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# Generation of Solar Cells: A Review of Materials, Operation and Limitation of Photovoltaic Technologies

Mohammed Liman Yerima<sup>1</sup> | Isah Muhammad<sup>2</sup> | Abdulrahman Bala Gambo<sup>2</sup>

## ABSTRACT

Clean and sustainable energy, as an alternative energy source is experiencing a rapid growth across the world thus making solar photovoltaic (PV) energy a key technology in the process of shifting to sustainable energy. The development of solar PV has gone through three generations, the first-generation crystalline silicon, the second-generation thin-film, and the new third generation emerging cells. This review is a brief assessment of every PV generation in terms of their operating principles, material structure, and limitations they have by design. The study performed a literature review by examining the most recent developments and issues in each of the categories. The high efficiency and technological maturity make first generation silicon cells to dominate the market. But they need very pure silicon wafers that are also very expensive and involve high-energy expenses. Amoebic silicon (a-si), cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) are thin-film technologies, reduced-cost and reduced-materials technologies and a-si and CdTe (as well as CIGS) technologies. They are more flexible and easier to manufacture, but tend to be less efficient and use scarce or poisonous elements. The use of new materials and structures offers the promise of ultra-high efficiency and low-cost fabrication with third-generation devices, such as dye-sensitized, organic, perovskite, quantum-dot, and multi-junction cells. An example of this is perovskite cells, which have reached efficiencies of over 25 percent when used in the laboratory. However, the emerging solar cells are faced with issues of long-term stability, material toxicity (e.g. lead) and scalability. The study concludes that there is a trade-off of performance, cost, and sustainability of each PV generation. First- and Second-generation cells have proven successful using commercials and will keep on providing most of the solar power, but other Third-generation cells will have technological advancements in efficiency and versatility. Our multi-generational approach is that the most viable way to proceed is taking advantage of the strengths of each technology and using them in complementary manner. The future studies are to focus on bringing emerging PV materials in terms of durability and environmental friendliness so that they can gain wide applications.

**KEYWORDS:** *Solar photovoltaic, Crystalline silicon photovoltaics, Thin-film solar cells, Emerging solar cells, Perovskite solar cells.*

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<sup>1</sup>Department of Metallurgical and Materials Engineering, School of Infrastructure, Process Engineering and Technology, Federal University of Technology Minna, Nigeria

<sup>2</sup>Mechanical Engineering Department, School of Infrastructure, Process Engineering and Technology, Federal University of Technology, Minna, Nigeria

*Corresponding Author's*  
Muhammad Isah

*Corresponding Author's E-mail:*  
kingladons@gmail.com



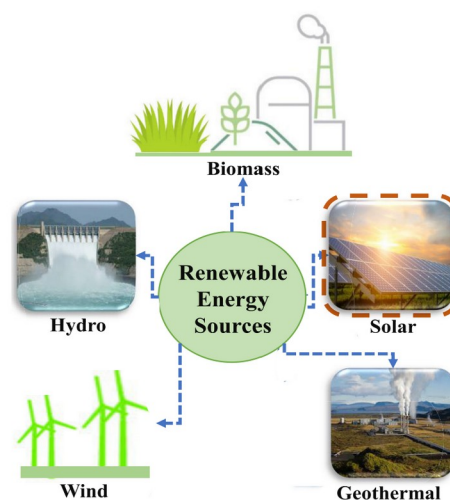
## 1 | INTRODUCTION

The current trend in the global energy demand continues to move upwards driven by the rapid increase in population, urbanisation and industrialisation across the world. This increased pressure puts a significant strain on the traditional energy systems that are still highly dependent on fossil fuels. Even though fossil fuels remain the foundation of the global energy portfolio, their non-renewable nature, as well as various other pressures like depleting reserves and fluctuating and unpredictable market prices, are coupled with high environmental and social costs that require the global shift to cleaner and more sustainable energy sources [1].

As a reaction, a variety of renewable energy technologies, such as wind [2], [5], hydropower, [7], biomass, [9], geothermal [8], and solar energy, [3], [4] (see Figure 1), are increasingly being recognized as central to the solution to the twofold problem of energy crisis and climate emergency on the planet. Many studies have examined these technologies in a variety of perspectives, including technological design, economic feasibility, optimisation, material usage, and socio-environmental analysis using a variety of analytical and modelling techniques.

As the global leaders acknowledged the importance of the situation, renewable energy capacity was the most critical issue at COP28, and the tripling of the capacity is planned to be achieved by 2030 [11], which is an ambitious goal which corresponds to the addition of 7,500 GW of renewable capacity and is likely to be primarily based on solar photovoltaics (PV), which should become the largest portion [6]. This transition is important because of the high levels of CO<sub>2</sub> emissions that stood at 36.8 Gt in 2022 [12]. Among the range of renewable technologies, solar PV stands out due to its rapidly declining cost, scalability, flexibility, and general sustainability, thus, making it a part of the global electricity transition [14], [15]. In addition, Solar energy is abundant, widely available, and has a relatively low environmental impact [10], [13]. In fact, the sun provides the earth with more energy than humankind uses in a year, in just one hour and

this explains why it has enormous potential as a sustainable energy source worldwide.



**Figure 1:** Renewable Energy Sources [16]

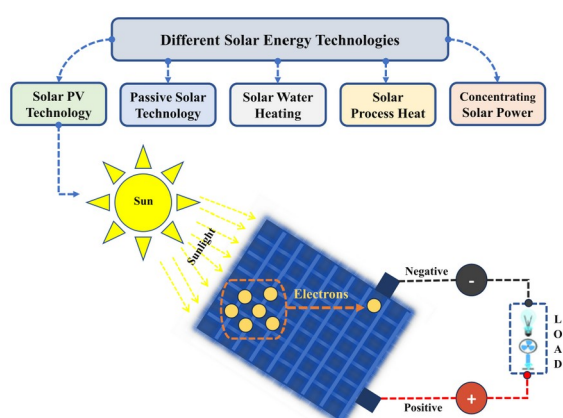
The technologies of solar energy (Figure 2) include a variety of different techniques; the most common is photovoltaic systems (PV), which have become the foundation of the energy revolution of the world economy [17]. The capacity of solar energy increased by approximately 22 in 2021-2022, which proves the attractiveness of the use of PV technologies around the whole world [18].

Photovoltaics (PV) use the photovoltaic effect to directly convert sunlight into electricity via semiconductor junctions [19], [20]. They have a number of benefits such as configurability, scalability, low maintenance needs and zero-emission operation [22], [23]. In comparison with other renewable energy sources like the wind or hydropower sources, PV systems can be installed on a wide range of scales, including utility-scale solar farms [21], to small, decentralised, rooftop installations, thereby being very flexible to a wide range of energy-access and sustainability objectives [15], [26].

Over the last decades, PV technology has evolved through three generations. The market is currently dominated by first-generation crystalline silicon due to its maturity, efficiency, and proven reliability [27]. Second-generation Thin-film technologies were introduced to overcome the limitations of cost and material intensity to decrease

semiconductor usage, minimise cost of manufacturing, and flexible usage [17], [19].

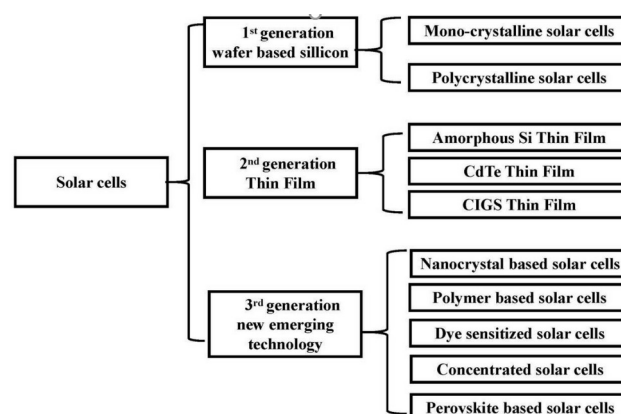
More recently, third-generation photovoltaic (PV) designs such as perovskite, organic, dye-sensitized, and quantum-dot solar cells, have been developed, with exceptional laboratory performance. However, their poor operation stability and the fact that they contain some toxic elements are some drawbacks that do not allow commercialization on large scale at the moment. These are intended to address the performance and material limitations of previous technologies in order to deliver increased efficiencies, reduced costs of production, and enhanced material sustainability [29], [30]. Nevertheless, as it was noted in recent research [31], PV technologies are now more often combined with other types of solar energy technologies, including solar thermal and energy-storage technologies, providing a more integrated and holistic way out to a sustainable future of global energy.



**Figure 2:** Solar Energy Technologies [32]

This review examines PV developments across three generations: first-generation crystalline silicon, second-generation thin-film (a-Si, CdTe, CIGS), and third-generation emerging devices (dye-sensitized, organic, perovskite, quantum-dot, and concentrator cells). Each generation is evaluated in terms of operating principles, material composition, and sustainability limitations. The major sustainability aspects such as material plentitude, toxicity and stability are highlighted. Through the examination of technological trade-offs, we advance a future look into the

adverse effects in which the three generations can collectively develop large-scale application of solar energy. The rest of the paper is structured in the following way. In detail, Section 2 examines the first-, second-, and third-generation solar cells. Section 3 presents the comparison analysis of these generations, which are considered in their merits and downsides. Section 4 reports on the future of PV technologies in the framework of sustainable energy goals. Section 5 ends with a conclusion and the future directions.



**Figure 3:** Classification of Solar Cells Based on Generations [33]

## 2.0 Generation of Solar Cells

### 2.1 The First-Generation Solar Cells

The earliest and most established step in the history of PV is first-generation photovoltaic (PV) cells which are mostly made out of crystalline silicon (c-Si). Currently, single-junction crystalline silicon is the most widely used in solar industry across the world; it takes up about 90-95 per cent of the overall PV market and hence silicon becomes a leading material in commercial solar modules.

The popularity of silicon can be attributed to its favourable characteristics to a large extent. Silicon has an optimum bandgap of 1.12eV that is in close relation to the solar spectrum on earth; it is stable, non-toxic and in great abundance, the second most abundant element found in the crust of the earth. Also, the industrial base of silicon is mature, in the sense that the industry of microelectronics (i.e., manufacture of transistors and integrated

circuits) also has similar manufacturing processes as silicon PV manufacturing.

Traditional wafer-based crystalline silicon cells include monocrystalline, polycrystalline (or multicrystalline), heterojunction with intrinsic thin layer (HIT) and microcrystalline. These technologies paved the way to the modern PV development and became the basis of the efficiency standards that the further generations were developed. Early devices consumed a lot of energy and needed large wafers, but could relatively easily convert energy into energy, creating a motivation to, nevertheless, keep advancing technology and efficiency through research and optimisation.

With time, great developments have been made in the improvement of crystalline silicon PV cells. There are two main types that prevail and these are monocrystalline silicon (m -Si) and polycrystalline or multicrystalline silicon (p -Si or mc -Si). Monocrystalline cells, which consist of one continuous crystal lattice, have a higher efficiency and performance stability, but require more production costs and increased energy payback times because of the need of ultra-pure solar-grade silicon and fine crystal-growth conditions.

In comparison, polycrystalline cells are less expensive and less energy-demanding to produce and show lower efficiencies, but are made out of multiple smaller crystals. However, they have a number of useful advantages, such as less energy consumption in production, shortened energy payback times, decreased greenhouse-gas emissions, and increased aesthetic openness in applications like building-integrated photovoltaics (BIPV).

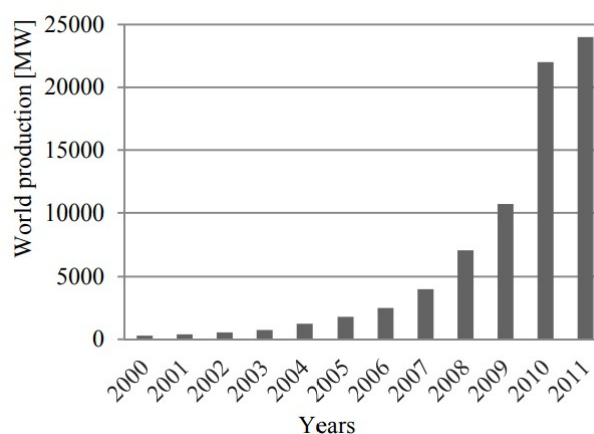
Commercial monocrystalline silicon cell has shown efficiency improvement of up to 25.0 -10 per cent as against about 10 per cent in the early 1980s. The continued development of Passivated Emitter and Rear Cell (PERC), Tunnel Oxide Passivated Contact (TOPCon), and Heterojunction with Intrinsic Thin Layer (HIT) technologies has continued to improve the performance of c -Si cells.

All in all, the first-generation crystalline silicon solar cells still serve as the foundation of the world-wide PV industry. Their high power-conversion efficiency (PCE), their long-term stability, and their technological maturity make them unavoidable in any large scale implementation of solar energy, despite the fact that their manufacturing is still expensive and resources-intensive. This has prompted the design of the thin-film solar cells, which seek to minimize the material consumption and the cost of production and still have a reasonable level of efficiency.

These trends have also been supported with comparative studies. As an example, an efficiency comparison of monocrystalline and polycrystalline cell concluded that monocrystalline silicon modules do not suffer performance losses due to temperature as much as polycrystalline modules.

### 2.1.1 Mono-crystalline silicon

Monocrystalline solar cells are photovoltaic cells that are designed using an unusual single continuous crystal form of silicon[39], [40], [41]. It is currently, one of the sectors with the highest growth is photovoltaic energy and Its growth dynamics are contrasted with the early stages of the microelectronics industry's progress. Over the past few years, the average yearly increase in solar cell production has been almost 43% (Figure 4). This rise is the consequence of technological and material advancements, as well as initiatives put in place in numerous nations to promote photovoltaics as a clean and safe source of electricity.



**Figure 4:** Global Solar Cell Production in MW[42], [43]

[44] produced a monocrystalline solar cell using conventional technology of fabrication of screen printing which was then used to build a demonstration PV system.

### 2.1.2 Poly-crystalline silicon

There are a number of advantages on crystalline solar cells. The technology is established and old with well-established manufacturing infrastructure, high conversion efficiencies, extended durations of operation (usually 25-30 years) and consistent functionality across different environmental factors.

[38] carried out an experiment in the performance of crystalline silicon solar panels with different light intensities of 2.21 to 331.01 W m<sup>-1</sup> to 50 cm out of the panel using artificial lighting. The findings established that the rise in the surface temperature decreases the power output of the solar panels. Furthermore, the thermal stability of the monocrystalline silicon (m -Si) panels was higher than the polycrystalline (p -Si) panels because the former showed a higher resistance to degradation due to temperature changes.

Despite these advantages, silicon cells of the first generation have a number of constraints. Their manufacturing entails purification and wafer-processing processes which consume energy and hence, are expensive when it comes to manufacturing. The hard and cumbersome structure of the technology also limits its application in the flexible or light application. In addition to this, efficiency is lost through high operating temperature and cut-kerf loss in wafer cutting, especially in polycrystalline cells as a result of grain-boundary recombination.

Essentially, crystalline silicon (c -Si ) solar cells are based on the photovoltaic effect where a semiconductor junction transforms sunlight directly to electrical power. It is the ratio of the amount of photogenerated charge carriers and the amount of recombination losses that define

the total current output mathematically expressed in Equation(1):

$$I = I_{ph} - I_0 \left( e^{\frac{qv}{nkt}} - 1 \right) \quad (1)$$

Where  $I_{ph}$  is the photocurrent,

$I_0$  is the reverse saturation current

$q$  is the electron charge

$v$  Is the terminal voltage

$n$  is the ideality factor

$k$  is the boltsman constant

$t$  is the cell temperature

The crystalline silicon cells are normally produced in monocrystalline or polycrystalline. High-purity single crystals produced through the Czochralski or Float-Zone process form Monocrystalline silicon, which is highly efficient but also expensive. Polycrystalline silicon, however, is made out of cast ingots with multiple crystal grains and defects, which minimizes the manufacturing cost, but also marginally reduces the performance.

Despite their technologic maturity and dominance in the world photovoltaic market, a steady stream of innovations, including Passivated Emitter and Rear Cell (PERC), Tunnel Oxide Passivated Contact (TOPCon), Heterojunction with Intrinsic Thin Layer (HJT), bifacial structure, and silicon-perovskite tandem designs, are steadily increasing the efficiency, cost-reduction, and expanded usage. As a result, the current and future deployment of solar-energy is based on crystalline silicon

## 2.2 Second Generation Solar Cells

Thin-film photovoltaic cells have many benefits, including reduced material prices, flexibility, and the possibility of large-scale production [62]. Moreover, this technology is favorable in circumventing the significant material and energy costs associated with c-Si cells, both economically and environmentally [63]. Because of this technology's great versatility, ease of installation, an approximate

12% diffuse light efficiency, and 25-year service life, its application has expanded recently [64]. To create a heterojunction barrier, thin layers of photovoltaic materials with a thickness of less than 2  $\mu\text{m}$  are deposited to create thin-film PV cells. The majority of thin-film semiconductor materials have a direct and wide bandgap of 1.5–1.8 eV, which allows 2G cells to function well in indirect light and have superior temperature coefficients [32]. Thin film cell technologies have different classifications which are predicated on the materials deposited. This comprises amorphous silicon (a-Si), I-III-VI semiconductors like CIGS, and II-VI compound semiconductors like cadmium telluride (CdTe) and cadmium sulfide (CdS). There are several methods for producing CdTe films, including metalorganic chemical vapor deposition (MOCVD), popping, and high vacuum evaporation (HVE) [65], [66]. Discussing the efficiencies, the high conversion efficiencies have been attained by CdTe thin-film solar cells, having set a record efficiency of 22.1% and also having high potential because of its great performance in real-world scenarios and being inexpensive for commercial applications [67]. Copper indium gallium selenide (CIGS) solar cells are also a noteworthy example of a second-generation thin-film technology that could be manufactured by electron beam deposition, MOCVD, spin coating, spray coating, or screen printing [68]. CIGS thin-film solar cell technology could achieve a record efficiency of 23.35% and may be used to create lightweight, inexpensive, and highly efficient solar cells that can be used for various applications like building-integrated PV and others [69].

Second-generation solar cells are built on the foundation of thin-layer PV technology. The light absorbing layer of silicon-wafer cells is around 350 micrometers thick, whereas thin-film cells have a layer that is only 1 micrometer thick [7]. Thin-layer cells are more cost-effective than silicon wafer cells, but the efficiency of the former is lower. Thin-film cells can be broadly categorized into three main families: amorphous silicon, CdTe, and CIGS.

The highest confirmed PCE for each type is reportedly 13.8%, 23.3%, and 23.4%, respectively [3], [6]. Low-temperature process can be implemented for amorphous silicon cells, thus permitting flexible substrates, such as low-cost polymer to be used. During manufacturing, the reverse side of the substrate is coated with doped silicone [3]. Amorphous silicon cells' major drawback is their instability and relatively low efficiency.

Second-generation cells utilize thin-film technology, where semiconductor materials are deposited in thin layers (nanometers to micrometers) on substrates such as glass, plastic, or metal. Common materials include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). The efficiency of this generation of solar cells typical range from 10–15% although, some CIGS thin films exceed 20% in laboratory conditions.

### 2.2.1 Amorphous Silicon (A-Si)

Amorphous silicon (a-Si) solar cells are an early example of commercially developed thin-film photovoltaic (PV) technologies, created as a cost-effective substitute to crystalline silicon. In contrast to crystalline silicon, which is long-range atomically ordered, a-Si is disordered, meaning it has a direct band gap of around 1.7–1.8 eV. This enables a-Si to capture sunlight much more efficiently per unit thickness, allowing films under 1 mm to be used in place of the crystalline silicon wafers of 200 mm (or so) per unit thickness [45].

### 2.2.2 Cadmium Telluride (CdTe)

This is a crystalline compound (Figure 5) that is comprised of cadmium and tellurium, it is compressed with cadmium sulphide to form a p-n junction photovoltaic cell. It is usually cheaper than conventional solar systems in terms of installation. The major disadvantage of this solar cell is that it uses rare materials which therefore limits its future availability. The benefit of using this material is its brilliant band gap semiconductor which makes its light intake

maximum thus increasing its efficiency. CdTe comprises of several layers which are synthesis of the polycrystalline material and glass shortlisting as one of its substrate, cadmium and telluride deposition layer by layer. The efficiency of this solar cell is usually between 9 to 11% [46]. Cadmium is however a very toxic material and this limits its application especially for domestic usage [47].

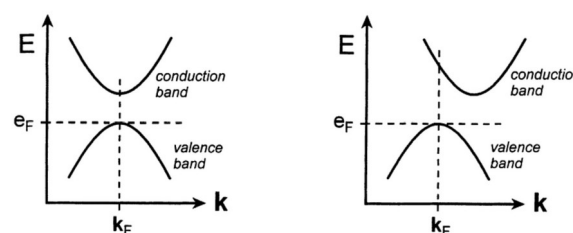
Glass
TCO
High resistive oxide
CdS
CdTe
Buffer
Back Contact

**Figure 5:** Schematics of CdTe Solar [48]

Compared to other thin-layer solar cells, CdTe is more cost-effective and economically viable. The manufacturing process for CdTe-based solar cells typically involves two main steps. Firstly, with polycrystalline materials used, the cells are synthesized and glass is usually selected as the substrate. Secondly, the cells go through a deposition process, in which the substrate is coated with multiple layers of CdTe. using economical techniques [3]. However, there is a debate over the use of cadmium in these cells. Several people believe that environmental issues have been caused by the toxic properties of cadmium. and their recycling can be highly expensive [49], [50]. On the other hand, there are some who argue that at least when it comes to acute exposure, CdTe is less toxic than elemental cadmium [50]. Additionally, in 2015, CdTe Photovoltaic modules have been suggested as the most ecofriendly among other current uses of cadmium. Figure 7 displays an illustration of a CdTe solar cell.

a

b

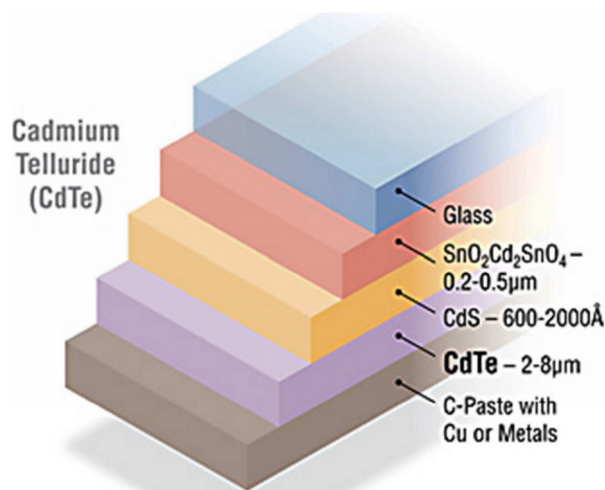


**Figure 6:** (a) Direct Band Gap Semiconductor, (b) Indirect Band Gap Semiconductor [51]

A direct band-gap semiconductor is one in which the highest valence band energy and the minimum conduction band energy occur at the same wave number or momentum shown in Figure 6 (a) and (b). The materials with a direct band-gap explain semiconductor's optical and electrical properties. One of the best examples of a direct band-gap semiconductor that may interact directly with photons is gallium arsenide (GaAs). An energy greater than the band-gap must be supplied in order to elevate an electron from the valence band to the conduction band. The bandgap energy of the GaAs semiconductor is 1.43 eV at 300 k and 1.52 eV at 0 k.

### 2.2.3 Copper Indium Gallium De-Seleniide (CIGS)

This solar cell is made up of four metals namely, copper-indium-gallium-selenium. These materials are direct band gap semiconductors which means no loss of momentum from its valence band to conduction band as shown in Figure 6. In order to manufacture these solar cells, a glass or plastic backing is deposited with a thin layer of CIGS. The front and back electrodes are to collect current [50]. CIGS can be deposited on a flexible substrate due to their thin layers and developments in low-temperature deposition, which are advantageous for generating highly pliable and lightweight solar panels [50].



**Figure 7:** Graphic Showing the Five Layers that Comprise CdTe Solar Cells [50].

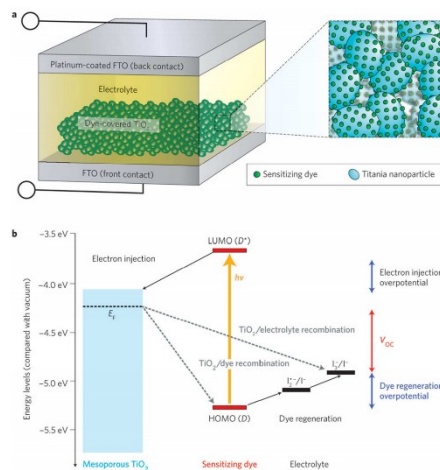
The advantages of this generation of solar cells include lower material consumption and reduced cost, lightweight and flexible, enabling integration into buildings (BIPV) and portable systems and their manufacturing requires less energy compared to crystalline silicon. The limitations is that they have a generally lower efficiency than first-generation cells, some materials are toxic (Cd in CdTe) or scarce (In in CIGS) and they possess a shorter operational lifespan [47].

Second generation solar cells are mostly thin-film based technologies, in which photovoltaic effect is used to convert sunlight into electricity by placing one or more thin layers of semiconductor material over a non-conductive substrate, typically glass, plastic or metal. Their primary material is cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si), which needs a much lower amount of semiconductor material than crystalline silicon, thus leading to a lower cost of production and making lightweight and flexible modules possible. These technologies have different efficiencies CdTe modules are at 17-19% (with laboratory results to 23%), CIGS modules between 15-18% (with 23% in research) and amorphous silicon at 7-10% (with light-induced degradation). Although these are its strengths, there is low efficiencies relative to crystalline silicon, environmental issues of toxic elements like cadmium and stability over time. However, the future of thin-film PV looks bright, especially in niche markets like

building-integrated photovoltaics (BIPV), hand-held devices and those where lightweight and flexible design are particular requirements, and the further development of materials and tandem integration could further enhance the cost-effectiveness of thin-film PV products in the renewable energy marketplace.

### 2.3 Third Generation Solar Cells

To overcome the shortcomings of the traditional crystalline and thin film solar cells, emerging photovoltaic technologies have been developed that are called third generation solar cells. They aim to use the latest concepts, nanotechnology, and new materials to realize greater sustainability, lower costs, and greater efficiency. Testing and research needs for third-generation solar cells, which include dye-sensitized (Figure 8), polymer-based, nanocrystal-based, and concentrated solar cells are still on [3]. Dye modules are used between the different electrodes to form the dye-sensitized solar cells, which are composed of a dye sensitizer, a redox mediator a semiconducting electrode, and a counter electrode. The advantages of these cells are low cost, flexibility, transparency, and simple conventional process methods, such as printing. The biggest challenge is deterioration and stability which still need research and improvements. The highest confirmed PCE of these cells is claimed to be 13% [6]. Thin functional layers that are connected in sequence comprise polymer-based solar cells, which have



polymer substrates [37]. The function principle of polymer solar cells is known as PV effects,

which is the same as other cells[37] . Nano-technology-based solar cells come in three types: quantum dot, hybrid organic, and dyesensitized solar cells [52], among which the first ones are usually referred to as nanocrystal-based solar cells [3]. Quantum dots are clusters of semiconductors at the nanoscale, possessing

remarkable optoelectronic properties that can be modified by quantum physical effects dependent on the size of the cluster [52]. The combination of different sizes of the quantum dot can expand the absorption spectrum, enhancing efficiency.

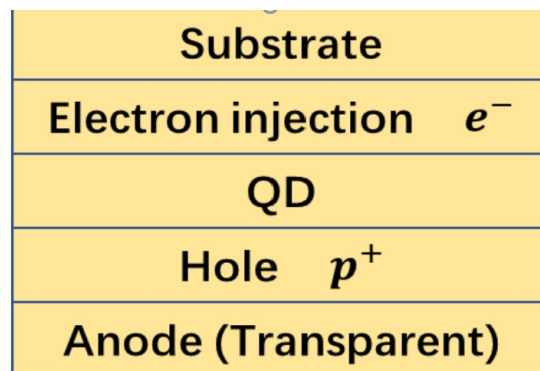
In addition, quantum dots possess remarkable optoelectronic properties that make them well-suited for use in solar cells. They are capable of inducing multiple electron-hole pairs with a single photon of the solar spectrum, whereas conventional solar cells can only generate one

**Figure 8: Dye-Sensitised Solar Cell Device Schematics and Operation [50]**

electron-hole pair per photon, resulting in lower electricity output and efficiency [10]. The highest confirmed efficiency of quantum dots solar cells is 18.1% [53].

Third-generation PV technologies are designed to overcome the limitations of earlier generations by achieving higher efficiency at lower cost by employing multi-junction architectures and bandgap engineering. This category includes: dye-Sensitized Solar Cells (DSSCs), organic Photovoltaics (OPVs), perovskite Solar Cells, quantum Dot (QD) Solar Cells (Figure 9) and multi-junction/Tandem Solar Cells. The efficiency ceiling of single-junction solar cells is constrained by the Shockley–Queisser limit, given as approximately 33% as shown in Equation 2.

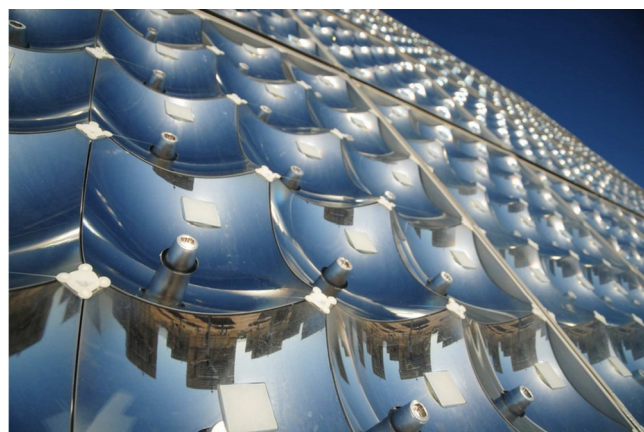
$$\eta_{max} \approx 33\% \text{ under one sun illumination} \quad (2)$$



**Figure 9: A Diagram of the QD Layer [54]**

These technologies exploit novel materials and physical mechanisms, including multiple bandgaps, nanostructures, and light absorption engineering.

Concentration solar cells are designed to collect tremendous solar energy and concentrate it onto a small area with a specific arrangement of large mirrors and lenses [55] . The concentration system can combine with several kinds of cells, like single-crystal silicon and multijunction solar cells. In the last several years, there has been a growing belief that multijunction solar cells represented the future of high-efficiency solar technology, and subsequent developments have largely supported this view. It was claimed that multijunction solar cells enjoyed the highest confirmed conversion efficiency as high as 47.6% in 2022 [37] . Figure 10 displays a diagram of a concentrated solar cell.



**Figure 10: Concentrated Solar Cells**  
The efficiency of this category is usually Perovskite solar cells: >30% in tandem with

silicon and Multi-junction cells: >40% efficiency in lab conditions. The advantages include high potential for ultra-high efficiencies beyond the Shockley–Queisser limit (~33%), lightweight, flexible, and potentially transparent and lower-cost, scalable manufacturing methods (e.g., roll-to-roll printing). The limitations of this is that it has a high stability and degradation issues (particularly perovskites) they lack of large-scale commercialization experience and it has serious challenges with long-term durability and environmental safety.

Third-generation solar cells represent a wide range of emerging technologies that work by taking advantage of new light-harvesting mechanisms, nanostructures, or new semiconductors to overcome the performance and cost penalties of previous PV generations. The most important materials are perovskite compounds (e.g., methylammonium lead halides), organic polymers and small molecules, systems based on dye-sensitized systems using photosensitive dyes and electrolytes as well as quantum dots with bandgaps that can be tuned. The materials make possible unique device architectures with high absorption potential, flexible and low-cost fabrication. Efficiency profiles have improved quickly: in the lab, perovskite solar cells have done more than 25 per cent, dye-sensitized cells do 8-13 per cent, organic solar cells do 18 per cent and quantum dot solar cells are at 12-16 per cent with high growth potential. Nevertheless, there are still serious problems, such as instability when exposed to long-term conditions of light, heat, and moisture, scalability issues in production, and in certain instances the toxicity of materials (i.e. lead in perovskites, heavy metals in quantum dots)[47]. Nonetheless, the future looks very bright for this generation of solar cells as further development should result in stable, scalable, and environmentally friendly compounds, and hybrid tandem devices, i.e. silicon-perovskite tandem, have already shown the world the highest efficiencies of over 33% [47], [56]and mark third-generation photovoltaics as a new frontier in transformative global energy transition.

### 3. Comparative Analysis

Table 2 provides a brief comparative discussion of the three generations of photovoltaic, discussing their working principle, their material, and their inherent limitations. The first-generation cells are based on the crystal silicon photovoltaic effect where the incident photons raise electrons across a silicon p-n junction; optimized mature manufacturing processes give them high efficiencies. These cells, however, require huge energy and capital investment. The second-generation cells use thin film materials for deposition which make the thickness of semiconductors a hundred times smaller and relatively less expensive with the cost reduction being offset by reduced efficiency and stability over time. The emerging generation cells build on new phenomena such as multiple bandgaps, excitonic effects, and multi-junction designs to overcome the high efficiency limits of single-junction designs; however, third-generation devices face the limitations of inadequate technological maturity and complicated material selections.

These differences are reviewed in a synthesized manner by the comparative analysis radar chart (Figure 11). It shows that first-generation cells are characterized by high operational maturity with moderate material impact and second-generation cells are the best in reducing resources but their level of maturity is average. On the other hand, third-generation technologies are quite innovative and show an evident decline in reliability with existing applications.

In the market-driven approach, crystal silicon remains a dominant player holding more than 90 per cent of all markets in the world in 2021. The remaining share is constituted by thin-film technologies which are mostly based on CdTe and CIGS platforms but have been enjoying comparatively low growth. The emergence of photovoltaic cells today has occupied a small market percentage; however, it is improving fast in research laboratories.

**Table 2.0:** Comparative summary of First, Second, and Third Generation Solar Cells

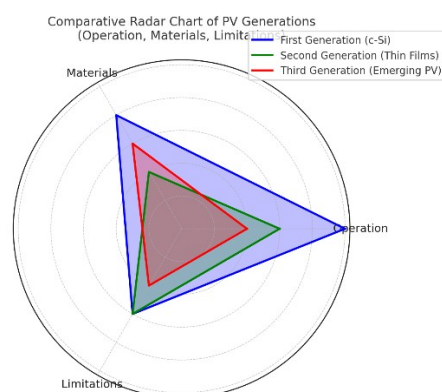
Gen.	Operation	Materials	Limitation	Ref.
1st	PV effect in crystalline silicon wafers with electrons across bandgap to produce	Monocrystalline	Environmental parameters such as light intensity and temperature determines output	[51], [57], [58], [59], [60]

	current	polycrystal line silicon		
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2 <sup>nd</sup>	Substrates convert light to electricity	CdTe, CIGS, amorphous silicon (a- Si)	Lower efficiency, stability issues, Cd toxicity, indium	[47], [61], [62]
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3 <sup>rd</sup>	Novel architectures exploiting nanostructures, excitonic effects, and tunable bandgaps	Perovskites, organics, dye-sensitized cells, quantum dots	Stability (moisture, heat, UV), toxicity (Pb, heavy metals), scalability challenges	[63] [47]
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As for the market proportion of different solar cells, crystalline silicon solar cells account for over 90% of the world's solar panel output, with thin-film solar cells accounting for the remaining 10% as of 2021 [64]. Despite the fact that crystalline silicon solar cells will continue to retain a sizable market share in the future due to their established foundation, third-generation solar cells are expected to gradually replace them and provide higher conversion efficiency at a lower cost. In particular, perovskite exhibits excellent power conversion efficiency while being very cost-effective in terms of materials [65].



**Figure 11:** Comparative Analysis of Solar Cells

The radar chart (Figure 11) represents a relative evaluation of photovoltaic generations in the three key areas under review, including operation, materials and limitations. Crystalline silicon cells, crystalline solar cells are most maturely operated and reliable since they have a time-tested manufacturing and deployment, but their material needs are energy-intensive and expensive, as indicated by average restrictions. Thin films show intermediate maturity of operation and much less material consumption, however, the dependence on rare or poisonous elements like cadmium and indium, and the low

efficiency stability limits the performance of the thin film. Emerging photovoltaics have low operational maturity because they are early stage development, and the materials being developed have good optoelectronic properties, but are experimental, and unresolved toxicity problems, which gives them high restriction. The graph brings out the trade-off between maturity and innovation where crystalline silicon seems to be strong today, thin films are able to have niche flexibility with material risks, and emerging technologies have high potential but due to stability and scalability issues.

#### 4. Discussion and Outlook

We briefly review the trade-offs and synergies that defined the three major photovoltaic (PV) generations. The first-generation crystalline silicon cells have the advantage of having a high efficiency previous history over the decades of incremental development [31]. They are about to continue being the backbone of PVs on a utility scale, particularly due to innovations like PERC, HJT, bifacial designs and the trend pulling the existing ones to better results. However, the exercise of producing silicon is very energy consuming implying notable sustainability issues.

Thin-film technologies offer some different benefits in prices and flexibility: lower materials per watt, light modules, and better performance in diffuse light [32], [33]. These characteristics make them rather appropriate to building-integrated PV (BIPV) systems and desert applications. Their dependence on limited or poisonous elements such as cadmium, tellurium and indium, and relative lack of long-term stability, however, are considered a notable downside [17],[34]. It can be assumed that the future of thin films will be concentrated on niche applications, but at the same time, such films will be better recycled and generally eco-friendly to their materials.

OTD efficiencies and cost savings with methods such as tandem architectures (e.g., silicon perovskite hybrids) and quantum-dot engineering, third-generation PV is anticipated

to achieve breakthrough levels of efficiencies and cost reductions. However, according to critics, the majority of 3G technologies are still in the phase of the prototype and are not commercialized yet. Among the main challenges are the stability of the operations in the real-world environment (perovskite degradation, e.g.), and mass production without any defects [26]. In addition, certain of the emerging cells are deliberately stacked to eliminate toxicity e.g. lead-free perovskites - and to utilize low-temperature, solution-based fabrication methods.

Upon discovering this, it becomes clear that there is no single PV generation that can boast of having monopolized on the silver bullet story. The most realistic direction is based on a multi-generational strategy that is complementary. Here, market PV that has been in existence since the 1980s is now seen providing base-load power, especially at large scale applications; thin-film modules are in response to the unique and developing applications that require minimal weight of modules or to bespoke form factors; and the third-generation cells represent the envelope-pushers to future improvements in efficiency and cost. This diversified approach should therefore be the one that is advocated by research agendas and policy frameworks. As a case in point, addition of perovskite layers onto silicon substrates in tandem cells would allow taking advantage of the existing silicon infrastructure, on the one hand, and, on the other hand, increase the efficiency of the aggregate system.

Lastly, sustainability issues that are hard to call in such areas like material scarcity, toxicity, and life-cycle use of energy should exist in all generations. Table 2 has shown the last column and the radar chart in Figure 11 shows that environmental constraints are now the most significant obstacle to PV development. Recycling (e.g. silicon recovery of obsolete modules, safe disposal of CdTe), eco-design as well as overall life-cycle analysis initiatives should be made to tread forward as the efforts towards efficiency improvements.

## 5. Conclusion

In conclusion, this review has shown that each generation of solar cell technology offers distinct benefits and faces specific challenges. First-generation crystalline silicon cells provide high, proven efficiency and long lifetimes, but at high cost and energy input. Second-generation thin films reduce costs and materials usage, yet struggle with lower efficiency and stability issues. Third-generation emerging cells can potentially unlock much higher efficiencies and lower manufacturing costs, but they currently suffer from technical immaturity, stability, and environmental concerns.

We highlight that no single PV technology will dominate all future markets. Instead, the global energy transition will benefit from a portfolio approach: utilising mature silicon technology for large-scale deployment, thin films for applications needing lightweight or low-cost modules, and emerging technologies to push the efficiency frontier. Crucially, we advocate continued research on overcoming the key limitations identified: improving material stability and reducing toxicity for new PV materials, and enhancing the environmental sustainability of manufacturing processes. With these efforts, solar PV can more fully realise its potential as a leading source of clean energy

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