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Review

Techno-Economic and Environmental Perspectives of Solar Cell Technologies: A Comprehensive Review

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Abstract: This paper provides a review of the implementation of different materials and how they have impacted the efficiency of solar cells. This work elaborates on all solar generation methods that have been developed in the past and covers disparate technologies that are being implemented in different generations. A review of the characterization and factors involved in these processes are also discussed briefly. Furthermore, the economic, environmental, and technical perspectives related to solar cells have also been expounded. This paper also provides some insights into potential research directions that can be pursued in the field of solar energy. Energy demands are increasing all over the world, and substantial amounts of fossil fuels are currently exhausted all over the world in order to meet those needs, which in turn contaminates our environment; moreover, non-renewable sources of energy are diminishing at higher rates as well. Solar energy is of prime importance in all renewable energy sources as the Sun shines at the Earth for 8 to 10 h on average. Thus, heat can be harnessed to generate electricity, but solar cells are not substantially efficient because the materials used in them are quite costly and waste a considerable amount of energy, mostly as heat, which subsequently reduces the efficiency of the cell and increases the overall price as well. These challenges can be dealt with by designing more efficient, economical systems of storage and manufacturing PV cells with high efficacy. Scientists and engineers are more inclined toward advanced technologies and material manipulation to enhance the efficiency of solar energy and reduce its cost. In this regard, substantial research is being carried out, especially on the structure of materials and advanced materials like nanomaterials and quantum dots. Due to their distinct electromechanical and material properties, carbon-based nanomaterials like carbon nanotubes, graphene, fullerene, and nanohybrids are being employed as the electrodes, transport layers, active layers, or intermediate (interfacial) layers of solar cells in this regard.

Keywords: nanomaterials; solar energy; carbon-based nanomaterials; characterization; PV cells

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1. Introduction

The conventional sources for generating electricity are fossil fuels, which have decimated our climate to considerable degrees as they are the major source of CO_2 emissions all over the globe. Other intricate issues associated with fossil fuels are not that easy to envisage; for instance, acid rain, which is caused by sulfur contents in fossil fuels, poses great threats to aquatic life, buildings, insects, and trees [1–3]. For one ton of consumed coal, around one ton of carbon dioxide is emitted into the atmosphere. This emitted carbon dioxide is perilous and toxic to the environment and a major driving force behind intense weather conditions, ozone depletion, changes in climate, and the greenhouse effect [4,5]. The Sun is considered to be the primary and major source of energy. The Sun emits substantial energy every second in the form of radiation, and this energy can be exploited to generate electric energy using photovoltaic cells [6,7]. Silicon, which is a semiconductor material, is considered to be the basic material that is employed in the fabrication of solar cells. In photovoltaic cells, the band gap of semiconductors characterizes the range at which solar energy is efficiently converted to charge carriers for a specific material. Not all solar energy that falls on solar cells can be converted to electrical energy. Semiconductor materials contain electrons in the valance band, and when incident light falls onto the surface of materials, these electrons move from the valance band to the conduction band if the band gap energy required to jump from the valance to conduction band is fulfilled by falling incident light [8]. If the band gap energy is not met, it would excite the electron and return to its valance band after vibrations without any prolific outcome. Moreover, if more energy is obtained than what is required for the band gap, it would change the material's properties. When incident light falls on semiconductor materials, electron–hole pairs are created, which are splintered by an electrical circuit, and power is generated. But, solar cells made from silicon material have very low efficiency and very high cost [9]. The major reason for the low efficiency of solar cells is the waste of solar energy in the form of surface reflection, losses due to recombination of electrons and holes via a process called auger recombination, the inadequacy of solar cells to meet the minimal band gap energy, and losses with respect to heat when there is more energy than required for the band gap. The last two contribute to half the number of losses in solar cells [10]. These two losses directly lead to a "Shockley-Queisser limit" of around 34%, which is the theoretically calculated amount of solar efficiency in solar cells as shown in Figure 1. Currently, nanotechnology and nanomaterials are being employed to enhance solar cells' efficiency beyond the "Shockley-Queisser limit" and to reduce costs [11].

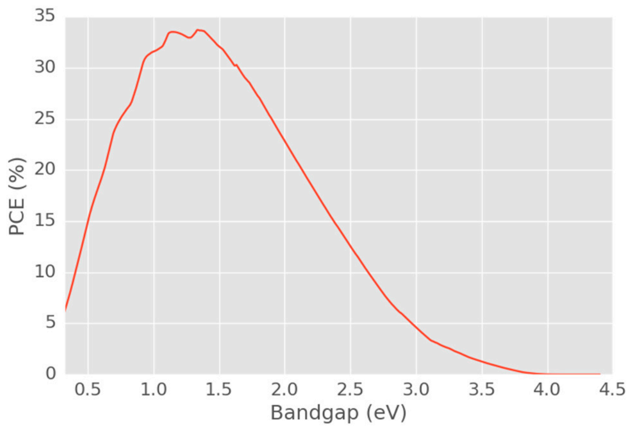

Figure 1. Shockley–Queisser limit at 1.2 eV which is 33.7%.

Nanotechnology is the technology of the 21st century, and it works at the tiny nanometer scale. The spatial structure shows that even at a billionth of a meter, materials can be exploited to serve many purposes in order to broaden the application scope of many technologies, especially solar cells. In particular, with respect to nanomaterials, their surfaces have some particulates called nanopowders, and they can alter the properties of base materials, like temperature, melting points, thermal conductivity, and electrical properties, compared to the larger constituents of the same particles. Material surfaces and structures that are composed of nanometer scales have larger surfaces and spatial structures, and they come into contact with each other as well. Specific structures in nanomaterial can create new effects like scattering (diffraction), which can be used to distribute light more homogenously on surfaces in order to make them more reflective and translucent [12,13]. Many losses of energy are caused by the material's interactions on the nanometer scale, as shown in Figure 2.

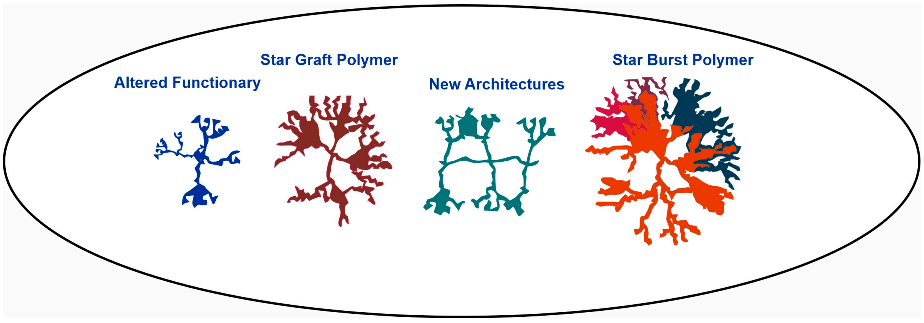

Figure 2. HBP-based synthesis (+model compound).

To increase the efficiency of solar cells, researchers started working on silicon wafers at nanometer scales by making bulk into more discrete forms. In this way, nanostructures would respond to different spectrums of light in productive ways. To carry this out, nanoparticles were dispersed in isopropyl alcohol and then distributed all over solar cells; after all alcohol evaporated, the particles were stuck to solar cells, and after observations, it was observed that the cells showed a spike of around 60 % in efficiency in the ultraviolet region of light for a film measuring 1 nanometer. But efficiency in the visible region was lower at about 3%, but as the 2.85-nanometer film was used, efficiency increased from 60% to 68% in the ultraviolet range and to 10% in the visible region of the spectrum [14]. There is a repertoire of technologies that are utilized to produce one- and three-dimensional structures in the field of nanostructuring; for example, a technique called laser ablation is used to generate nanostructures on textile fabrics via laser radiation. During laser ablation, high-power laser irradiation is applied on the surface of precursor materials, and the materials were vaporized; as a result of this process, nanoparticles were formed [15]. Other techniques include focused electron beams (FEB/FIB), chemical vapor deposition (CVD), biomimetic methods, and nanoreplication. In FEB, the finest nanostructures on materials were deposited using focused electron beams, as evident from the name [16]. With respect to chemical vapor deposition, carbon nanotubes and fine particles are produced. Using CVD, a thin coating on the surface of substrate materials is produced by the chemical reactions of the vapor phase of materials [17,18]. Biomimetics is a technique that comprises methods that use nanostructures on natural materials [19]. Nanoreplication involves techniques by which large-area nanostructures are made using stamping methods [20]. The techniques and methods that endorse the nanostructuring of objects at larger scales are indispensable in terms of decreasing costs and increasing the use of nanomaterials in the energy sector [21].

2. Methodology

In this paper, a quantitative review of solar cell generation is provided. The main emphasis of the paper is to target recent developments in solar technology and the techno-economic and environmental impacts of PV technology. A detailed analysis was completed after researching and reviewing the recent scientific literature. Many studies on PV technologies were identified; however, updated data describing current improvements in the performance of solar cells up until 2023 were not available. In addition, the growing economic impact on research and the application of advanced developing technologies are expounded. On the basis of statistical data, we noted the tendencies of various PV technologies, compared their performances, and forecasted their future growth. The techno-economic and environmental impacts of the latest reports published by internationally recognized organizations were taken into consideration. The methodology of the review was similar for all papers as they discussed different generations of solar cells along with various aspects affecting solar cell development. This study discusses the development of each solar generation in a more comprehensive way compared to previous studies. This review study was carried out by reading the already existing literature and recent developments in a critical way in order to identify significant points. The organization of this paper is as follows: Section 3 discusses all generations of solar cells in detail. Section 4 provides comparisons of the confirmed recent efficiencies of solar cells. Section 5 provides a concise review of the trends in power generation from PV technology across the world. Section 6 discusses the factors involved in the characterization of PV modules. Section 7 discusses a few present and future perspectives on PV technology. Section 8 provides some insights and suggestions for future applications. In Section 9, a brief summary is provided, while Section 10 concludes the paper. Table 1 shows the selection criteria for reference papers and numbering of papers cited for specific part of this review paper.

Table 1. Selection criteria for cited papers.

Sr. No	Selection Criteria	Cited Papers
1	First-Generation Solar Cells	[10–26]
2	Second-Generation Solar Cells	[27–48]
3	Third-Generation Solar Cells	[49–76]
4	Concentrated Solar Cells	[77–83]
5	Comparison of Efficiency of solar cells	[84]
6	Global and regional Trends	[85,86]
7	Characterization of PV modules	[87–93]
8	Current and Future Perspectives of PV technology	[94–103]

3. Development of the Generation of Solar Cells

3.1. First-Generation Solar Cells

Wafer-based solar cells: It is quite evident from a historical perspective that the oldest material that is employed in solar cells all over the world is silicon because of its abundance in nature and band gap energy of around 1.17 eV. The manufacture of incipient Si solar cells gave rise to first-generation solar cells. These devices consisted of semiconductors with a p-n junction and are considered to be the most dominating solar cells in the market because of the excessive availability of high-quality silicon and its usage in microchips [10]. After the invention of solar cells based on silicon back in 1954, the efficiency of solar cells has been a major problem, and substantial research has been carried out on this. The initially estimated efficiency of these cells was around 22%. Efficiency mainly depends upon the band gap of solar cells, which is around (~15–22%) for crystalline solar cells. Some essential parameters define the efficiency of solar cells: short circuit current I_{sc}, open circuit voltage $V_{oc,}$ maximum power, and efficiency. Mathematically, they can be related as follows.

$$\eta = \frac{\text{Vmax} \cdot \text{Imax}}{\text{Psun}} = \frac{\text{VOC} \cdot \text{ISC} \cdot \text{FF}}{\text{Psun}} \tag{1}$$

There are some other factors that, if accounted for, reduce the efficiency of solar cells considerably compared to the estimated solar cell's efficiency. The physical structure of cells contributes substantially to the determination of solar efficiency. Based on physical structure, solar cells are categorized as mono-crystalline or polycrystalline [9]. Mono-silicon crystals are made from single silicon crystals via a process called the "Czocharlski Process". In this process, large crystals are sliced and recrystallized, and this is a sophisticated process that requires precision, which increases the price of mono-crystal solar cells. The efficiency of these cells is 26.1%. Mono-crystalline solar cells exhibit stability, high performance, and long life. The major problems with these cells are that they are sensitive to temperature, have high production costs and there is material loss during the manufacturing process [6]. Polycrystalline cells consist of multiple crystals joined together to form a single cell. This process is more economical compared to mono crystals. Silicon is molded into a graphite mold, which is further cooled. Polycrystalline cells are most widely used all around the globe because they have low production costs [22]. To reduce the price and enhance the efficiency of first-generation solar cells, emitter wrap-through solar cells were implemented. Using this technology, both the fill factor and efficiency increased. A sequential simplified process is employed instead of back-to-back junction solar cells, and high open-circuit voltages are obtained. Resistance is also optimized in the path between the base and emitter to improve the overall fill factor [23]. An experiment was conducted in 2011 for n-type silicon solar cells, and an efficiency of around 21.6% was achieved [24]. The latest achieved efficiency of multi-crystalline solar cells is 23.3% [25]. Compared to mono-crystalline solar cells, polycrystalline cells are simple to manufacture and economical, and during production, lower amounts of materials are squandered, and they have better electrical characteristics. The drawbacks of these cells include higher sensitivity to temperature and decreased efficiency [10,26]. Overall, first-generation solar cells have matured and are more efficient at lower temperatures, and they produce more power per unit. They also occupy more of the market compared to any other generation of solar cells. The main disadvantage of this generation is their poor performance at high temperatures.

3.2. Second-Generation Solar Cells

Thin-film solar cells are regarded as second-generation solar cells and are praised for being more affordable than the previous generation. They have light-absorbing layers measuring around 1 micrometer in thickness [27]. They are divided into three categories: amorphous silicon, cadmium telluride (CdTe), and copper indium gallium di-selenide (CIGS).

3.2.1. Amorphous Silicon Thin Films

Amorphous silicon (a-Si) solar cells are the most rudimentary solar cells that were developed at the industrial scale. They can be fashioned at very low temperatures, resulting in many low-cost polymers and substrates that have highly flexible applications. They are widely available because of their low cost. As evident from the name, they have disarranged non-crystalline lattice structures [28]. As for their disordered and dangling atomic structure, their charge carrier mobility is quite poor. This is one of the main reasons why mono-crystalline solar wafers made of silicon are more efficient than both thin-film amorphous silicon cells and polycrystalline cells. They are created by covering the doped silicon on the substrate's back. These solar cells have a silvery conductive side, and the reflective side is usually brown. Although they have low costs, their efficiency is also low, and the efficiency of amorphous silicon solar cells has a theoretical limit of about 15% [29]. Amorphous silicon is not a prolific semiconductor when it comes to efficiency, but if hydrogen is added to the structure, efficiency improves considerably. By adding hydrogen, the suspended sites in amorphous silicon establish bonds with hydrogen, and as a result of this, photoconductivity is enhanced. The optically optimized cell, which is the best-in-class amorphous solar cell, achieved an energy conversion efficiency of 14% [30]. The comparison of efficiency in all three technologies based on silicon is compared in Figure 3. One of the major drawbacks of a-Si is the degradation they experience as they are deployed, and this persists over a period of time. The degradation of a-Si:H was studied by Osayemwenre and Meye, and they observed that efficiency decreased considerably during the monitored time period. Efficiency was reduced by 0.2% with each degree of increase in temperature [31].

Figure 3 describes the efficiency of silicon-based solar cells from 1975 to 2022. The theoretically calculated efficiency of various silicon solar cells is also depicted. The Shockley–Queisser limit is around 33% for pure silicon solar cells. The semiempirical efficiency is 22%, and the original efficiency value is 30%. Monocrystalline solar cells and polycrystalline solar cells exhibited almost the same efficiency of around 14% in 1980; currently, monocrystalline solar cells have reached an efficiency of around 26%, while the efficiency of polycrystalline is measured at 24%. Hydrogenated silicon solar cells have a semiempirical solar cell efficiency of around 18%. The original value of efficiency was 27%, while the modern value measures up to 28%. Currently, a-Si:H racked up the highest efficiency of 14%.

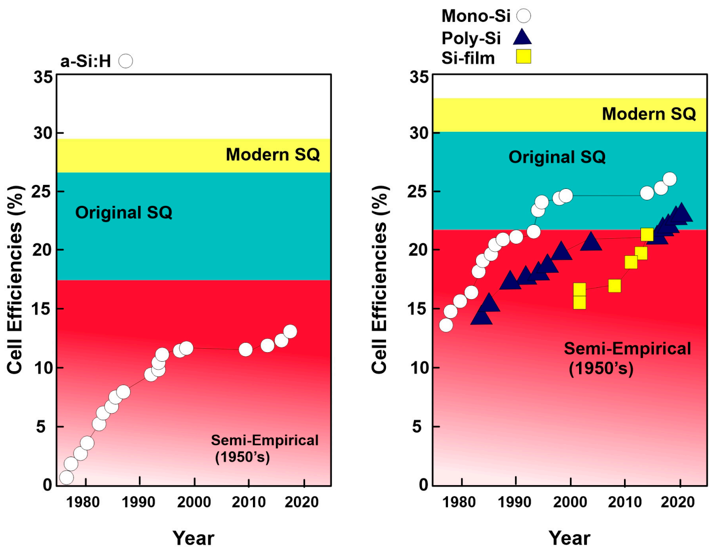

Figure 3. Efficiency of solar cells from 1975 to 2022.

3.2.2. Cadmium Telluride Thin Solar Film (CdTe)

Another type of solar cell that is being developed under the spectrum of second-generation solar cells comprises cells that are composed of cadmium telluride. Cadmium telluride is a perfect material for making polycrystalline solar cells because of its optoelectronic and chemical properties, and it would have low costs as well. CdTe is a direct band gap material with a band gap value of 1.5 eV and an absorption coefficient of ~10^5/cm in the visible region, subsequently making it a perfect absorber for around 90% of the incident light, and it measures only a few millimeters in thickness. This is because high-temperature deposition films are usually deposited with lower quantities of Cd, which gives rise to p-type conductivity. Due to the increased number of ions (around 70%) in CdTe, the crystals are usually more passivated, and they exhibit rugged chemical bonding and around 5.75 eV with respect to energy, which imparts increased chemical and thermal stability upon them. It has been demonstrated that CdTe solar cells are exceptionally resistant to deposition techniques. Solar cells are made based on CdTe junctions [32]. The record laboratory efficiency for a CdTe solar cell is 22.1% even though their supposedly predicted efficiency is about 33% [33]. In 25 years, their efficiency has been boosted from 15.8% [34] to 22.1% [25,35]. The slow progress in efficiency boost is because of the lack of R & D with respect to CdTe, and this is perhaps due to concerns regarding the environment and its toxicity [36,37].

3.2.3. Copper Indium Gallium Di-Selenide (CIGS) Solar Cells

CIGS solar cells were first developed in 1974 in the laboratory with an initial efficiency of around 6%. In 1975, by adding CdS to CIGS, efficiency galloped to 12%, which exhibited the potential of the material's development on an industrial scale. CdS is an n-type semiconductor material, and when added to CIGS, it acts as a buffer layer, which subsequently allows the separation of charge carriers. In an experiment in 2017 at the University of Santa Clara, the United States, four buffer layers (InS, ZnO, ZnS, and ZnSe) instead of CdS were employed in CIGS cells, and it was observed that ZnS turned out to be better among all competitors with an efficiency of around 20.7% [38,39]. CIGS has some exceptional photovoltaic properties like greater absorption coefficient and high radiation tolerance, which makes it quite a suitable material for applications in solar cells [40]. Sulfur in these solar cells has a very rapid diffusion rate during deposition, even at lower temperatures, which halts the fabrication and development of these cells [41,42]. Sputtering, evaporation, electrochemical coating, printing, and electron beam deposition are methods used to treat CIGS. Sputtering can either be a one-step reactive process or a two-step procedure that involves first depositing the material and then interacting with selenium. Evaporation can be carried out with multiple steps or single steps, similarly to sputtering. The substrate that is used for CIGS technology can either be glass, polymer, steel, or aluminum. The advantages of using CIGS include higher efficiency and a low degradation rate, which means that these solar cells would have longer life [43–45]. $CuInSe_2$ has a more benign nature from an electrical perspective, and its band gap can also be varied depending on the light spectrum, subsequently making it an indispensable material for enhancing efficiency. CuInSe2 films are an equally effective kind of electrical material compared to their single crystalline cousin. Due to this characteristic, the material is less sensitive to impurities, grain size, and crystalline flaws. An efficiency of around 22.8% [46] was achieved compared to crystalline silicon (c-Si)-wafer-based solar cells [47] for small areas, and 15% efficiency was achieved for large areas by tailoring the band gap according to the spectrum of light. Superior performance can be attained by matching the junction with the band gap energy of the solar spectrum. The latest achieved efficiency for CIGS solar cells is 23.6%, as reported by NREL [25]. Although these cells have achieved remarkable efficiencies and promise a bright future in enhancing efficiency, due to the usage of alloy in their formation, some intricate processes are involved, and they require precise control during deposition and composition, which is not easy to achieve. The modules are also vulnerable to water ingress, and humidity can jeopardize the stability of non-encapsulated CIGS solar cells [48]. The utilization of materials like indium and gallium also increases the overall cost. Figure 4 shows an Excel graph plotted using values acquired from NREL, and it shows the overall efficiencies of second-generation solar cells.

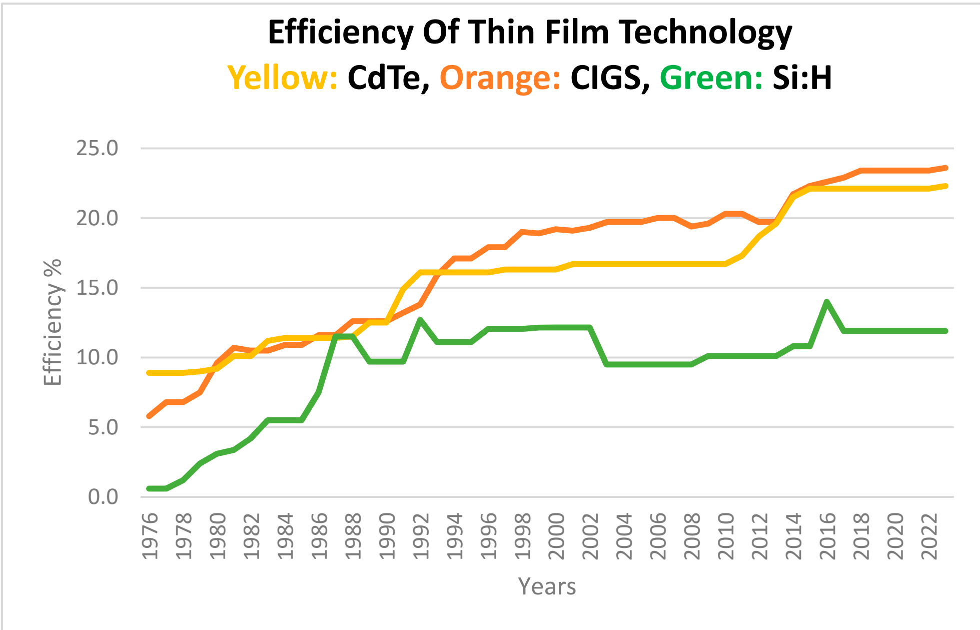

Figure 4. Efficiency of thin film technology.

The graph above shows the efficiency of thin film technology within the span of four decades. Yellow, orange, and green colors show the efficiency trends of cadmium telluride, copper indium gallium, and hydrogenated solar cells from 1976 to 2022.

3.3. Third-Generation Solar Cells

Third-generation solar cells are the successors of the second generation, and they promise greater efficiency at lower costs. The major purpose behind the creation of this generation is to surmount the shortcomings of the second generation. One of the remarkable advantages of this generation is the fallout of power costs from 80% to 50% at larger scales compared to second-generation solar cells. The other major advantage is that this generation utilizes a variety of materials, like organic materials, dyes, perovskites, and quantum dots, whereas the second generation only uses CdTe and CIGS. Under the umbrella of third-generation solar cells, various cells have been developed, with promising results. Third-generation cells entail organic solar cells, dye-sensitized solar cells, quantum dot solar cells, perovskite cells, and nanomaterial-based solar cells, which are explained in detail in the upcoming sections.

3.3.1. Organic Solar Cells

These solar cells use organic materials such as polymers and small molecules as active layers. They are cheap to manufacture, flexible, and lightweight. The general materials used for PV solar cells comprised inorganic materials. Thus, research studies are conducted to find new ways of improving efficiencies by developing novel materials. After the formation of a semiconducting polymer, these materials were incorporated into organic solar cells, which showed an unexpected improvement. This kept costs low and boosted performances beyond conventional materials [49]. Organic solar panels mainly consist of at least four layers with a translucent substrate, as shown in Figure 5. The substrate is used to protect materials from impurities, and the device is illuminated through this substrate. It could be made up of glass or polyester. In organic solar cells, a donor–acceptor heterostructure is formed by donor–acceptor moieties, which come into close contact with each other to form an organic solar cell. When a donor absorbs a photon with sufficient energy, the electron leaps into the lowest unoccupied molecular orbital (LUMO), rendering a hole in the highest occupied molecular orbital (HUMO), and this engenders an exciton.

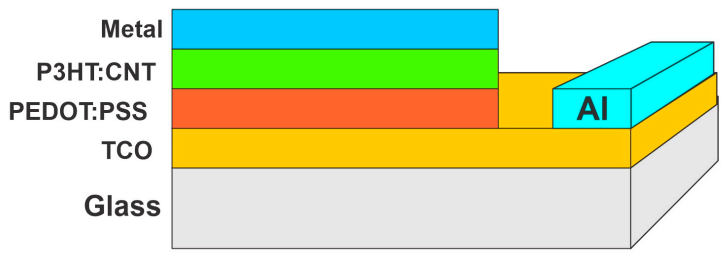

Figure 5. Schematic diagram for a typical basic organic cell with CNTs as acceptors within the active layer.

The difference in energy between the orbitals determines which wavelength of light would be absorbed. Unless immediately separated, the exciton recombines. To dissolve the exciton, the acceptor material must offset the exciton's binding energy in the donor. The charge transfer at the interface is only possible if the following conditions are met:

$$E^{A}{}_{A} - E^{D}{}_{A} > U_D \tag{2}$$

where E_A stands for electron affinity, and U_D stands for the exciton's binding energy in the donor; the acceptor and donors are represented by superscripts A and D. The electron generated from a photon of light moves to the acceptor's LUMO if the acceptor exhibits greater electron affinity compared to the donor. Moreover, organic semiconductors exhibit lower charge carrier motilities compared to inorganic semiconductors. Organic solar cells fall behind traditional silicon PV as their highest single-junction solar cell reached a PCE of 19.2%. On the other hand, single-junction silicon solar cells surpassed the efficiency by 35.5%, reflecting the highest performance [50–52]. As PCEs in laboratory-scale devices (1 mm^2) reach the target of 20%, vast-area device modules with moderate PCEs have been produced. The PCE for a module is commonly known to exhibit roughly 5% less efficiency than that of laboratory-scale devices in the OSC sector. In recent papers, a power conversion efficiency (PCE) of 5.6% was obtained by using a module with an active area of 216 cm^2 (16 elementary cells are coupled), and this is a key step toward large-scale organic solar cell applications [53]. The reason for the lower efficiency is the additional assistance (energetic cost) needed to separate and extract charges. Although most leading companies are making significant progress in large-surface-area deposition and encapsulation, scaling from small devices remains a challenge today. Critical efficiency, the stability of the device under ambient working conditions, enhanced lifetime, low-cost production technologies for mass production, and a greater absorption coefficient are considered major challenges that need to be overcome in emerging and efficient organic solar cells (OSCs). To improve these critical aspects, many researchers, scientists, and academics are working to commercialize this new technology and obtain feasible standards with respect to efficiency, reliability, and stability. The major strength of organic photovoltaic cells is their higher throughput and lower cost, but they cannot be marked as superior with respect to performance.

3.3.2. Dye-Sensitized Solar Cells

DSSCs are electrochemical cells that mimic plants for energy production. Energy is harnessed by the combined effect of chemical processes and light energy. These solar cells use a layer of dye molecules to absorb light and transfer electrons to a semiconductor material. It is potentially cheaper and more efficient than conventional silicon solar cells [54,55]. DSSC uses a photo anode, sensitizer, electrolyte, and counter electrode. Light is absorbed by a sensitizer, which is fastened to the surface of a wide-band semiconductor. At the interface, charge separation happens via the injection of photo-induced electrons from the dye into the solid's conduction band [56]. Carriers are carried to the charge collector via the semiconductor's conduction band. By combining sensitizers with a wide absorption band with oxide coatings with a nano-crystalline shape, a considerable amount of sunlight can be absorbed. The quantitative conversion of incident light photons to electric current is accomplished over a broad spectral range stretching from UV to near-IR areas [57]. The conventional manifestation of dye-sensitized solar cells consists of two translucent conducting oxide (TCO)-coated glass electrodes; typically, the substrate glass is coated with fluorine-doped tin oxide (FTO). Among these, one of the substrates is coated with a photo electrode (PE) made of 10–15-micrometer-thick layer of interconnected titanium dioxide (TiO_2) particles that are sensitized using dye molecules usually comprising an organometallic compound made of ruthenium. The other substrate is coated with a catalyst, such as platinum, and works as a counter electrode (CE). To prevent short-circuiting between both electrodes, they are segregated via a thermoplastic spacer or a thick and porous insulating layer [55]. During the operation of these cells, by using a liquid electrolyte that contains a redox mediator that is usually made up of iodide/triiodide-based redox shuttles, charges are exchanged between both PE and CE. The mediator is diffused not only through the porous TiO_2 electrode but also through the porous spacer and the large phase of the electrolyte as well. Therefore, the thickness of the thermoplastic spacer and porous insulator directly impacts the performance of dye-sensitized solar cells via mass transport and the diffusion resistance of the bulk electrolyte [55]. Under typical conditions, the best co-sensitized solar cells demonstrated a power conversion efficiency of 15.2%, while larger devices with an active area of 2.8 cm^2 demonstrated an even greater efficiency ranging from 28.4% to 30.2%. These outcomes are outstanding and show the capability of DSSCs for high efficiency [58].

3.3.3. Perovskite Solar Cells

These solar cells use a class of crystalline materials called perovskites to absorb light and generate electricity. By absorbing light over a wider spectrum of wavelengths, multijunction (tandem) solar cells (TSCs), which are made up of several light absorbers with noticeably distinct band gaps, have significant potential with respect to surpassing the Shockley–Queisser (S-Q) efficiency limit of a single-junction solar cell [59]. Due to their customizable band gaps, high PCE of up to 25.8%, and simple manufacturing process, perovskite solar cells (PSCs) are excellent candidates for TSCs. Narrow-band-gap PSCs and dye-sensitized, organic, and quantum dot solar cells are just a few of the numerous solar cell types that can be easily combined with PSCs with high PCEs, which are commonly made by using a low-temperature solution approach. In fact, since their initial invention, perovskite TSCs have sparked tremendous interest in science and the industry [60]. Figure 6 explains the composition of materials in thin-film perovskite solar cells and perovskite deposited on silicon tandem solar cells.

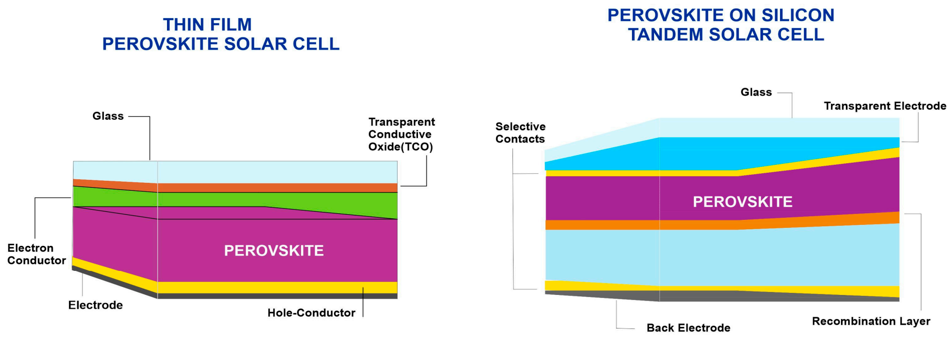

Figure 6. Material composition of thin-film perovskite solar cells vs. perovskite on silicon tandem solar cells.

Excellent light absorption, charge-carrier mobilities, and lifetimes provided by perovskite materials lead to high device efficiencies and potentially low-cost, commercially viable technologies. Furthermore, via the unique control of optoelectronic properties, perovskite thin-film technology has the potential to reach the theoretical efficiency limit for single-junction solar cells [61]. Device stability and device upscaling are two constraints that prevent perovskite solar cells from becoming commercially viable. Temperature [62], humidity [63], composition [64], and light [65] are all elements that contribute to degradation [61]. These cause material degradation and a decline in performance over time. We must overcome obstacles relating to stability and environmental compatibility in order to accomplish this promise, but if these issues are resolved, perovskite-based technology holds revolutionary potential for quick terawatt-scale solar deployment. Due to the fundamental features of the material, hybrid perovskite solar semiconductors are being studied for their usage in a broader class of energy applications, which extends beyond conventional electrical and optical systems. Perovskite materials' superior light absorption, charge-carrier mobility, and lifetimes result in high device efficiencies and the possibility of a cheap, marketable technology. Obstacles relating to stability and environmental compatibility need to be overcome to realize this potential, but if these issues are addressed, perovskite can be used [66].

Perovskite has attracted global attention due to its remarkable efficiency growth. Monolithic perovskite/silicon tandem showed consistent improvements in their efficiency in the past decade. As can be seen in Figure 7, in 2018, the performance of the perovskite/SI tandem has risen exponentially within a duration of two years, and it obtained a PCE of 33.7%. In contrast, this was not attained by single-junction perovskite for a decade until now. By analyzing the improvement in efficiency, it can be predicted that the monolithic perovskite tandem has the ability to surpass the Shockley–Queisser limit [67]. After resolving the concerns regarding its stability, it can be manufactured at massive scales that could contribute to decreasing carbon emissions.

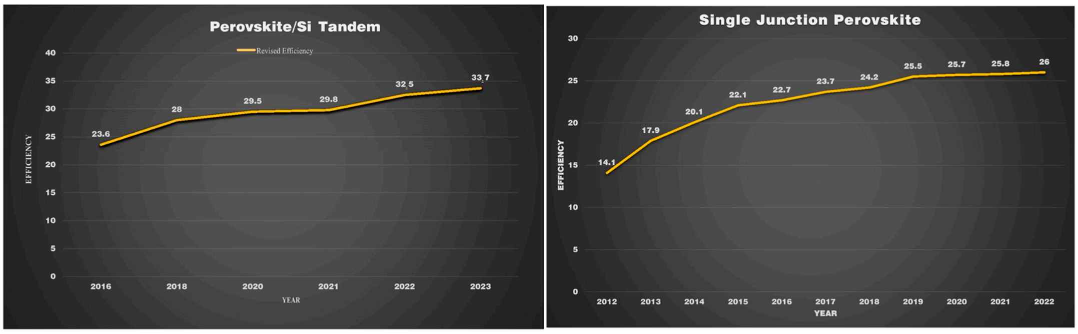

Figure 7. Efficiency records for perovskite PV cells compared to other PV technologies, with current records of 26% for single-junction perovskite devices and 33.7% for tandem perovskite–silicon devices.

3.3.4. Quantum Dot Solar Cells

These solar cells use tiny semiconductor particles called quantum dots to absorb light and generate electricity. The highest thermodynamic efficiency for turning solar energy into electrical or chemical energy was determined to be 31% by Shockley and Queisser in 1961 [68]. This limit results from the heat-loss processes of electron–phonon scattering and phonon emissions caused by the relaxation of photo-generated hot carriers relative to band edges. Several strategies have been proposed to overcome this restriction, such as stacking numerous cascaded p-n junctions with band gaps that are better matched to the solar spectrum and making use of the hot carriers before they relax in the band's margins. By generating a higher photovoltage or photocurrent, hot carrier solar cells can improve the efficiency of photon conversion [69]. Hot holes often cool more quickly than hot electrons despite the electrons' substantially lower effective mass. Hot holes and hot electrons typically cool at different rates, with electrons cooling more slowly due to their substantially lower effective masses. The amount of cooling is also impacted by the density of photo-generated hot carriers [70]. Another initiating point to increase the efficiency of solar cells is to use semiconductor quantum dots. By using quantum dots, the band gap energy can be manipulated to respond to longer light wavelengths, subsequently enhancing the efficiency of solar cells. Quantum cells can produce power at all hours of the day. This is because they can be configured to emit infrared light in addition to visible light even though nighttime generation would be far less abundant than daytime output [71]. As the material for these quantum dots, the conglomeration of different materials is preferred, such as Si/Ge, Si/Be, and Te/Se [64,65]. To enhance the efficiency of solar cells, substantial research has been carried out on the absorption layer of quantum dots. Up until now, an efficiency of around 18.1% has been gained [72]. But, by improving the absorption property of the Si-QD layer, higher efficiency can be achieved, and recent experiments have revealed that higher efficiencies were achieved by carrying this process out. The QD secondary deposition method has been employed in the past to enhance QD loading; however, it creates new recombination centers, which are inefficient for enhancing the photovoltage and fill factor.

New adsorption sites are created without the addition of new recombination centers by adopting the authors' novel QD secondary deposition method. The QD pre-sensitized photoanodes are surrounded by a metal oxy-hydroxide layer in this method. Zn, Cu, In, S, and Se (ZCISSe) QD-sensitized TiO_2 film electrodes were used to research this secondary deposition technique. The experimental results demonstrate that the new strategy enhances QD loading, and as a result, the photocurrent, photovoltage, and fill factor have all significantly improved. ZCISSe QDSCs now have an average power conversion efficiency (PCE) of 15.31%, up from the original 13.54%, and a new certified PCE record of 15.20% for liquid-junction QDSCs has been attained [73]. The development of a metal oxy-hydroxide layer over QD-presentive TiO_2-film electrodes allows for secondary depositions without the addition of extra recombination centers. It can be seen in Figure 8, that metal oxide layers have been widely used as barrier layers around pure TiO_2-film electrodes in dye-sensitized solar cells (DSCs) to increase sensitizer loading and reduce charge recombination [74,75]. Here, metal oxy-hydroxides were produced from equivalent metal chloride aqueous solutions by a simple hydrolysis and condensation method. It was discovered that the oxy-hydroxides of Mg^{2+}, Ti^{4+}, Ca^{2+}, and Sr^{2+} could significantly enhance QD loading and produce a profoundly helpful impact on the photovoltaic performance of the corresponding QDSCs.

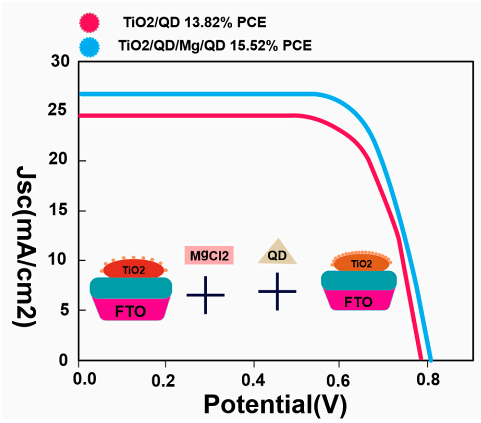

Figure 8. The average PCE of the resulting ZCISSe QDSCs increased from the initial 13.82% to 15.52%.

A thicker photoanode film enhances the loading amount of QD sensitizers and light-harvesting capacity, resulting in a high photocurrent. However, it can also increase the distance for photo-generated electrons to travel and result in undesired charge recombinations, leading to a deterioration of photovoltaic performance. From Figure 9, it can be noted that optimizing the thickness of the photoanode film is significant for high-performance QDSCs. In this study, TiO_2-film electrodes containing a transparent TiO_2 layer with different thicknesses were prepared, and QDSCs based on these TiO_2 films with different thicknesses were constructed. The optimum thickness for the TiO_2-film electrode was determined to be 19.0 μm, which resulted in the best photovoltaic performance. The influence of the TiO_2 film's thickness on the performance of TiO_2/QD/Mg/QD QDSCs was further investigated using electrochemical impedance spectroscopy (EIS). The results showed that a thin TiO_2 film is superior for the suppression of charge recombination, and the charge recombination rate is slower with a larger Rrec value [73].

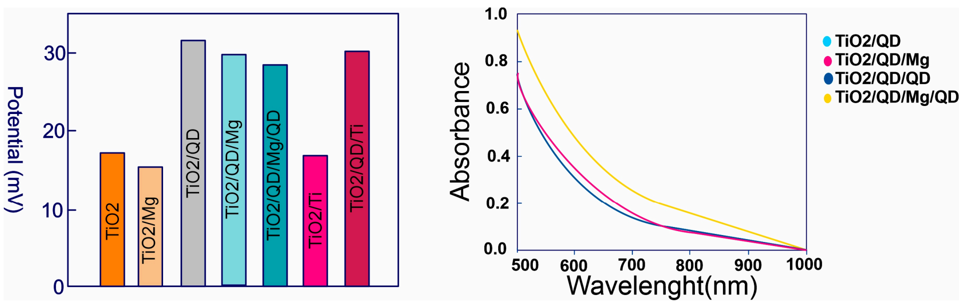

Figure 9. Potential values for different TiO_2 QD/Mg/QD samples with three rounds of QD deposition in film electrodes.

Increasing the interaction between the TiO_2 matrix and QD would result in high performance. Secondary (TiO_2/QD/Mg/QD) deposition has increased the interaction, resulting in higher efficiency due to the creation of new adsorption sites and improved QD loading as seen in Table 2.

Table 2. Photovoltaic parameters of TiO_2/QD, TiO_2/QD/QD, and TiO_2/QD/Mg/QD QDSCs based on Cu_2S/Brass CEs [74].

Photo Anode	Jsc (mA/cm^2)	Voc (V)	Fill Factor	PCE (%)
TiO_2/QD	24.69 ± 0.27	0.634 ± 0.003	0.640 ± 0.001	10.03 ± 0.07
TiO_2/QD/QD	24.56 ± 0.57	0.631 ± 0.002	0.639 ± 0.005	9.90± 0.19
TiO_2/QD/Mg/QD	26.79 ± 0.16	0.644 ± 0.003	0.652 ± 0.001	11.25 ± 0.10
TiO_2/QD	25.03	0.632	0.637	10.11
TiO_2/QD/QD	25.19	0.634	0.634	10.12
TiO_2/QD/Mg/QD	27.03	0.645	0.651	11.35

Quantum dots are also inexpensive, and multi-function cells use a hybrid design to make them more stable and efficient compared to polymers and have overall reduced power consumption. Substantial R&D operations still need to be carried out, and financing might be a concern for several companies, but quantum dots could potentially beat conventional silicon PV cells.

3.3.5. Concentrated Solar Cells

Normally, PV cells respond efficiently to direct sunlight, but most light in the designed environment is diffused as phenomena like scattering and reflections due to buildings, trees, clouds, and shade, which most commonly reduce the efficiency of cells. To combat these challenges, concentrated solar cells play a significant role. Concentrated solar cells were first developed in 1974, and the concept has become quite dominant in the market after 2010 [76,77]. The basic idea behind concentrated solar cells is to focus the maximum amount of light onto a very small area above the PV cell, as depicted in Figure 10. Using the same principle as utilized in optics, sunlight is concentrated onto a specific area by using mirrors and lenses. Hence, a massive amount of heat energy is produced by focused solar radiation [78]. When a solar cell is subjected to a concentrated solar light, it generates more current per area; hence, efficiency increases. Voltage increases logarithmically and so does efficiency. In the realm of solar PV cells, concentrated solar cells have shown considerable potential. Concentrated solar cells are advantageous in many ways as they entail solar cells that have an efficiency of more than 40%, no moving components, little thermal bulk, quick response times, and scalability to a variety of sizes [79]. It is expected that concentrated solar cells would be installed in large numbers in sunbelt countries by 2030. Because light is specifically concentrated in these cells, this increases the temperature of the overall cell despite employing the best cooling efforts. Usual heat sinks or other cooling systems are utilized with concentrated solar cells to decrease the overall temperature of solar cells. For instance, organic and silicon solar cells are sensitive to heat, so if a concentrator and a tracking system are utilized with these cells, excessive heat can be detrimental to these cells. For these cells, a low-concentration system (1–100 sun) is used, which does not require a tracking system, and this reduces the overall price as well. In the same way, medium–high concentration systems are utilized using gallium arsenide and multijunction solar cells. These cells perform well under high temperatures and have also exhibited high conversion efficiencies [80,81]. Concentrated solar cells have substantial potential in achieving carbon reduction at low prices if high-voltage DC infrastructure is readily available [82].

Figure 10 above shows the schematic for concentrated solar cell technology. Light hits the lens and is concentrated in solar cells. The heat sink keeps the solar cell from becoming hot to avoid burning and hot spot formation.

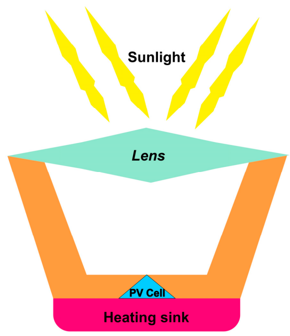

Figure 10. Schematic of the concentrated solar cell.

4. Comparison of the Efficiency of Disparate PV Cells

A comparison of the efficiency of various solar cells is presented in the tables below. Table 3 represents the efficiency of single-junction solar cells, and Table 4 shows the efficiency of multijunction solar cells. These data were prepared by various research centers around the world. The criterion for including different solar cells is that they must be measured independently at a specific test center. Among the single-junction solar cells, in the class of silicon solar cells, crystalline solar cells have exhibited the highest efficiency of 26.8% with an active area of 274 cm^2 followed by silicon wafers with an efficiency of 24.4% and an active area of 267.5 cm^2. In the silicon family, thin-film silicon solar cells have the lowest efficiency of 10.5% with an active area of 94 cm^2. In the class of III-V cells, with an active area of 0.998 cm^2, Alta devices confirmed an efficiency of 29.1% in 2018 followed by InP, which is crystalline in nature, and its efficiency was recorded to be 24.2% by NREL in 2013 for an active area of 1.008 cm^2. The lowest efficiency of around 18.4 % in this family was exhibited by GaAs (a multi-crystalline solar cell). In the thin-film single-junction solar cell category, cadmium-free CIGS solar cells have displayed the highest efficiency of around 23.35% with an active area of around 1.043 cm^2 back in 2018, followed by CdTe, CIGSSe (submodule), CZTSSe, and CZTS cells displaying efficiencies of 21%, 19.8%, 11.3%, and 10.2% with an active area of 1.0623 cm^2, 665.4 cm^2, 1.1761 cm^2, and 1.1131 cm^2, respectively. In the class of amorphous solar cells, hydrogenated amorphous silicon solar cells with an active area of 1.001 cm^2 displayed an efficiency of 10.2% in 2014, while microcrystalline exhibited an efficiency of around 12% with an active area of 1.044 cm^2 in 2017. In the classification of perovskite solar cells, perovskite (cell) displayed an efficiency of 23.7% for an active area of 1.602 cm^2 while the minimodule of perovskite exhibited an efficiency of 22.4% with an active area of 26.02 cm^2. A single dye-sensitized solar cell with an active area of 1.005 cm^2 showed the highest efficiency of 11.9% while its minimodule and submodule had low efficiencies of 10.7% and 8.8% with active areas of 26.5 cm^2 and 398.8 cm^2, respectively. Similarly to perovskite solar cells, a single organic solar cell also outperformed submodules with the highest efficiency of 15.2 % for an active area of 1.015 cm^2.

Table 4 shows the efficiency of multijunction solar cells and submodules at AM1.5. In III-V multijunction solar cells, five junction solar cells have displayed the highest efficiency of 38.8% with an active area of around 1.021 cm^2. In the category of multijunction crystalline solar cells, silicon cells doped with gallium indium phosphide have shown the highest efficiency of 35.9% with an active area of 3.987 cm^2, followed by GaInP/GaAs/Si (mech. stack), GaAsP/Si (monolithic), GaAs/Si (mech. stack), perovskite/Si, GaInP/GalnAs/Ge, Si (spectral split), and GaInP/GaAs/Si (monolithic) with efficiencies of 35.9%, 23.4%, 32.8%, 31.3%, 34.5%, and 25.9% and active areas of 1.002, 1.026, 1.003, 1.167, 27.83, and 3.987 in cm^2. Among the notable exceptions, GaInP/GaInAs and GaInAsP/GaInAs have shown the greatest efficiency of around 47.6% while six junction solar cells exhibited an efficiency of 39.2%.

Table 3. Confirmed single-junction terrestrial cell and submodules efficiencies at AM1.5 [83].

Classification	Efficiency (%)	Area (cm^2)	Voc (v)	Isc (mA/Cm^2)	FF (%)	Test CDate	Description
Silicon							
Si (Crystalline Solar)	26.8 ± 0.4	274.4	0.7514	41.45	86.1	ISHF (8/22)	LONGI, n-type HJT
Si (DS wafer cell)	24.4 ± 0.3	267.5	0.7132	41.47	82.5	ISFH (8/20)	Jinko Solar, n-type
Si (thin transfer submodule)	21.2 ± 0.4	239.7	0.687	38.5	80.3	NREL (4/14)	Solexel (35 µm thick)
Si (thin-film module)	10.5 ± 0.3	94	0.492	29.7	72.1	FhG-ISE (8/07)	CSG Solar (<2 µm on glass)
III–V Cells							
GaAs (thin-film cell)	29.1 ± 0.6	0.998	1.1272	29.788	86.7	FhG-ISE (10/18)	Alta Devices
GaAs (multi-crystalline)	18.4 ± 0.5	4.011	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate
InP (crystalline cell)	24.2 ± 0.5	1.008	0.939	31.15	82.6	NREL (3/13)	NREL
Thin Film Chalcogenide							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043	0.734	39.58	80.4	AIST (11/18)	Solar Frontier
CIGSSe (submodule)	19.8 ± 0.5	665.4	0.688	37.96	75.9	NREL (12/21)	Avancis, 110 cells
CdTe (cell)	21.0 ± 0.4	1.0623	0.8759	30.25	79.4	Newport (8/14)	First Solar, on glass
CZTSSe (cell)	11.3 + 0.3	1.1761	0.5333	3357.00%	63	Newport (10/18)	DGIST, Korea
CZTS (cell)	10.0 + 0.2	1.113	0.7083	21.77	65.1	NREL (3/17)	UNSW
Amorphous/Microcrystalline							
Si (amorphous cell)	10.2 ± 0.3	1.001	0.896	16.36	69.8	AIST (7/14)	AIST
Si (microcrystalline cell)	11.9 ± 0.3	1.044	0.55	29.72	75	AIST (2/17)	AIST
Perovskite							
Perovskite (cell)	23.7 ± 0.5	1.062	1.213	24.99	78.4	NPVM (5/22)	U.Sci.Tech., Hefei
Perovskite (minimodule)	22.4 ± 0.5	26.02	1.127	25.61	77.6	NPVM (7/22)	EPFLSion/NCEPU, 8 cells
Dye-sensitized							
Dye (cell)	11.9 ± 0.4	1.005	0.744	22.47	71.2	AIST (9/12)	Sharp
Dye (minimodule)	10.7 ± 0.4	26.55	0.754	20.19	69.9	AIST (2/15)	Sharp, 7 serial cells
Dye (submodule)	8.8 ± 0.3	398.8	0.697	18.42	68.7	AIST (9/12)	Sharp, 26 serial cells
Organic							
Organic (cell)	15.2 ± 0.2	1.015	0.8467	24.24	74.3	FhG-ISE (10/20)	Fraunhofer ISE
Organic (minimodule)	14.5 ± 0.3	19.31	0.8518	23.51	72.5	JET (12/21)	ZJU/Microquanta, 7 cells
Organic (submodule)	11.7 ± 0.2	203.98	0.8177	20.68	69.3	FhG-ISE (10/19)	ZAE Bayern, 33 cells

Table 4. Confirmed multijunction terrestrial cell and submodule efficiency at AM1.5 [84].

Classification	Efficiency (%)	Area (cm^2)	Voc (v)	Isc (mA/Cm^2)	FF (%)	Test Centre/Date	Description
III–V Multijunction							
5 junction cells (bonded) (2.17/1.68/1.40/1.06/0.73 eV)	38.8 + 1.2	1.021	4.767	9.564	85.2	NREL (7/13)	Spectrolab,2-terminal
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047	3.065	14.27	86.7	AIST (2/13)	Sharp, 2 term.
GaInP/GaAs (monolithic)	32.8 ± 1.4	1	2.568	14.56	87.7	NREL (9/17)	LG Electronics, 2 term.

Table 4. *Cont.*

Classification	Efficiency (%)	Area (cm^2)	Voc (v)	Isc (mA/Cm^2)	FF (%)	Test Centre/Date	Description
Multijunction with c-Si							
GaInP/GalnAsP/Si (wafer bonded)	35.9 ± 1.3	3.987	3.248	13.11	84.3	FhG-ISE (4/20)	Fraunhofer ISE, 2 term
GaInP/GaAs/Si (mech. stack)	35.9 ± 0.5	1.002	2.52/0.681	13.6/11.0	87.5/78.5	NREL (2/17)	NREL/CSEM/EPFL, 4-term
GaAsP/Si (monolithic)	23.4 ± 0.3	1.026	1.732	17.341	77.7	NREL (5/20)	OSU/UNSW/SolAero, 2-term
GaAs/Si (mech. stack)	32.8 ± 0.5	1.003	1.09/0.683	28.9/11.1	85.0/79.2	NREL (12/16)	NREL/CSEM/EPFL, 4-term
Perovskite/Si	31.3 ± 0.3	1.1677	1.9131	20.47	79.8	NREL (6/22)	CSEM/ EPFL, 2-term
GaInP/GalnAs/Ge; Si (spectral split)	34.5 ± 2.0	27.83	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina, 4-term
GaInP/GaAs/Si (monolithic)	25.9 ± 0.9	3.987	2.647	12.21	80.2	FhG-ISE (6/20)	Fraunhofer ISE, 2-term.
Other Multijunction							
Perovskite/CIGS	24.2 ± 0.7	1.045	1.768	19.24	72.9	FhG-ISE (1/20)	HZB, 2-terminal
Perovskite/perovskite	26.4 ± 0.7	1.044	2.118	15.22	82.6	JET (3/22)	SichuanU/EMPA, 2-term
Perovskite/ perovskite(minimodule)	24.5 + 0.6	20.25	2.157	14.86	77.5	JET (6/22)	Nanjing/Renshine, 2-term.
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4	1.045	1.922	9.9	73.4	AIST (5/16)	AIST, 2-term
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4	1	1.342	13.45	70.2	AIST (10/14)	AIST, 2-term.
Notable Exceptions							
GaInP/GaAs (mqw)	32.9 ± 0.5	0.25	2.5	15.36	85.7	NREL (1/20)	NREL/UNSW. multiple QW
GaInP/GaAs (mqw)/GaAs	39.5 ± 0.5	0.242	2.997	15.44	85.3	NREL (9/21)	NREL multiple QW
GaInP/GaAs/GalnAs	37.8 ± 1.4	0.998	3.013	14.6	85.8	NREL (1/18)	Microlink (ELO)
6 junctions (monolithic) (2.19/1.76/1.45/1.19/ 0.97/0.7 eV)	39.2±3.2	0.247	5.549	8.457	83.5	NREL (11/18)	NREL, inv. Metamorphic
Perovskite/Si (large)	26.8 ± 1.2	274.22	1.891	17.84	79.4	FhG-ISE (11/21)	Oxford PV,
Perovskite/perovskite	28.0±0.6	0.0495	2.125	16.42	80.3	JET (12/21)	Nanjing U, 2-term.
Perovskite/organic	23.4 ± 0.8	0.0552	2.136	14.56	75.6	JET (3/22)	NUS/SERIS
GaInP/GaInAs; GaInAsP/GaInAs	47.6 ± 2.6	0.0452				FhG-ISE (5/22	hG-ISE 4J bonded

5. Global and Regional Trends in Electrical Energy from PV Cells

Figures 11 and 12 below elucidate the global and regional trends of solar energy. Figure 11 shows that the overall 942 GW of energy was generated from solar cells until 2021, and around 70% were installed in the last 7 years. The overall market grew by 174 GW in 2021 alone. It is estimated that the leveling off cost by grid and PV cells would be achieved by 2030. In the next few years, solar cells could be more economical compared to fossil fuels in regions with moderate to high solar irradiation. In Figure 12, regional trends in solar energy generation can also be observed. Overall, after 2010, an exponential increment in PV installation can be observed in major regions of the world. It can be observed that Asia has taken a great leap with respect to solar generation after 2012. The majority of the cumulative market was occupied by the Asian region in 2021, and the total installed capacity of Asia Pacific was the highest among major regions of the world, which was around 500 GW. China alone installed 324 GW of solar PV cells. European countries installed around 150+ GW of solar PV panels. North America also installed around 100 GW of solar PV cells, followed by Germany with 50 GW of the overall installation until 2021. Middle East and African countries have also started deploying solar PV cells, and the market is growing in these regions as well. The last two years were observed to be tough on the solar market due to the disruption in the supply chain's demand. An increment in the prices of raw materials was observed due to the shortage, especially polysilicon materials, which increased the prices of modules. The outbreak of COVID-19 in China disrupted the supply chain, as the majority of materials used in the manufacture of panels are produced in Asian markets. Furthermore, seaports and airports were closed, so the shipping of raw materials was almost squelched, and this impeded investments in solar farm development and manufacturing processes in almost all regions of the world [84]. Currently, the supply chain has recovered from the repercussions of COVID-19, and prices are expected to decrease even further, which would further enhance the deployment of PV cells in the upcoming years [85].

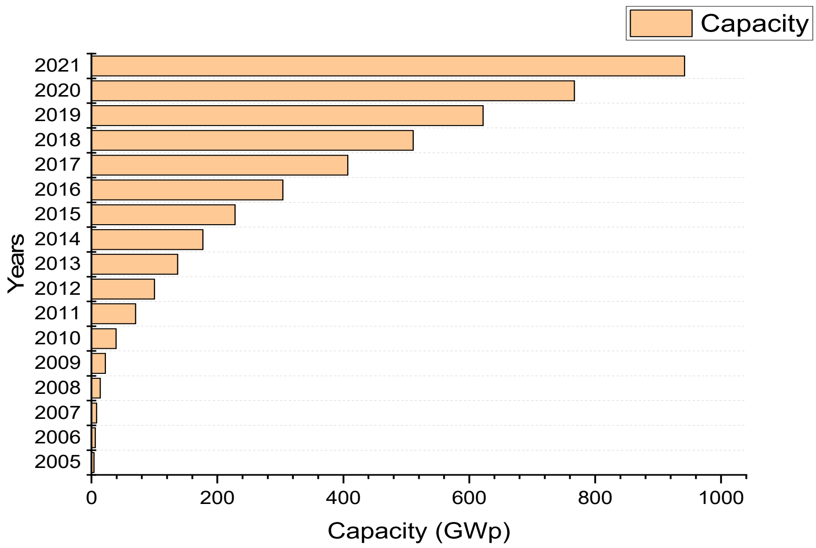

Figure 11. Trends of the total installed capacity of solar energy until 2021.

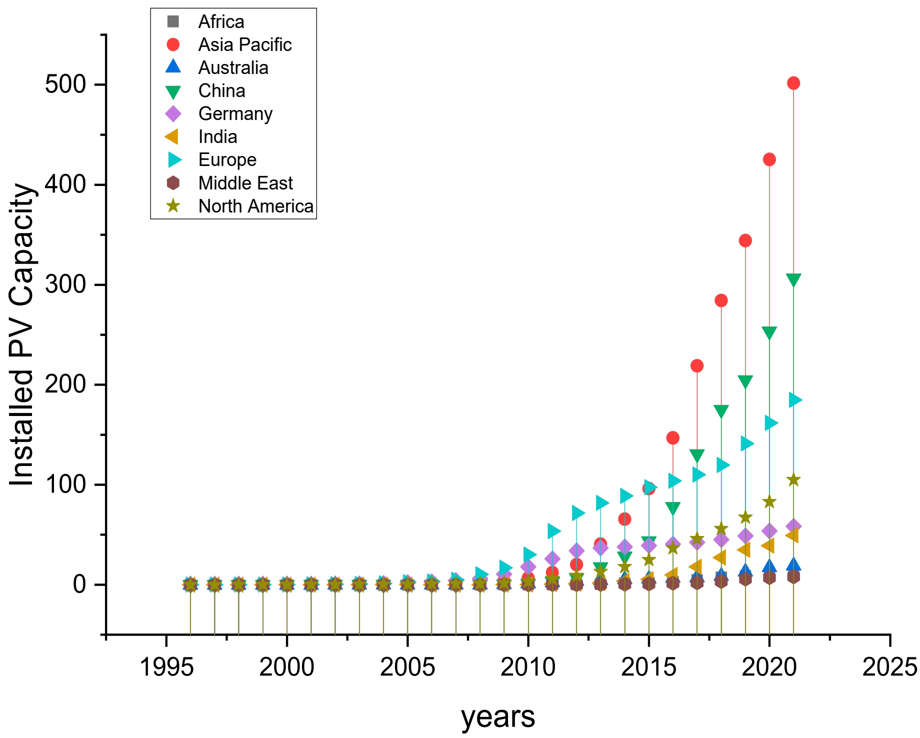

Figure 12. Regional solar trends.

6. Characterization of PV Modules

The accurate characterization of PV modules has become an indispensable issue; there is a collection of factors that determine the characterization of PV cells, and they affect the overall efficiency of solar cells as well. PV cells can be characterized in terms of safety, overall reliability, spectral responsivity, I-V curves, and failure susceptibility.

6.1. Safety

6.1.1. Mechanical Safety

Mechanical tests are performed to determine whether the materials that are utilized to fabricate the modules are considered with respect to their mechanical properties. According to IEC 61215, 61646, and 61730 standards, a 2400 Pa load is applied, and some modules may fail this test because of their augmented size. A few measures are adopted to overcome this issue, mainly enhancing mounting clamps with rubber inlays, placing extra supports at the back of modules, using extra cross bars on the frame, and utilizing stiffer materials at the rear of the modules [86].

6.1.2. Electrical Safety

Electrical problems occur due to poor isolation between the active cell area and metallic structure and later on due to moisture ingress, which reduces the overall efficiency. Electrical isolation tests are performed using various methods. The high-voltage method (1 kV plus twice the system's voltage for the IEC 61215 standard and 2 KV plus four times the system's voltage for IEC 61730-2 class A) is applied between the terminals and the conducting foil, which is wrapped around the module. If the resistance of the module is less than 40 $M\Omega/m^2$, the module is considered to have failed. A wet leakage current test is performed by drowning the module; around 500 volts or the maximum system voltage is applied, and resistance is measured. If resistance is less than 40 $M\Omega/m^2$, the module is rejected; other than this, to forecast the overall usability of modules along with the above-mentioned tests, a damp heat test (1000 h at +85 °C and 85% relative humidity), a thermal cycling test (200 times between −40 °C and +85 °C), and a humidity test (10 fast drops from 85 °C to −40 °C at 85% humidity) are also performed. To avoid the moisture penetration conundrum, wrap care sealant is applied on the module's frame, the metal around the edge is tapped, glass bonding is applied, and in-laminate sealant is used by manufacturers [87,88]. If the module is placed in a gusty and arid environment, then the load is increased from 2400 Pa to 5400 Pa with a safety factor of 3.

6.2. Reliability

Hot spot formation, sometimes in module cell currents in single cells, is reduced due to the dirt on modules or shadows cast on some plates, and this limits the overall efficiency of cells. If the string of cells is long enough, the voltage of shadowed or dirty cells surpasses the negative threshold voltage, and power is dissipated as heat when some parts of the cells are demolished; the destroyed parts give rise to hotspots, and this phenomenon reduces the overall efficacy and the life of module as well. To avoid this bypass, diodes with a low breakthrough voltage are used, or the overall voltage is reduced. Another way to avoid this decrement is the proper cleaning of these solar panels. In a research paper published by Ra'Ed Nahar Myyas et al., the authors proposed a novel and efficient method for cleaning solar panels. By properly cleaning solar panels, hot spot formations can be alleviated, and efficiency can be improved [89,90].

6.3. Spectral Responsivity

Spectral responsivity or quantum efficiency is a significant process for examining current production and recombination and collecting mechanisms in PV cells. The mathematical relation for spectral responsivity is given as

$$QE(\lambda) = \frac{qS(\lambda)}{\lambda hc} \tag{3}$$

where $\frac{hc}{q} = 0.8065$, λ is measured in µm, and "$S(\lambda)$" is considered in units of ampere/watts.

It is measured in terms of electron-hole pairs inferred per photon, which is incident on the surface or expressed as the current produced per unit of power. Multiple systems have been developed to measure spectral responsivity, entailing those based on interference filters, grating monochromators, and interferometers. In a filter-based system, broadband light is shined through interference filters, and using mirrors, the light is further directed to the device subjected to the test to measure spectral responsivity. For periodic monochromatic signals, a lock-in simplifier is used, and if there is an ac voltmeter available for measuring the signal, a shutter is utilized, as shown in Figure 13. Pyro-electric radiometers or a Si detector is used to measure monochromatic light. Grating-based systems can measure a broad wavelength range from 400 nm to 3200 nm and provide high spectral resolutions. Using a double-grating monochromator, stray UV light can also be eradicated. For suppressing shorter wavelengths, order-passing filters are utilized. If a single-grating monochromator is used, a band pass filter is also required for within the range of 300–600 nm at both shorter and longer wavelength modes. The usual grating-based systems have lower optical throughput (handle low intensity), but they provide high spectral resolutions compared to filter-based systems. A typical grating-based system is shown in Figure 14. Light enters from a source and is filtered using filters that are fitted with three single gratings and a GPIB interface, which is connected to a computer for measurements. An optical chopper is used to modulate the light, which is focused onto focusing mirrors that direct light onto the object under observation. A few uncertainties can occur when measuring photocurrents, the light source, and monochromatic light, some of which are included here: errors due to electrical instrumentation (I–V convertor, noise, calibration, ac voltmeter errors, and signal errors due to a lock-in amplifier); errors due to a PV module (which entail errors related to the temperature, light polarization, device sensitivity, and response time); and mechanical errors due to stray cut-off monochromatic light, mechanical vibrations, and the movement of optics. A few typical error sources that can occur during the measurement of light sources are fluctuations in the intensity of light filaments, real-time calibration errors due to source-light polarization, signal-to-noise ratio, and detector characteristics, and some errors may erupt due to the associated electronics (gain, phase offset, linearity, and accuracy) within the system; moreover, if the light exhibits monochromatic errors like wavelength offsets, wavelength errors, and temperature errors, more errors related to the beam's wavelength and the wavelength's measurement can also occur using such devices [40,91].

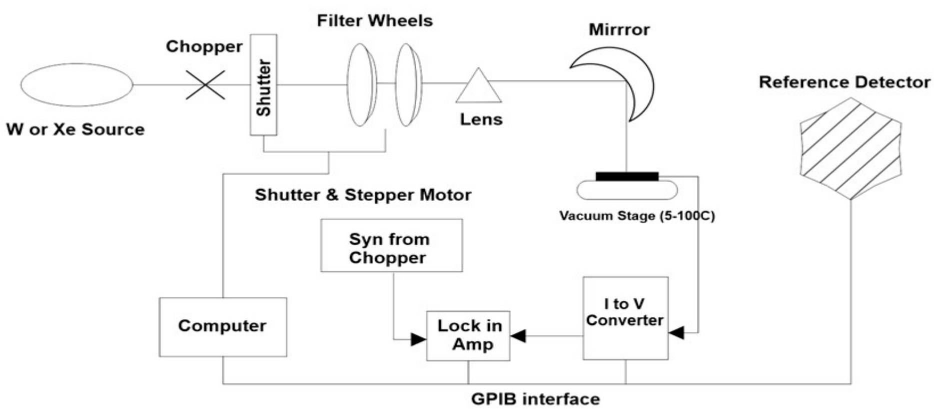

Figure 13. Filter–based spectral responsivity measurement system [93].

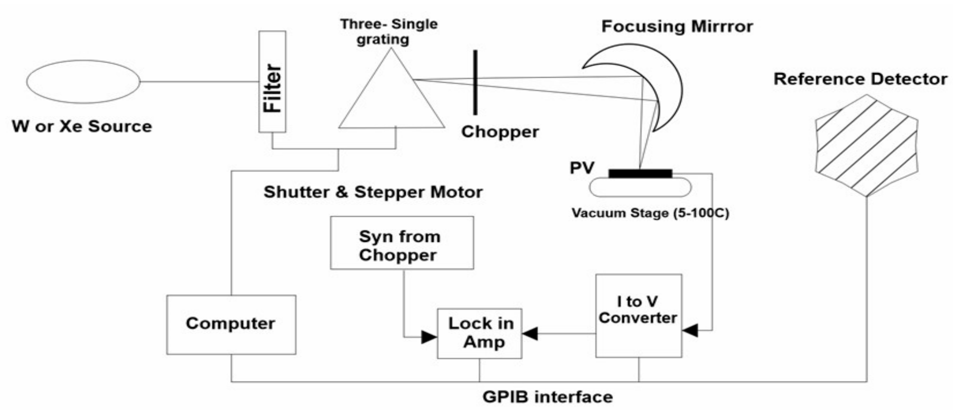

Figure 14. Grating–based spectral responsivity measurement system [93].

6.4. Current–Voltage Measurement

The current and voltage are determined in order to measure the maximum power of PV modules. The most common method that is used for this is to use a light source, a place to fix a PV cell, a power supply to control/change current and voltage, sensors, and a data acquisition system to determine the values of voltage and current. A Kelvin connection is attached to the system to eradicate losses in the voltage and current caused by resistance. Sometimes, natural light is used, but solar simulators are preferred as light can be varied depending on the application. Figure 15 shows a general system for measuring the I–V characteristics of solar cells. Shunt resistance is utilized here to measure the value of the current. The voltage is observed to be juxtaposed relative to the current connections in the system. Figure 16 depicts a typical curve of PV cells with 50 W of power. By observing the I–V characteristics of PV cells, critical parameters like short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power (P_{max}) can be found. Usually, the value of the open circuit is determined using the linear interpolation of two points on the I–V curve closest to the zero current, or a linear regression is applied on more than two points to diminish the uncertainty. The value of the short circuit's current is ascertained by interpolating two points on the I–V curve near zero voltage. To further deescalate the uncertainty in values, a linear curve fit is employed on more than two points. The highest point on the I–V curve is considered the maximum power that a cell can produce. A more accurate method is to carry out a linear fit involving a fourth-order or even higher polynomials within 80–85% of the maximum power on power versus voltage data points [40].

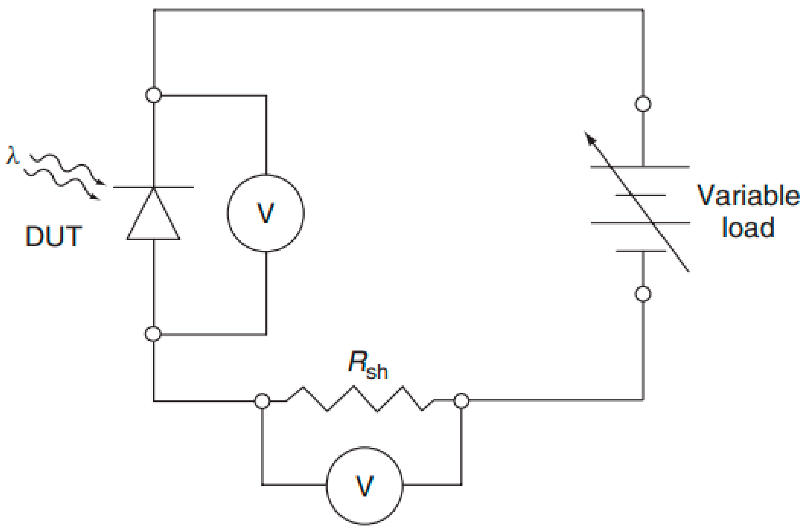

Figure 15. General current–voltage measurement system [93].

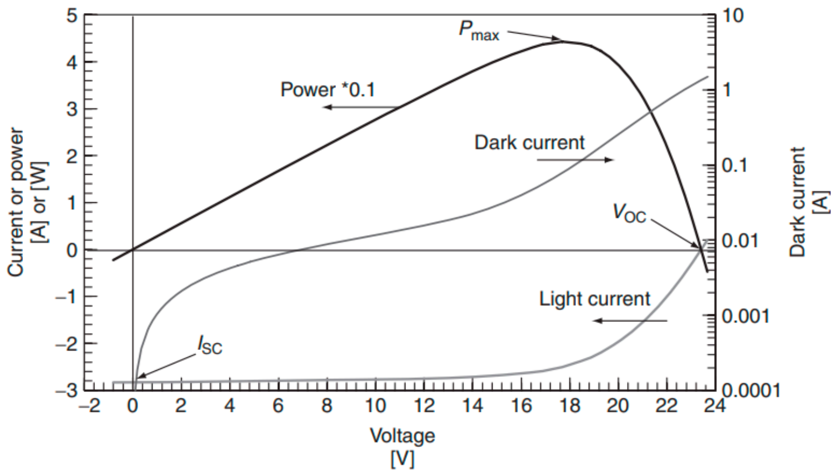

Figure 16. I–V characteristics of a 50 W module [93].

All the above-mentioned factors are imperative in determining the efficiency and overall characterization of PV cells. All of these factors play a critical role in characterizing PV modules and are essential from both the manufacturer's and consumer's point of view.

7. Current and Future Perspectives of PV Technology

Solar energy is the most abundant, environmentally friendly, and sustainable form of energy available on Earth. As more research and development are being carried out all over the world, PV cells are expected to improve, and they could penetrate the energy market quite considerably in the next 20 to 30 years. Solar cells are speculated to occupy around 20–30% of the total energy generation in the next few years, but there are a few critical factors that are involved in this process, and they can either expedite or halt the process of solar cell ingress in the market. There are technical, economic, and environmental aspects that are discussed below.

7.1. Technical Developments, Challenges, and Impacts

The two major technical issues at hand regarding solar PV cells are the efficiency of solar cells and storage-related issues. Efficiency-related issues are mostly concerned with the availability of materials and research and development with respect to novel technologies like quantum dots, concentrated solar cells, and tandem cells. Solar cells only produce electricity until sunlight is available, but the extra energy generated from cells can be stored for use at night. For this, a colossal amount of research on storage systems is required, although many systems like capacitors, super capacitors, fuel cells, flywheels, lead acid batteries, metal–air cells, and NiCd batteries are being employed [92–94]. The major concern regarding both PV cells and storage systems is the availability of minerals to design economical storage systems and efficient solar cells. Critical mineral requirements related to the electricity sector are set to jump from 7 Mt per year to 11 Mt in 2030 and 13 Mt in the Stated Policies Scenario (STEPS). Copper for solar cells and lithium for PV cells would be of prime importance. Copper prevails in the overall demand for critical minerals, and its demand could increase even further to 10 Mt from 5 Mt in 2030 and to 13 Mt in a few reports. A battery storage system plays a crucial role in smoothening the daily cycle of PV- based energy generation systems as they are often paired with rooftop solar systems. The cost of batteries can decline by carrying out perpetual innovation in battery chemistry. Although there are some difficulties involved in the availability and affordability of minerals that are required to manufacture batteries and obstructions with respect to both can halt the decrease in cost, there are other options that can be considered to mitigate these conundrums [95,96].

Figure 17 shows the demand for critical minerals in the upcoming years, which are utilized in the development of solar cells and energy storage systems in different policies scenario. The demand for silicon and lithium is expected to increase drastically by 2030 and 2050 both in STEPS and APS policies.

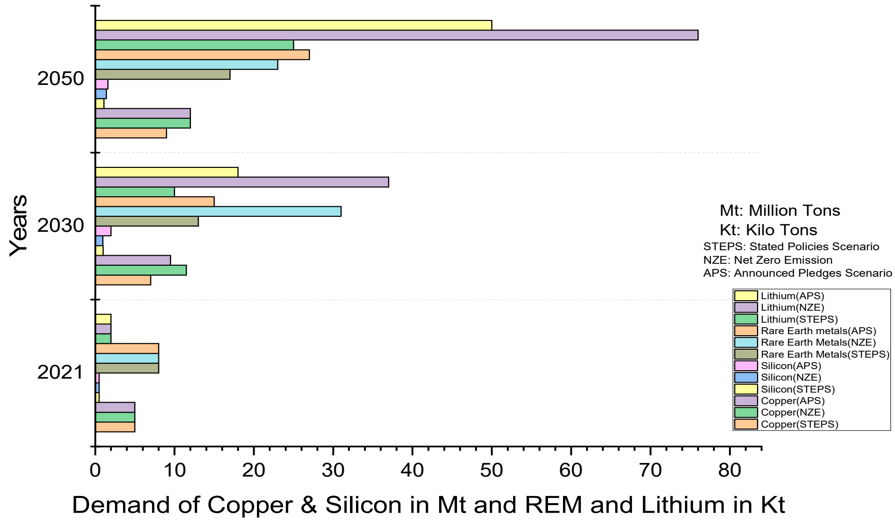

Figure 17. Annual demand for selected critical minerals utilized in PV cells and storage systems in 2021–2050.

7.2. Economic Developments, Challenges, and Impacts

There has been a great shift in PV cells in the last couple of decades, and the prices of solar cells have plummeted quite dramatically. For instance, the decrement in prices from 2010 to 2018 was around 77%, which is quite remarkable. In 2018, an auction in Abu Dhabi, Saudi Arabia, Mexico, and other countries showed that a global weighted average levelized cost (LCOE) of USD 0.03 per kilowatt is possible in various national contexts, and it can even fall to USD 0.02 by 2030. The globalization of solar PV cells has played a decisive role in decreasing the prices of overall solar cells. Overall investments in solar cells have elevated from USD 77 billion in 2010 to USD 114 billion in 2018, and they are forecasted to peak up to USD 165 billion by 2030. Such enormous investments in the solar industry could also create job opportunities for many people. Around 3.8 million jobs were provided by the solar industry until 2019, which was threefold the number compared to 2012, and it is predicted that the number of jobs can spike to 11.5 million by 2050. The figures below show the decline in the costs of solar PV cells and their projection up until 2050 [97]. Figure 18 shows the overall cost of solar energy in 2019 compared to 2013 in different countries, and in Figure 19, a dramatic reduction in the installed and levelized cost of solar PV cells from 2010 to 2019 can be observed. From Figure 18, itis observed that the prices decreased by more than 40% in the majority of countries until 2019. The overall global weighted costs also decreased from USD 4702 to USD 995. It is speculated that by 2050, installation costs could plunge dramatically by around 96% from the prices in 2019. The major challenge related to the overall PV solar industry is to reduce the balance of the system (BoS), which contributes mostly to the total cost of the installed system, and this can be alleviated by decreasing the cost of cell fabrication and increasing efficiency even further, which requires exuberant research and development in many areas, like exploiting materials for greater efficiency, recycling used cells, and diminishing the cost of maintenance and operation [98]. Table 5 also provides further insights into the decrease in cost with respect to electricity generated from solar cells in major stakeholder countries. In the majority of countries, both capital prices and the levelized cost of electricity are supposed to decrease by more than 50% until 2050.

Table 5. Technology cost of major energy sources in selected regions of the world.

	Capital Cost USD/KW			Levelised Cost of Electricity USD/MWh		
United States	**2021**	**2030**	**2050**	**2021**	**2030**	**2050**
Wind offshore	4040	2200	1500	120	60	40
Wind onshore	1380	1270	1190	35	30	30
Solar PV	1090	620	430	50	30	25
Gas CCGT	1000	1000	1000	80	130	n.a.
Coal	2100	2100	2100	165	n.a.	n.a.
Nuclear	5000	4800	4500	100	100	100
European Union						
Wind offshore	3040	1800	1240	60	35	25
Wind onshore	1590	1470	1380	55	50	45
Solar PV	810	470	340	50	35	25
Gas CCGT	1000	1000	1000	145	195	n.a.
Coal	2000	2000	2000	230	n.a.	n.a.
Nuclear	6600	5100	4500	140	115	115
China						
Wind offshore	2860	1640	1120	100	50	35
Wind onshore	1160	1060	1000	45	40	35
Solar PV	630	360	250	35	20	15
Gas CCGT	560	560	560	105	130	n.a.
Coal	800	800	800	100	n.a.	n.a.
Nuclear	2800	2800	2500	65	65	65
India						
Wind offshore	2780	1560	1080	120	65	45
Wind onshore	930	840	790	45	35	35
Solar PV	590	320	210	35	20	15
Gas CCGT	700	700	700	75	100	n.a.
Coal	1200	1200	1200	60	n.a.	n.a.
Nuclear	2800	2800	2800	75	65	65

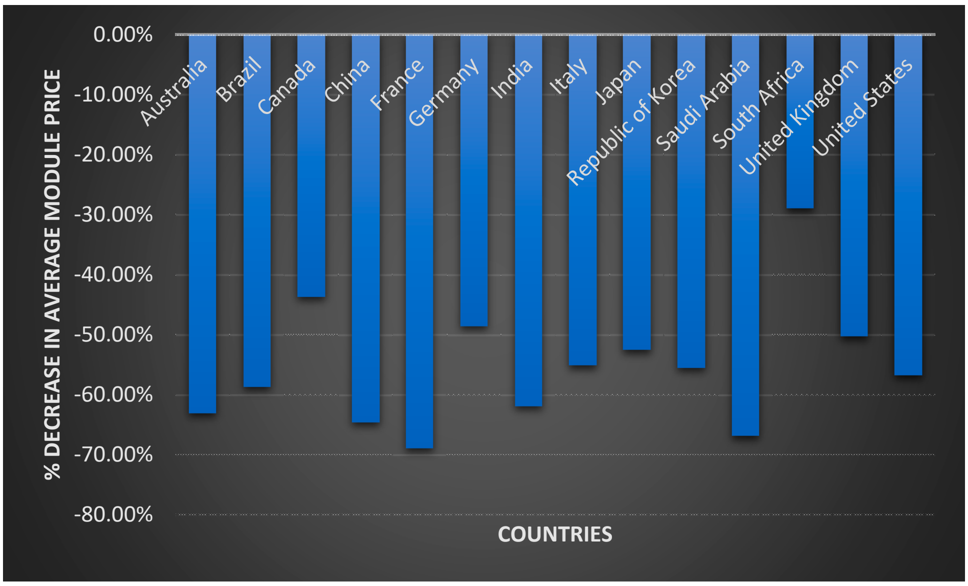

Figure 18. Average yearly price of modules.

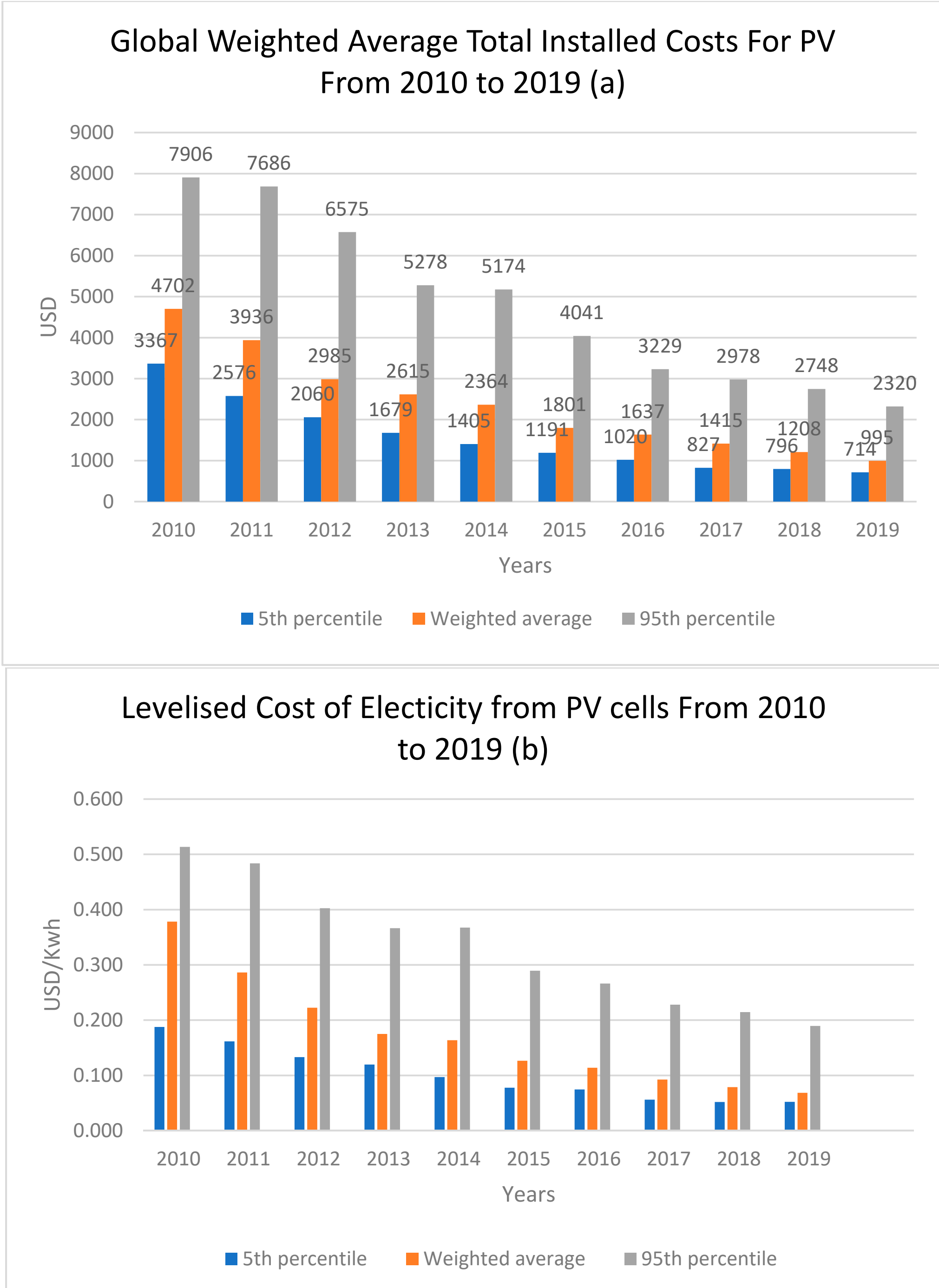

Figure 19. Global weighted average total installed cost (**a**) and LCOE from PV Cells (**b**) (2010–2019).

7.3. Environmental Developments, Challenges, and Impacts

Climate change has become a major issue in the last few years, and the excessive release of CO_2 has decimated the environment quite considerably; moreover, climate change is also linked to an increase in temperature all over the globe. There are roaring signs that climate change is driving frequent intense weather situations in the world. Considering this intense situation, an agreement was struck between major stakeholders (Paris Agreement in 2015) to hamper the emission of CO_2. This agreement requires countries to reduce the emission of CO_2 by 3.5% per year until 2050 and to keep the temperature increase below 2 °C. Moreover, due to the substantial emissions of CO_2, the air is highly polluted, and around 19,000 deaths occur due to this [99,100]. The major advantage of solar energy is its environmentally friendly nature. Exploiting solar energy via PV cells can aid in decarbonization. Installing more than 8500 GW of solar cells by 2050 can produce more than 25% of the total energy requirement of the world, which in turn can extenuate a significant amount of CO_2 emissions. If this amount of deployment can be carried out successfully, it could reduce around 21% of overall emissions in the next three decades. In Figure 20, it can be observed that by sticking to current plans and policies, there would not be any specific reduction in carbon emissions, but by integrating renewable energy sources, a substantial reduction can be attained. Similarly, Figure 21 depicts the percentage contribution of various renewable energy sources in reducing carbon emissions. Solar energy is speculated to contribute about 21% if energy transformation policies are adopted [101].

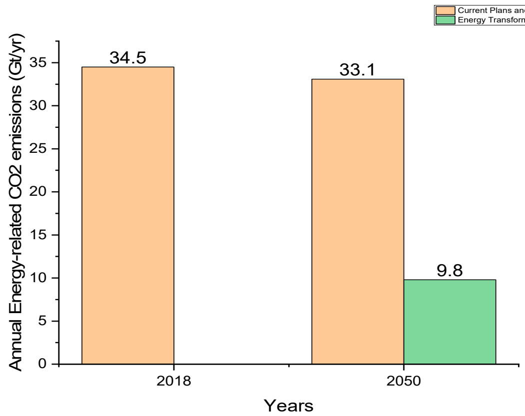

Figure 20. Comparison of CO_2 emissions in current policies and energy transformation plans.

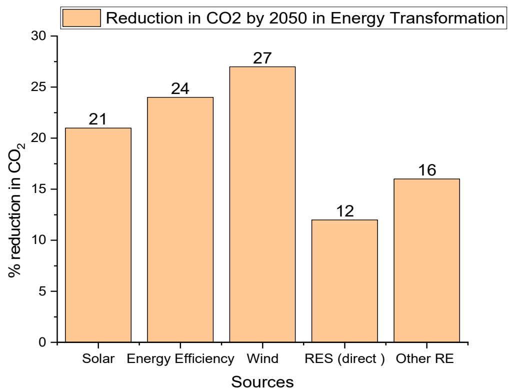

Figure 21. % CO_2 reductions in 2050 by major RES.

8. Future Suggestions

In this portion, our vision for possible research areas in solar PV cells is expounded along with some suggestions for the market ingress of PV technology. The major issue associated with solar PV technology is its low efficiency and high price. The primary focus of research and development should be to increase the efficiency of solar cells and decrease the overall price in order to make them affordable for both domestic and industrial utilization. In-depth and extensive research is required in the field of material sciences to understand the molecular structure of materials in order to manipulate the materials and increase the efficiency of cells. Third-generation solar panels are already available in the market, with efficiencies of over 40%, so it is viable to research materials and techniques used in the production of these third-generation solar panels. Research in the field of mining and metallurgy should be focused on the excavation, exploration, and processing of materials, such as CdTe with silicon. This will confirm the abundance of materials for manufacturing PV cells. Further research is required in the areas of battery storage and battery management systems in order to store and use energy intelligently for the time when solar energy is not available. Regarding battery storage systems, the major problem with battery storage systems is low energy density and high costs. Lithium-ion batteries are widely used all over the world for storage purposes. Lithium-ion batteries have low energy density and high prices [102]. Currently, researchers are working on sodium-based dual-ion batteries as they have a high potential for larger storage capacities [103]. However, their anodes cannot sustain sodium ions; although most latest research has promised some feasible solutions for this, extensive research and development are still required with respect to high-performance anodes [104]. Net metering policies need to be revised to benefit consumers who inject solar energy into the grid. Policies should be devised in such a way as to underpin the local manufacture of solar cells or their components like glass sheets, outer metal bodies, etc. The solar cells that could serve their purpose must be disposed of safely via biodegradation, and it should be among one of the prime future goals. Solar energy is intermittent in nature, and integrating solar PV cells into the grid is not simple because of the non-continuous nature of the source. For this purpose, extensive research and development is required in the area of microgrids and smart grids for the proper utilization of solar energy [105].

9. Summary

Solar energy has the potential to change the dynamics of the field of electrical power, and it has several advantages over non-renewable energy sources. It is a viable alternative to the rising demands of energy all over the world. Substantial research work in the field is being conducted to enhance the efficiency of solar cells and to make them available in both industrial and residential areas. Recent development in new multijunction solar cells and concentrated solar cells have exhibited high efficiency and low costs. Moreover, to deal with the increasing concerns regarding the environment, like carbon emissions and global temperature increment, solar energy can play a pivotal role. To fulfill the Paris Agreement and to mitigate the global temperature increment and increasing levels of carbon dioxide, major stakeholders like China, India, and America have invested quite a considerable amount in the solar industry. It is estimated that by 2050, temperature increments would be reduced to 1.3 degrees annually from 3 degrees, and solar cells would contribute around 25% of the overall energy generation.

10. Conclusions

Overall, the major findings of this study are epitomized below:

- Photovoltaic cells are divided into three major generations: first-, second-, and third-generation solar cells. First-generation solar cells are composed of silicon-based solar cells that are further divided into mono- and polycrystalline solar cells. The highest efficiency achieved by first-generation solar cells for single-crystalline solar cells is 26.1% while multi-crystalline solar cells have an efficiency of around 23.1%. Overall, first-generation solar cells are more developed and are suitable at mediocre temperatures. Second-generation solar cells are based on thin-film solar cells consisting of amorphous silicon cells, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). Amorphous silicon solar cells have achieved an efficiency of around 14% in the latest research studies. CdTe-based solar cells have achieved an efficiency of around 22.1% recently despite concerns regarding cadmium being toxic and hazardous to the environment. CIGS has recently racked up an efficiency of around 23.6%. Overall, second-generation solar cells operate better at high temperatures. Third-generation solar cells include organic solar cells, dye-sensitized solar cells, quantum dot solar cells, and perovskite cells. Organic solar cells are flexible and lightweight, and the recent efficiency achieved by them is around 19%. Dye-sensitized solar cells have acquired an efficiency of around 30%, and they have a high capacity in achieving higher efficiency. Quantum dot solar cells use nanotechnology, and quantum dots are inexpensive and also use a hybrid design. They recently achieved an efficiency of 18.1%. Perovskite solar cells have good light absorption capabilities, and they have recently achieved an efficiency of 25.8%. Overall, third-generation solar cells have a great capacity for high efficiency and market ingress. Furthermore, third-generation solar cells are more versatile compared to the other two generations. Concentrated solar cells have also demonstrated great potential in achieving high efficiencies. They use fewer materials while concentrating light on a specific area. By utilizing a precise tracking system using these cells, greater amounts of energy can be harnessed.

- It can be observed that in the last two decades that the world has shifted substantially toward solar energy, with Asia providing enormous contributions in the last 7 to 8 years.
- Solar cells are characterized by many factors. Mechanical and electrical safety tests are performed to determine the mechanical strength and electrical insulation properties of materials that are used to fabricate solar cells, respectively. A reliability test is performed to check hot spot formation in solar cells. The formation of hot spots after deployment decreases the efficiency of solar cells. Spectral responsivity elucidates how currents are generated in solar cells and the collection mechanism in PV cells. Via spectral responsivity, how much current would be produced by the incident light that falls on solar cells is determined. The behavior of I-V curves shows the maximum power obtained from solar cells.
- There are some technical, environmental, and economic challenges that hamper the overall integration of solar energy in the power sector. Technical challenges are related to the efficiency of solar cells and the storage of energy after sunlight goes away. Because the PV industry is supposed to develop explosively in the few next years, the availability of materials to fabricate both solar cells and batteries that store energy is crucial. Research and development on a broader scale are required to decrease the price of batteries and to manufacture efficient and sustainable storage systems. Economic issues are related to the per unit price of energy obtained from solar cells and the overall price of PV panels. In the last decade, overall, the prices of solar cells have declined by around 77%. Massive investments in solar energy have also been observed in the last decade, which have created job opportunities for people in the solar industry. In the next three decades, as this industry grows even further, more jobs will be available. The major environmental problem is the uncontrolled and enormous emissions of CO_2, which have decimated the environment considerably in the last 50 years. PV cells can play a pivotal role in decarbonization. It is speculated that around 21% of CO_2 could be reduced by solar PV cells in the next three decades.

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