology	Potential for enhanced light absorption, novel applications	Limited commercial maturity, fabrication complexity, additional manufacturing cost

Figure 6 shows the cost and expected efficiency of different generations. The overall goal of development is to reduce the cost of electricity production per watt while increasing the efficiency of converting light into electrical energy, especially in third-generation technologies and above.

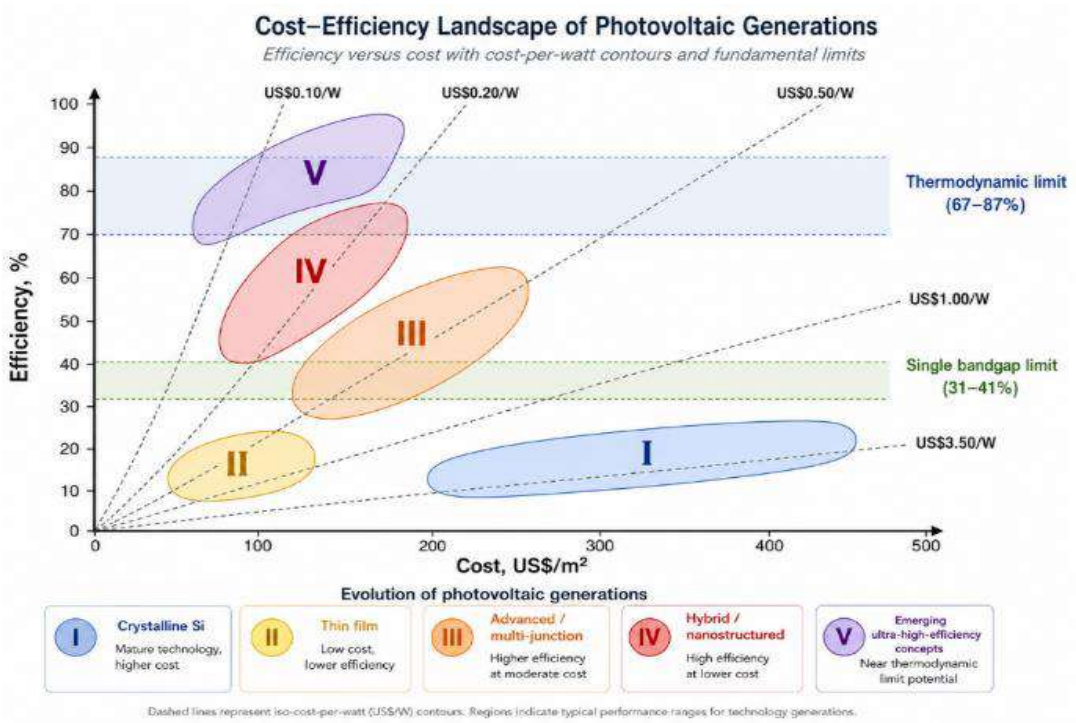


Figure 6: Efficiency ranges and expected cost for generations of photovoltaic cell systems [38]

IV. BIFACIAL PHOTOVOLTAIC TECHNOLOGY

One of the most recent breakthroughs in photovoltaic (PV) module design is bifacial PV technology. Bifacial PV modules can be used to harness solar radiation absorbed by both sides of the module, whereas traditional monofacial PV modules primarily capture solar radiation on the front surface of the module. The front side receives direct and diffuse solar irradiance; the backside receives reflected and scattered ground and surface irradiance. This means that bifacial modules can boost the overall energy production of a PV system by extending the energy production area while keeping the installation space unchanged [39].

Bifacial PV modules work on the same PV effect as traditional PV cells.

Figure 7 illustrates the structural difference between n-type and p-type bifacial cells, with front and back contact locations and ARC and BSF layers that allow light collection from both sides. Often a traditional opaque backsheet is not used and instead glass-glass encapsulation is applied to facilitate rear-side illumination and enhance mechanical durability [40].

The bifaciality factor is one of the important factors used to assess bifacial modules. This factor is the ratio of rear-side efficiency to front-side efficiency of the module. A higher bifaciality factor means that more electricity can be produced on the backside. Bifacial PV system energy gain is not just a function of the bifaciality factor; however, it is also dependent upon the installation geometry and the environment [41].

One of the major factors that affect bifacial PV performance is ground albedo. Albedo is the ratio of the solar radiation reflected by a surface to that incident upon it. Bifacial gain can be enhanced by using high-reflectance surfaces like white gravel, concrete, sand, snow and light-colored roofing products on the rear side. The dark areas, such as soil, asphalt, vegetation, or shaded surfaces, on the rear side of the module, on the other hand, will decrease the amount of reflected radiation reaching the rear surface of the module [42].

Other important factors in bifacial PV performance include the mounting configuration. A height adjustment of the module above the ground may help to distribute reflected irradiance under the module. To obtain maximum energy yield, the appropriate tilt angle, row spacing and minimising shading from the mounting structure on the rear of the panels are also required. Large scale PV systems frequently feature bifacial modules in combination with single axis tracking systems, which help to maximize the solar radiation received during the day [43]. Bifacial PV technology is especially viable in desert and semi-arid climates, where the average solar irradiance is typically high, and the ground surface reflectivity is relatively high. This can have a positive effect on the rear-side contribution of energy and increase the solar power plant's performance [44].

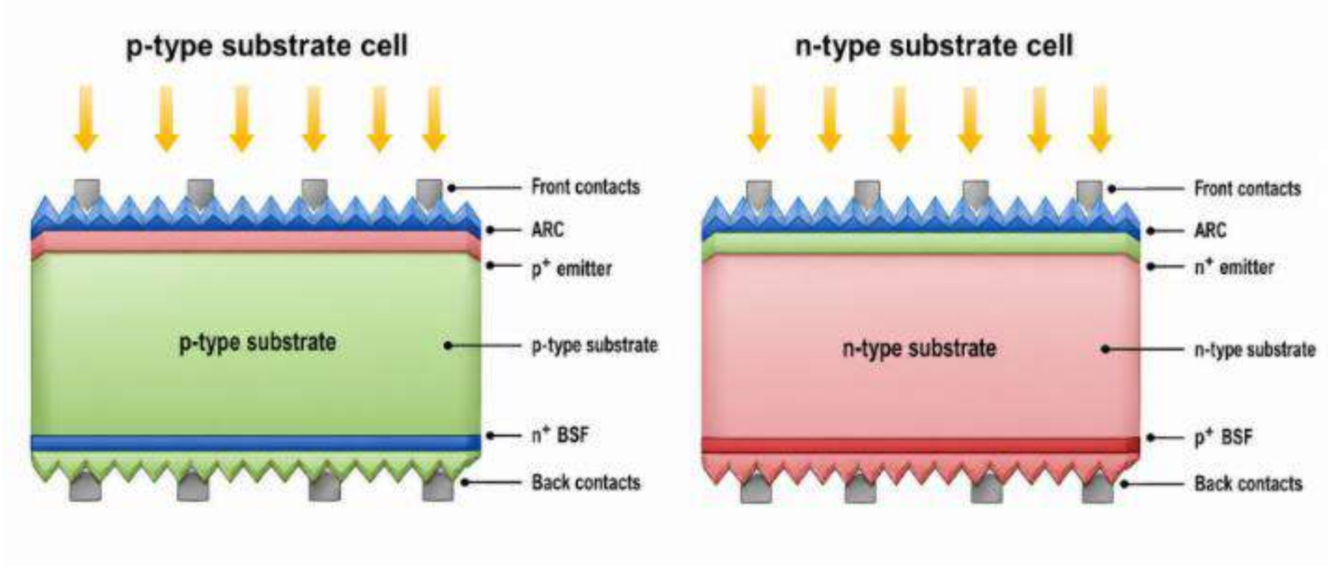


Figure 7: Section of standard n-type and p-type bifacial crystalline solar cells

In below Figure 8 presents a schematic and functional comparison of several structures and configurations used in silicon solar cells and modules. The data are organized into numbered rows, each representing a different photovoltaic cell design. The first column includes the serial number of each configuration, while the second column shows the schematic representation of the cell or module, including the layer arrangement, silicon substrate type, doping areas, emitter positions, back surface area, passivation and antireflective coating layers, and the positions of the front and back metal contacts. The third column provides a brief structural and functional description highlighting the key characteristics of each design and the role of its components in enhancing photovoltaic performance. The configurations shown include p-type and n-type silicon cells, cells with single or double antireflective layers, and structures based on pyramidal or woven surfaces to maximize light retention and minimize optical reflection. The table also presents models that utilize boron- or phosphorus-doped back-surface domains and configurations with localized or overlapping back contacts to minimize charge carrier recombination and improve current collection efficiency. It includes designs for bifacial cells capable of receiving solar radiation from both the front and back surfaces, along with a description of the layered construction of bifacial modules, including low-iron glass, EVA encapsulation, transparent backsheets, and metal frames. The table further highlights several advanced architectures, such as PERC and PERPoly cells and heterojunction cells, as well as configurations employing thin oxide layers, doped polycrystalline silicon, transparent conductive layers, and metal meshes or wires and ribbons for current collection. This presentation aims to clarify the relationship between the structural design of the cell and its functional performance, as surface properties, grafting type, layer sequence, contact system, and passivation materials directly affect light absorption, reduction of optical and electrical losses, reduction of recombination rate, and improvement of charge carrier transport and collection.

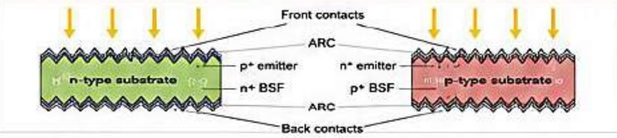
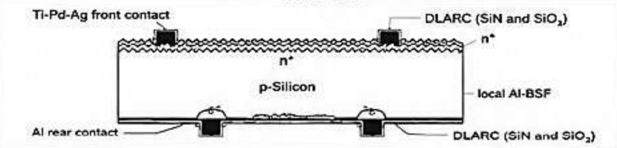
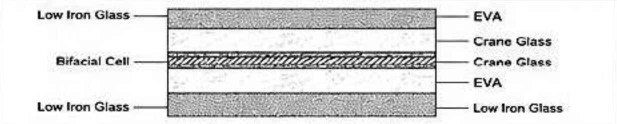
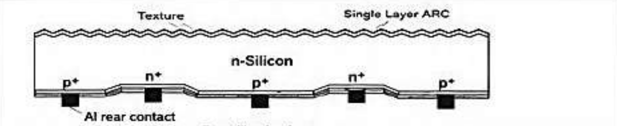
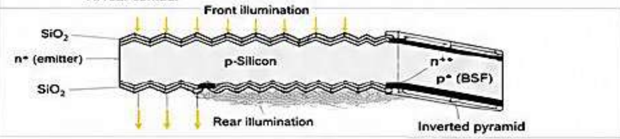
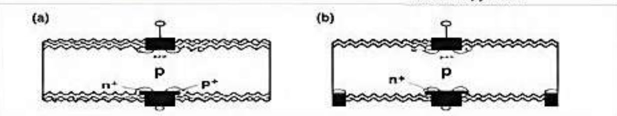
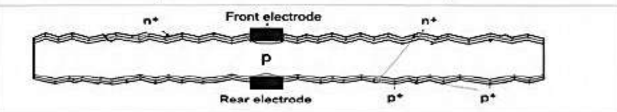
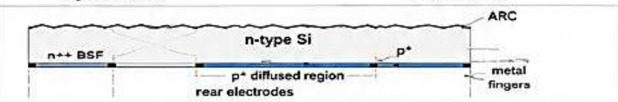
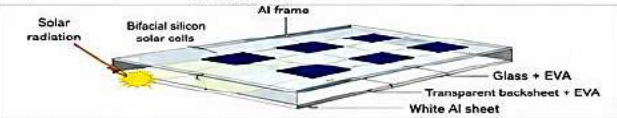
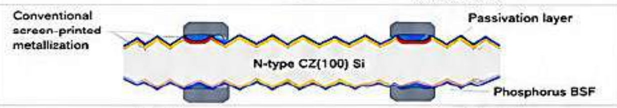
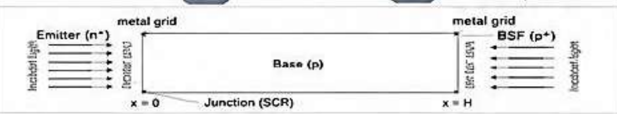
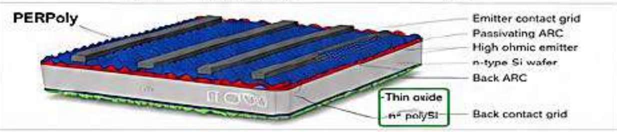
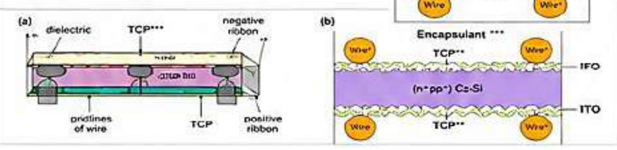
No.	Schematic Configuration	Structural Features and Functional Description
1		Cross-section of a bifacial solar cell. Both sides are textured and passivated with an anti-reflection coating (ARC). The front side has a p+ emitter on n-type Si, while the rear side has an n+ emitter on p-type Si. The back surface field (BSF) reduces surface recombination, improving current collection.
2		Silicon solar cell with Ti-Pd-Ag front contacts and a dual-layer anti-reflection coating (DLARC) of SiN/SiO_2. The front side has n+ emitter regions on n-type surface. The rear side includes a local aluminum BSF for full-area passivation and improved ohmic contact.
3		Layer structure of a bifacial solar module: low-iron glass / EVA / glass / bifacial cell / glass / EVA / low-iron glass. The low-iron glass improves transparency. EVA encapsulant bonds the layers and provides protection and optical coupling.
4		Silicon solar cell with a textured front surface and a single-layer ARC. Alternating n+ and p+ regions are formed on the rear surface with a full-area aluminum back contact to enhance carrier collection and reduce recombination.
5		Inverted pyramid textured silicon solar cell to enhance light trapping. The front side uses an n+ emitter, while the rear side has a p+ BSF. SiO_2 layers provide surface passivation. The inverted texture increases the optical path and reduces surface reflection.
6		Comparison of rear contact configurations: (a) Full-area rear p+ emitter on p-type base with front n+ emitter. (b) Localized rear p+ contacts with front n+ emitter—reduces shading and improves current collection and fill factor.
7		Back-contact solar cell structure with n+ emitter regions at the front and p+ rear contacts. All metal contacts are located on the rear side, reducing front-side shading and improving light absorption.
8		n-type silicon solar cell with boron (p-type) emitter on the front and phosphorus BSF (n-type) on the rear. Ag/Al metallization provides low-resistance contacts for efficient current collection.
9		Detailed front surface of an n-type Si cell with ARC and front p+ emitter regions under metal fingers. Rear side has n++ BSF to reduce recombination and improve carrier collection.
10		Bifacial module structure with bifacial silicon cells encapsulated by EVA film and glass on the front side. The rear side uses transparent backsheet + EVA and a white aluminum sheet for reflectivity and mechanical support.
11		N-type CZ (100) silicon cell with screen-printed metallization grid. A passivation layer covers the front and rear surfaces to reduce surface recombination. Phosphorus BSF provides rear-side passivation.
12		Schematic of a solar cell in the x-direction. n+ emitter on the front side and p+ BSF on the rear side. Metal grids collect current while allowing incident light to enter. The junction (SCR) is formed at x = 0.
13		PERPoly cell with thin oxide and n+ poly-Si passivation layer. High-ohmic emitter, ARC on both sides, and front emitter contact grid provide high performance with reduced recombination.
14		PERC-type cell. Front side: Ag/Al contacts with SiO_2/SiN_x passivation and p+ emitter. Rear side: n+ BSF with SiO_2/SiN_x stack. (b) Cross-section showing wire interconnection embedded in encapsulant and TCP layers.
15		Heterojunction cell architecture. (a) Cross-sectional stack with IFO (front transparent oxide), TCP (tunneling contact), and ITO (rear transparent oxide) with gridlines and ribbons. (b) Top view cross-section showing wires embedded in encapsulant with TCP layers for low-resistance contacts.

Figure 8: Comparison of solar cell architectures and their structural and functional characteristics [45]

Figure 9 compares the power during one day. The dual cell gives higher power than the unicellular cell during most of the daytime hours due to the exploitation of direct and reflected light.

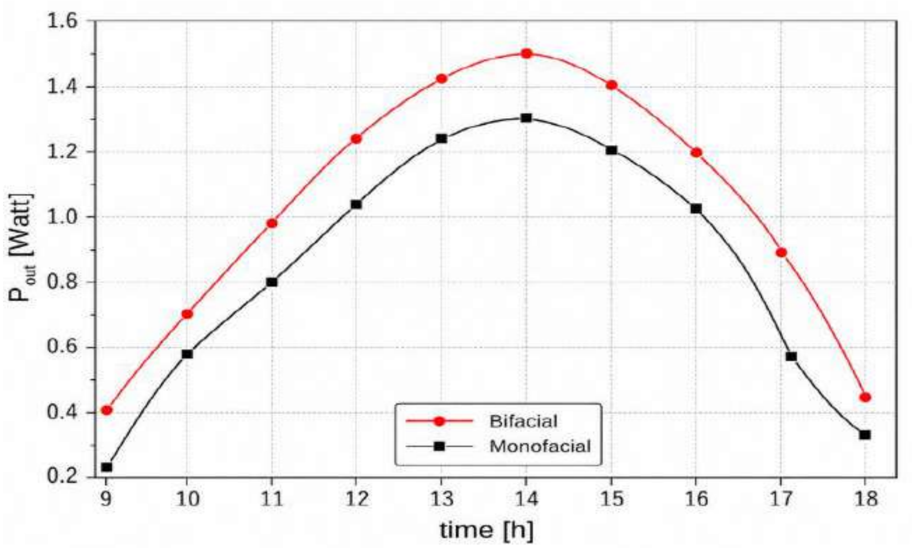


Figure 9: The resulting power was measured over a one-day period in mid-April for bifacial and monofacial cells [45]

Figure 10 illustrates the monthly variation in measured and simulated energy yield for a TBC system at 30° and 85° tilt angles. The results show that the 30° tilt angle achieves a higher energy yield for most months of the year compared to the 85° angle, both in terms of actual measurements and simulation results. A higher yield is observed during the middle months of the year, with the highest values recorded around the third month, followed by a gradual decline in some subsequent months. Overall, the measured values were higher than the simulated values in most cases, with a relatively similar trend in the monthly variation between them. This indicates that the tilt angle significantly affects the amount of energy produced, and that the 30° angle appears to be more suitable for achieving better annual performance under the study conditions.

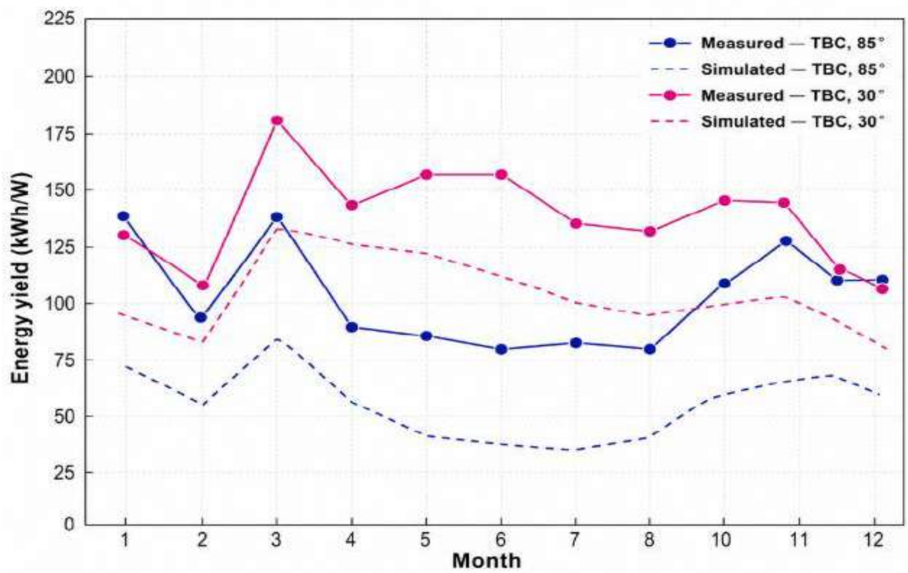


Figure 10: Compares the monthly energy yield between measured and simulated values for TBC systems at tilt angles of 30° and 85° [45]

Table 2 provides a detailed comparison of the operating characteristics, power generation performance, and typical applications of monofacial and bifacial photovoltaic modules. The first column presents the evaluated parameters, including front-side performance, rear-side power contribution, stability, and typical applications, while the second and third columns provide the corresponding characteristics of monofacial and bifacial modules, respectively. Monofacial PV modules primarily utilize solar irradiance incident on the front surface, whereas bifacial modules can generate electricity from solar irradiance received on both the front and rear surfaces [40].

The rear-side power contribution of bifacial modules is strongly influenced by environmental and installation-related factors, particularly ground albedo, module tilt angle, mounting height, row spacing, and system configuration [43][46]. The fourth column indicates the potential additional power gain associated with rear-side energy generation in bifacial modules. However, this gain is not constant and may vary considerably depending on site conditions, module configuration, and the amount of solar irradiance reaching the rear surface [43][46]. The final column summarizes relevant remarks and typical applications.

Bifacial PV modules are particularly advantageous in environments with high ground reflectivity, where increased rear-side irradiance can enhance their energy yield [43][46]. They are also well suited to tracking configurations, which can further increase the solar irradiance available to the modules throughout the [40][46]. Overall, the comparison presented in Table 2 highlights the potential advantages of bifacial PV technology in terms of energy yield and application flexibility and provides useful information for the design and selection of photovoltaic systems.

Table 2: Comparison between Bifacial vs Monofacial PV Modules

Parameter	Monofacial	Bifacial	Gain (%)	Notes
Front-side Efficiency	Comparable	Comparable	–	Depends on cell and module technology [40].
Rear-side Contribution	None	Variable	Site-dependent	Depends on albedo, tilt angle, mounting height, and system configuration [40, 47].
Energy Yield	Reference	Higher	~5–15%*	Higher gains are possible under favorable conditions [47,48].
Applications	Standard rooftop and ground-mounted systems	Desert and semi-arid regions, agrivoltaics, and tracking systems	–	Particularly advantageous under high-albedo conditions [47, 34].

Figure 11 illustrates the time-dependent power output variation of both the regular and bifacial modules during daylight hours. The curve shows that power production starts low in the early morning, gradually increasing with the intensity of solar radiation until it reaches its peak around midday, and then gradually declines towards evening. It is clear that the bifacial module achieved higher power output than the regular module for most of the measurement period, with both curves maintaining a nearly identical overall trend. This behavior reflects the bifacial module's ability to utilize not only the direct radiation incident on its front surface but also the reflected or scattered radiation absorbed from the back, resulting in improved overall power output compared to the single-phase module.

Figure 12 presents a time-dependent comparison of the performance of the regular and bifacial modules. However, the curve here exhibits relatively irregular fluctuations in power production throughout the day. Although the overall trend still indicates increased production from morning until peak hours, followed by a decline later, the curve includes a relative dip near midday, followed by a new rise in the later hours before a final decline begins towards sunset. This behavior can be explained by the influence of certain operational or environmental conditions, such as variations in solar radiation intensity, the passage of intermittent clouds, differences in the angle of incidence, or the effects of reflection and heat on conversion efficiency. Nevertheless, the performance of the dual-phase unit remained higher than that of the conventional unit at most measurement points, confirming the superiority of this type of unit in terms of utilizing different lighting conditions and improving daily energy output.

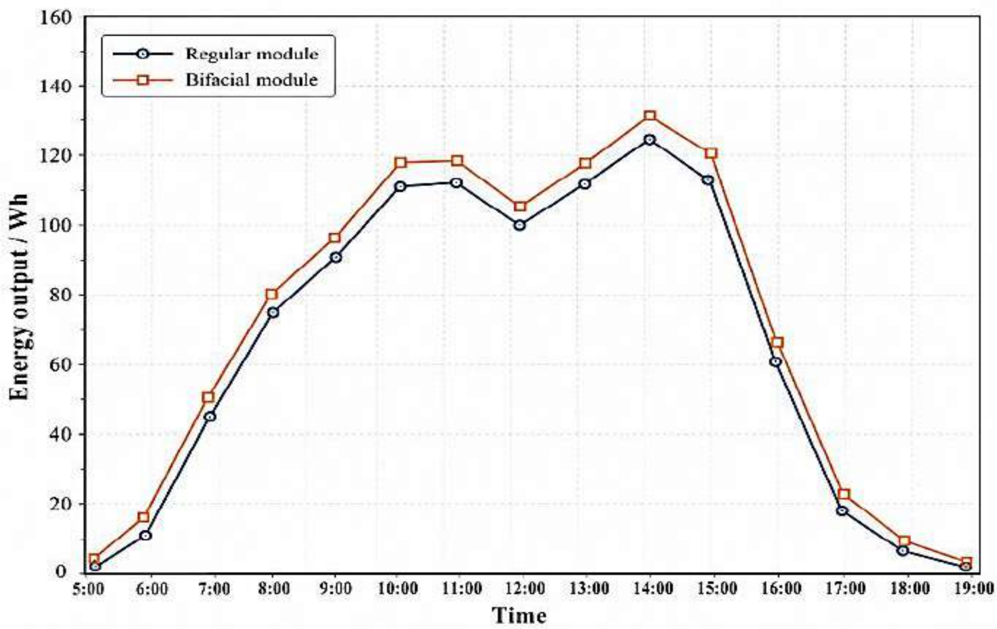


Figure 11: Compares the energy production between bifacial and regular solar panels on a sunny day [45]

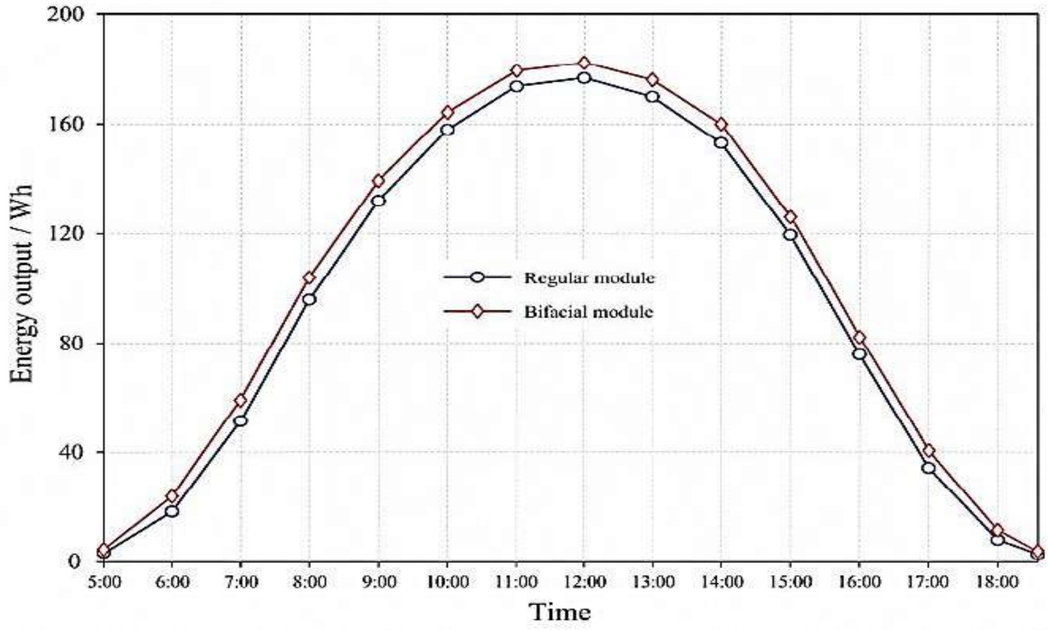


Figure 12: Compares the energy production between bifacial and regular solar panels a cloudy day [45]

Figure 13 illustrates the relative stability of five generations of solar cells, from 1 (unstable) to 5 (stable). The diagram shows that first-generation silicon cells, among the various technologies, have the highest long-term reliability, while newer technologies, such as DSSC and organic photovoltaic cells, have lower long-term reliability. This highlights the importance of balancing efficiency with durability and lifespan in photovoltaic technologies when considering practical applications.

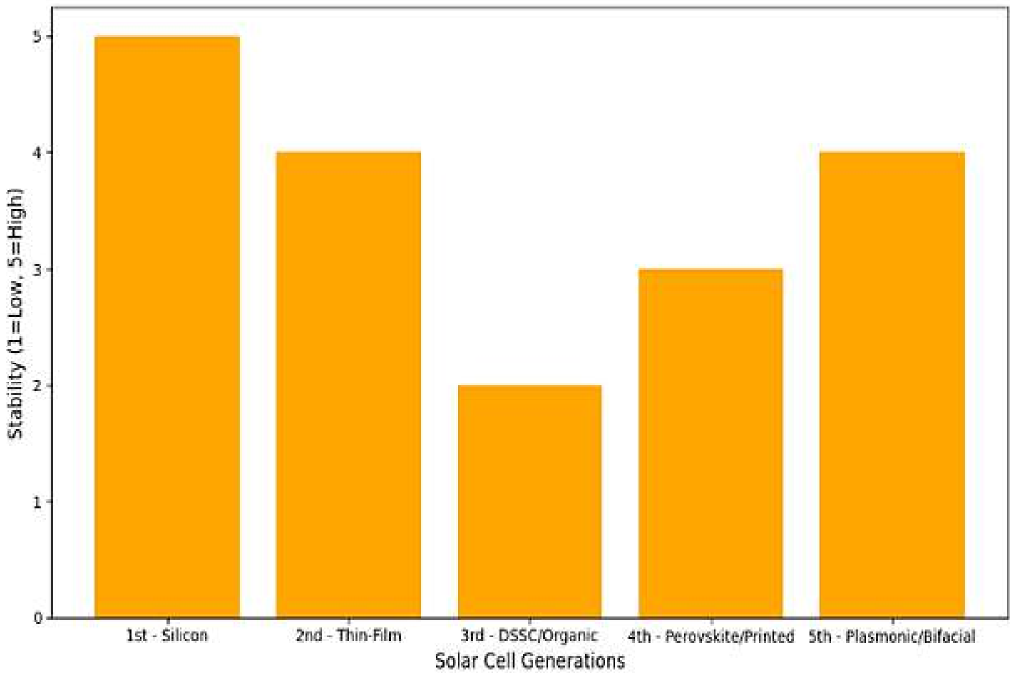


Figure 13: Relative stability of solar cell generations

In below Figure 14 illustrates the relationship between the number of solar cell generations and the relative cost of the cell. It shows the trade-offs between material use, manufacturing cost, and cell performance, and demonstrates that while higher efficiency can be achieved with some thin-film and perovskite cells, they typically require less material and have lower manufacturing costs. Beyond technological advancements, this graph should guide readers in considering economic factors, particularly when selecting the most cost-effective photovoltaic solar energy solutions.

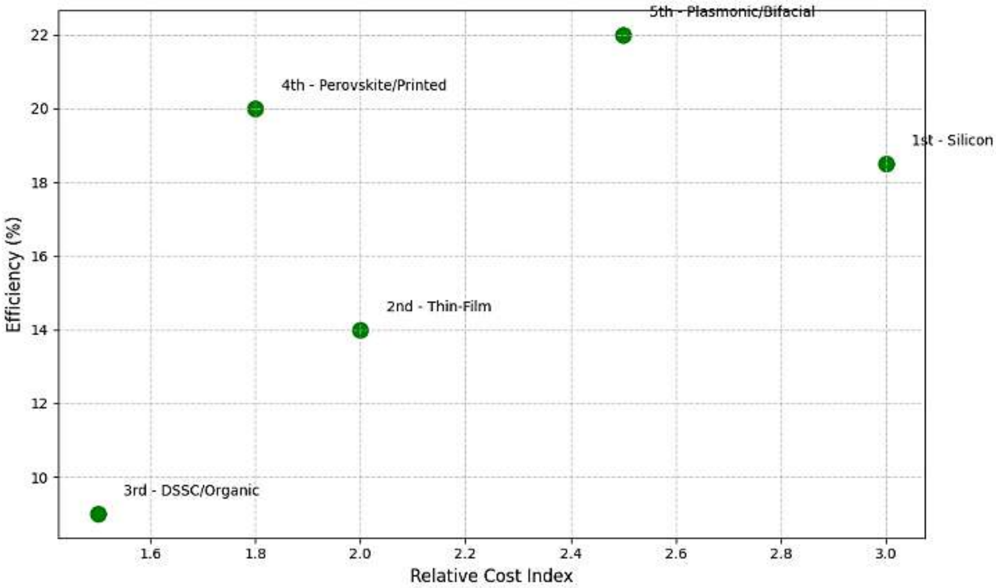


Figure 14: Efficiency vs relative production cost

V. CONCLUSION

This study reviewed the evolution of photovoltaic cell technologies across five generations, analyzing their key characteristics, efficiency, new materials, and applications. Starting with conventional silicon technology, and progressing through thin films, DSSC/organic cells, perovskite cells, and plasmonic/bifacial cells, the focus was on the incremental improvements in cell efficiency, material usage, and system design. Trends in efficiency, production costs, stability, and energy gain analyses in bifacial cells indicate that these new photovoltaic technologies have the potential to achieve significant increases in energy production while maintaining economic competitiveness. The introduction of bifacial cell technology highlights the need for optimization, consideration of ground reflectivity, and environmental factors when maximizing performance. While challenges exist, such as material stability, humidity sensitivity, and long-term durability for some third- and fourth-generation cells, the rapid development and advancements in photovoltaic technologies point to promising prospects for overcoming these challenges. Meanwhile, photovoltaic cells are expected to become more prevalent in industrial, commercial, and residential environments, thanks to advancements in single-phase and bifacial cell systems. Overall, photovoltaic technology is among the most promising clean energy technologies. This new generation of solar cells has the potential to revolutionize sustainable energy generation worldwide through improved efficiency, innovative materials, and system-level enhancements. This overview provides a comprehensive and structured perspective to inform future research, technology development, and the deployment of advanced photovoltaic systems.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] H. Jie, I. Khan, M. Alharthi, M. W. Zafar, and A. Saeed, "Sustainable energy policy, socio-economic development, and ecological footprint: The economic significance of natural resources, population growth, and industrial development," *Utilities Policy*, vol. 81, art. no. 101490, 2023. Available from: https://doi.org/10.1016/j.jup.2023.101490

[2] J. P. Ram, H. Manghani, D. S. Pillai, T. S. Babu, M. Miyatake, and N. Rajasekar, "Analysis on solar PV emulators: A review," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 149–160, 2018. Available from: https://doi.org/10.1016/j.rser.2017.07.039

[3] R. A. Marques Lameirinhas, J. P. N. Torres, and J. P. de Melo Cunha, "A photovoltaic technology review: History, fundamentals and applications," *Energies*, vol. 15, no. 5, art. no. 1823, 2022. Available from: https://doi.org/10.3390/en15051823

[4] M. Al-Maghalseh, A. Hammad, M. Hamdan, and E. Abdelhafez, "Thermal comfort of buildings integrated photovoltaics (BIPV)," *Wadi Alshatti University Journal of Pure and Applied Sciences*, pp. 146–164, 2026. Available from: https://doi.org/10.63318/waujpasv4i1_16

[5] M. Farji, "Development of photovoltaic cells: A materials prospect and next-generation futuristic overview," *Brazilian Journal of Physics*, vol. 51, no. 6, pp. 1916–1928, 2021. Available from: https://doi.org/10.1007/s13538-021-00981-w

[6] J. Jang and K. Lee, "Practical performance analysis of a bifacial PV module and system," *Energies*, vol. 13, no. 17, art. no. 4389, 2020. Available from: https://doi.org/10.3390/en13174389

[7] S. S. Hegedus and A. Luque, "Status, trends, challenges and the bright future of solar electricity from photovoltaics," *Handbook of Photovoltaic Science and Engineering*, pp. 1–43, 2003.

[8] M. Bošnjaković, "Advance of sustainable energy materials: Technology trends for silicon-based photovoltaic cells," *Sustainability*, vol. 16, no. 18, art. no. 7962, 2024. Available from: https://doi.org/10.3390/su16187962

[9] O. D. Abdulrazig, R. C. Al-Zuhairy, A. A. Nadhim, M. Elmnifi, D. T. Aleksandrovna, A. M. Elbreki, *et al.*, "Enhancing solar cell efficiency via nanotechnology: A CFD-driven comparison with conventional models," *Mathematical Modelling of Engineering Problems*, vol. 12,

no. 6, 2025. Available from: https://doi.org/10.18280/mmep.120633

[10] A. Khatibi, F. Razi Astaraei, and M. H. Ahmadi, "Generation and combination of the solar cells: A current model review," *Energy Science & Engineering*, vol. 7, no. 2, pp. 305–322, 2019. Available from: https://doi.org/10.1002/ese3.292

[11] P. Sharma and R. K. Mishra, "Comprehensive study on photovoltaic cells' generation and factors affecting its performance: A review," *Materials for Renewable and Sustainable Energy*, vol. 14, art. no. 21, 2025.

[12] M. M. Musztyfaga-Staszuk and C. Mele, "Structural and electrical analysis of crystalline silicon solar cells: The role of busbar geometry in first-generation PV technology," *Materials*, vol. 18, no. 21, art. no. 4979, 2025. Available from: https://doi.org/10.3390/ma18214979

[13] R. Garg, A. Sharma, A. Awasthi, Y. S. Bisht, A. Alkhayyat, and A. Sharma, "Comparative analysis of efficiency for first generation solar cells using PSIM simulation," in *Proc. 2023 Global Conference on Information Technologies and Communications (GCITC)*, pp. 1–6, 2023. Available from: https://doi.org/10.1109/GCITC60406.2023.10426589

[14] A. S. Al-Ezzi and M. N. M. Ansari, "Photovoltaic solar cells: A review," *Applied System Innovation*, vol. 5, no. 4, art. no. 67, 2022. Available from: https://doi.org/10.3390/asi5040067

[15] O. Vetterl, F. Finger, R. Carius, P. Hapke, L. Houben, O. Kluth, *et al.*, "Intrinsic microcrystalline silicon: A new material for photovoltaics," *Solar Energy Materials and Solar Cells*, vol. 62, no. 1–2, pp. 97–108, 2000. Available from: https://doi.org/10.1016/S0927-0248(99)00140-3

[16] O. Vigil-Galán, M. Courel, J. A. Andrade-Arvizu, Y. Sánchez, M. Espíndola-Rodríguez, E. Saucedo, *et al.*, "Route towards low cost-high efficiency second generation solar cells: Current status and perspectives," *Journal of Materials Science: Materials in Electronics*, vol. 26, no. 8, pp. 5562–5573, 2015. Available from: https://doi.org/10.1007/s10854-014-2196-4

[17] J. Pastuszak and P. Węgierek, "Photovoltaic cell generations and current research directions for their development," *Materials*, vol. 15, no. 16, art. no. 5542, 2022. Available from: https://doi.org/10.3390/ma15165542

[18] H. Moria and M. Elmnfi, "Feasibility study on the potential and challenges of renewable energy in Libya," *International Journal of Advanced Science and Technology*, vol. 29, no. 3, pp. 12546–12560, 2020.

[19] N. Eswaramoorthy, R. Syamsai, S. Nallusamy, S. Pitchaiya, and M. R. Venkatraman, "Recent progress of carbonaceous materials in third generation solar cells: DSSCs," *Handbook of Porous Carbon Materials*, pp. 165–188, 2023.

[20] S. D. B. George, A. Soosaimanickam, and S. Sundaram, "Third-generation photovoltaics: Introduction, overview, innovation, and potential markets," in *Photovoltaics Beyond Silicon*, pp. 75–110. Elsevier, 2024. Available from: https://doi.org/10.1016/B978-0-323-90188-8.00020-8

[21] B. K. Korir, J. K. Kibet, and S. M. Ngari, "A review on the current status of dye-sensitized solar cells: Toward sustainable energy," *Energy Science & Engineering*, vol. 12, no. 8, pp. 3188–3226, 2024. Available from: https://doi.org/10.1002/ese3.1815

[22] M. Grätzel, "Dye-sensitized solar cells," *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, vol. 4, no. 2, pp. 145–153, 2003. Available from: https://doi.org/10.1016/B978-0-12-811165-9.00006-5

[23] N. Shah, A. A. Shah, P. K. Leung, S. Khan, K. Sun, X. Zhu, and Q. Liao, "A review of third generation solar cells," *Processes*, vol. 11, no. 6, art. no. 1852, 2023. Available from: https://doi.org/10.3390/pr11061852

[24] I. Mora-Sero, S. Giménez, F. Fabregat-Santiago, R. Gómez, Q. Shen, T. Toyoda, and J. Bisquert, "Recombination in quantum dot sensitized solar cells," *Accounts of Chemical Research*, vol. 42, no. 11, pp. 1848–1857, 2009. Available from: https://doi.org/10.1021/ar900134d

[25] H. Tang, S. He, and C. Peng, "A short progress report on high-efficiency perovskite solar cells," *Nanoscale Research Letters*, vol. 12, no. 1, art. no. 410, 2017. Available from: https://doi.org/10.1186/s11671-017-2187-5

[26] S. Rühle, M. Shalom, and A. Zaban, "Quantum-dot-sensitized solar cells," *ChemPhysChem*, vol. 11, no. 11, pp. 2290–2304, 2010. Available from: https://doi.org/10.1002/cphc.201000069

[27] F. Sunny, S. Kurukkal Balakrishnan, and N. Kalarikkal, "An overview on lead halide perovskite based composites and heterostructures: Synthesis and applications," *ChemNanoMat*, vol. 10, no. 3, art. no. e202300484, 2024. Available from: https://doi.org/10.1002/cnma.202300484

[28] M. F. Mohamad Noh, C. H. Teh, R. Daik, E. L. Lim, C. C. Yap, M. A. Ibrahim, *et al.*, "The architecture of the electron transport layer for a perovskite solar cell," *Journal of Materials Chemistry C*, vol. 6, no. 4, pp. 682–712, 2018. Available from: https://doi.org/10.1039/c7tc04649a

[29] H. Savin, P. Repo, G. Von Gastrow, P. Ortega, E. Calle, M. Garín, and R. Alcubilla, "Black silicon solar cells with interdigitated back-contacts achieve 22.1% efficiency," *Nature Nanotechnology*, vol. 10, no. 7, pp. 624–628, 2015. Available from: https://doi.org/10.1038/nnano.2015.89

[30] S. Mohammadi, S. A. Nia, B. D. Bruce, and G. Riazi, "Photosystem I enhanced perovskite–organic tandem solar cell efficiency," *Materials Research Bulletin*, vol. 181, art. no. 113077, 2025. Available from: https://doi.org/10.1016/j.materresbull.2024.113077

[31] P. A. Makode, S. P. Muduli, and P. Kale, "A perspective of GaAs//Si tandem photovoltaic cell: Architecture, fabrication, and performance," *Materials Research Bulletin*, vol. 190, art. no. 113504, 2025. Available from: https://doi.org/10.1016/j.materresbull.2025.113504

[32] K. I. Jayawardena, L. J. Rozanski, C. A. Mills, M. J. Beliatis, N. A. Nismy, and S. R. P. Silva, "'Inorganics-in-Organics': Recent developments and outlook for 4G polymer solar cells," *Nanoscale*, vol. 5, no. 18, pp. 8411–8427, 2013. Available from: https://doi.org/10.1039/c3nr02733c

[33] Maxeon Solar Technologies, "Maxeon launches fifth-generation shingled bifacial solar panels for global power plant market," 2020. Available from: https://solarquarter.com/2020/07/24/maxeon-launches-fifth-generation-shingled-bifacial-solar-panel-for-global-power-plant-market/

[34] R. O. Yakubu, L. D. Mensah, D. A. Quansah, and M. S. Adaramola, "A systematic literature review of the bifacial photovoltaic module and its applications," *The Journal of Engineering*, vol. 2024, no. 8, art. no. e12421, 2024. Available from: https://doi.org/10.1049/tje2.12421

[35] D. Cheng and Y. Gao, "A critical review on the fracture of ultra-thin photovoltaics silicon wafers," *Solar Energy Materials and Solar Cells*, vol. 274, art. no. 112999, 2024. Available from: https://doi.org/10.1016/j.solmat.2024.112999

[36] M. A. Green, E. D. Dunlop, M. Yoshita, N. Kopidakis, K. Bothe, G. Siefer, and J. Y. Jiang, "Solar cell efficiency tables: Version 68," *Joule*, vol. 10, no. 7, 2026. Available from: https://doi.org/10.1016/j.joule.2026.102494

[37] J. Zhu, H. Chen, R. Zhang, X. Zhu, Y. Sun, F. Gao, *et al.*, "Efficiency, stability and scalable deployment of organic photovoltaics," *Nature Reviews Clean Technology*, pp. 1–21, 2026. Available from: https://doi.org/10.1038/s44359-026-00202-0

[38] N. Kant and P. Singh, "Review of next generation photovoltaic solar cell technology and comparative materialistic development," *Materials Today: Proceedings*, vol. 56, pp. 3460–3470, 2022. Available from: https://doi.org/10.1016/j.matpr.2021.11.116

[39] A. Garrod and A. Ghosh, "A review of bifacial solar photovoltaic applications," *Frontiers in Energy*, vol. 17, no. 6, pp. 704–726, 2023. Available from: https://doi.org/10.1007/s11708-023-0903-7

[40] R. Guerrero-Lemus, R. Vega, T. Kim, A. Kimm, and L. E. Shephard, "Bifacial solar photovoltaics–A technology review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1533–1549, 2016. Available from: https://doi.org/10.1016/j.rser.2016.03.041

[41] J. S. Stein, C. Reise, J. B. Castro, G. Friesen, G. Mauger, E. Urrejola, *et al.*, *Bifacial Photovoltaic Modules and Systems: Experience and Results from International Research and Pilot Applications*, Report IEA-PVPS T13-14:2021, 2021.

[42] P. Merodio, F. Martínez-Moreno, R. Moretón, and E. Lorenzo, "Albedo measurements and energy yield estimation uncertainty for bifacial photovoltaic systems," *Progress in Photovoltaics: Research and Applications*, vol. 31, no. 11, pp. 1130–1143, 2023. Available from: https://doi.org/10.1002/pip.3728

[43] A. A. Baloch, S. Hammat, B. Figgis, F. H. Alharbi, and N. Tabet, "In-field characterization of key performance parameters for bifacial photovoltaic installation in a desert climate," *Renewable Energy*, vol. 159, pp. 50–63, 2020. Available from: https://doi.org/10.1016/j.renene.2020.05.174

[44] M. Kivambe, A. Abdallah, B. Figgis, G. Scabbia, M. Abdelrahim, and J. Lopez-Garcia, "Assessing vertical east-west bifacial photovoltaic systems in desert environments: Energy yield and soiling mitigation," *Solar Energy*, vol. 279, art. no. 112835, 2024. Available from: https://doi.org/10.1016/j.solener.2024.112835

[45] M. Vimala, G. Ramadas, M. Perarasi, A. M. Manokar, and R. Sathyamurthy, "A review of different types of solar cell materials employed in bifacial solar photovoltaic panel," *Energies*, vol. 16, no. 8, art. no. 3605, 2023. Available from: https://doi.org/10.3390/en16083605

[46] W. Gu, T. Ma, S. Ahmed, Y. Zhang, and J. Peng, "A comprehensive review and outlook of bifacial photovoltaic (bPV) technology," *Energy Conversion and Management*, vol. 223, art. no. 113283, 2020. Available from: https://doi.org/10.1016/j.enconman.2020.113283

[47] N. Riedel-Lyngskær, P. B. Poulsen, M. L. Jakobsen, P. Nørgaard, and J. Vedde, "Value of bifacial photovoltaics used with highly reflective ground materials on single-axis trackers and fixed-tilt systems: A Danish case study," *IET Renewable Power Generation*, vol. 14, no. 19, pp. 3946–3953, 2020. Available from: https://doi.org/10.1049/iet-rpg.2020.0580

[48] R. Kopecek and J. Libal, "Bifacial photovoltaics 2021: Status, opportunities and challenges," *Energies*, vol. 14, no. 8, art. no. 2076, 2021. Available from: https://doi.org/10.3390/en14082076

ABOUT THE AUTHORS

Monaem Elmnifi is a researcher and lecturer in the field of mechanical and energy engineering. He is affiliated with Bright Star University, Libya, and has pursued postgraduate studies at Belgorod State Technological University named after V. G. Shukhov. His research interests include renewable energy systems, solar energy, photovoltaic technologies, power generation, energy efficiency, thermal engineering, and environmental sustainability. He has contributed to several scientific studies addressing the performance, optimization, and environmental impacts of conventional and renewable energy systems. His research activities particularly focus on developing sustainable energy solutions, improving power system performance, and applying advanced engineering approaches to energy conversion and utilization.

Yasser F. Nassar is a researcher and academic specializing in mechanical engineering, renewable energy, and sustainable energy systems. He is affiliated with the Faculty of Engineering at Wadi Alshatti University, Libya. His research interests include solar energy, renewable energy technologies, energy efficiency, power generation, energy storage, environmental assessment, and sustainable development. He has contributed to numerous scientific studies addressing the technical, economic, and environmental aspects of energy systems. His research activities particularly focus on the development and optimization of renewable energy technologies, assessment of energy and environmental performance, and implementation of sustainable solutions for electricity generation and energy systems.

Ibrahim Imbayah Alzayani is affiliated with the Department of Energy Engineering, College of Renewable Energy, Tajoura, Libya. He received his B.Tech. degree in Electrical Engineering from the College of Technical Sciences, Sebha, Libya, in 2007, his M.Tech. degree from NIMS University, Jaipur, India, in 2012, and his Ph.D. degree from Jamia Millia Islamia, New Delhi, India, in 2018. His research interests include renewable energy, solar photovoltaic systems, green hydrogen, distributed generation, smart energy systems, hybrid energy systems, and electric vehicles. He has contributed to numerous scientific studies focusing on renewable energy technologies, sustainable power generation, and energy-system optimization.

Asiye Aslan is an Associate Professor in the Department of Electricity and Energy at Gönen Vocational School, Bandırma Onyedi Eylül University, Türkiye. She received her B.Sc., M.Sc., and Ph.D. degrees in Mechanical Engineering from Balıkesir University, Türkiye. She has extensive academic and professional experience in energy systems and power generation. Her research interests include combined cycle power plants, gas and steam turbines, renewable energy systems, energy efficiency, waste heat recovery, machine learning applications in energy systems, power plant performance analysis, and greenhouse gas emissions.

Ali Osman Büyükköse is a mechanical engineer and energy professional working in the power generation sector. He received his B.Sc. degree in Mechanical Engineering from Balıkesir University and his M.Sc. degree in Alternative Energy Sources from Bandırma Onyedi Eylül University, Türkiye. His professional experience covers combined cycle power plants, plant operation and maintenance, reliability and integrity management, energy efficiency, and performance monitoring. His research interests include combined cycle power plant performance, gas and steam turbines, renewable energy systems, machine learning applications in energy systems, energy efficiency, and greenhouse gas emissions.