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Comparative Study of four mini Photovoltaic Power Plants of different Technologies and Inclinations for Grid Injection

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CHAPTRE II

PHOTOVOLTAIC CELLS

I. Introduction

Energy production will be a critical challenge in the coming years. Currently, the majority of energy produced worldwide originates from fossil fuels, which significantly increase greenhouse gas emissions and adversely affect the environment. The overuse of natural resources is leading to their depletion, driving the development of technical solutions that will enable better management of these resources and the successful deployment of renewable energy sources.

Although traditional fossil fuel-based energy sources have adverse environmental effects, solar energy use is expanding quickly. Solar cells provide a practical and effective way to capture the abundant and dependable energy of the sun. According to Liu (2009), the sun's energy output to the Earth's atmosphere is roughly 1367 W/m^2. Around 1.8×10^{11} MW of solar energy is absorbed worldwide, which is enough to meet everyone's electricity needs.

Solar photovoltaic technology has become a prominent renewable energy source that can generate electricity that is more cost-effective, scalable, dependable, and clean. This has prompted governments all over the world to encourage the advancement and application of solar PV technologies. Key initiatives involve promoting partnerships for industrial research, government-funded scientific research and development (R&D), programs for technology transfer, production subsidies, and the execution of innovations driven by research .

This chapter provides a thorough analysis of the several solar panel technologies that are currently available, emphasizing their lifetime and efficiency. Every solar cell technology is examined, emphasizing its distinct benefits and drawbacks. Furthermore, the text provides a historical overview of the development of solar cells, highlighting their evolution and significant milestones in their creation.

Finally, a comparative analysis of these technologies is presented, emphasizing their specific characteristics to provide insights into their suitability for various applications.

II. A Brief History and Development of Solar Cells

Since the beginning of time, people have considered the sun as a divine entity and a representation of the force that sustains all life on earth. Later, as the industrial and learning eras developed, people came to understand that the sun was a source of energy. When it has been established that the exploitation of fossil fuels for energy generation influences global temperatures, the significance of such a finding has peaked. On an energy day, the sun provides 10,000 times the amount of energy required on Earth. Ancient human civilizations relied on water, wind and bioenergy as energy sources all of which ultimately originated from solar energy in some form **[1] .**

In 1839, Alexandre Edmund Becquerel created the first solar power cell by coating platinum electrodes with silver chloride or silver bromide (Fonash, 2010) **[2].** Decades later, in 1882, Charles Fritts developed the first workable photovoltaic (PV) cell using selenium as a photosensitive material. Although it was expensive, it had only a 1% efficiency (Czochralski, 1918) **[3].** In 1916, polish chemist Jan Czochralski created a method, now known as the Czochralski technique, to cultivate single-crystal semiconductor materials (Chapin et al., 1954) **[4].** In 1954, a group of researchers at Bell Laboratories in the United States used the Czochralski process to create the first usable crystalline silicon solar cell, which had an efficiency of about 6% (Loff, 2023) **[5].** Solar cells became increasingly important in 1958 when they were incorporated into Vanguard-1, the first satellite powered by solar energy (Yamaguchi et al., 2021) **[6],** Launched by the United States Space Agency (NASA). Initially, NASA was hesitant about the advantages and necessity of solar power systems for its extraterrestrial products **[7].** Although this novel method of power generation resulted in multiple successful missions, it also provided solar panels with an opportunity to demonstrate their effectiveness. After two months, the Russian space program launched Sputnik-3, a satellite powered by photovoltaic solar energy. Since then, photovoltaic power sources have become crucial for space projects **[8,9,10].** This progression is elaborated further in **Table II.1,** which outlines essential dates related to the development of photovoltaic (PV) solar energy technology.

Table II.1 : Key Dates in Photovoltaic Solar Energy Conversion .

Year	Scientists and innovation
1839	Becquerel discovers the photovoltaic effect
1876	Adams and Day notice photovoltaic effect in selenium
1900	Planck claims the quantum nature of light
1930	Wilson proposes Quantum theory of solids
1940	Mott and Schottky develop the theory of solid-state rectifier (diode)
1949	Bardeen, Brattain and Shockley invent the transistor
1954	Charpin, Fuller and Pearson announce 6% efficient silicon solar cell
1954	Reynolds et al. highlight solar cell based on cadmium sulphide
1958	First use of solar cells on an orbiting satellite Vanguard 1

As the power conversion component of a PV system with real-world applications, the creation of the first silicon solar cell marked a turning point in the development of solar technologies. These silicon cells are put together into modules rather than being utilized separately. Even though there are many different kinds of solar cells on the market today, research and development activities are still being conducted to improve and expand these energy gatherers.

The competition to explore space was unquestionably a significant factor in the advancement of photovoltaic technology **[8,10].** Achieving public applications was always a goal. However, the lack of optimized manufacturing processes and, consequently, the high cost of commercialization were the main barriers to this progress. Joseph Lindmeyer, a Communications Satellite Corporation (Comsat) employee, created a method in the 1970s that boosts silicon solar cells' efficiency by 50%. Lindmeyer departed from the company in 1973 and, along with Peter Varadi, co-founded Solarex, aiming to develop solar cells for public applications. Although Comsat owned the patent for this process and not Lindmeyer or Solarex, by 1980, Solarex held approximately 50% of the photovoltaic industry market. Although a modest market, it has been expanding due to the oil crisis since 1973, a few months after Solarex was founded **[8,9].**

The scientific community became more interested in photovoltaic technology as a result of this issue. In an effort to lower production costs, new technologies emerged that used novel and varied materials intended to lower the cost of manufacturing. A monocrystalline silicon, was utilized until 1973. After that, poly-Si and a-Si, took the market by storm because their techniques were less expensive and more straightforward [8, 9, 11]. Since then, photovoltaic technology has been enhanced through various techniques. New solar cells have emerged, leading to the classification of these cells into two and later into three different generations **[11-13].** Currently, some researchers and manufacturers are advocating a new division, leading to the creation of a fourth. These research papers **[12-15]** also evidently show that the materials and production methods are the source of these generational classifications.

Additionally, advancements in areas like electronics, photonics, and quantum mechanics have enhanced photovoltaic cells. Flexible solar cells and even painted solar cells are now possible **[14,16-18].**

The NREL (National Renewable Energy Laboratory) highlights advancements in the efficiency of various solar cell technologies **[11].** This chart is frequently presented and referenced in various research works, and it is organized and updated by the NREL. NREL maintains a chart showcasing the highest confirmed conversion efficiencies for various research cells, covering a range of photovoltaic technologies from 1976 to the present **[11].** This chart will be examined and discussed in the following sections. A comparison of various technologies and generations will follow. However, it is already clear that the field of photovoltaic technology research has been particularly noteworthy over the decades, especially in the past ten years, as indicated by the increasing milestones on the NREL chart.

The evolution of materials and structures will determine how far this technology may advance, but maintaining maximum power at the lowest possible cost will always be the aim. Moreover, the perception of a photovoltaic system has evolved to encompass not only the photovoltaic cells themselves but also key components such as inverters, batteries, and the cables used to connect these elements **[19–22].** Improvements in any of these devices contributed to enhanced system efficiency, which in turn improves the overall benefits of photovoltaic technology.

III. Operating Principles of Solar Cells

In Photovoltaic (PV) technology is pivotal in harnessing solar energy to meet the global demand for sustainable and clean energy. At its core lies the PV cell, the fundamental unit responsible for converting sunlight into electrical energy through the photovoltaic effect a phenomenon combining physical and chemical principles. When sunlight strikes a solar cell, photons are absorbed by silicon layers, exciting electrons to higher energy states.

The energy dissipated as heat during this process allows electrons to return to their ground state, enabling current generation. This mechanism relies on the chemical bonds within the silicon matrix. A typical solar cell comprises two silicon layers: one doped with boron to create a p-type region and another doped with phosphorus to establish an n-type region (**Fig 16.3**) **[23].**

The photovoltaic effect drives the generation of direct current (DC) electricity by forming electron-hole pairs in the semiconductor material. The depletion region, enriched with minority carriers, facilitates the movement of these carriers toward quasi-neutral regions. This movement generates a photo-generated current **[24].**

To utilize the generated energy, a load is connected across the p-n junction electrodes, allowing current flow. As the current flows, the potential difference across the load decreases, which leads to an increase in the recombination current and a corresponding reduction in the electrostatic potential of the depletion region **[23].**

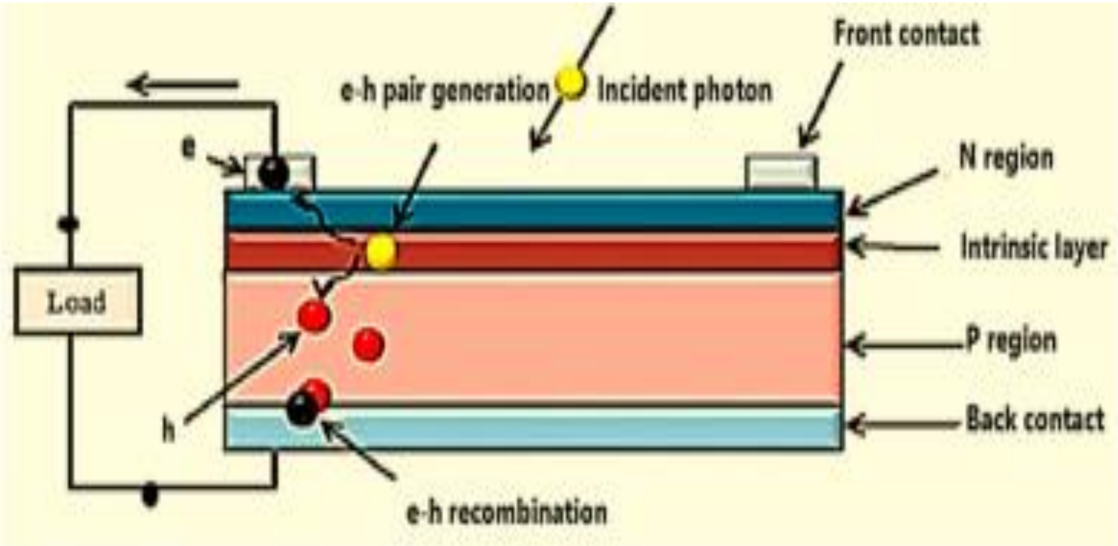

Fig II .1. Fundamentals of Solar Cells: The p-n Junction PV Cell **[25].**

Commonly referred to as photoelectric cells, solar cells are characterized by their electrical properties, such as power, voltage, and current. To enhance energy output and meet practical power demands, multiple solar cells are interconnected to form a solar module, also known as a solar panel. Typically, a single solar cell generates a maximum open-circuit voltage of 0.6 V and a short-circuit current of 7.34 A.

To enhance energy output and meet practical power demands, multiple solar cells are interconnected to form a solar module, also known as a solar panel. Solar panels consist of cells connected in series and parallel configurations to achieve the desired power output. For example, connecting six cells in series results in an ideal voltage of 3 V (6 × 0.5 V), while maintaining the same current as a single cell. Additionally, series cells can be connected in parallel to increase current capacity. For instance, a series-parallel structure of twelve cells (two sets of six cells in parallel) can produce 4 A and 3 V, effectively doubling the current output compared to a single series string.

The process of solar cell operation involves several key stages. It begins with the absorption of sunlight by the semiconductor material and concludes with the recombination of some charge carriers. During this process, sunlight is primarily converted into electrical energy, although some energy is also lost as heat or light. These fundamental stages, as illustrated in **Fig II. 2**, form the basis of how solar cells work and how they are integrated into solar panels for energy generation.

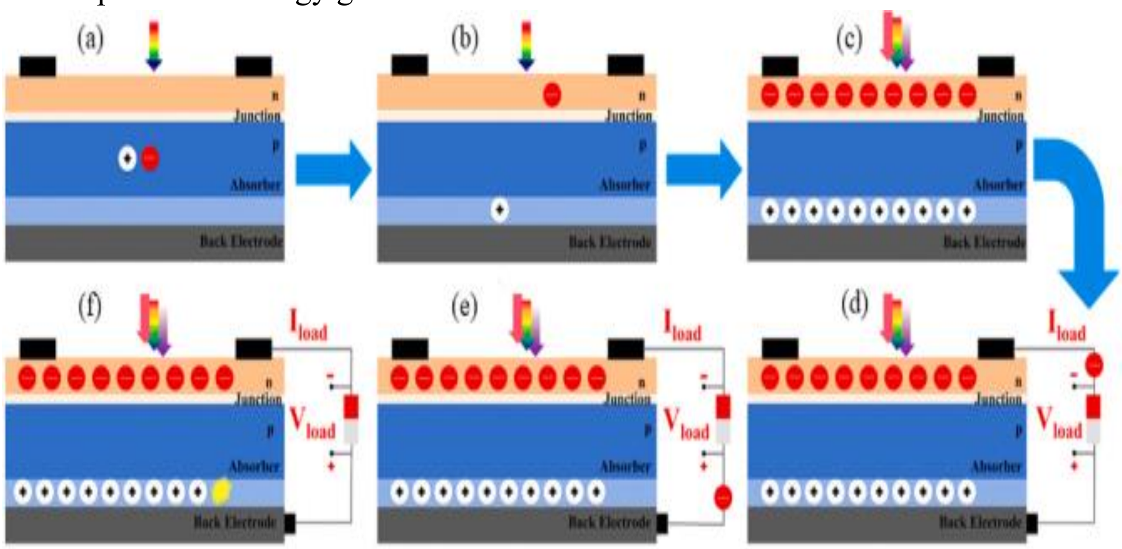

Fig II .2. Photovoltaic Energy Conversion Process (a) Absorption, (b) separation of charge carriers, (c) continuous generation and separation, (d) connection of external load, (e) the transfer of a charge carrier from high to low potential, (f) recombination of carriers [26] .

IV. Photovoltaic Cells Generation

Solar cells are classified into Four generations based on their materials and production techniques. The first generation consists of wafer-based silicon cells, which dominate the market and accounted for 95% of global solar power generation in 2020 **[27].** These cells are efficient and commonly used in traditional applications. The second generation utilizes thin-film technologies, which offer flexibility and cost reduction. While these cells initially had lower efficiencies, improvements have been made over time. The third generation of solar cells builds on thin-film principles by incorporating novel materials such as perovskites and organic compounds. These advancements enable adjustable band gaps and multi-junction designs, which contribute to higher efficiency and open new possibilities for solar energy applications **[28].** However, these technologies are still under development. **[28].** The fourth generation of photovoltaic (PV) technology integrates low-cost, flexible thin-film polymers with durable nanostructures, including inorganic materials like metal oxides and organic materials such as graphene, carbon nanotubes, and their derivatives. This hybrid approach improves efficiency, stability, and scalability, making it suitable for a variety of solar energy applications **[29].**

The classification of solar cell generations provides a clear framework for understanding advancements in photovoltaic technology, as shown in the figures below. A detailed discussion of each generation will follow in the next section.

IV .1- First generation Wafer-based Solar Technology

The first generation of solar cells is based on wafers, , meaning their manufacturing techniques were adapted from those used in integrated circuit production. This allowed them to leverage existing expertise in silicon wafer production **[30].**These cells typically consist of a single layer of light-absorbing material (single-junction) or use numerous physical configurations (multi-junctions) to apply various methods for charge separation and absorption **[31].**The first generation of solar cells consists of crystalline silicon cells, such as polysilicon and monocrystalline silicon.

The upper surface of the solar cell consists of a thin layer of p-type material, which facilitates efficient light absorption (**see Fig II. 3**). Metal rings are positioned around the p-type and n-type materials, serving as the positive and negative output terminals, respectively. Together, these semiconductor materials create a single unit of the photovoltaic (PV) cell **[32].**

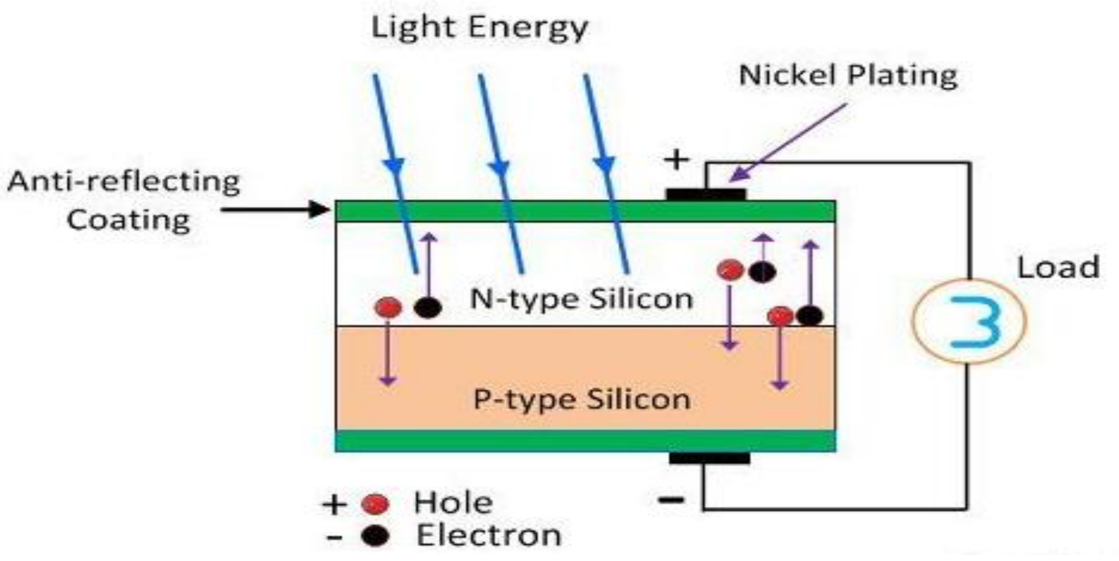

Fig II . 3. Wafer-based Solar Technology (Circuit Globe (n.d.)) **[33].**

The collaboration with the integrated circuit industry not only provided access to essential materials but also greatly advanced the development of first-generation photovoltaic technology, utilizing existing silicon wafer manufacturing expertise.

IV .1.1- Monocrystalline Solar Cell

Monocrystalline solar PV modules, a first-generation photovoltaic technology, have been in use for decades, demonstrating their reliability, durability, and longevity. Many of the early installations from the 1970s are still producing electricity today. These modules are the most widely used solar technology and constitute about 80% of the global photovoltaic market. They are expected to maintain their dominance until more efficient and cost-effective alternatives become available. These cells utilize crystalline silicon p-n junctions to convert solar energy into electricity. Their established performance and widespread use demonstrate their enduring viability in the industry.

Monocrystalline solar cells **(Fig II.4)** are produced using a single crystal of silicon (Si), which is typically grown through the Czochralski process **[34].** This method ensures high precision, starting with large ingots that are refined to create high-quality material. Historically, monocrystalline cells have achieved an efficiency of around 16%, but advancements in technology have led to efficiencies of up to 24.4% in laboratory conditions **[35].** Multicrystalline silicon cells have also seen improvements in efficiency, reaching 19.8% due to enhancements such as thermally formed oxide coatings and isotropic etching.

These techniques create a hexagonally symmetric 'honeycomb' surface texture, which helps reduce unfavorable electronic processes.

Dobrzanski et al. **[36]** described the traditional screen-printing process used in the manufacturing of monocrystalline silicon solar cells. These cells were equipped with Schottky and Zener diodes for protection and were integrated into photovoltaic (PV) modules to generate electricity **[37].** One practical application of these modules is in traffic lighting for pedestrian crossings, showcasing their versatility and effectiveness.

Fig II .4. Monocrystalline Solar Panel (Sendy 2017) **[38].**

IV . 1.2- Polycrystalline Solar Cell (Poly-Si or Multicrystalline)

Polycrystalline silicon, also called multi-crystalline silicon, is a high-purity material extensively used in the solar photovoltaic industry. It is primarily produced through the Siemens process, which involves the distillation of volatile silicon compounds followed by decomposition at high temperatures. Alternatively, upgraded metallurgical-grade silicon purification methods can be used. Poly-Si comprises small crystals, or crystallites, that give it a distinctive metallic flake appearance. Multi-crystalline solar cells, commonly referred to as polycrystalline cells, dominate the expanding photovoltaic (PV) market due to their lower production costs compared to monocrystalline cells. Despite their slightly lower efficiencies, which can reach up to 19.8%, as noted by Zhao et al. (1998) **[39],** their cost-effectiveness makes them widely preferred. The production process involves melting silicon and solidifying it to form rectangular ingots, which are subsequently sliced into thin wafers or shaped into wafer-thin ribbons using methods like those developed by Evergreen Solar.

Transitioning from mono-silicon to multi-silicon manufacturing reduces metal contamination defects and enhances crystal structure, making it a preferred option for large-scale PV module production. Producing 1 MW of conventional solar modules requires approximately 5 tons of poly-Si, underlining its critical importance in the solar industry see **Fig II.5.**

Fig II.5. Polycrystalline Solar Panel (Indiamart (n.d.)) **[40].**

IV. 1.3- Emitter wrap-though cells

Emitter wrap-through cells (**Fig II .6**) improve efficiency by focusing on enhanced cell design rather than material advancements. Small laser-drilled holes connect the rear n-type contact to the emitter on the opposite side, enabling optimized performance .

By removing the front contacts, the metal lines' masking is eliminated, allowing the entire surface area of the cell to absorb more solar radiation. Several tests **[41]** have shown that placing the contacts on the backs of solar cells offers manufacturing benefits. Companies like Advent Solar **[42]** and SunPower Corp **[43].** These are examples of those utilizing EWT technology in the US. Utilizing EWT has resulted in a 15–20% increase in efficiency. One significant drawback of this technology is apparent in large-area EWT cells, where it suffers from high series resistance that limits the fill factor. See **Fig II.6.**

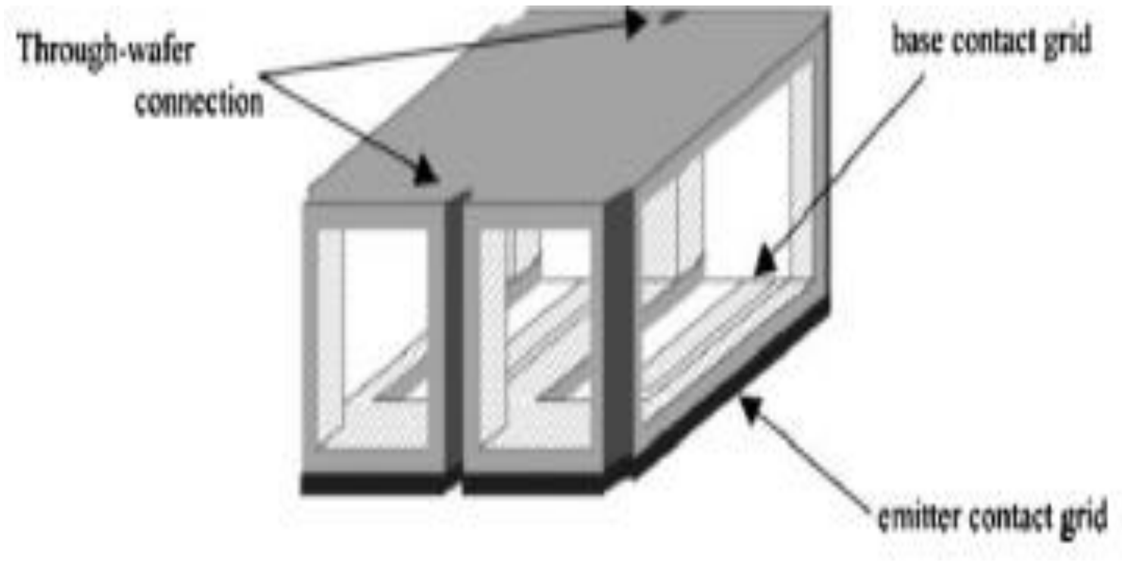

Fig II .6. Schematic illustration of an emitter wrap-through solar cell **[41].**

IV. 1.4- Silicon crystalline investment

Photovoltaic systems require a considerable initial capital investment, though they provide low ongoing operation and maintenance costs. The cost of delivered energy decreases as the lifespan of the system increases, with silicon-based technology modules typically lasting between 20 and 30 years. However, most photovoltaic (PV) systems experience lengthy payback periods unless they receive strong government incentives. To tackle this issue, research is concentrating on reducing initial capital costs, shortening payback periods, and improving the feasibility of photovoltaics as a self-sustaining energy source that does not heavily rely on subsidies.

First-generation silicon-based PV cells have maintained their dominance in the market, contributing to an impressive 95% of the power output from 2020 to the present. Concurrently, the advancement of second-generation thin-film solar cells focuses on minimizing manufacturing expenses, lowering module costs, boosting efficiency, and enhancing durability. This shift aims to achieve 'grid parity,' a point where the cost of electricity generated by photovoltaic systems equals that of traditional energy sources. Although this goal is still challenging, advances in technology have greatly reduced the cost per watt, making it more achievable .Adopting these innovations accelerates progress toward grid parity and creates a more sustainable energy future.

IV. 2 The Second-generation Thin film technology

Second-generation solar photovoltaic technologies are single-junction devices that use less material while maintaining the efficiency levels of first-generation photovoltaic cells. These include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS) cells. Commonly used in large photovoltaic power stations, they provide excellent performance even in cloudy conditions. See **Fig II.7.**

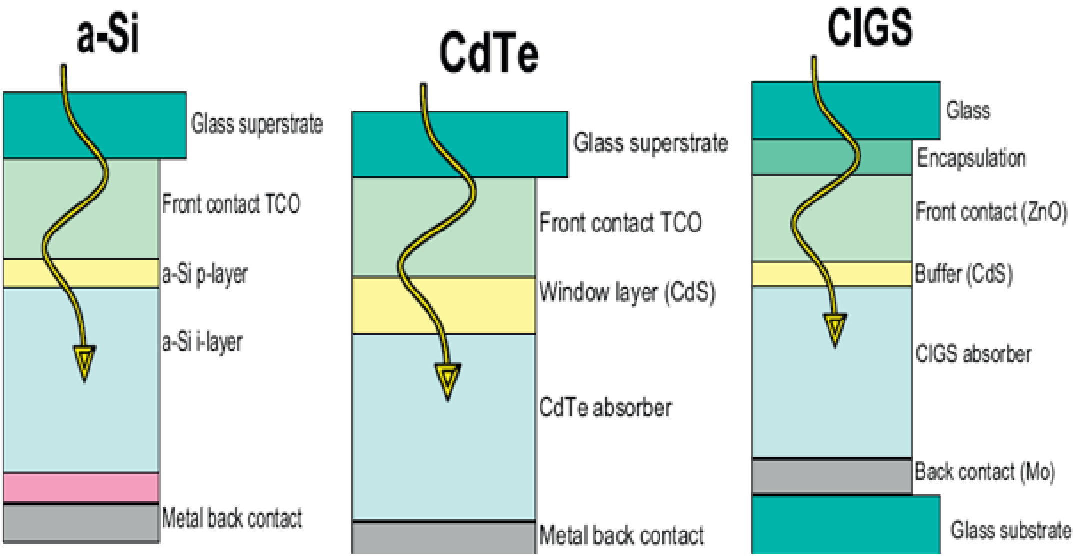

Fig II.7. Schematic Diagrams of a-Si, CdTe, and CIGS Thin-Film PV Technologies .

IV .2 .1- Amorphous Silicon Solar Cell (a-Si)

This type of solar cell is widely recognized as the most prevalent among thin films and has been commercially available for over 15 years. It has been widely used in pocket and desktop calculators, as well as in solar panels, for both domestic and utility-scale electricity generation. They are readily available owing to their low cost. These materials can be manufactured at very low temperatures, leading to numerous low-cost polymers and substrates with highly flexible applications.

Amorphous silicon is the most commonly and developed non-crystalline form of silicon. It is particularly popular in thin-film technology, although it is prone to degradation. Due to its random structure, amorphous silicon (a-Si) has a high band gap of 1.7 eV (Boutchich et al., 2012) **[44],** which results in a light absorptivity rate that is 40 times higher than that of monocrystalline silicon (Mah, 1998). Also it holds the top position in the market among all thin film materials. Carlson and Wronski (1976) reported the first amorphous thin-film solar cell of 1 mm thick with an efficiency of 2.4%. In addition, Rech and Wagner (1999) detailed further improvements and potential of thin-film solar cells. A table presented by Mehreen Gul et al. **[45]** shows a list of 49 companies involved in the manufacturing and trading a-Si modules . According to this list, Stion Corporation (US13) in the USA manufactures a-Si modules with the highest efficiency of 13.8%. In contrast to monocrystalline and multi-crystalline modules, over half of the companies are based in China and Germany . The table shows that there is over a 10% difference between the lowest and highest efficiencies of commercially available modules.

Additionally, it is notable that most companies produce modules with efficiencies ranging from 5% to 9.9% efficiency. When comparing a-Si modules see Table 4 in **[45]** to monocrystalline and Table 2 in **[45]** and multi-crystalline modules presented in Table 3 [45], it is evident that the maximum efficiency of a-Si modules is 13.8%. This value is among the lowest efficiency ranges for monocrystalline and multi-crystalline modules. While, as compared to the highest efficiency of monocrystalline and multi-crystalline modules, a-Si modules are still behind by 6.6% and 3.1% see Tables 2 to 4 in **[45].** By examining the range of commercially available a-Si modules and comparing them with monocrystalline and multi-crystalline options, it is clear that they require significant research and development to enhance their performance. See Fig II.8.

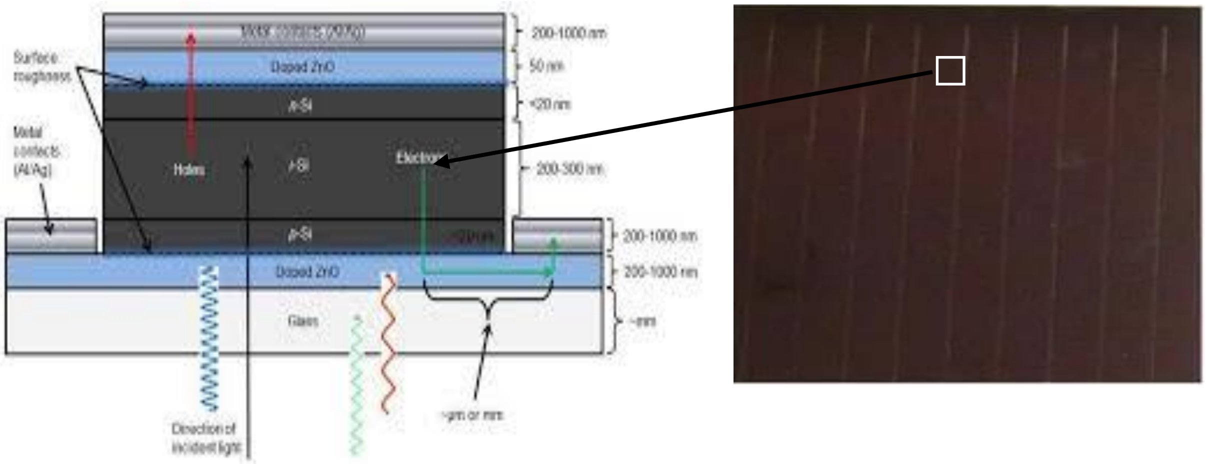

Fig II . 8. Amorphous Silicon Solar Cell Composition (Yang T.C. (2016) **[46] .**

IV .2.2- Cadmium telluride/cadmium sulphide (CdTe / CdS) solar cell .

Cadmium telluride (CdTe) solar cells are a promising category within second-generation photovoltaic technologies. CdTe is an ideal material for polycrystalline solar cells due to its excellent optoelectronic and chemical properties, combined with low production costs. As a direct band gap material with a band gap of 1.45 eV and an absorption coefficient of approximately 10^5/cm in the visible spectrum, CdTe effectively absorbs around 90% of incident light with a thickness of just a few millimeters. This makes it a highly efficient light absorber for photovoltaic applications. High temperature deposition techniques typically result in films with lower cadmium content, imparting p-type conductivity. Furthermore, the high ion density in CdTe crystals (about 70%) contributes to enhanced passivation, robust chemical bonds, and significant chemical and thermal stability, with an energy reference of approximately 5.75 eV. These properties ensure that CdTe solar cells maintain stability under various conditions and exhibit strong resistance to degradation during deposition processes.

CdTe photovoltaic solar cells are considered the second most widely used solar photovoltaic technology globally after c-Si, representing 7% of the market in 2014. The highest recorded laboratory efficiency for a CdTe solar cell is 22.1% , achieved by First Solar, while its theoretically predicted efficiency is approximately 33%. Over the past 25 years, efficiency has improved from 15.8% **[47]** to 22.1% **[48,49].** This slow progress in efficiency is largely attributed to a lack of research and development focused on CdTe, partly due to environmental concerns and the toxicity associated with its materials. See **Fig II.9.**

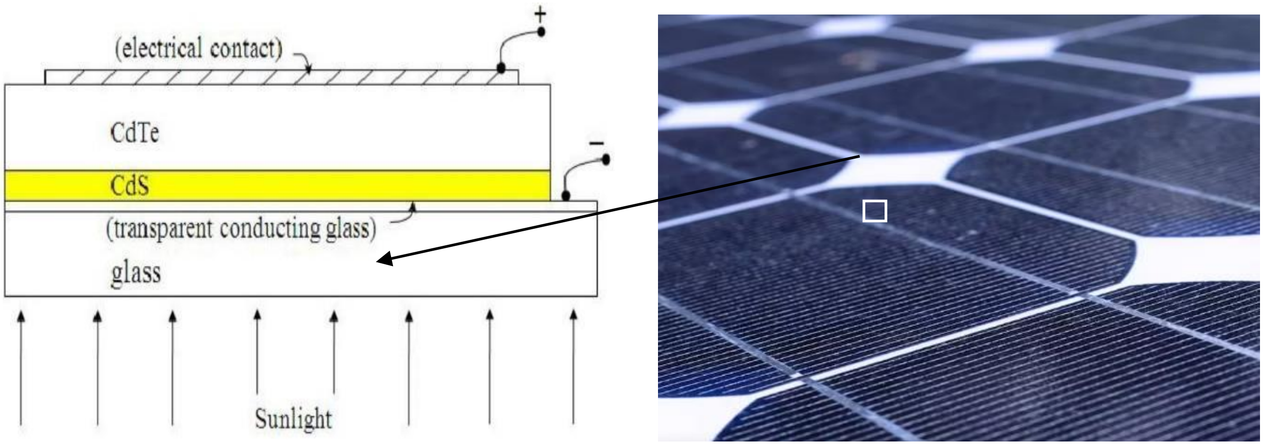

Fig II .9. CdTe Thin Film Solar Cell Layers. (Dharmada et al. (2014)) **[50].**

IV.2. 3- Copper Indium Gallium Di-Selenide (CIGS)

CIGS solar cells, which stand for Copper-Indium-Gallium-Selenide, are thin-film photovoltaic devices designed to convert sunlight into electricity. These cells are created by depositing a thin layer of copper, indium, gallium, and selenium onto a glass or flexible plastic substrate, with electrodes on both the front and back to collect the current (Figure 6) **[51].** The right side of Figure 6 presents a transverse section of a real device obtained using a scanning electron microscope. Due to their high absorption coefficient, only a very thin film is needed, reducing material usage compared to other semiconductor technologies.

Copper indium gallium diselenide (CIGS) photovoltaic solar cells exhibit the highest energy production among thin-film photovoltaic technologies. Their power conversion efficiency on glass substrates is now nearing 20%, with some achieving an efficiency of 22.8%. This level of performance competes favorably with crystalline silicon (c-Si) wafer-based solar cells **[52].** Additionally, CIGS solar cells generally outperform CdTe solar cells in terms of efficiency, making them a preferred option for high-performance applications. Recent advancements in the field of CIGS have shifted towards flexible

photovoltaic devices using polyamide or metal foil substrates. The flexible nature, resistance to solar radiation, and high specific power of CIGS solar cells have led to their increasing use in space applications. Additionally, CIGS solar cells exhibit a high absorption coefficient at a band gap of 1.5 electron volts, , enabling effective absorption of the solar light spectrum **[54].** See **Fig II.10.**

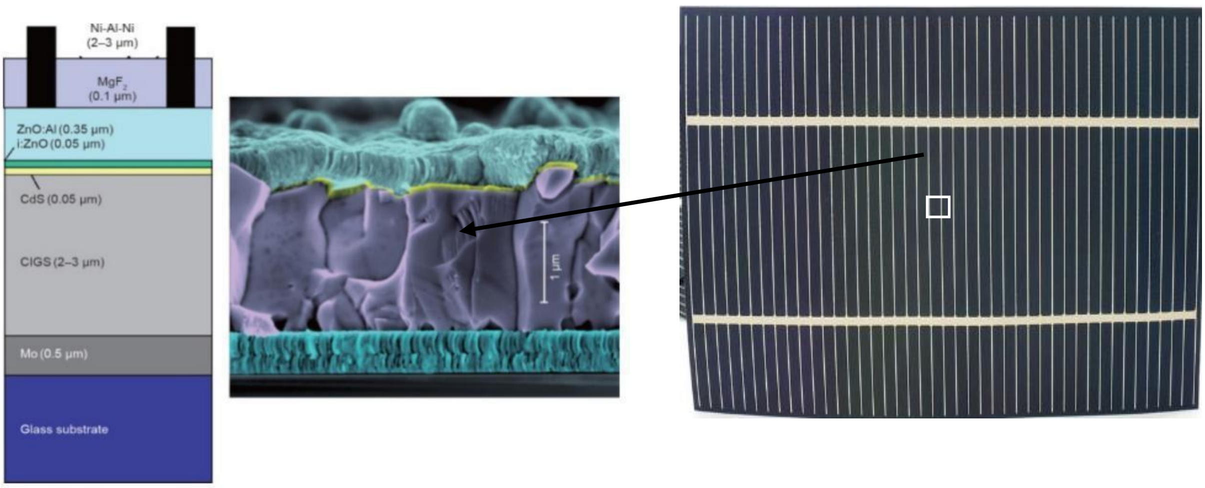

Fig II . 10. Copper Indium Gallium Di-Selenide (CIGS) Solar Cell Composition (Powalla et al. (2017)) **[53]**

IV.3. The Third Generation of photovoltaic Technologies (PV Solar Cells)

Third-generation photovoltaic (PV) technologies represent a significant leap in solar energy innovation, leveraging novel chemical compounds and advanced materials to overcome the limitations of traditional silicon-based and second-generation thin-film technologies. These systems incorporate cutting-edge materials such as nanocrystalline films, quantum dots, and perovskite structures, which offer unique advantages like tunable bandgaps, enhanced light absorption, and the potential for exceeding traditional efficiency limits. Research and development efforts aim to optimize these materials for improved efficiency, cost-effectiveness, and scalability. Despite their promising potential, many third-generation PV technologies remain in the experimental phase, facing challenges related to material stability, large-scale production, and long-term performance. Nevertheless, they hold the promise of reshaping the future of solar energy by enabling more efficient, flexible, and versatile applications compared to their predecessors.

- **The third generation of solar cells encompasses:**

IV.3. 2 - Nano-crystalline solar cells [55]

IV.3. 3 - Polymer Solar Cells (PSC) [55]

IV.3. 4 - Organic Solar Cells (OSC) [56]

IV.3. 5 - Perovskite Solar Cells (PSC) [55]

IV.3. 6 - Dye-sensitized Solar Cells (DSSC) [55]

IV.3. 7 - Quantum Dot (QD) Solar Cells [56]

IV.3. 8 - Multi-junction Solar Cells [57] , [56]

Third-generation photovoltaic cells are often described as 'emerging concepts' due to their limited market penetration, despite some having been studied for over 25 years **[57].**

IV.4. The Fourth-Generation of Photovoltaic Technologies (PV Solar Cells)

Fourth-generation photovoltaic (PV) technologies, known as hybrid inorganic cells or nano photovoltaics, integrate low-cost, flexible materials with durable and stable nanostructures. These technologies combine the lightweight and cost-effective properties of polymer thin films with the enhanced stability and functionality of advanced inorganic and organic nanomaterials. Key components include metal oxides, metal nanoparticles, and carbon-based nanostructures, such as graphene, carbon nanotubes, and their derivatives **[58] , [59]. [56].**

By integrating these innovative materials, fourth-generation PV cells address critical challenges faced by earlier generations, such as material stability, efficiency, and scalability. The incorporation of nanostructured materials enables unique properties, including:

- Improved light absorption and scattering using nanomaterials such as metal nanoparticles and graphene derivatives to capture a broader spectrum of sunlight.
- Enhanced charge transport and carrier mobility due to graphene's and carbon nanotubes' superior conductivity.
- These cells have customizable flexibility and durability, making them suitable for emerging applications like wearable devices, portable solar panels, and building-integrated photovoltaics (BIPV).

Fourth-generation photovoltaic technologies strive to combine high efficiency with low costs, positioning them as promising candidates for widespread solar energy adoption. Although many of these devices are still in experimental or early development stages, They hold the potential to transform solar energy systems by integrating the best features of both organic and inorganic materials .

V. Structure of Photovoltaic Cell Generations

In the past decade, photovoltaics have become a significant contributor to the ongoing energy transition. Advances in materials and manufacturing methods have greatly facilitated this progress. However, several challenges remain before photovoltaics can provide cleaner, low-cost energy.

The main function of a photovoltaic cell is to capture solar radiation as light and convert it into electrical energy through a process known as the photovoltaic effect. Multiple technologies are involved in the manufacturing process of photovoltaic cells, which utilize material modifications that vary in photoelectric conversion efficiencies within the cell components. With the emergence of various non-conventional manufacturing methods for creating functional solar cells, photovoltaic technologies can be categorized into four main generations, as illustrated in **Fig II.11 [60].**

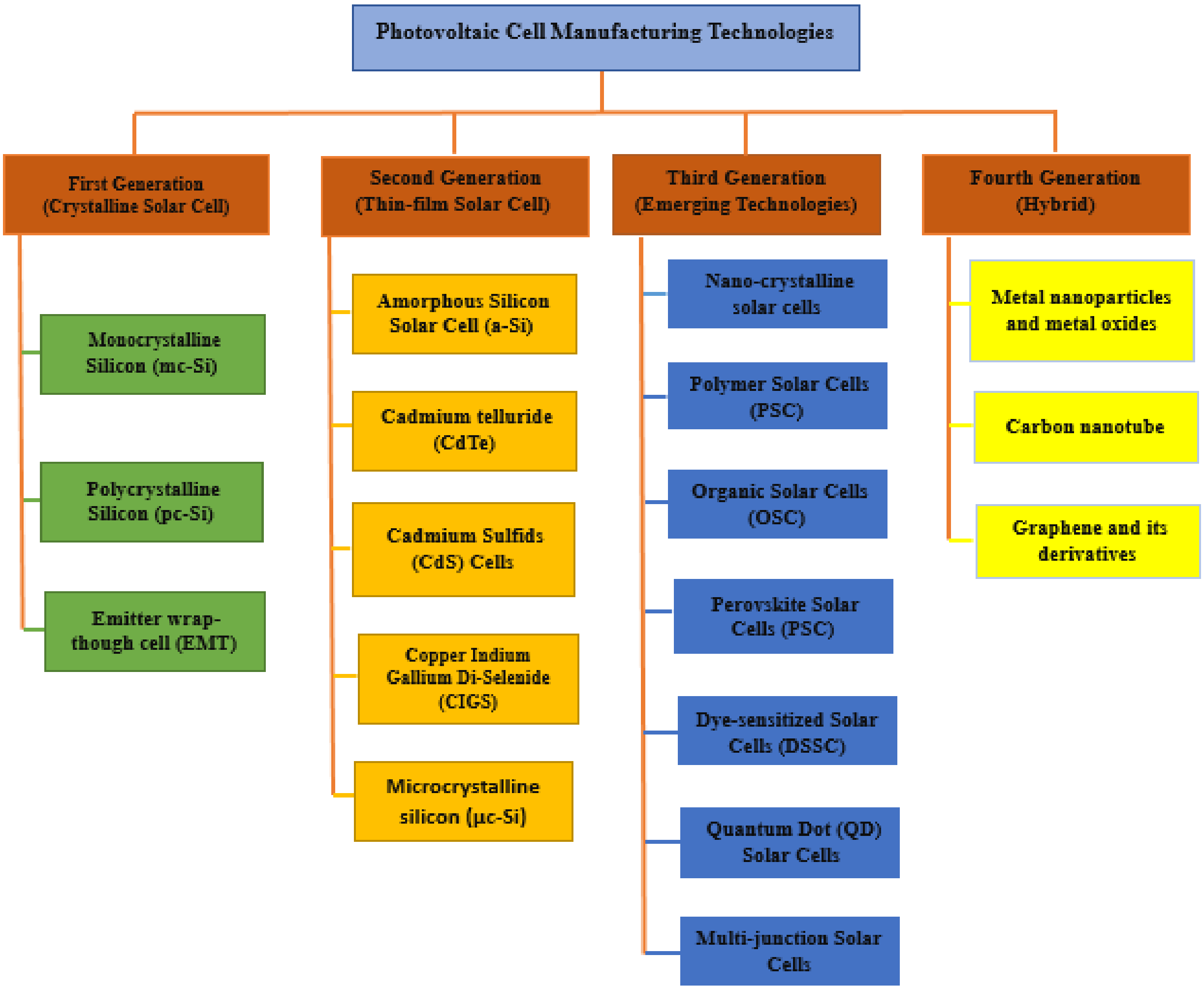

Fig II .11 . Evolutionary Different types of solar cells and the latest advancements in this field **[56,61].**

VI. Photovoltaic Generation Technologies: Efficiency, Advantages, and Disadvantage

Photovoltaic (PV) efficiency refers to the capability of a photovoltaic device, such as a solar cell or solar panel, to convert sunlight into usable electrical energy . It is expressed as a percentage, representing the ratio of electrical power output to the input of sunlight (solar energy).Photovoltaic efficiency is calculated by measuring the electrical power output of solar cells or panels under standard test conditions (STC), which involve specific light intensity and temperature. Efficiency is computed by dividing the electrical power output by the incident solar power. The resulting value is then multiplied by 100 to express it as a percentage. Multiple factors affect the efficiency of photovoltaic devices: the properties of materials, cell design, temperature, solar spectrum, losses from reflection and absorption, dirt, and shading, inverter efficiency **[62].**

Each generation of photovoltaic cells has its advantages and limitations, and research continues to improve efficiency, durability, and cost-effectiveness **[63].**

The adoption of solar photovoltaic (PV) technology encounters several challenges. These include high costs for energy storage, intermittency , resource constraints, competition from other energy sources, initial cost barriers, difficulties integrating into existing infrastructure, and environmental concerns. To ensure the sustained growth and widespread adoption of solar PV technology, it is essential to address these challenges through research, innovation, and supportive policies **[64].**

The table below highlights the advantages and disadvantages of each generation of technology, along with the efficiency levels of different solar cell generations.

Table II. 2. Comparative Analysis of the Three Generations of Photovoltaic Solar Cells: Efficiency Ranges, Advantages, and Disadvantages **[56],[65],[66],[67], [55] .**

Photovoltaic Cells					
First Generation Crystalline Solar Cell					
Photovoltaic Technologies	**Efficiency (%)**	**Band gap**	**Life Span**	**Advantages**	**Disadvantages**
Monocrystalline silicon (m-Si)	15 to 24%	~1.1 eV	25 years	- Stability -high performance - long service life	- High manufacturing cost. - More temperature sensitivity. - Absorption problem. - Material loss.7
Polycrystalline silicon (p-si)	10 to 18%	~1.7 eV	14 years	- Manufacturing procedure is simple - Profitable . - Decreases the waste of silicon. - Higher absorption compared to m-si .	- Lower efficiency - Higher temperature - Sensitivity.
Single III-V junctions (GaAs)	28 to 30%	~1.43 eV	18 years	- High stability - Lower temperature sensitivity. - Better absorption than m-si .	- Extremely expensive

				- High efficiency.	
Emitter wrap Though (EWT)	15 to 20%	~1.1 eV	20–30 years	-Increased Efficiency(By eliminating front metal contacts). -Improved Aesthetics (The absence of visible front metal lines) - Enhanced Light Absorption (The design allows more solar radiation to be captured).	- High Series Resistance (limiting the fill factor and reducing overall performance). - Complex Fabrication - Potential Heat Generation (lead to localized heating, which can degrade performance over time).
Second Generation Thin-Film Solar Cell					
Photovoltaic Technologies	**Efficiency (%)**	**Band gap**	**Life Span**	**Advantages**	**Disadvantages**
Amorphous silicon (a-si)	5 to 12%	~1.7 eV	15 years	- Less expensive. - Available in large quantities. - Non-toxic. - High absorption coefficient .	- Lower efficiency. - Difficulty in selecting dopant materials. - Poor minority carrier lifetime.
cadium telluride/cadium sulfide (CdTe/CdS)	15 to 16%	~1.45 eV	20 years	- High absorption rate. - less material required for production	- Lower efficiency. - Cd being extremely toxic, Te being limited. - More temperature sensitive.
copper indium gallium selenide (CIGS)	20%	~1.7 eV	12 years	- Less material required for production	- Very high-priced. - Not stable. - More temperature-sensitive. - Highly unreliable
The Third-Generation Emerging technologies Solar Cell					
Photovoltaic Technologies	**Efficiency (%)**	**Band gap**	**Life Span**	**Advantages**	**Disadvantages**

Nano-Crystalline Solar Cell (Quantum dots (QD))	16.6%	1.2 to 1.7 eV	05 years	- Lightweight and Flexible. - High Absorption Coefficient . - Band Gap Tunability (Allows for better solar spectrum utilization).	- Lower Stability in Outdoor Conditions -Efficiency Degradation Over Time. -Thermal Instability (sensitive to temperature fluctuations)
Polymer Solar Cells	3 to 8 %	~1.4 eV to ~ 2 eV	05 years	- Light weight and flexible, thus easy to size and shape . - Ease of storage and transportation. - Organic in nature, hence are environmentally friendly.	- Very low efficiency. - Faster degradation in outdoor situations. - Shorter lifespan .
Organic and polymeric photovoltaic cells (OPC).	9 to 11%	~1.4 eV to ~ 2.0 eV	- 05 years (advancements have extended this to approximately 15–20 years as of 2020).	- Low processing cost. - Lighter weight, flexibility. - Thermal stability.	- Low efficiency.
- Perovskite Solar Cells	21%	~ 1.5 eV to ~ 2.3 eV	- 05 years	- Low-cost and simplified structure. - Light weight, - Flexibility, - High efficiency. -Low manufacturing cost.	- Unstable. -Toxicity (Many perovskite materials contain lead). - Scalability Issues.
Dye-sensitized photovoltaic cells (DSSC)	5 to 20%	/	-10 years (recent advancements have extended this to 15–30 years as of 2020) .	- Lower cost. - low light and wider-angle operation. - lower internal temperature operation, - robustness, and extended lifetime	-Problems with temperature stability. - poisonous and volatile substances
quantum dots solar cells (QDSC)	11 to 17%	~ 0.5 eV to ~2.5 eV .	- 1 to 10 years (ongoing research aims	- Low production cost. - low energy consumption	- High toxicity in nature. - degradation.

			to extend this to 25 years).		
Multi-junction solar cells	36% and higher	~0.7 eV to ~1.9 eV.	20 –30 years.	- High performance	- Complex. - expensive

VII . Advantages and Disadvantages of the Fourth Generation of Solar Cell (Hybrid) .

This research paper provides a general overview of the different generations of solar cells. Currently, fourth-generation technologies including graphene and its derivatives, carbon nanotubes, metal nanoparticles, and metal oxides are still in the research and development phase. Due to the experimental nature of these materials and its components , precise data regarding their lifespan, bandgap values, and efficiency are not yet consistently defined across various studies. Consequently, this section will outline the general advantages and disadvantages of each fourth-generation solar cell technology discussed in this chapter.

VII.1- Metal Nanoparticles and metal oxides in Solar Cells

Advantages

- ✓ Enhanced light-harvesting efficiency due to improved optical properties.
- ✓ Potential to reduce the thickness of active layers, contributing to material and cost savings.

Disadvantages

- ✓ Compatibility Limited compatibility with existing solar cell materials, requiring advanced integration techniques.
- ✓ High cost of noble metals such as gold and silver, which can impact scalability.

VII.2- Carbon Nanotubes (CNTs) in Solar Cells

Advantages

- ✓ High electrical conductivity and excellent charge transport properties.
- ✓ Flexibility and lightweight nature.

- **Disadvantages**
  - ✓ Difficulty in large-scale production and uniformity.
  - ✓ Integration with other solar cell materials can be complex.

VII.3- Graphene and Its Derivatives in Solar Cells

- **Advantages**
  - ✓ High electrical conductivity and flexibility.
  - ✓ Potential to replace indium tin oxide (ITO), reducing costs.
- **Disadvantages**
  - ✓ Achieving uniform and defect-free graphene layers.
  - ✓ High-quality synthesis methods remain expensive.

❖ Each technology's efficiency, cost, lifespan, and application can vary widely based on the specific product and manufacturer **[68] .**

The efficiency of solar cells can be improved by reducing various losses that affect their overall performance. Since 1976, the National Renewable Energy Laboratory (NREL) has maintained a record of the highest verified research cell conversion efficiencies across different photovoltaic technologies (see Figure II.12). Cell Efficiency results for various semiconductor families are presented, including multi-junction cells, gallium arsenide single-junction cells, crystalline silicon cells, thin-film technologies, and emerging photovoltaic technologies. The most recent world record for each specific technology is highlighted by a flag on the right edge, which includes the efficiency value and the corresponding technology symbol **[69].**

This chart, known as the Best Research-Cell Efficiency Chart, is regularly updated to reflect the latest findings in research **[69].** See **Fig II.12.**

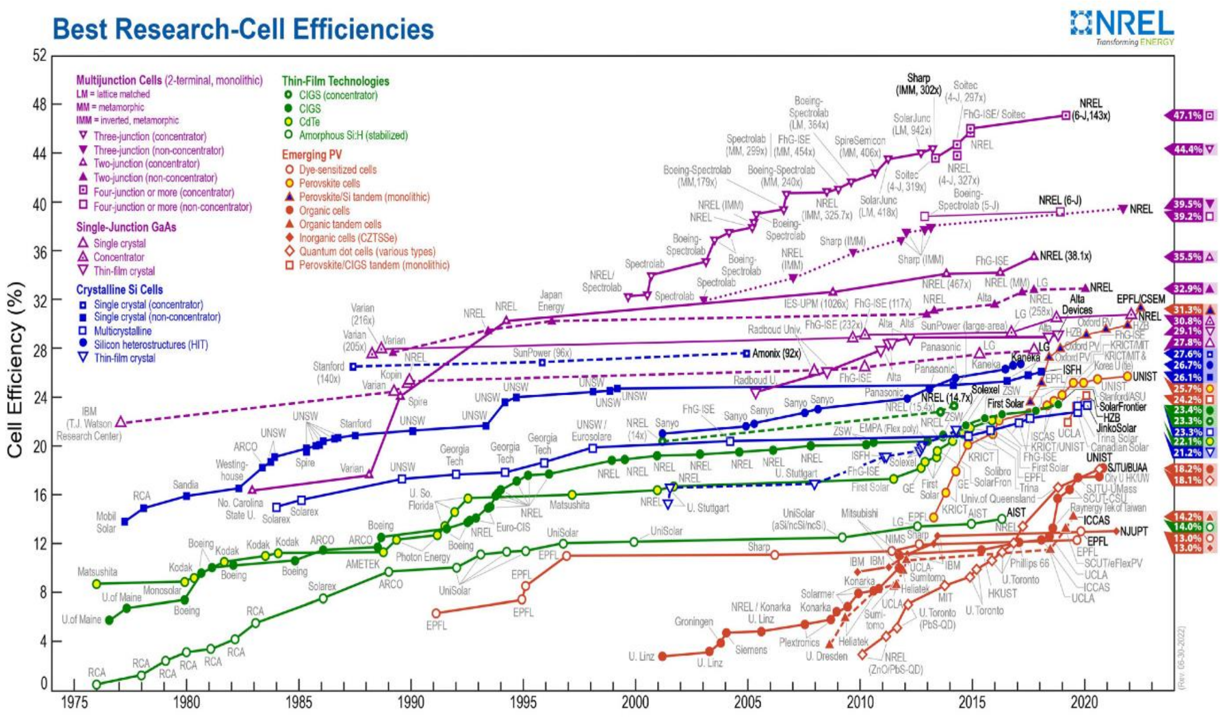

Fig II .12. NREL Best Research-Cell Efficiencies chart **[69] .**

- ✓ Here are the current highest confirmed efficiency values for different types of solar cells, as listed on the NREL chart:
- **Multijunction Solar Cells: 47.1% (research grade).**
- **Concentrator Solar Cells: 46.1% (research grade).**
- **Silicon Solar Cells (single junction): 27.6% (commercial grade).**
- **Tandem Perovskite/Silicon Solar Cells: 29.5% (research grade).**
- **Organic Solar Cells: 18.9% (research grade).**

These efficiency values pertain to research-grade solar cells and may not accurately reflect the commercial products currently available on the market **[70] .** Furthermore, these values may not be achievable in all conditions and can vary depending on the specific application and location **[71].** However, these values reflect the latest advancements in solar cell research and development, highlighting the potential for further improvements in solar energy technology .

VIII. Applications of photovoltaic cells

The applications of photovoltaic (PV) cells are broad and varied. While they are primarily designed to convert solar energy into electrical power, their use extends to several sectors, including residential buildings, industrial facilities, agriculture, transportation, and military operations. PV cells provide a source of clean, renewable energy, making them crucial in addressing global energy demands while reducing environmental impact. As the focus on sustainable energy solutions grows, PV technology is increasingly being integrated into emerging areas, such as remote power systems, portable electronics, and grid-connected infrastructure.

VIII.1 – Household Applications of Solar Cells

Photovoltaic solar cells are a modern and efficient solution that is increasingly adopted in both residential and commercial buildings. They offer numerous advantages, including reduced energy costs, enhanced environmental sustainability, and decreased reliance on traditional energy sources. In the residential sector, solar energy has diverse applications. These include electricity generation through the installation of photovoltaic panels on rooftops or adjacent land, which can power household appliances as well as heating and cooling systems. In addition, solar thermal systems are employed for domestic hot water production, supplying showers, taps, and underfloor heating. Other common uses include outdoor solar lighting equipped with rechargeable batteries and solar-powered ventilation systems that expel hot and humid air from enclosed spaces.

Furthermore, PV panels can be architecturally integrated into building elements such as facades, roofs, or railings, combining aesthetic design with functional energy production. To maximize efficiency, solar cells are often coupled with residential energy storage systems, such as home batteries, which store electricity for use during periods of low solar availability or power outages. These varied applications highlight the versatility and growing importance of solar cells in supporting the transition toward cleaner, more sustainable energy within the residential sector **[72].**

VIII. 2- Integration of solar energy in industrial and agricultural applications

Solar energy is increasingly being utilized across various industrial sectors to meet energy demands, reduce costs, and promote environmental sustainability. In agriculture, solar energy powers water pumps, irrigation systems, and greenhouses, which reduces reliance on fossil fuels and lowers associated costs. In manufacturing, solar energy is harnessed to power production processes, helping to decrease energy expenses and carbon footprints. In construction, solar panels are used to power electrical equipment on construction sites and in completed buildings. They can be integrated into roofs, facades, and structural elements, providing a renewable energy source and contributing to cost savings.

In information and communications technology, solar energy powers data centers and telecommunications networks, reducing operating costs and reducing carbon footprint. It is also used in the transportation sector to power signaling and road lighting systems, charging infrastructure for electric vehicles and electrified public transit systems although its direct use to power vehicles remains limited.

In the oil and gas industry, solar energy powers drilling, pumping, and processing facilities, reducing dependence on diesel generators and fossil fuel-based energy sources. Likewise, in the mining industry, solar energy provides electricity for equipment at extraction sites, leading to cost savings and lower carbon emissions.

Across these sectors, solar energy significantly contributes to reducing greenhouse gas emissions, mitigating the impacts of climate change, and promoting environmental sustainability, providing a reliable, clean, and renewable energy alternative **[72].**

VIII.3- Applications of Photovoltaic Cells in the Military Sector

Photovoltaic cells are primarily used in the military sector to provide autonomous, stable, and reliable power to military bases and camps, particularly those located in remote locations or difficult-to-access environments. This technology helps reduce dependence on fossil fuels and strengthen the resilience and energy continuity of military infrastructure while reducing costs and environmental impact.

Among these systems, the Eneria Hybrid Sunbox provides a compact and rapidly deployable solution for military sites. In France, the Ministry of the Armed Forces is heavily investing in solar projects that cover the rooftops of military buildings, such as the 5,600 m^2 photovoltaic panel installation at the Hexagone Balard site. This initiative generates significant energy savings and reduces dependence on electricity produced from fossil fuels.

The eco-camp concept aims to integrate solar energy production and storage to enhance the self-sufficiency and energy efficiency of military bases, especially during external operations. In addition to electricity generation, solar thermal panels supply hot water to military camps even during cloudy conditions, improving living standards and comfort on site **[73-74].**

- **Conclusion**

In this chapter, we examine the various types of solar cells used in solar panels, highlighting their critical role in affecting performance and operation. We also review in detail the materials, manufacturing processes, construction, and configurations of solar cells, as well as their working principles.

Further, this study offers an extensive overview of the photovoltaic (PV) technologies that are either currently available or anticipated to launch on a commercial scale. It delivers a thorough comparative analysis focusing on efficiency and technological processes, highlighting the most promising options. Recent advancements in materials have paved the way for innovative and more cost-effective power generation solutions, which are crucial for meeting the rising energy demands of the future. This paper provides a systematic examination of the four generations of photovoltaic cells, comparing their fabrication methods, properties, and photoelectric conversion efficiencies, along with their advantages and disadvantages.

In summary, photovoltaic (PV) technologies have the potential to transform the energy sector by offering a clean, efficient, and cost-effective source of electricity. As we strive for a sustainable future, it is essential to continue supporting the development and implementation of innovative PV technologies to harness their capabilities thoroughly.

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