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REVIEW PAPER

Comprehensive study on photovoltaic cell's generation and factors affecting its performance: A Review

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Abstract

The utilization of fossil fuels for power generation results in the production of a greater quantity of pollutants and greenhouse gases, which exerts detrimental impacts on the ecosystem. A range of solar energy technologies can be employed to address forthcoming energy demands, concurrently mitigating pollution and protecting the world from global threats. This study critically reviewed all four generations of photovoltaic (PV) solar cells, focusing on fundamental concepts, material used, performance, operational principles, and cooling systems, along with their respective advantages and disadvantages. The manuscript analyzes various materials, including their performance, physical properties (electronic and optical), biodegradability, availability, cost, temperature stability, degradation rate, and other parameters. The sensible engineering of effective solar devices made of cutting -edge materials along with nanostructured ternary metal sulphides, and three-dimensional graphene are also briefly discussed which are more versatile, stable, thin and light weight with high performance as compare to third generation solar cells. The impact of material alterations is delineated in PV, where the efficiency of solar cell technology has improved from 4% to 47.1%. Further the research article deals with different internal and external stress factors affecting the solar PV module performance.

Keywords Photovoltaic effect · Amorphous silicon · Thin film structure · Dye-sensitized · Quantum-dot solar cells · Perovskite and concentrated solar cells

Abbreviations

AQI	Air Quality Index
ARC	Anti Reflective Coating
a-Si	Amorphous Silicon
BOM	Bill of Materials
CdS	Cadmium Sulphide
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CNTs	Carbon Nanotubes
CPV	Concentrated Photovoltaics
c-Si	Crystalline Silicon
CZ	Czochralski
CZTS	Copper Zinc Tin Sulphide
DC	Direct Current
DSCC	Solar Cells with Dye Sensitivity
EU	European Union
FF	Fill Factor
GaAs	Gallium Arsenide
GW	Giga Watt
IEA	International Energy Agency
ITO	Indium Tin Oxide
ITRPV	International Technology Roadmap for Photovoltaic
LCOE	Levelised Cost of Electricity
mc-Si	Monocrystalline Silicon
MJSC	Multiple Junction Solar Cell
nm	Nanometers
PCE	Power Conversion Efficiency
PERC	Passivated Emitter and Rear Cell
PSC	Perovskite Solar Cell
PV	Photovoltaic
QDs	Quantum Dots
QDSC	Quantum Dot Solar Cells
SJ	Single-Junction
SWCNT	Single-Walled Carbon Nanotube
TCO	Transparent Conductive Glass Substrate
TOPcon	Tunnel Oxide Passivating Contacts

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USD	United State Dollar
UV	Ultraviolet
UVA	Ultraviolet-A
UVB	Ultraviolet-B
ZnTe	Zinc Telluride

Introduction

Solar PV systems play a pivotal role in harnessing solar energy for the purpose of generating electricity. The Sun serves as an abundant reservoir of energy. Only a fraction of the solar energy we receive is utilized by human beings. It is plausible that the solar radiation reaching the Earth's surface has the potential to meet the increasing demands for energy. In the year 2022, there was a notable increase in the production of solar PV energy, with a significant rise of 286 gigawatts (GW), which means about 26% growth. This surge led to a total solar PV output of nearly 1200 GW [1] and this is the first time, it surpassed wind energy in terms of absolute generation increase. It is projected that solar PV manufacturing investment in India and the United States will amount to over 25 billion United State Dollar (USD) throughout the period of 2022–2027. This represents a substantial growth of seven times when compared to the previous five-year period. India is projected to witness a significant increase in its renewable power capacity, with an estimated addition of 145 GW, resulting in nearly a doubling of its current capacity, during the period of 2022–2027. The generation of electricity from wind and solar PV sources is projected to experience a significant increase over the next five years, resulting in a more than two-fold growth. By the year 2027, these renewable energy sources are expected to contribute over 20% of the total worldwide power generation, as shown in Fig. 1 [2].

Throughout history, humanity has heavily depended on a variety of traditional energy sources, including fossil fuels, coal, natural gas, agricultural waste, and many more. The prolonged utilization of these limited reserve energy sources has given rise to a multitude of environmental hazards, encompassing but not limited to atmospheric pollution, aquatic contamination, alterations in climate patterns, and a perilous impact on biodiversity. Therefore, sustainable and environmentally friendly energy sources, also known as non-conventional energy sources is preferred. It is possible to get energy repeatedly from a variety of sustainable energy sources, including solar, wind, biomass, fuel cell, geothermal and tidal energy. Solar power is accessible to the entire world, making it an extremely desired and suitable replacement for fossil fuels.

According to a recent assessment by the International Energy Agency (IEA), solar energy continued its dominance as the primary contributor to the expansion of worldwide renewable capacity in 2022, with a capacity of 286 GW. By the year 2024, it is projected that the capacity will increase to over 310 GW. This growth can be attributed to the declining costs of modules, increased adoption of distributed PV systems, and a governmental emphasis on the widespread implementation of large-scale PV installations. According to the main-case prediction of the IEA, it is projected that global renewable capacity will witness a substantial growth of around 2,400 GW, representing a significant rise of nearly 75%, during the period from 2022 to 2027 [2, 3]. To meet the world's energy needs while also protecting the environment, renewable energy technologies have a great deal of potential. In addition, this technology is the most advantageous and effective renewable energy source currently available. Solar PV technology is a major force behind electrifying rural areas in developing nations [4].

The main benefit of employing PV cells is the direct conversion of solar energy into direct current (DC). Additionally, operating solar energy is significantly simpler, directly used at operational sites, require small capital for establishment, safe at anywhere even residential areas and requires fewer people than producing conventional electricity. The operation of these solar cells is characterized

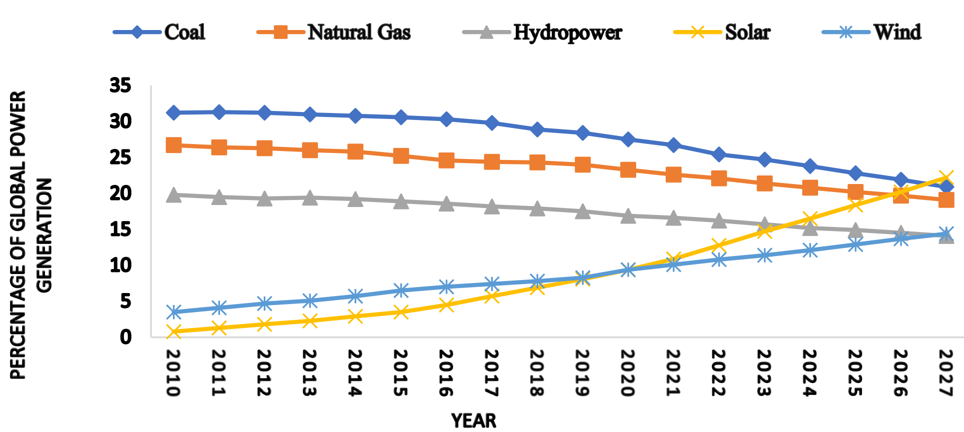


Fig. 1 Share of Global power generation by different technologies, 2010–2027. Source: IEA analysis based on World Energy Outlook 2022

by a lack of noise, which distinguishes them from typical power pumping systems. PV panels are widely regarded as having low maintenance and operational expenses due to their absence of mechanical components. An additional advantage of solar PV technology is, its capacity to accommodate the installation of extra solar panels on rooftops and various surfaces, while minimizing any potential disruptions to the surrounding community [5, 6]. Due to an easing in land access and rooftop installation, the solar tariff was cut from ₹18/kWh (in 2011) to lowest 2.29/kWh in December 2022 [7]. India, being situated in a tropical region, experiences consistent solar radiation throughout the year, with an average of 2800–3000 h of sunshine annually. The area in question experiences sun radiation ranging from 4 to 7 kWh per square meter per day. [8]. As of 31 December 2023, India's solar power installed capacity reached at 73.109 GW.

The main reason behind this enhancement is low cost of solar panel. The production prices of this particular energy source have shown a significant decline over the past decade, rendering it not only cost-effective but also frequently the most economical option for generating power. Between 2010 and 2022, solar module prices plummeted by up to 88% as shown in Fig. 2. During the same period, Fig. 3 elaborate that, there was an 88% reduction in the global weighted-average levelised cost of electricity (LCOE) for utility-scale solar PV projects. LCOE from newly installed utility-scale solar PV plants dropped to $0.053/kWh in 2023. By 2050, it expected to decline to $0.021/kWh [1, 9]. The Global and India evolution of cumulative solar PV installation between 2011 and 2023 is shown in Fig. 4. Country wise total PV installation is shown in Fig. 5. The total PV installation up to the end of 2023 is 1,418,016 MW, with the major contribution from China (609,921), the USA (139,205 MW), Japan (89,077 MW), Germany (81,739 MW), and India (73,109 MW) as shown in Fig. 5. Europe's contribution to solar PV installation is also appreciable with 288,644 MW [10].

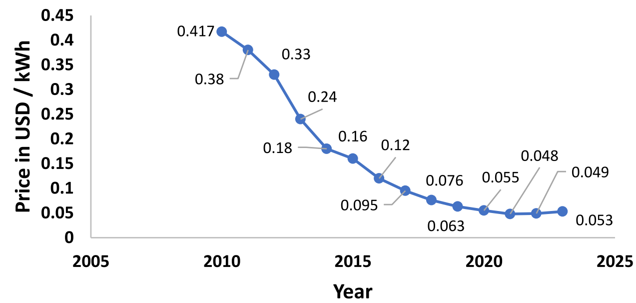
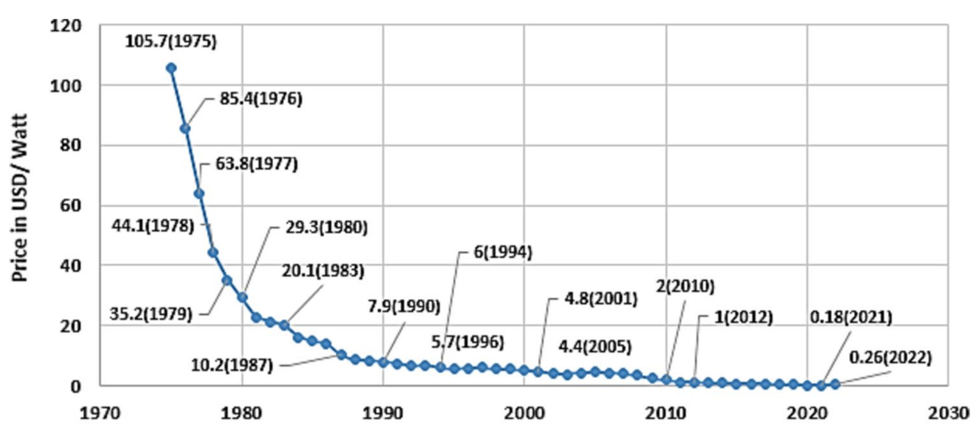


Fig. 3 Levelised cost of electricity for solar PV module in USD/kWh

The PV effect refers to the conversion of solar energy into electrical energy directly by utilizing semiconductor sheets, often known as solar cells. In order to maximize the amount of sunlight that can be harvested, solar cells have evolved through three generations. First generation PV solar cells are conventional mono and polycrystalline solar cells. Second generation thin-film cadmium telluride (CdTe), cadmium sulphide (CdS), Copper Indium Gallium Selenide (CIGS) and copper zinc tin sulphide (CZTS) technology cells are cost-effective and easy to fabricate. Due to performance, environment issues, and disposal issues in second generation solar cell materials like cadmium, third generation solar cell technology comes into the picture. Third generation solar cells include multi-junction, dye-sensitized, quantum dots, perovskite and concentrated solar cells, where PCE improved to 47.1% with low-material and production cost, low-maintenance, high-durability and light weight features. In order to maximize their economic efficiency, modified third-generation solar cells—such as tandem and/or organic–inorganic configurations—are developing as fourth-generation solar cells. The utilization of solar energy is subject to limited constraints. There are three primary limitations associated with the subject under consideration. Firstly, it lacks accessibility during night time hours. Secondly, it exhibits fluctuations, rendering it inconsistent.

Fig. 2 Crystalline PV solar module cost in USD/ Watt



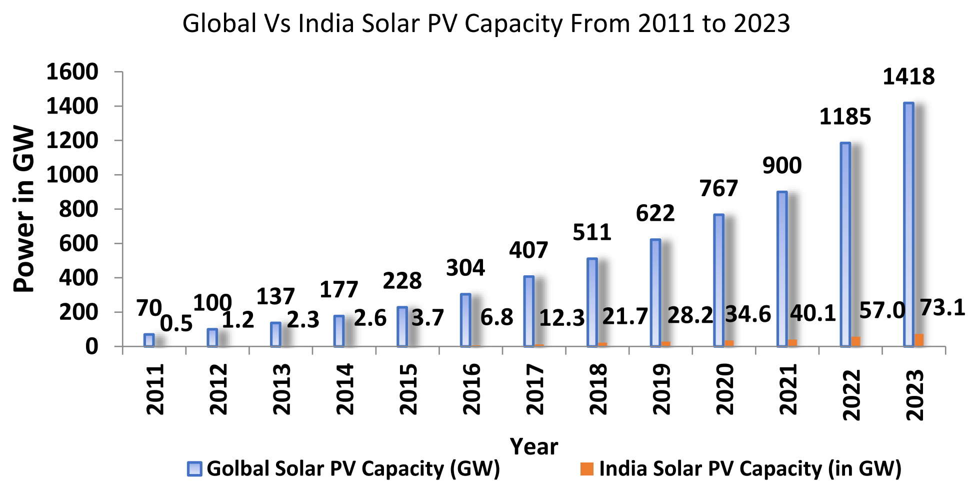


Fig. 4 Global evolution of solar photovoltaic [10]. * Source: iea-pvps.org

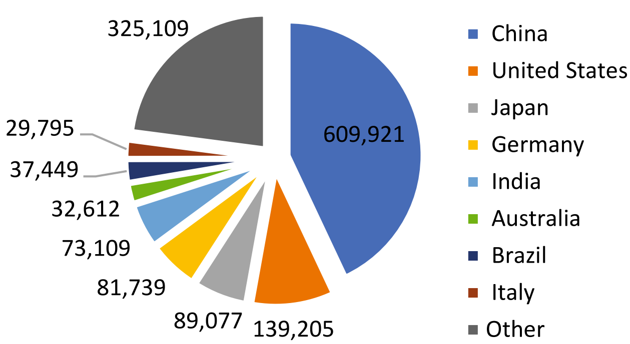


Fig. 5 Country-wise total PV Capacity in MW [10]. International Renewable Energy Agency (IRENA-2024)

Lastly, its reliability is compromised by inclement weather conditions, particularly cloud cover. The incident solar radiation that reaches the Earth's surface undergoes traversal via multiple atmospheric layers, each of which harbours diverse particulate matter. The incident solar radiation on the Earth's surface exhibits significant variability due to factors such as geographical location, seasonal variations, diurnal cycles, and atmospheric conditions including water vapor content, particulate matter, air pollution levels (air quality index-AQI), atmospheric pressure, and cloud cover [11].

The primary objective of the manuscript is to provide a critical comparative analysis of the four generations of PV module technologies and various internal and external stress factors affecting its performance. The research aims to evaluate and bifurcate these technologies based on PCE, working principle, material usage, environmental impact, production cost, and other parameters. This article also analyzes the possibilities of future technologies, emphasizing minimal residual waste, improved cost efficiency, enhanced performance, reduced weight, increased stability, and elevated temperature tolerance. The current paper introduces a novel approach by offering a consolidate comparison between all four PV cell generations with various factors affecting its performance considering material science, environmental impact, and production cost in a unified framework. This study is the first of its kind to deeply explore the future potential of PV technologies along with PV technology's evolution. It will serve as a valuable resource for researchers, manufacturers, and policymakers aiming to optimize PV technology for a sustainable future.

The literature review presented herein highlights some of the contemporary research in the areas related to PV cells during the last four decades, which will be useful for researchers, academicians, and industry. This paper is organized with Sect. "Photovoltaic Technology" covering the PV effect to better understand this technology and its working, while Sect. "Generations of Photovoltaic Solar Cells" develops and presents the probable research avenues that were deciphered from the different types of PV cells in various generations to understand the journey of development. Sect. "Comparison Between Various Generations of Solar Cells" elaborate the comparison of PV cell technology in terms of different parameters, and Sect. "Factors Affecting PV Cell Performance" discusses the various factors affecting the performance of PV solar cells during manufacturing, installation and operation. Section 6 concludes the paper with incorporating future direction.

Photovoltaic technology

Every PV cell contains multiple layers of a semi-conducting material. The generation of electricity occurs due to the establishment of an electric field across many layers of a semiconductor material upon the incidence of light on the solar cell. The power received by the cell is contingent upon the intensity of the incident light. The Earth's capacity to harness solar power is estimated to be approximately 1.8×10^{11} MW, a far higher magnitude than the present rate of world energy consumption. PV cells are constructed using semiconductor materials, such as silicon [12]. Silicon, possessing four valence electrons, is frequently utilized in the production of PV cells. When a donor with N-type characteristics, with five valence electrons like phosphorus, is introduced to one side of the cell, the silicon material acquires loosely bound valence electrons, resulting in an abundance of negatively charged carriers. Boron demonstrates a higher electron affinity than silicon due to its three valence electrons, which act as p-donors. The proximity of p-type silicon to n-type silicon facilitates electron diffusion, resulting in the formation of a p–n junction. The process of diffusion involves the recombination of holes and electrons across the p–n junction. The presence of an electric field induces the development of a diode, resulting in the promotion of current flow in a single direction, as depicted in Fig. 6 [13, 14]. An anti-reflective coating (ARC) refers to a thin layer of dielectric material that is applied onto the silicon substrate with the purpose of mitigating optical losses caused by reflection. By enhancing the transmittance of light, the ARC contributes to an overall improvement in the efficiency of solar cells. Metal conductors (metal grid) are used to connect the n- and p-type sides of solar cells to an external load. The charge carriers present in the cell receive energy when a light in the form of photons strikes them. Electric fields divide electrons and holes, which are both differently charged carriers. The extraction of electricity occurs when the circuit is completed by the connection of an external load. The typical single junction silicon solar cell has an open-circuit voltage of about 0.5–0.6 V [15].

Photovoltaic (PV) Effect

Alexandre-Edmund Becquerel, a French physicist, achieved the discovery of voltage in 1839 while experimenting with an electrolytic cell made up of two metal electrodes set in an electricity-conducting medium solution. The PV effect is the name of this phenomenon. The basis of solar cell technology is the PV effect. In solids like selenium, the PV effect was first investigated in 1870. It was expensive and only had a 1–2% efficiency [16]. The Czochralski (CZ) process was created in 1940 and 1950 to obtain pure silicon crystals [17]. In the PV effect, incident photons with energy equal to that of the semiconductor material's energy gap are absorbed, resulting in electrons and holes as charge carriers and moves to higher energy state. When n-type and p-type semiconductors are combined, a junction region is formed, resulting in the generation of an electric field. This electric field arises due to the movement of electrons towards the positively charged p-side and the migration of holes towards the negatively charged n-side. This phenomenon induces the unidirectional movement of negatively charged particles and the counter-directional motion of positively charged particles. This electron mobility generates an electric current in the cell.

The absorber layer in a PV solar cell plays a critical role in capturing sunlight and converting it into electrical energy. The physical properties, specifically electronic (such as bandgap energy, carrier mobility, carrier lifetime, recombination rate, doping concentration, and electrical conductivity) and optical characteristics (such as absorption coefficient, refractive index, optical bandgap, reflectivity, and photoluminescence), are essential for assessing the efficiency and overall performance of the solar cell. Non-toxic and abundantly available materials exhibiting a high absorption coefficient ($> 10^5$ cm^{-1}) and an appropriate bandgap (1–1.5 eV) have garnered significant interest as PV absorber layers. Silicon, CZTS, CdTe, perovskites, quantum dots and dye-sensitized cells are various absorber used as absorbing layer in a PV solar cell. It plays a critical role in capturing sunlight and converting it into electrical energy. The determination of the bandgap of PV semiconductors is of paramount importance as it provides insights into the specific wavelengths of light that can be absorbed

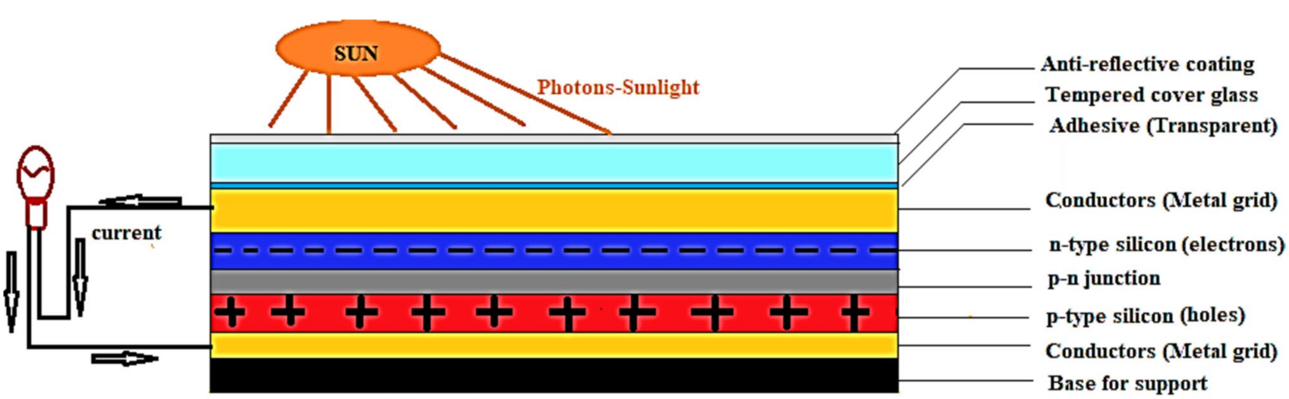


Fig. 6 Photovoltaic-cell with current flow

by the material and subsequently converted into electrical energy. The PV cell demonstrates optimal energy utilisation when the bandgap of the semiconductor aligns with the wavelengths of incident light. If the band gap is excessively high, the PV effect will not occur for the majority of photons. Conversely, if the band gap is too low, the majority of photons will possess an excess of energy that is above the threshold required to stimulate electron excitation across the band gap. Consequently, this surplus energy will be wasted [18]. The derivation of the maximum power output, fill factor (FF) and power conversion efficiency (PCE), and of the solar panel is shown in Eq. 1–3.

$$P_{max} = I_{MP}V_{MP} \tag{1}$$

$$FF = \frac{I_{MP}V_{MP}}{V_{OC}I_{SC}} \tag{2}$$

where, P_{max} is the maximum output power. I_{MP} and V_{MP} is the current and voltage at maximum power respectively. V_{oc} and I_{sc} is the open circuit voltage and short circuit current. Accordingly, the efficiency η of a PV panel can be determined by the following derivation:

$$\eta = \frac{P_{max}}{Radiation\ Intensity * Area\ of\ the\ solar\ panel} \tag{3}$$

Furthermore, the loss in efficiency, denoted as η_{loss}, of a PV panel can be expressed as:

$$Loss\ in\ \eta = \frac{(Efficiency\ of\ Reference) - (Efficiency\ of\ Panel\ for\ the\ Sample)}{Efficiency\ of\ Reference} \tag{4}$$

Historic development

The PV effect has been recognized by scientists for over a century and a half. The inception of silicon solar cells can be attributed to Russell Ohl in 1946 [19]. Figure 7 presents an overview of the initial developments in PV technology, where the first PV effect was demonstrated in 1839 and the first study by Albert Einstein in 1904 to advance material PV modules.

Generations of photovoltaic solar cells

Solar cells can be categorized into various categories. The majority of solar cells, approximately 90%, are comprised of silicon cells that are wafer-based. Wafer-based silicon solar cells typically have a thickness ranging from around 180 to 200 µm. The predominant silicon materials employed in the manufacturing of solar cells include single crystalline (mono), multi-crystalline (poly), amorphous silicon (a-si), cadmium-telluride (CdTe), copper-indium-gallium-selenide (CIGS), gallium arsenide (GaAs), and graphene [20–23]. Figure 8 illustrates the categorization of solar cell technology alongside its corresponding site efficiency. PV cell technologies can be categorized into four generations, which are determined by their production materials and the extent of their commercial development.

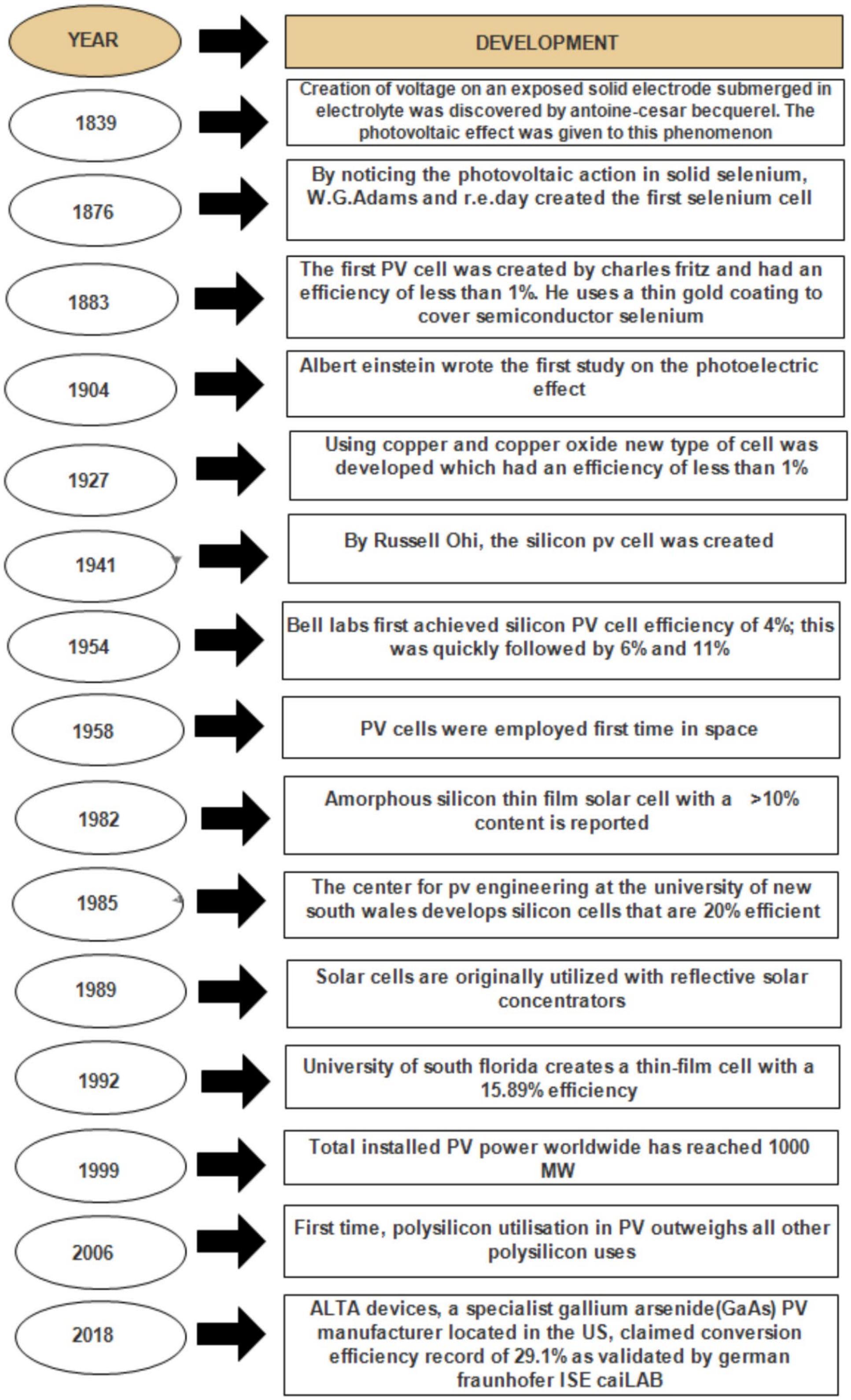
First-generation solar cell

The solar cells under consideration are based on crystalline Silicon (c-Si) wafers. The present technology is derived from c-Si, which is the expensive approach to obtaining pure silicon crystal. Following oxygen (O_2), silicon (Si) is the second most abundant element on Earth. Solar cells are widely employed globally and have the highest level of commercial efficiency [11, 23]. The two primary categories of first-generation solar cells are single crystalline, also known as monocrystalline silicon (mc-Si), and multiple crystalline, sometimes referred to as polycrystalline (poly-Si). Based on the thirteenth edition of the International Technology Roadmap for Photovoltaic (ITRPV), it is projected that mc-Si will dominate the industry with a market share of approximately 90% in 2022, with expectations for this proportion to further increase [24]. It has been shown that the efficiency of polycrystalline solar cells is comparatively lower when compared to monocrystalline solar cells.

Mono crystalline solar cells (Single Crystalline)

The CZ technique is employed for the fabrication of monocrystalline solar cells from silicon crystals, as its name suggests. During the production process, the ingots of significant size undergo a cutting procedure to transform them into silicon crystals. The process of "recrystallization" of exceptionally large single crystal materials requires meticulous processing techniques. The efficiency of mono-crystalline silicon solar cells ranges from 17% to 22% under normal operating conditions, while it reaches 26.7% under standard settings of 1000 W/m^2 at 25 °C [25]. In the year 2020, the installation of crystalline silicon (c-Si) modules reached a significant capacity of more than 145 GW, representing a dominant share of 95% in the overall PV market. As of 2023, around 700 GW of crystalline silicon modules have been installed. According to a study, it is anticipated that between the years 2040 and 2050, c-Si photovoltaics have the potential to surpass all other forms of electricity generation worldwide, based on various compelling factors [26].

Fig. 7 Evolution of Photovoltaic Technology



The market share of Passivated Emitter and Rear Cell (PERC) is currently seeing significant growth, reaching over 75% [27]. This can be attributed to its enhanced cell architecture, which has proven to be more effective. In the year 2021, the market shares of contemporary and enhanced cell designs, such as tunnel oxide passivating contacts

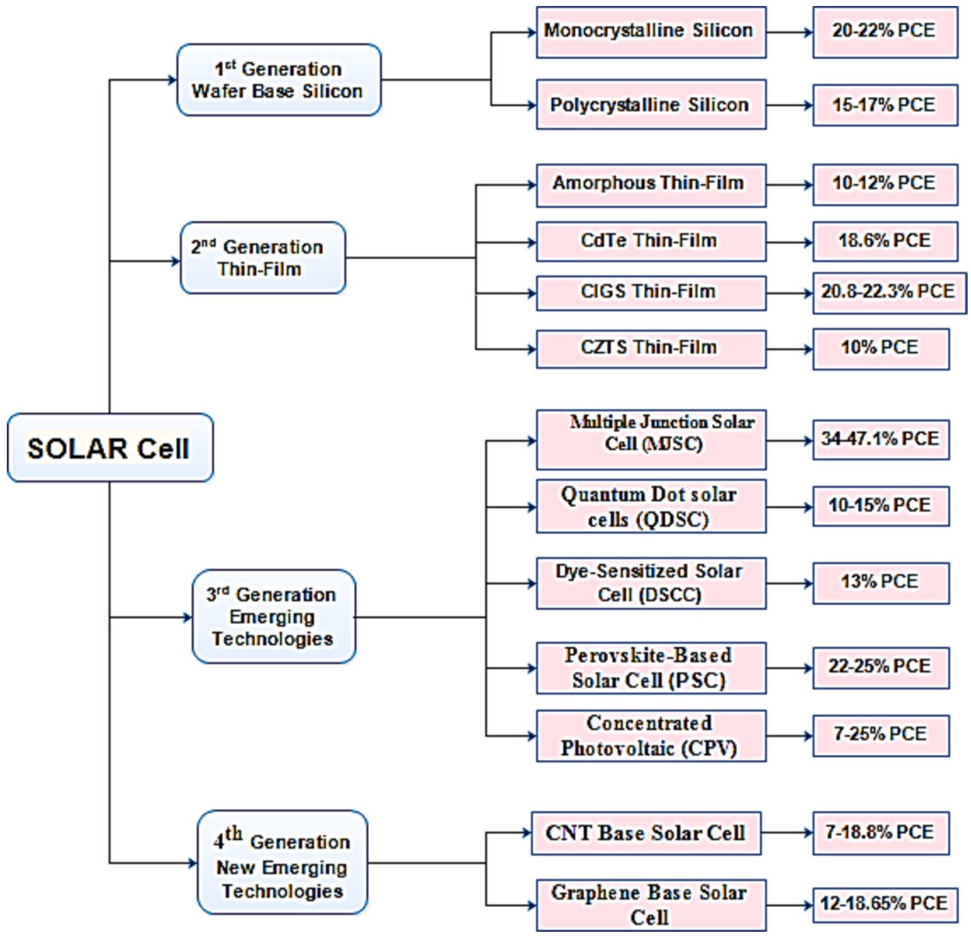


Fig. 8 Classification of Solar PV cell technology with its efficiencies

(TOPCon), heterojunction, and back contact technologies, had a notable increase to approximately 20%. As a follow-up to passivated emitter and rear contact cells, TOPCon are passivating contacts made of an ultrathin silicon oxide (SiOx) layer and a doped poly-Si layer. This growth can be attributed to the expanded scale of commercial production operations. Monocrystalline silicon, due to its additional recrystallization with the CZ process, is characterised by higher cost and enhanced semiconductor performance compared to polycrystalline silicon [28].

Polycrystalline Solar Cells

Polycrystalline PV modules, alternatively referred to as polysilicon or Poly-Si, often have multiple discrete crystals that are interconnected within a solitary cell. Polycrystalline silicon solar cells can be manufactured at a lower cost by a production method involving the cooling of a graphite mould containing molten silicon. Polycrystalline panels have traditionally been the most cost-effective option for households seeking to install solar power systems, while seeing minimal reduction in panel performance. The efficiency ratings of polycrystalline panels generally exhibit a range between 15% and 22.3%. The study conducted by Zhao et al. [29] showed that the utilisation of honeycomb-like features in polycrystalline solar cells resulted in an approximate efficiency of 19.8%.

Schindler et al. [30] demonstrate a verified world record efficiency of 22.3% for a mc-Si solar cell. Polysilicon is a highly attractive material for the fabrication of PV owing to its abundant availability, inherent stability, low toxicity, and comparatively lower cost in comparison to single crystals. The deposition of polycrystalline silicon for solar cell fabrication does not necessarily require a silicon wafer as a substrate. Instead, it can be deposited on alternative, more cost-effective materials, hence resulting in a reduction in overall production costs.

Second-generation solar cell

The primary objective of second-generation PV solar cells is to minimize costs, which was a major concern with first-generation cells. This can be accomplished by the use of thin-film technologies, which involve reducing the amount of material used while enhancing its quality.

Amorphous silicon solar cells

The crystal wafer technology is considered costly because of its predominant utilisation of pure crystalline silicon. The acquisition of pure silicon necessitates a challenging and costly procedure. Amorphous solar panels are created through the deposition of non-crystalline silicon onto a substrate made of glass, plastic, or metal, as opposed to the utilisation of solid silicon wafers characteristic of mono- or polycrystalline solar panels. The silicon layer of an amorphous solar panel can have a thickness as low as one micrometer, which is significantly smaller than the diameter of a human hair. The reduction in cost of solar cells can be achieved by depositing thin silicon films with a thickness of 1 μm. In contrast to wafer-based technology, thin film technology utilises a significantly less quantity of silicon. The development of thin films of a-Si implanted was first carried out by R. Chittick [31]. The a-Si thin film solar cells have garnered significant attention among PV researchers due to its ability to generate power at a reduced cost, mostly attributed to the utilisation of a less quantity of silicon [32]. a-Si exhibits superior temperature coefficient of resistance compared to crystalline-based solar panels and demonstrates enhanced resistance against shading in comparison to other thin film cells. In a standard PN junction solar cell, the generation of minority carriers due to photo-absorption occurs, and these carriers undergo diffusion within the P and N regions throughout the whole extent of the junction, where optical absorption takes place. This diffusion process is facilitated by the presence of significantly large diffusion lengths, often about 200 μm. Nevertheless, it is worth noting that in the context of an a-Si solar cell, the diffusion lengths for minority charge carriers are remarkably limited, measuring approximately 0.1 μm. Consequently, the only reliance on diffusion as a means of gathering minority charge carriers becomes unfeasible [33]. The observed trend of efficiency with rising cell temperature is characterised by a relatively small deviation, which can be attributed to the low power temperature coefficient of a-Si cells (0.1–0.2%/°C) [34].

Thin film technique is employed in the fabrication of multi-junction, heterojunction, and homo-junction solar cells as well. The utilisation of thin film solar cell technology offers several advantages, as indicated by previous research [35].

- The utilisation of materials is kept to a minimum.
- Decreased energy payback period
- Minimal residual waste.
- Incorporation of integration into a singular entity
- Utilisation of modules possessing a substantial surface area
- Alteration of material properties to enhance adaptability
- Enhanced optimisation of spatial utilisation within the modules
- Implementation of processes characterised by low temperatures
- The creation of transparent modules is possible.

The aforementioned advantages render this technique more appealing, with the exception of its efficiency, which ranges from 10% to 13% [36].

Half-cell technology

The utilisation of half-cell technology exhibits significant appeal in the context of expanding solar module manufacturing capabilities. Half cells provide a straightforward pathway to attain significant enhancements in power output within solar modules. Based on the findings of ITRPV 2018 [37], it is projected that the market share of half-cell solar modules would approach around 40% within a decade. An optimised module architecture has the potential to achieve a power increase of up to 5% without altering its size. Furthermore, larger modules can potentially achieve a power gain of up to 8% [38]. The manufacturing process of solar modules employing half-cell technology necessitates the division of each solar panel along its longitudinal axis. As a consequence, two smaller cells are generated, which are subsequently interconnected in a series configuration to constitute a module. The utilisation of half-cell technology offers several advantages. One potential approach to improve the efficiency of the module is reducing the series resistance of the cells. This phenomenon occurs as a result of halving the current flowing through each cell, hence reducing the losses associated with Joule heating. One additional advantage is that half-cell modules exhibit less susceptibility to the occurrence of hot spots. The phrase "hot spot" denotes a specific area within a module that experiences a more rapid increase in temperature compared to the surrounding regions, primarily due to concentrations of electric current. The implementation of half-cell modules can contribute to the mitigation of hot spot occurrences by effectively distributing the electrical current across two individual cells.

Moreover, it is possible that half-cell modules exhibit a higher degree of shadow tolerance. When a section of a module gets darkened, the present output of the module decreases. This phenomenon could potentially lead to a decrease in efficiency or even cellular damage. The occurrence of this phenomenon is less likely due to the division of the current between two cells in half-cell modules. Finally, it is possible that half-cell modules exhibit more resilience. Due to their reduced size, the cells exhibit a decreased susceptibility to potential damage during the manufacturing or installation processes. Furthermore, the likelihood of cracking due to thermal expansion and contraction is also reduced. Mittag et al. [39] found that half-cell modules could boost power output by 2–4% while only incurring a 0.6–1.2% cost premium. Whereas, Sarniak [40] presents a mathematical model that elucidates the functioning of half-cell solar modules under conditions of partial shading. The employed model is utilised to examine the effects of different shading strategies on the output power of the module. Figure 9 illustrates solar modules utilising half cell technology, specifically employing N-type TOPcon technology in conjunction with double glass bifacial construction, resulting in an impressive efficiency rating of 23%.

Cadmium Telluride (CdTe) thin film solar cell technology

CdTe is considered to be a highly significant variant of thin film solar cells from an economic perspective due to its lower cost and greater economic viability [41]. A p-n heterojunction diode is formed through the utilization of p-doped CdTe and an n-doped CdS layer. Additional materials employed in the fabrication of thin film CdTe solar cells include Fluorine-doped tin oxide (SnO_2:F), Zinc telluride (ZnTe) and Copper (Cu) for the purpose of establishing metallic connections. The technology of thin-film solar cells utilizing CdTe is illustrated in Fig. 10.

The manufacturing process involves the initial production of polycrystalline CdTe-based solar cells, with the substrate material being selected as glass. Furthermore, multiple layers of CdTe solar cells are applied onto the substrate using diverse and economically efficient methods. CdTe solar cells are fabricated by employing p-n heterojunctions consisting of a p-doped CdTe layer and an n-doped CdS layer [42]. CdTe thin-film solar panels are highly favorable options for investors due to their cost-effectiveness and ease of production. By the year 2023, the installed capacity of modules based on CdTe exceeds 30 gigawatts peak (GWp). The average efficiency of CdTe panels is commonly reported as 18.6%, Whereas First Solar company has conducted laboratory experiment yielded CdTe solar cells with exceptional efficiencies of 22.1% [43]. Nevertheless, the toxic properties of cadmium (Cd), which is classified as one of the 126 priority pollutants, give rise to a multitude of environmental concerns due to its potential for bioaccumulation in humans, animals, and plants. The ecology is negatively impacted by the continued recycling and disposal of hazardous Cd [20]. In the literature, Britt and Ferekides [44] achieved notable cell efficiencies ranging from 15 to 16% for solar cells utilizing CdTe. Based on the findings presented in Haymore's publication [45], it has been demonstrated that the efficiency of CdTe solar cell technology is approximately 21%.

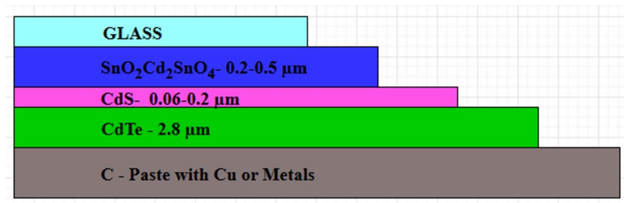
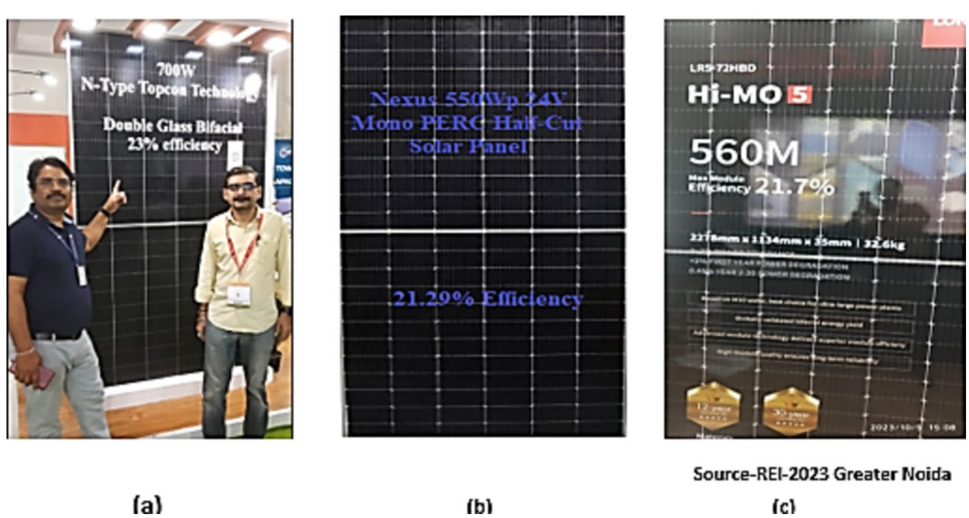


Fig. 10 Cadmium Telluride- CdTe Solar Cell Schematic diagram

Fig. 9 Half- Cell Technology



Copper Indium Gallium Selenide (CIGS) solar cells

This thin film solar cell is composed by deposition of copper, indium, gallium, and selenium on a glass or plastic substrate, which includes front and back electrodes for the purpose of current collection. The requirement for a minimal thickness of material (approximately 1/100th of traditional solar cell) arises from the semiconductor compound's significant absorption coefficient. Previous research has demonstrated that the substitution of sodium and potassium with heavier alkali elements such as cesium and rubidium during the deposition process enhances the experimental resolution of

CIGS solar films with high efficiency [46]. The thin film method utilising ternary chalcopyrite Cu(In, Ga) Se_2 (CIGS) has been shown to achieve an efficiency of 20.8% when applied on flexible substrates. Conversely, when applied to rigid substrates, it has shown an efficiency of 22.3%. When comparing it to CdTe thin film technology, it is seen that the former exhibits lower toxicity, higher stability, lower degradation rate in the field, lower efficiency and a more expensive manufacturing method [47]. The potential utilisation of thin-film solar panels in space applications is currently under investigation [48].

Copper Zinc Tin Sulphide (CZTS) thin film solar cells

Cu_2ZnSnS_4 (CZTS) is a quaternary semiconducting compound that is extensively employed in the field of thin film solar cell technology. This compound is favoured due to its vast availability on Earth. Indium (In) is found to be less abundant compared to Tin (Sn) and Zinc (Zn). Sn and Zn being approximately 45 and 1500 times more abundant than In, respectively. Additionally, the cost of indium is roughly twice as high as that of Sn and Zn. The CZTS thin film solar cell has drawn significant interest because of its optimal direct energy gap, high absorption coefficient, and desirable electrical characteristics. The direct energy band gap and absorption coefficient of CZTS were determined to be approximately 1.45 eV and 1.0×10^4 cm^{-1}, respectively, while the efficiency was seen to be around 8–10% [49–51]. According to Chatterjee et al. [52], the efficiency of thin film PV technology is said to be about 6%, in contrast to the significantly higher output rate of approximately 94% for crystalline Silicon (c-Si) PV technology.

Third-generation solar cells

Solar cells have undergone three rounds of development in order to optimise their efficiency in capturing sunlight. To enhance economic efficiency, researchers are currently focusing their efforts on the advancement of PV components, such as multi-junction cells, intermediate band gap cells, perovskite materials, concentrated solar cell components and printable solar cell components like quantum dots [53]. Third-generation PV cell technology encompasses single junction solar cells that have the potential to exceed the power efficiency limit of 31–41% known as the Shockley-Queisser limit [54]. In order to optimise efficiency, it is imperative for the solar cell to absorb all photons present in the incident sunlight. The resolution of this issue is beyond the capabilities of a solitary junction solar cell. Hence, the multi-junction solar cell is considered a prospective resolution to this problem. Primarily, the prevailing forms of 3rd generation solar cells can be categorised as follows [24]:

1. Multiple Junction Solar Cell (MJSC).
2. Quantum Dot Solar Cells (QDSC).
3. Solar Cells with Dye Sensitivity (DSCC).
4. Perovskite Solar Cell (PSC).
5. Concentrated PV (CPV).

Multiple Junction Solar Cell

In contrast to single junction cells, multi-junction solar cells are comprised of many layers consisting of diverse semiconductor materials. Subsequent layers have the capacity to capture a greater amount of light per unit area, hence generating a higher quantity of power, as they are capable of absorbing radiation that traverses the initial layer. Consequently, it can be observed that the efficiency of single junction solar cells is comparatively lower when compared to that of multi-junction solar cells. The presence of discrete bandgaps in many layers allows for the capture of light that passes through the initial layer, resulting in increased light absorption per unit area and enhanced electricity generation. The application of semiconductors from group III and V elements in the periodic table is observed in the utilisation of multi-junction solar cells. The extensive utilization of single-junction (SJ) silicon-based solar cells in the PV sector is primarily attributed to its affordability and rapid industrialization. Nevertheless, the primary obstacle hindering the wider use of these systems is their suboptimal efficiency, which is limited to a theoretical maximum of 29.4%. The use of multiple PV materials in the method suggests that multi-junction (MJ) solar cells could serve as a significant approach to transcend the efficiency limitation of single-junction (SJ) silicon-based solar cells. A novel PV device, known as the III-V/Si tandem solar cell, has been developed with the aim of mitigating the limitations associated with existing solar cell technologies and enhancing overall cell efficiency [55]. The GaInP/GaAs/Ge (1.82/1.42/0.67 eV) lattice-matched triple-junction cells have been widely used and proven to be highly efficient, achieving efficiencies exceeding 30%. These cells have successfully served many space applications over the course of the last twenty years [56]. Aho et al. [57] conducted

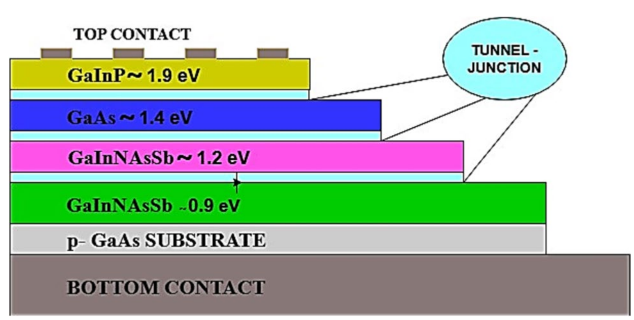


Fig. 11 Architectural diagram of Multi-Junction (4J) solar PV cell

an evaluation of the performance of four-junction GaInP/GaAs/GaInNAsSb/GaInNAsSb solar cells manufactured using molecular beam epitaxy on p-GaAs substrates. These solar cells had bandgaps of 1.88, 1.42, 1.17, and 0.93 eV, as illustrated in Fig. 11. The electrical performance of the four-junction cell remained satisfactory even under high solar intensities of up to 1000 suns, exhibiting an efficiency of 39% when exposed to 560 sun illumination. In 2020, Geisz et al. [58] demonstrates the architecture of the most efficient III-V semiconductor multi-junction solar cells with six monolithic junctions, which are fabricated using an inverted metamorphic process. These cells have achieved a remarkable record efficiency of 47.1% under 143 Suns concentration.

Quantum dot solar cells

Quantum dots (QDs) are minute particles with a diameter of nanometers (nm) (1–6 nm), employed in solar cells to capture incident photons from sunlight and generate the PV phenomenon. QDs exhibit distinct optical and electrical properties in comparison to bulk materials, rendering them suitable for applications such as nanocrystalline solar cells, as depicted in Fig. 12 The utilisation of ARC, a scientific methodology, serves to enhance the efficiency of solar cells by reducing reflection and enhancing light absorption. The manipulation of quantum dots' size, shape, and composition allows for exact control over the emitted light frequency. Quantum dots of various sizes and types exhibit distinct light emission frequencies, which can be precisely tailored to fulfil specific requirements [59]. Quantum dots are synthesised by a range of methodologies, such as laser ablation, electrochemical carbonization, microwave irradiation, hydrothermal/solvothermal treatment, and more techniques. In lieu of employing organic dyes, a range of compounds such as CdS, CdSe, PbS, PbSe, Ag2S, and InAs are utilised as photosensitizers due to their versatile optical and electrical qualities that are essential for PV solar cells. Cd chalcogenide quantum dots (QDs) are preferred due to their superior stability in comparison to other types of QDs, as indicated by previous studies [60, 61]. Today, a significant advancement was made in the field of QD solar cells by employing a combination of colloidal QDs and perovskites. This novel approach resulted in a notable enhancement of the record efficiency, reaching 16.6% [62]. Moreover, in laboratory settings, the efficiency was further improved to 18.1% when compared to the theoretical limits. The ability to adjust the bandgap and the potential for up-conversion and down-conversion processes play a crucial role in enhancing the efficiency of energy conversion devices beyond their theoretically predicted limits. [63, 64].

Dye sensitivity solar cells

DSSCs have attracted considerable scientific interest for more than two decades owing to its capacity to achieve comparable PCE at reduced material and production expenses, relative to conventional silicon solar cells. Titanium dioxide (TiO_2) is a widely utilised and cost-effective material for DSSCs, known for its environmentally sustainable properties. This technology is classified in the thin-film third generation solar cell category [65]. Figure 13 is a schematic representation of DSSCs. The system comprises four essential components: (1) a photoanode, which consists of a mesoporous oxide layer (typically TiO_2) that is deposited on a transparent conductive glass substrate (TCO); (2) a monolayer of dye sensitizer that is covalently bonded to the surface of the TiO2 layer, serving to capture light and generate photon-excited electrons; (3) an electrolyte containing a redox couple (usually I-/I-3) dissolved in an organic solvent, which functions to collect electrons at the opposite end of the electrode and facilitate the regeneration of the dye; and (4) a counter electrode composed of a conductive glass substrate coated with platinum [66]. The main challenges impeding the commercialization of dye-sensitized solar cells (DSSCs) pertain to the stability of the cells and their relatively suboptimal photoelectric conversion efficiency.

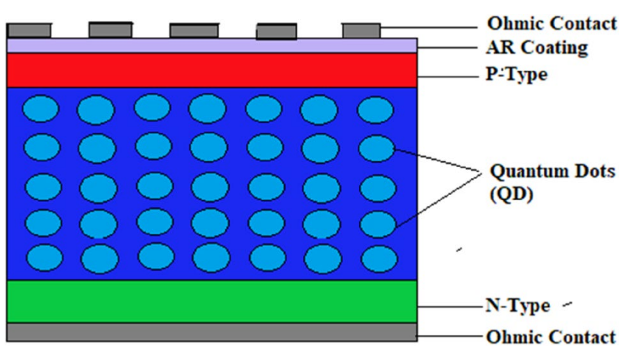


Fig. 12 Physics of Bulk material and Quantum dot

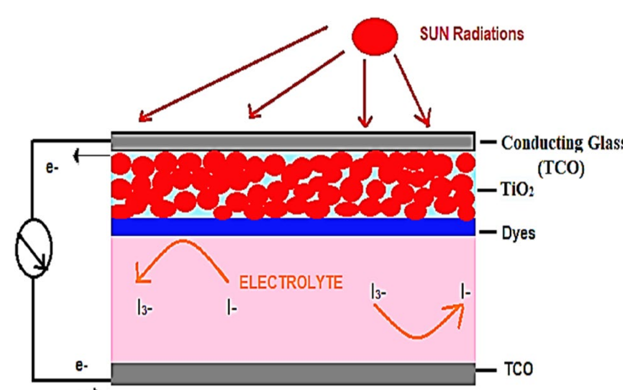


Fig. 13 Schematic illustration of DSSCs

Theoretical predictions suggest that the maximum attainable energy conversion efficiency for DSSCs is 32%. However, the most notable efficiency achieved thus far, as described in the literature, is only 13% [67]. The efficiency of DSSCs has a consistent behaviour, attaining its peak value within the temperature range of approximately 30 to 40 °C, beyond which it experiences a gradual decline. In a study conducted by Tomar et al. [68], it was shown that increasing the temperature from 25 to 60 °C resulted in a significant decrease of 48% in the PCE of DSSCs. Furthermore, by subjecting the system to a simultaneous increase in temperature and humidity, specifically from 25 to 60 °C and 75% to 100% respectively, a notable reduction of around 67% in the PCE was observed. Elevated temperature and humidity conditions have been observed to induce electrolyte breakdown, dye desorption from the semiconductor surface, and an augmentation in charge recombination. The adverse impact of elevated humidity and temperature on the J_{SC} (short-circuit current) and V_{OC} (open-circuit voltage) was seen, resulting in a decline in the overall performance of the device [69–71].

Perovskite solar cell

Perovskite solar cells (PSCs) have garnered much scientific attention in recent years due to remarkable optoelectronic characteristics and cost-effective manufacturing methods [72]. The fundamental component of PSCs is halide perovskite, denoted by the chemical formula ABX_3. In this formula, A represents $CH_3NH_3^+$ (methylammonium—MA), $CH_2(NH_2)^{2+}$ (formamidinium—FA), or Cs^+ (cesium); B represents Pb^{2+} or Sn^{2+}; and X represents Cl, Br, or I. PSCs have gained significant attention as a promising solar cell technology due to their remarkable optical and electrical characteristics. These qualities encompass high absorption coefficients, exemplified by a bandgap energy (E_g) of 1.5–1.6 eV for methylammonium lead iodide ($MAPbI_3$). Additionally, PSCs offer the advantage of tunable bandgaps, ambipolar transportation properties, excellent charge-carrier mobilities, extended charge-carrier lifetimes and substantial carriers. It achieves a maximum certified PCE of 25.7% as a result of advancements in interface and electrode materials, together with the implementation of high-quality perovskite films using low-temperature fabrication procedures [73, 74]. The progression from an initial value of 3.8% in 2009 [75] has resulted to a significant increase, surpassing 25% in 2022 [76]. Al-Ashouri et al. [77] claimed the existence of a certified monolithic perovskite/silicon tandem solar cell, which demonstrated a PCE of 29.15%. As of 2016, perovskite solar cells have been the most rapidly progressing solar technology. Perovskite solar cells have become commercially attractive due to their potential for obtaining superior efficiency and low production costs. The primary obstacles encountered in the field of PSCs encompass concerns related to moisture, thermal and UV stability, photocurrent hysteresis behaviour, flexibility, large-scale production, and environmental implications associated with the use of lead [78]. The impact of realistic temperature conditions on the performance of PSCs is investigated by Lopez et al. [79] and Zhang et al. [80]. Zhang conducted an assessment indicating that perovskite solar cells exhibited a decline in performance, with their efficiency decreasing from 16 to 9% when subjected to temperatures exceeding ambient conditions. Table 1 presents an overview of the investigation conducted on high-performing tandem solar cells based on the 2 T (Two-Terminal) perovskite technology [77, 81–85].

The decrease in the quantity of conductive layers inside the 2 T architecture leads to a reduction in parasitic absorption. Furthermore, it should be noted that the 2 T monolithic architecture offers the advantage of requiring only a single external circuit and substrate support, hence resulting in reduced production costs for the final product [86]. The depicted structure in Fig. 14 illustrates the cross section of a conventional perovskite solar cell, consisting of the following layers: FTO (Fluorine-doped Tin Oxide) as the bottom electrode, TiO_2 as the electron transport layer, $MAPbI_3$ as the perovskite absorber layer, Spiro-OMeTAD (Spiro-MeOTAD) as the hole transport layer, and Au (Gold) as the top electrode. To achieve a significant increase in the PCE above

Table 1 The best-performing perovskite-based tandem solar cells

Subcells	Type	Perovskite composition	J_{sc} (mA cm^{-2})	V_{oc} (V)	FF	PCE (%)	References
PSC/Organic	2 T	$FA_{0.8}Cs_{0.2}Pb(I_{0.5}Br_{0.5})_3$	14	2.15	80	24.0[b]	[82]
PSC/CIGS	2 T	$Cs_5(MA_{17}FA_{83})_{95}Pb(I_{83}Br_{17})_3$	19.17	1.68	71.9	23.26[a]	[77]
PSC/Si	2 T	$Cs_{0.05}(FA_{0.77}MA_{0.23})_{0.95}Pb(I_{0.77}Br_{0.23})_3$	19.23	1.9	79.4	29.15[a]	[83]
PSC/CZTSSe	2 T	$(FA_{0.7}MA_{0.15}Cs_{0.15})Pb(I_{0.85}Br_{0.15})_3$	17.67	1.46	68	17.5[c]	[84]
PSC/QDs	2 T	$Cs_{0.05}FA_{0.8}MA_{0.15}PbI_{2.55}Br_{0.45}$	16.3	1.55	69	17.1[b]	[85]

[a]PCE (Certified)

[b]PCE (Stabilized)

[c]Best-performing cell

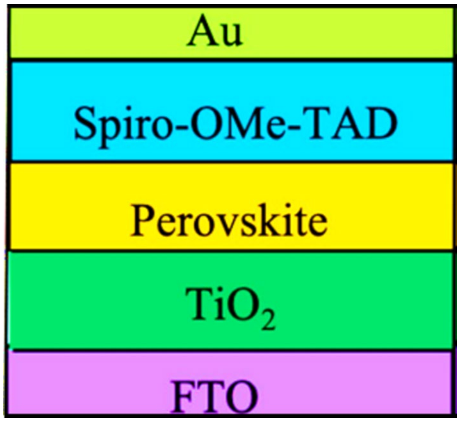


Fig. 14 Cross-section of a typical perovskite solar cell (FTO/TiO2/ MAPbI3/ Spiro-OMeTAD/Au)

the limitations imposed by single p-n junctions, researchers have found that employing several absorbers with distinct band gaps is the most efficacious approach to enhance light harvesting [87, 88].

In general, it can be observed that the V_{oc} decreases as the temperature increases, although the J_{sc} experiences just a slight increase. Both the FF and PCE exhibit a decrease as temperature increases, and the degradation of PCE is mostly attributed to a fall in V_{oc}. In order to optimise the efficiency of solar cells, it is crucial to undertake thorough examinations into the influence of temperature. Based on the data presented in Fig. 15b, it can be inferred that the diminished FF observed at lower temperatures (250 K) can be attributed to the heightened resistance to charge carrier diffusion within the MAPbI3 layer. The increase compensates for the unavoidable decrease in V_{oc} observed at elevated temperatures, usually over 260 K, as depicted in Fig. 15a. Consequently, PCE exhibits an upward trend with increasing temperature, as depicted in Fig. 15, and attains its peak value at 300 K [80]. A study conducted by Tress et al. [89] showed that the decline in PCE observed at low temperatures and temperatures over 300 K can be ascribed to temperature-induced transfer of charges in charge transport layers, specifically spiro-OMe-TAD. Perovskite solar cells exhibit a substantial and adjustable band gap throughout

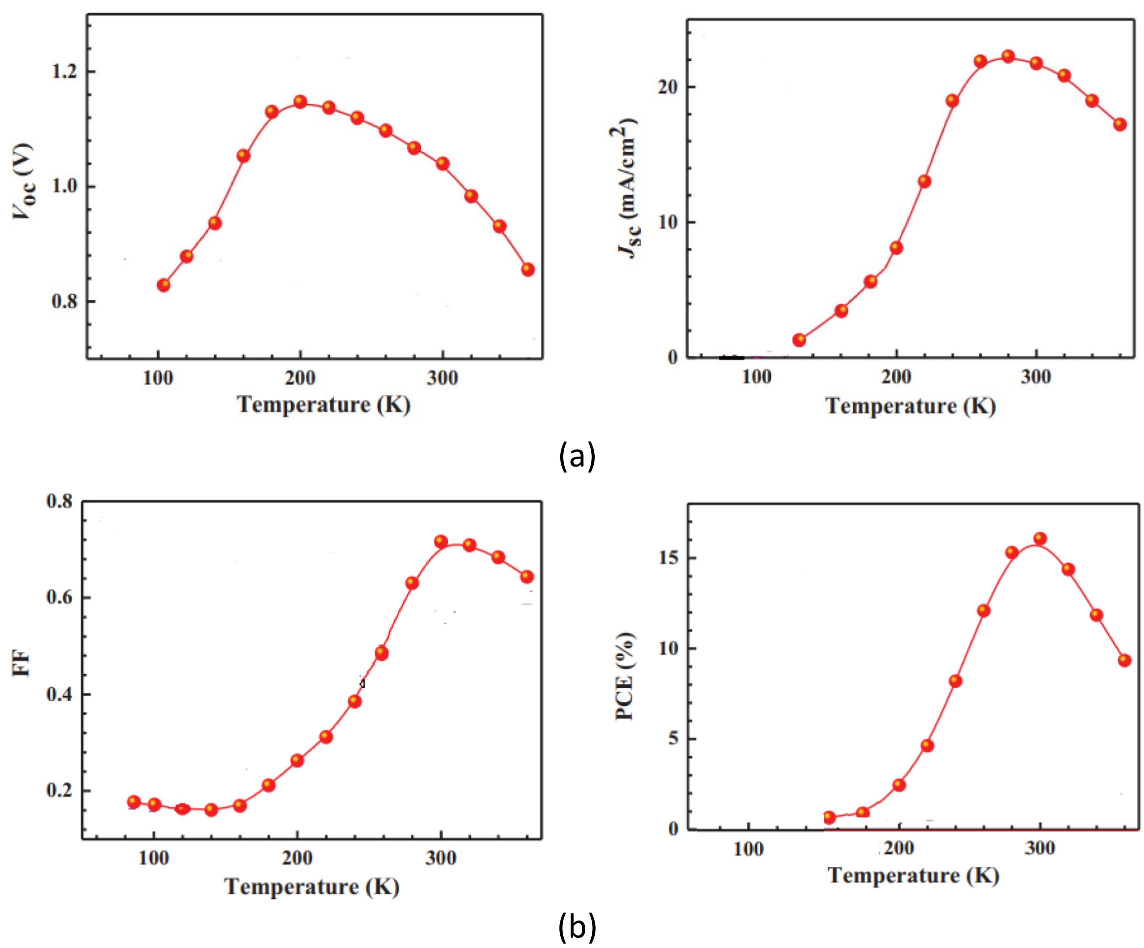


Fig. 15 Performance analysis of PSC with various parameters [80]

a broad spectrum of energy levels, possess a wide operational temperature span ranging from 288 to 323 Kelvin, and demonstrate a notable efficiency above 25%. The primary drawback associated with PSCs pertains to their adverse environmental impact, particularly in the case of lead-based PSCs. In contrast to lead perovskites, tin perovskites provide numerous environmental benefits, albeit with a trade-off in terms of PCE [90].

Concentrated Photovoltaics (CPV)

The emergence of concentrated solar cells represents a novel technological advancement. Figure 16 illustrates the fundamental principle underlying concentrated solar cells, where significant quantity of solar energy is gathered and concentrated onto a small surface area through the utilisation of lenses and optical components. The key advantages of CPV include their low cost, high efficiency, limited area requirements, and environmental friendliness. However, it is important to note that CPV systems are associated with certain drawbacks, such as elevated cell temperatures, which can negatively impact their lifespan, diminish conversion efficiency, and increase the probability of failure. Several examples of CPV systems include fresnel lenses, parabolic troughs, dishes, luminous glass, and compound parabolic concentrators [91]. The enhancement of space utilisation, recycling of component materials, and the use of less environmentally damaging substances in the manufacturing of PV cells have all experienced ongoing advancements through the implementation of CPV [92]. Several cooling system strategies are employed to decrease temperature and improve performance. Several cooling methods have been employed in various applications, including forced air circulation, water-based cooling systems, plate-fin heat sinks [93], liquid immersion cooling methods, fin-based cooling, fan-based cooling systems, and multi-channel heat sinks [94]. In their study, Tan et al. [93] conducted a comprehensive analysis of the thermal efficiency of heat sinks by the utilisation of computational fluid dynamics (CFD) modelling. The researchers examined several designs of heat

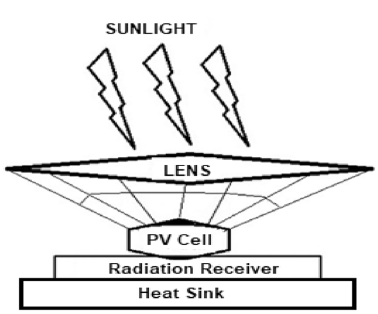


Fig. 16 Concentrated Solar Cell

sinks, including different fin thicknesses and fin heights. Wang et al. [94] presented a range of designs pertaining to both active and passive cooling approaches. In a study conducted by Bahaidarah et al. [95], an active water cooling system was employed to enhance the efficiency of PV panels. The researchers observed a significant gain of 9% in panel efficiency, which was attributed to the substantial reduction in module temperature to approximately 20%. All of these active and passive cooling solutions contribute to the reduction of surface cell temperature and the enhancement of conversion efficiency by up to 39.5%. Numerous alternative designs for active and passive cooling systems have been proposed by various authors. Among these, the water cooling system stands out for its heightened complexity and power consumption in comparison to the air-cooled system [96]. Martinez et al. [97] demonstrated the functionality of a newly developed hybrid bifacial high-concentration PV module known as the bifacial EyeCon under variable conditions (temperature, irradiance). The system consists of Fresnel lenses that efficiently concentrate direct sunlight 321 times onto III-V triple-junction solar cells. The solar cells are located on the front side of the p-PERC bifacial c-Si cells.

Fourth generation solar cell technology

The term "hybrid inorganic cells" is often used to refer to fourth-generation PV cells. These cells are characterised by their ability to combine the cost-effectiveness and adaptability of polymer thin films with the durability of organic nanostructures, including metal nanoparticles, metal oxides, carbon nanotubes, graphene, and its derivatives. These nano-photovoltaic components have the potential to usher in a promising era for solar technology [98].

CNT base solar cells (2-D Material Based Solar Cell)

The exceptional optical characteristics, small diameters, and low weight of 2D materials like molybdenum disulphide (MoS2), graphene, tungsten disulphide (WS2), and tungsten diselenide (WSe2) have garnered significant interest in the field of fourth-generation PV technology. The mechanical strength, tuneable band gap, transparency, good heat and electricity conductivity, high carrier mobility as well as the presence of the quantum Hall effect and magnetic anisotropy are well-known characteristics of these 2D materials [99]. Due to their remarkable optical and electrical properties, carbon nanotubes (CNTs) have emerged as very promising materials for the development of solar cells. CNTs are frequently employed in solar cells as thin films or incorporated into the active layers, serving as a charge-transport layers or electrode interfacial layers to facilitate charge extraction [100]. Figure 17 displays a schematic representation of a

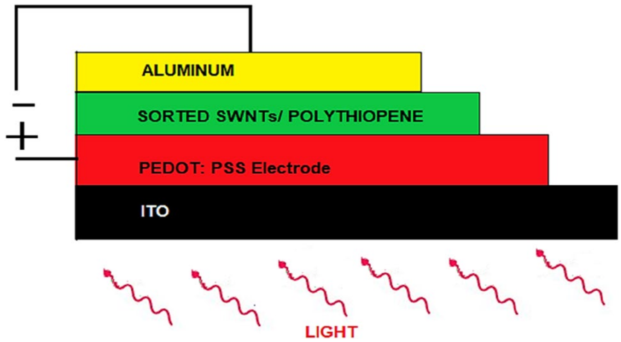


Fig. 17 Schematic representation of a Single-walled Carbon Nanotube

single-walled carbon nanotube (SWCNT). The conducting electrodes in this picture are typically coated with indium tin oxide (ITO), which is covered by a 40 nm sublayer of poly (3,4-ethylenedioxythiophene) (PEDOT) and poly (styrene-sulfonate) (PSS). PEDOT and PSS are utilised to enhance the smoothness of the ITO surface, resulting in a reduction in the occurrence of pinholes and mitigating current leakage along shunting paths [101].

CNTs have the potential to be employed in several types of solar cells, such as Si solar cells, dye-sensitized solar cells, organic solar cells, and perovskite solar cells, depending on the active-layer material [102]. Jiang et al. [103] conducted an experiment to evaluate the impact of incorporating a CNTs-spiro layer on the PCE of paintable carbon-based PSCs. The researchers found that PSCs with the CNTs-spiro layer exhibited a PCE of 10.45%, which was 17.51% higher than the efficiency of PSCs without this layer (8.62%). Zhao et al. [104] employed a combination of TiO_2-coating and HNO_3-doping techniques to enhance the efficiency of solar cells to a value above 18% at an active area of 0.09 cm^2, under standard test conditions of air mass 1.5 and an incident power density of 100 mW/cm^2. The integration of oxide-enhanced carbon nanotube-silicon solar cells presents a promising avenue for the development of advanced silicon-based PV systems in the future. These solar cells leverage the advantages of both traditional semiconductors and state-of-the-art nanostructures, offering a potential pathway towards achieving high-performance PV technologies. Jeon et al. [105] conducted a study in which they have shown that triflic acid doped CNTs exhibit superior performance as transparent electrodes in perovskite solar cells compared to their metal counterparts, achieved PCE of 18.8%.

Graphene base solar cell

Graphene, a two-dimensional material, is widely recognised for its exceptional electrical conductivity and optical transparency. Graphene solar cells are fabricated by interposing a layer of graphene between two electrodes. These electrons are then transported to the electrodes, where they are utilised to generate an electric current. Graphene solar cells have several potential advantages in comparison to traditional solar cells. Due to their enhanced capacity for solar absorption, they exhibit heightened efficacy. Transparent materials like this can be highly advantageous for applications such as windows and other contexts where visibility is of utmost importance. Graphene solar cells possess pliability and lightweight characteristics, rendering them highly suitable for utilisation in portable electronic devices and other applications that have limited spatial constraints [106]. Graphene-based materials are now under evaluation as potential alternatives to traditional materials in PV devices [107]. This is primarily attributed to the unique properties exhibited by graphene, including high carrier mobility, low resistance and transmittance, as well as its two-dimensional lattice packing structure [108]. The material has ambipolar electrical transport, enabling it to function as both an anode and a cathode [109]. The current stage of development for graphene solar cells is considered to be in its early stages. The production expenses of these solar cells exceed those of traditional counterparts, while their efficiency and stability have not yet reached comparable levels. Researchers are currently working towards resolving these challenges, indicating a potential future for the commercial production of graphene solar cells [110].

In a study conducted by Zhang et al. [111], it was shown that graphene is utilised as the cathode (emitter) in order to enhance electron emission capacity. This is attributed to the unique advantages offered by graphene, such as its exceptional mobility, superior thermal conductivity and high thermal stability (up to 4000 K). The temperature has a considerable impact on the performance of solar cells based on graphene. In general, the PCE of a solar cell tends to decrease as the temperature increases. This phenomenon occurs due to the narrowing of graphene's bandgap as temperature increases, hence facilitating a higher rate of charge carrier recombination prior to their capture by the electrodes [112]. Graphene-based perovskite solar cells (G-PSCs) exhibited a notable PCE of 18.65% and 20.3% when placing them among the highest recorded efficiencies for conventional perovskite solar cells (C-PSCs) [113]. Figure 18 (1) depicts the schematic diagram of a solar cell based on graphene. Meanwhile, Fig. 18 (2) illustrates the output performance parameters of hetero-junction solar cells utilising graphene with varying work functions. The performance analysis of changing the graphene work functions (WFs) was conducted, and different parameters such as PCE, J_{sc}, FF and V_{oc} were recorded [99]. Numerous research methodologies have been developed with the aim of enhancing the efficiency of PV systems. These strategies encompass modifications in materials, improvements in light trapping

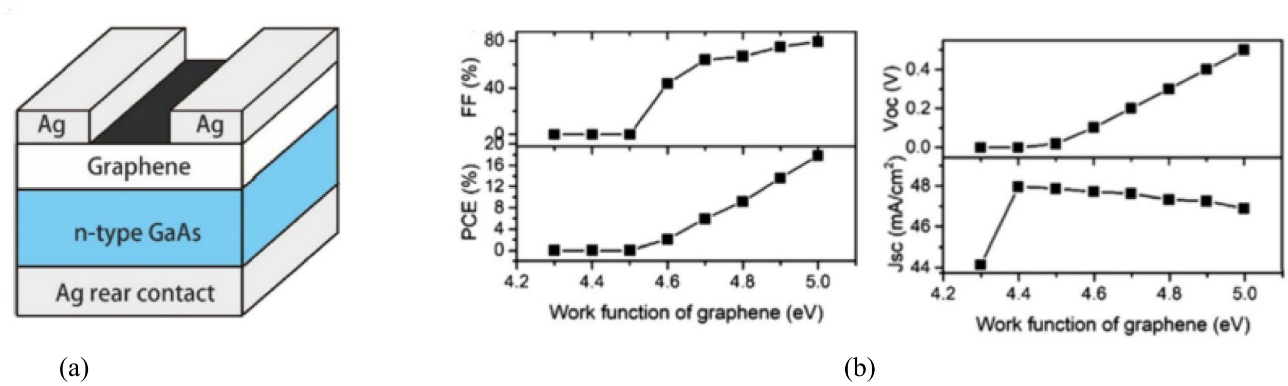


Fig. 18 **a** Schematic diagram of Graphene solar cell **b** Performance parameter with different Work Functions (WFs)

techniques, utilisation of quantum dots, implementation of multiple excitation generation cells, creation of multiple-junction structures, and incorporation of plasmonic carrier cells. Fourth-generation solar cell technologies, which offer enhanced efficiency, low area capture, and higher FF, are currently available.

However, their commercial viability is yet to be established. There are several factors that contribute to the commercially viable nature of these technologies being less stable compared to traditional solar cells. These factors include the greater cost of materials and the use of innovative and unproven materials in these technologies. Despite the challenges, it is worth noting that fourth-generation solar cell technology have the capacity to revolutionise the solar sector. These cells have the potential to be employed in the production of solar panels that exhibit enhanced versatility, cost-effectiveness, and efficiency across a wide range of applications [114].

Comparison between various generations of solar cells

The efficiency of PV solar cells can be enhanced by changing either the material or their shape in several technologies. The primary objective of novel materials is to enhance sensitivity, carrier generation, spectrum absorption, flexibility, and long-term sustainability while reducing degradation rate, losses, and production costs. Another important concern is the use of environmentally friendly materials. In the future, the market shares of upcoming innovative technologies will expand. Figure 19 depicts the anticipated distribution of solar PV modules by technology for the year 2030. In 2030 crystalline silicon share will reduced to only 70.40% from 90% [115]. Table 2 provides a comprehensive analysis of the comparative variations across successive generations of PV solar cells in terms of their efficiency, cost, band-gap, high-temperature performance, material utilisation, as well as their pros and disadvantages.

Fig. 19 Technology-wise projected market share of PV solar modules by 2030

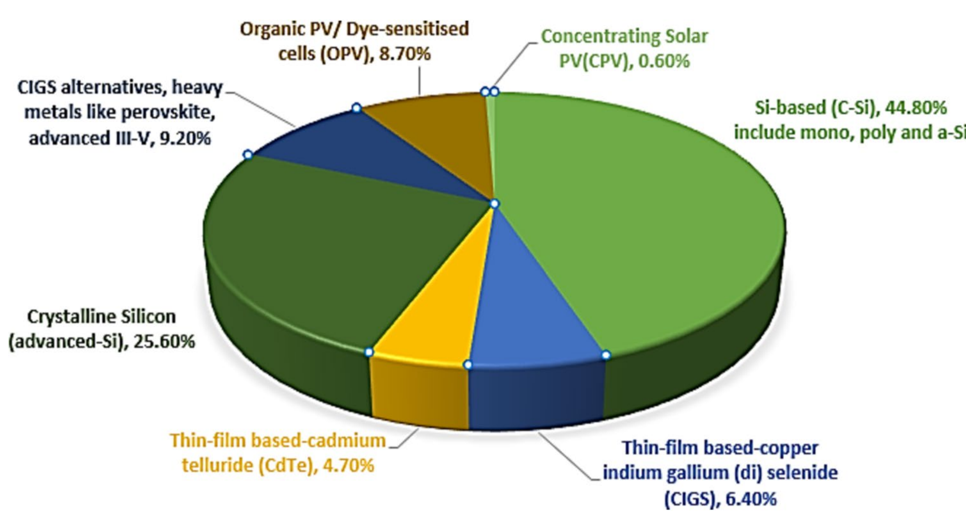


Table 2 Comprehensive analysis of the comparative variations across successive generations of PV solar cells

Generation	Type of cell	Efficiency	Cost	Band Gap (eV)	High temp Performance	Pros	Drawback	Material Use	References
First Generation	Single/mono crystalline solar cells (mc)	20–22%	Higher than polycrystalline solar cell	1.11	High temperatures hurt performance (drops 10–15%)	High efficiency, silicon is most abundant material on earth	More expensive than pc, production is less efficient and creates material wastage	Mono-crystalline silicon	[25, 26, 28]
First Generation	Polycrystalline solar cells (pc)	15–17%	Cheaper than mono-crystalline solar cell	1.12	Performs poorly at high temperatures (drops 20%)	Cost-effective, more stability, and low toxicity	Less efficient and require more space for the same power as compare to mc	poly-crystalline silicon	[29, 30]
Second Generation	Amorphous silicon solar cell	10–12%	Less than conventional solar cell due to less silicon usage	1.7	Minor variation at high temperature	Less material means less toxic, extremely bendable and less susceptible to cracks	Less efficient and lower power capacities,	Amorphous silicon	[32, 34, 35]
Second Generation	Cadmium Telluride (CdTe) Thin Film Solar Cell	18.6%	Less than conventional solar cell due to less silicon usage	1.5	Decreases sharply with increasing temperature	Low cost, Easy Manufacturing, high absorption and high efficiency	Cadmium is a toxic heavy metal, less efficient than traditional panels	Cadmium and Telluride	[41, 43, 44]
Second Generation	Copper Indium Gallium Di – Selenide (CIGS)	20.8–22.3%	Less than conventional solar cell due to less silicon usage	1.55	Efficiency does not decrease as quickly as silicon panels at high temperatures	Low temperature coefficient, high absorption, tandem CIGS devices is possible	Toxic but less than Cd and Te, very expensive	Copper, Indium, Gallium and selenide	[46, 47]
Second Generation	Copper Zinc Tin Sulphide thin film solar cells (CZTS)	10%	Less than conventional solar cell due to less silicon usage	1.4	Decreases with increasing temperature, increase dark current and decreases Voc	High absorption coefficient, optimum direct energy band gap, good electrical properties, greater stability and cheaper production process	Less efficiency	Copper, Zinc, Tin, Sulphide	[49–52]
Third generation	Multiple junction solar cell (MJSC)	34–47.1%	Expensive to manufacture	0.67–1.88	Lower temperature sensitivity as compare to single junction	More efficient than single junction cells	Limited to few applications due to its cost, complex manufacturing	Gallium Indium Phosphide or Indium Gallium Arsenide	[56–58]

Table 2 (continued)

Generation	Type of cell	Efficiency	Cost	Band Gap (eV)	High temp Performance	Pros	Drawback	Material Use	References
Third generation	Quantum dot solar cells (QDSC)	10–15%	Low cost	1.3–2.5	Decreases continuously with increasing temperature	High absorption coefficient, tuneable bandgap, light weight,	Highly toxic to people and the environment,	CdS, CdSe, PbS, PbSe, Ag_2S	[60–63]
Third generation	Solar cells with dye sensitivity (DSCC)	13%	Low material and production costs	1.3–2.2	Decreases continuously with increasing temperature	Working in low light conditions, low cost of material, easy manufacturing process, light weight, flexibility	Toxic electrolytes, low efficiency, very sensitive to temperature and humidity	TiO_2, redox couple, TCO	[65, 67, 69, 70]
Third generation	Perovskite solar cell (PSC)	22–25%	Low cost almost half as compare to traditional solar cell	1.5–2.3	Decreases with increases in temperature	Low cost, easy to manufacture, and have a high absorbance, tuneable bandgap	Too unstable for large-scale use	Cs^+, Pb^{2+}, Cl	[73, 74, 79–81, 86, 87]
Third generation	Concentrated photovoltaics (CPV)	7–25%	Low cost	1.4–1.5	Does not function well in high-temperature environments	Great efficiency, small area captures, and environment friendly	High failure rate, PCE, Toxic for environment	GaAs, CdTe, CIGS, Glass	[92, 94, 95]
Fourth Generation	Carbon nanotubes Solar Cell (CNT)	7–18.8%	Low cost	0.3–2.7	Decreases with increases in temperature	Stable, Very thin and flexible, broadband light absorption, tuneable band gap	Low efficiency, inefficient conversion	WO_3 layer, molybdenum disulphide, TiO_2	[99, 102, 103]
Fourth Generation	Graphene Solar Cell	12–18.65%	High cost	1.42	Decreases with increases in temperature	More versatile, cost-effective, and high absorption, pliable, light weighted, transparent	Less stability and inefficient	Graphene	[106–108, 113], [114]

Second generation thin-film technology is a better option than the conventional approaches in terms of cost, performance and material usage. In future second generation CIGS, CdTe, CZTS will definitely overtake the conventional cell market. Table 2 shows that third generation PV solar cells are more efficient than second generation but the main issue is higher cost and complex fabrication process. Third generation MJSC, DSSC, perovskite solar cells technology has the capability to provide better performance than previous one. Figure 20 illustrate different PV technologies on timeline to understand the evolution.

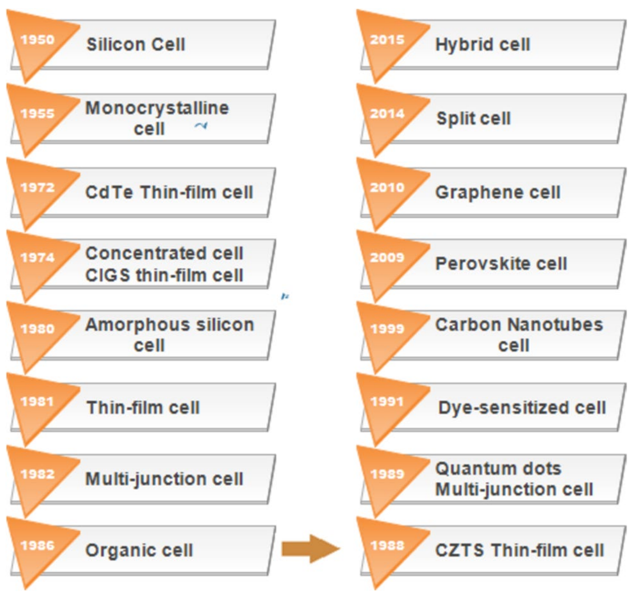


Fig. 20 Types of PV Cell on a timeline

Electronic and optical properties

Table 3 delineates the standard electrical and optical characteristics of several absorber materials employed in PV solar cells. The utilization of advanced materials, including perovskites, quantum dots, dye-sensitized compounds, graphene, and carbon nanotubes, as absorbers to exceed efficiency thresholds. These features encompass the bandgap, absorption coefficient, charge carrier mobility, fill factor, recombination rate, refractive index, among others.

Table 3 Electronic and optical properties of PV Solar cell materials

Property	Crystalline Silicon (c-Si)	Perovskite Solar Cells	CdTe Solar Cells	CIGS Solar Cells	Graphene	CNT
Electronic Properties						
Bandgap Energy	1.1 eV	1.5 – 2.3 eV	1.5 eV	1.55 eV	0 eV	0.3–2.7 eV
Carrier Mobility	~1350 $cm^2/V\cdot s$ (electrons)	~10 – 30 $cm^2/V\cdot s$	~320 $cm^2/V\cdot s$ (electrons)	~100–300 $cm^2/V\cdot s$	~200,000 $cm^2/V\cdot s$	~100,000 $cm^2/V\cdot s$
Carrier Lifetime	~1–10 ms	~1 µs	~2–10 ns	~1–10 ns	~1 fs	~100 ps–1 ns
Carrier Diffusion Length	~100–300 µm	~1 µm	~1–5 µm	~1–5 µm	~1–5 µm	~100 nm–1 µm
Open Circuit Voltage	0.6–0.7 V	1.0–1.2 V	~0.85 V	~0.7–0.8 V	0.7–1.0 V	0.6–0.9
Fill Factor (FF)	0.75–0.85	0.75–0.85	0.7–0.8	0.7–0.8	0.6–0.85	0.6–0.8
Recombination Rate	Low	Moderate	Moderate	Moderate	Very Low	Moderate
Optical Properties						
Absorption Coefficient	~10^4 cm^{-1} at 1.1 µm	10^4–10^5 cm^{-1}	~10^5 cm^{-1}	~10^5 cm^{-1}	~10^5 cm^{-1}	~10^5 cm^{-1}
Absorption Range	300–1100 nm	300–850 nm	400–860 nm	300–1200 nm	200–2500 nm	200–1800 nm
Refractive Index	~3.4	~2.3	~2.7	~2.4	~2.6	1.4–1.9
Light Trapping	Textured surface for reflection reduction	Light trapping with layers	Light trapping with thin film	Surface texture for efficiency	transparent electrode with plasmonic effects	surface plasmon resonance
Photoluminescence Efficiency	Low	High	Moderate	Moderate	Low	High

Factors affecting PV cell performance

The long-term dependability and performance of PV modules are influenced by several internal and external stress factors that occur during real-world operation. Internal stress variables are attributed to the bill of materials and processing-related consequences of the PV module, whereas external stress elements are influenced by the surrounding environment. This section provide detailed information regarding both internal and external stress variables. This section examines many aspects that have an impact on the efficiency of PV cells. These elements include solar irradiance, ambient temperature, moisture, soiling, shading, processing, ageing, chemicals and others as shown in the Fig. 21.

External stress

Irradiance

The fundamental attributes of sun irradiance on PV modules encompass spectral distribution, power and incidence angle. The solar spectrum irradiance (AM 1.5G), which is considered as the global standard, encompasses wavelengths ranging from 280 to 4000 nm. This range is equivalent to 1000 W/m^2 integrated solar output [62]. The ultraviolet (UV) spectrum (280–400 nm) accounts for only 4.6% of the total power, although it poses the greatest risk to polymeric materials over prolonged exposure. This is due to the high energy of UV photons, which have the capability to break C–C and C–O bonds usually present in the main chain of polymer and this leads to the polymer's embrittlement and discolouration [116, 117].

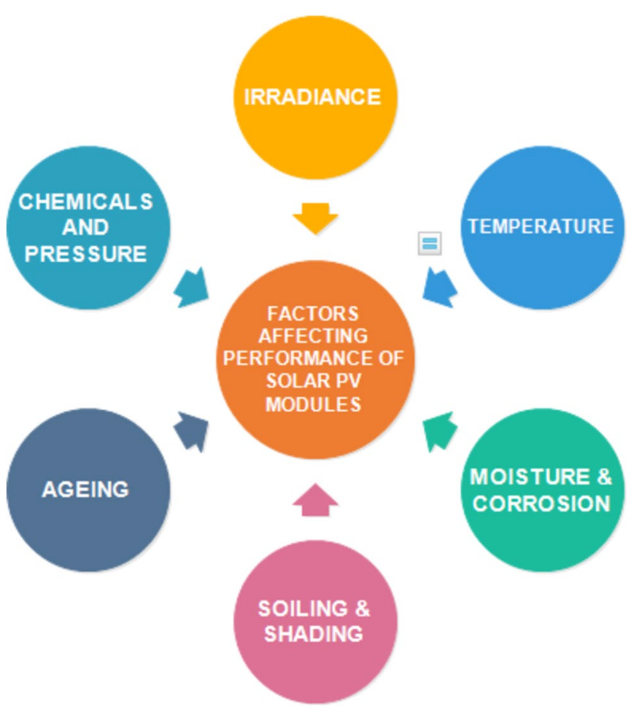


Fig. 21 Factors affecting performance of solar PV modules

The spectral distribution and intensity level of incident irradiation are influenced by multiple factors like variations in stratospheric ozone with latitude and season, air pollution, cloud cover, surface reflection, tilt angle from the horizontal, and azimuth (compass angle). According to the reference spectrum, it is observed that Ultraviolet-B (UVB) radiation (280–315 nm) poses the highest risk among various wavelengths of UV light. This is particularly true for polymeric materials used in PV modules. The power proportion of UVB radiation is quite low, at 1.5%, when compared to ultraviolet-A (UVA) radiation (315–400 nm), which accounts for 98.5% of the total power. The aforementioned proportion exhibits variability in response to incident ultraviolet (UV) radiation, with higher values observed during the summer season, at lower latitudes, and during daylight hours when solar radiation is most intense. Higher value of UV radiations leads to faster rate of degradation [118]. The increase in solar irradiation leads to a greater number of charge carriers transitioning from the valence band to the conduction band, resulting in rapid fluctuations in the output power.

Temperature

The thermal environment in which a solar cell operates, plays a crucial role in determining its power output. Solar cells are typically designed to function optimally at a standardised temperature of 25 °C. However, an increase in the surrounding temperature leads to a decline in the effectiveness of the solar cell. The output voltage in a PV cell is significantly influenced by temperature, although the impact of temperature on the output of current is minimal. The lifespan and efficiency of a solar cell are reduced when it is operated at elevated temperatures on a continuous basis. The cell exhibits minimal damage when exposed to temperature below the standard range, as indicated by previous studies [119, 120]. Singh et al. [121] conducted a study to investigate the influence of temperature on the performance of solar cells within the temperature range of 273–523 K. Their findings revealed that when the temperature increases, there is an observed increase in the reverse saturation current and a drop in the open circuit voltage. These changes ultimately affect the FF and, consequently, the overall efficiency of the solar cells. Furthermore, it has been noted that rising temperature cause a drop in bandgap width, which lowers saturation current and raises energy cell efficiency [122]. Temperature is the main reason to accelerate module degradation process related to chemical reaction and diffusion.

Potential outcomes of module surface degradation include deformation, cell breaking, and delamination. The cyclic thermo-mechanical loads induced by temperature variations occurring both within a day and throughout a year might contribute to the degradation of different components within a module, ultimately resulting in failures [123].

Moisture & corrosion

The presence of moisture poses a notable source of stress on PV modules, primarily because it has an ability to deteriorate adhesive bonds located at the interfaces between different components of the module [124]. The presence of moisture infiltration has been recognised as a prominent factor that establishes a connection between climatic conditions and the deterioration of modules. This phenomenon is observed in surroundings marked by high level of humidity and warmth, as evidenced by prior investigations conducted by Hulsmann et al. [125]. According to Segbefia et al. [126], the interaction between moisture ingress and ambient temperature has a significant role in influencing the rate at which various life-limiting processes occur, such as material deterioration and general corrosion in solar cells and modules.

The process of degradation can give rise to delamination, which then leads to the degradation of passivation and the deterioration of ARC [127]. Furthermore, the presence of moisture might lead to the corrosion of the metallization components present in the modules. Various forms of moisture can be observed in the external environment, including water mist, condensation, and precipitation in the form of rain, snow, and ice. Due to its gaseous state, water vapour has the ability to infiltrate polymeric packaging materials, accumulate within construction modules, and cause degradation of the constituent components of these modules [128]. The occurrence of more water infiltration can result in mechanical stresses arising from the expansion and contraction of the hydrodynamic volume. The existence of this phenomenon possesses the capacity to intensify the electrical shielding characteristics of dielectric materials, ease the dissolution of ions, and cause the manifestation of leakage current [129]. The cyclic process of freezing and thawing has the potential to cause changes in volume, resulting in mechanical pressures being applied on the external surface of the PV module. This possesses the capacity to inflict harm onto the structural integrity of the frame or lead to the separation of layers in front glass [127]. When a module attains moisture saturation, a decrease in temperature may lead to an increase in moisture levels above its saturation threshold. This phenomenon can lead to the creation of water droplets, especially at boundaries, on the surfaces of cells, and on metallization components. The length of time required to achieve the state of equilibrium moisture concentration is a crucial variable that impacts the durability of solar panels [130]. Geographical areas, that are marked by elevated temperatures and high levels of humidity are more prone to experiencing harmful consequences, as opposed to those with milder climates [131, 132].

Soiling & shading

The presence of dust particles on the surface of PV modules has a negative impact on their efficiency. This is mostly due to the obstruction of incoming irradiance caused by the dust, as well as the accumulation of dust on the surface of the PV modules. Therefore, it is advised to include the presence of dirt or dust accumulation on modules during the wet season while estimating system output performance [133]. Based on a study conducted by the California Energy Commission in 2001, it was found that the "100 W module" saw a reduction in power output to 79 W due to the accumulation of dust on the module. The primary constituents found in dust are examined in the studies conducted by Jathar et al. [134] and Hosseini et al. [135] to assess their impact on the performance of PV cells, specifically focusing on the influence of dust deposition and wind speed. The output power of PV systems has been found to decrease with increasing dust density on PV modules. Researchers have made efforts to develop a mathematical relationship between the density of mass deposition and its influence on the efficiency of solar modules across various geographical regions.

Chanchangi et al. [136] have undertaken a complete literature assessment on the topic of dust deposition and the corresponding cleaning methodologies employed. Based on the findings, it has been observed that the collection of dust in desert regions can lead to substantial reductions in power efficiency, with potential losses reaching up to 80%. The investigator conducted a study to assess the influence of the aggregation of thirteen distinct specimens, comprising ash, avian excrement, carpet debris, clay, cement, charcoal, coarse sand, loam soil, salt, sandy soil, stone debris, and wood debris, on the efficiency of PV systems. In their work, Lasfar et al. [137] undertook an investigation into the effects of dust deposition on the surface of PV modules. The research findings suggest that the existence of dust particles hinders the transmission of solar radiation, resulting in a reduction in the efficiency of PV modules. In particular, panels that are covered in dust demonstrate a decrease in output power by 21.57% in comparison to panels that are free of dust.

The degree of soiling has impacted by multiple aspects, encompassing the surface characteristics of the modules, the location of installation, and the mounting arrangement of the modules, such as the inclination angle and elevation from the surface. The issue of dust soiling is a notable obstacle in regions characterised by arid climate. The study conducted by Salamah et al. [138] provides a comprehensive analysis of the influence of dust on the transmittance of PV modules and their electrical characteristics. The subject is examined by the authors through an analysis of the physical characteristics of the dust found at the module's specific position, as well as the circumstances surrounding its installation. Bird droppings can be categorised as a sort of biological soiling; nevertheless, it is important to note that their impacts vary in comparison to pollution and other forms of biological soiling [139]. The research conducted by Shaik et al. [140] reveals that bird droppings of varying weights (10, 20, 30, 40, and 50 g) were shown to contribute significantly to the reduction in efficiency, ranging from 46.42% to 89.18%. This reduction was deemed to be substantial in nature. In contrast, according to Table 4, the effect of coal dust to the overall efficiency loss was about 13%.

Chemicals

The corrosion of PV modules can occur as a result of the presence of specific chemical species that are generated through industrial activities or exist in the natural environment. The primary pollutants commonly found in various places are ammonia in rural agricultural areas, sulphuric and nitric acid in industrialised zones, and salt mist in coastal sites. It is worth noting that salt mist poses a significant risk in tropical conditions [141]. The forces stated above possess the capability to cause degradation in several components of PV modules, such as backsheets, junction boxes, wiring, connectors and adhesive edge sealants. The insufficient insulation of the modules could potentially affect both the safety and efficiency aspects.

Ageing

The phenomenon of ageing plays a substantial role in the deterioration of performance. Nemhe et al. [142] presents a mathematical model in their research that measures the efficiency of PV systems in relation to their operational lifespan. Solar PV panels sometimes experience accelerated degradation during the initial phases of their operating lifespan. Typically, solar panels demonstrate an annual degradation rate of approximately 0.5% with respect to their rated power output. Singh et al. [121] study shown that thin film PV modules, specifically those made of a-Si, CIGS, CdTe exhibit a higher susceptibility to degradation in comparison to modules employing crystalline silicon (c-Si). The occurrence of deteriorating processes might show in several manners, such as chemical, electrical, thermal, or mechanical factors [143–145]. Table 5 displays the average annual decline in output for several solar module technologies.

Table 5 Average yearly output loss of PV cells

PV cell type	Output loss (% /)year
Monocrystalline Silicon (mc-Si)	0.36%
Cadmium Telluride (CdTe)	0.4%
Polycrystalline Silicon (Poly-Si)	0.64%
Amorphous Silicon (a-Si)	0.87%
Copper Indium Gallium Selenide (CIGS)	0.96%

Internal stress

In addition to the external stresses discussed earlier, it is important to acknowledge that internal factors, including module design, processing-related impacts and the bill of materials (BOM) can also play a role in or contribute to the deterioration of modules. The lamination process has a substantial impact on the quality, dependability, and long-term performance of PV modules. The probable occurrence of thermal stress-induced micro-cracks in solar cells might be attributed to the application of heat and tension during the lamination and stringing processes [146, 147].

Table 4 I-V characteristics of the panel at 12.91 tilt angle

Dust Particles		I_{SC} 12.91	V_{OC} 12.91	I_{MAX} 12.91	V_{MAX} 12.91	P_{MAX} 12.91
1	Clear Panel	0.27	19.4	0.229	16.49	3.784
2	Black Soil- 40	0.16	18.6	0.136	15.81	2.15
3	Red Soil- 40	0.14	18.8	0.119	15.98	1.902
4	Desert Soil- 40	0.14	18.6	0.119	15.81	1.882
5	Coal Dust-40	0.25	18.5	0.213	15.73	3.342
6	Bird Droppings- 10	0.17	18.7	0.145	15.9	2.297
7	Bird Droppings- 20	0.13	18.4	0.111	15.64	1.728
8	Bird Droppings- 30	0.11	17	0.094	14.45	1.351
9	Bird Droppings- 40	0.09	15.5	0.077	13.18	1.008
10	Bird Droppings- 50	0.05	10	0.043	8.5	0.361

Solar cells can undergo misalignment, gap formation, and increased stress on the PV ribbon and solder bonding due to the substantial thermal expansion of ethylene vinyl acetate during lamination. The BOM and the module design both exert considerable influence on the kinetics and pathways of deterioration [148].

Conclusion and future scope

Key component of a PV solar cell technology is the basic material used for their fabrication. Recently, significant advancements have been achieved in this domain to enhance performance, decrease production costs, ensure environmental safety, promote biodegradability, reduce weight, increase stability, lower degradation rates, and alleviate the impact of elevated temperatures. All four generations of PV solar cells are examined in detail, accompanied by a tabular chart that elucidates their development, electrical and physical properties, as well as the effects of temperature and environmental effects. Recent advancements in solar cell technology, including multi-junction, quantum-dot, perovskite, and tandem solar cells, are examined alongside graphene-based and carbon nanotube-based technologies, paving the way for future study in this domain. Environmentally sustainable, biodegradable, and high-performance materials that minimize hazardous emissions should be utilized in the production of future PV solar cells, enabling their application in wearable technology, electric vehicles, building-integrated photovoltaics (BIPV), and flexible electronics. This study also examines the internal and external stressors impacting the performance of PV solar cells. In 2022, PV technology averted 1,399 metric tons of carbon dioxide (CO_2) emissions. Furthermore, PV systems exhibit negligible material waste during production, hence enhancing their environmental sustainability.

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Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval No ethical approval was required as it did not involve the collection or analysis of data involving human or animal subjects.

Consent for Publication Yes.

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