energies

MDPI

Review

A Comprehensive Review of Solar Photovoltaic (PV) Technologies, Architecture, and Its Applications to Improved Efficiency

Sai Nikhil Vodapally and Mohd Hasan Ali *

Department of Electrical and Computer Engineering, The University of Memphis, Memphis, TN 38152, USA
* Correspondence: mhali@memphis.edu

Abstract: Since the discovery of Photovoltaic (PV) effect, numerous ways of utilizing the energy that can be generated by the free everlasting solar radiation using solar panels were put forward by many researchers. However, the major disadvantage of solar panel to date is its low efficiency, which is affected by the panel temperature, cell type, panel orientation, irradiance level, etc. Though there are certain multi-junction solar panels that offer higher efficiencies, their application is very minimal due to high manufacturing cost. With the growing demand for the reduction of carbon footprint, there is a need to use and manufacture these panels in the most effective way to harness the maximum power and increase their efficiency. Another major concern is the availability of land/space for the installation of these panels. Several authors have focused on discussing the different technologies that have evolved in the manufacturing of the PV cells along with their architectures. However, there exists a gap that needs to be addressed by combining the latest PV technologies and architectures with a focus on PV applications for increasing the efficiency. Due to the technical limitations on the efficiency of PV panels, applications are to be designed that can extract the maximum power from the PV systems by minimizing the technical difficulties. Considering all these factors, this paper presents an overview of the types of silicon based solar cell architectures with efficiencies of at least 25%, and different integration methods like Building integrated PVs (BIPV), floating PVs, which can increase the efficiency by harnessing more power from a limited space. An extensive bibliography on the PV cell structures and methods of maintaining the efficiencies in real world installations are presented. The challenges with the integration of solar panels and the future work are also discussed. This work benefits the readers and researchers and serves as a basis to understand the solar panel efficiency structure and ways to improve the efficiency and associated challenges to come over in the successful implementation of these systems.

Keywords: Solar Photovoltaic (PV); solar cell architecture; solar cell efficiency

check for updates

Citation: Vodapally, S.N.; Ali, M.H. A Comprehensive Review of Solar Photovoltaic (PV) Technologies, Architecture, and Its Applications to Improved Efficiency. *Energies* **2023**, *16*, 319. https://doi.org/10.3390/en16010319

Academic Editor: Carlo Renno

Received: 27 November 2022
Revised: 17 December 2022
Accepted: 23 December 2022
Published: 28 December 2022

1. Introduction

With the electricity supply and demand gap widening every day and the fossil fuels declining in volume, the countries across the globe have been looking for alternate ways for the generation of electrical energy. With a major concern about global warming and a rapid climatic change all over the world, there is an increased pressure on the power system utilities to look for alternate sources of energy. In the recent past, distributed generation has also gained importance with the generation of electricity energy in a close proximity to the load centers to reduce the transmission losses with improved overall efficiency of the power system. Distributed generation is mainly comprised of multiple renewable energy sources with/without an energy storage element to cater to the local electricity demands or loads. The major renewable energy source that has been used extensively in the recent past in distributed generation are the Photovoltaic (PV) systems/solar systems. Unlike the other generations methods, where it is required to have 24/7 monitoring, maintenance and geographical limitations, solar cells can be left unattended and require very minimal maintenance, and due to its flat plate design, it can be installed almost anywhere (even on the roof for electric/hybrid vehicles) with minimal restrictions. These solar cells work on the PV effect.

The PV effect is the principle of generating electric energy using solar irradiation. It was first observed by a French Scientist Alexandre Edmond Becquerel in 1839 [1]. It states that when sun light hits the surface of the semiconductor materials, the electrons acquire the energy, which is in the form of photons and become active enough to participate in the conduction. This results in electric current and hence the electric energy is generated. Since then, many techniques have evolved using the PV effect to generate electricity. Several semiconducting materials were experimented for this effect, varying from silicon, germanium, selenium, tellurium, etc. An abundant number of compounds have been developed by numerous scientists and laboratories that can generate electricity using the PV effect.

Charles E. Fritts, in his work in 1883, has presented that a new form of selenium cell has a variable resistance (with resistance lowering from 500 ohms to nearly 9 ohms) which can be affected by light [2]. In 1884, he was the first to install a solar array on a building rooftop in New York city and achieved an efficiency of 1–2%. It was in 1888 that Edward Weston mentioned, about his invention in US patent 389124A, a new apparatus for converting solar radiant energy to electric energy which can then be turned into mechanical energy [3]. Russel Ohl in US patent 2402662 has stated that silicon is superior to selenium or copper oxide materials in photo effect and mentioned the p-n junction [4]. He achieved a maximum efficiency of 1% with silicon cells [5]. The major milestone in the improvement of efficiency of PV cells was a work conducted in [6] with a mentioning of nearly a 6% efficiency. It was later enhanced by nearly 10% to 15% by the year 1961 with the work done by Hoffman Electronics [7]. In the work [6], it was stated that a wavelength of light rays of less than 1.2 μm can generate an electron-hole pair, but the efficiency of energy conversion from light to electricity decreases with lower wavelengths, thus reducing the maximum theoretical efficiency of the single junction solar cells.

Multi-junction solar cells were developed to further boost the solar cell efficiencies. These cells employ multiple p-n semiconductor junctions that are connected in series. These multi-junction cells can absorb multiple wavelength ranges of the available solar spectrum, thereby improving the conversion efficiencies of light to electric energy [8]. One of the most widely used multi-junction solar cells is a three-junction solar cell which has three semiconductor absorbers separated by tunneling junction. A five-junction solar cell with an efficiency of 35.8% for space applications and 38.8% efficiency for terrestrial applications were developed over the next 30 years [9]. In their work in [10], the authors demonstrated a 47.1% efficiency of solar conversion using a monolithic stack with a six-junction inverted metamorphic structure.

In the solar cell efficiency table (version 60) [11], the confirmed single junction crystalline silicon terrestrial cell has a maximum efficiency of 26.7%, measured at 1000 W/m^2 and 25 °C, while the III-V semiconductor cells of the GaAs (Gallium-Arsenic) thin film had an efficiency of 29.1%. For multiple junction terrestrial cell configurations at the same irradiance and temperature, the five-junction bonded cell has an efficiency of 38.8%.

Of all the semiconductor materials that are used for making solar cells, silicon is the most extensively used, with a major share of 95% of all the total solar modules sold [12]. With the support of government subsidies, the purification of silicone and production of silicon solar cells have become more affordable, despite the fact that they are quite fragile and rigid. The silicon solar cells are more efficient when compared to the organic solar cells that employ carbon-based materials and organic electronics. The organic solar cells are lighter and have a long duration, but their power conversion efficiency is still reeling at 16.5% for single-junction devices [13]. The Dye-Sensitized Solar Cells (DSSC) are thin film solar cells and have low toxicity with higher ease of production, but they have been recording nearly 12–13% efficiency, which is considerably lower than that of older generation solar cells [14].

Many researchers have focused on the developments and manufacturing of the PV cells and their architectures. Of all the available technologies, single junction silicon solar cells are proved to be promising. Several researchers in the literature have worked on different applications of improving PV energy efficiency by incorporating new approaches to maximize the PV power output by minimizing the technical difficulties. However, there exists a gap that needs to be addressed by combining the latest PV technologies and architectures with a focus on PV applications for increasing the efficiency. In this background, this paper presents a comprehensive review on the silicon based single-junction solar cells architectures that proved to have a conversion rate of at least 25%. Though these cells have proved to be highly efficient cells to date, their conversion efficiency is only at the favorable conditions set up in the laboratories. For better utilization of these solar cells in the real word, and to extract the maximum power output on a commercial scale, different integration methods that address the drawbacks of the solar PV systems are also reviewed. Unlike the previous literature, this paper also provides a comprehensive approach to how the PV energy output can be maximized with minimal manual effort after installation. Moreover, a future research direction considering the growing technology that can be implemented for these PV systems and the issues related to these future technologies is proposed.

This paper is organized in the following way. Section 2 provides a review of the highly efficient silicon based single-junction solar cell architecture and their background. Section 3 reviews the different integration methods and aspects related to the installed panels that can help to maintain the efficiencies. The future research directions were discussed in Section 4 and concluding remarks are presented in Section 5.

2. Highly Efficient Solar Cell Architecture

Since the first silicon solar cell patents were granted during the 1940s, it always suffered the drawback of lower efficiencies, which are less than 1% [4,5]. This fueled the researchers in developing methods and to make the solar panels more efficient. In 1954, Bell laboratories succeeded in developing a solar cell with 4–5% [15] efficiency and in 1963, they were able to raise it to 6% [15]. Soon after, many different approaches from different laboratories proposed higher efficiency cells in the following years, and in 2009, the 25% efficiency milestone was reached [16]. W. Shockley and Hans J. Queisser published a paper in 1961 on the theoretical efficiency limit for a single-junction solar cell considering only the radiative recombination loss, which is also known as the detailed balance limit or Shockley-Queisser limit (SQ-Limit) [15,17]. In theory, the maximum efficiency or the SQ limit of a single junction p-n solar cell is 30% at 1.1 eV. The record lab efficiency for a single-junction solar cell is about 27%, which is less than the SQ-limit. This SQ limit can be also extended to use with the multi-junction solar cells and the SQ limit of such solar cells is provided by [18] to be 86.8%. Achieving a higher efficiency solar cell will help in reducing the cost of an installed PV system. The efficiency of a PV module is always less than the efficiency of a PV cell, due to the resistive losses in the interconnected series and parallel connections of the solar cells and also due to the variations in individual solar cell efficiencies.

Several technologies were developed for solar cell structures to improve their efficiencies, out of which the Bifacial Solar cell structure, interdigitated back contact (IBC), is one of the most common technologies. In a bifacial solar cell, the cell has the potential to absorb the light from both the front and back surface and is able to generate the electricity. Due to these advantages, there is an increase in the power generated by these cell structures. Below is the different silicon based single-junction solar cell architectures that proved to have at least 25% conversion efficiency. Moreover, a summary of structural difference between these solar cells and their maximum efficiencies achieved to date are presented in Table 1.

Table 1. Highly Efficient silicon based single-junction solar cells.

Cell	Max. Efficiency	Structure
PERC	22.8% [19]	Silicon wafer cell with passivation layer that helps to absorb more light.
Bifacial PERC	up to 25% [20]	Double sided PERC cell.
PERL	24.5% [21]	Addition of P^+ passivation layer to reduce the rear surface recombination rate.
HIT	26% [11]	Intrinsic a-Si layer is inserted between p-type a-Si and n-type a-Si for passivation.
HJ-IBC	26.7% [11]	HIT cell with interdigitated back contacts that has the collection region and contact on the rear side.
TOPCon	26.1% [22]	Tunnel oxide layer is inserted followed by a highly doped p-type or n-type poly silicon layer.

2.1. *Passive Emitter and Rear Cells (PERC) Solar Cell*

The aluminum back surface field (Al-BSF) design based solar cells has been around 90% of the global production for decades. Though the fabrication of these solar cells is simple and reliable, the major drawback is its moderate efficiency. Due to its better efficiency when compared to the Al-BSF solar cells, the PERC solar cells have seen a rapid increase in the PV production industry [23]. The major difference between these two solar cells is that the PERC cells have very low surface recombination and higher carrier generation due to the optical reflectivity of the rear side passivated layer generated by the laser contact opening (LCO) process [24,25]. The difference between these two solar cells in light absorption due to the passivated layer is shown in Figure 1. When the photons in the sunlight strike the surface of the solar cell, it is either absorbed, reflected, or transmitted through the cell. In the Al-BSF solar cell, due to the absence of the passivated layer the unabsorbed light is just passed through the cell. Whereas, in the PERC cell, this unabsorbed light is reflected back due to the passivated layer and can be absorbed to generate the electron-hole pair, thereby boosting the efficiency of the cell [26].

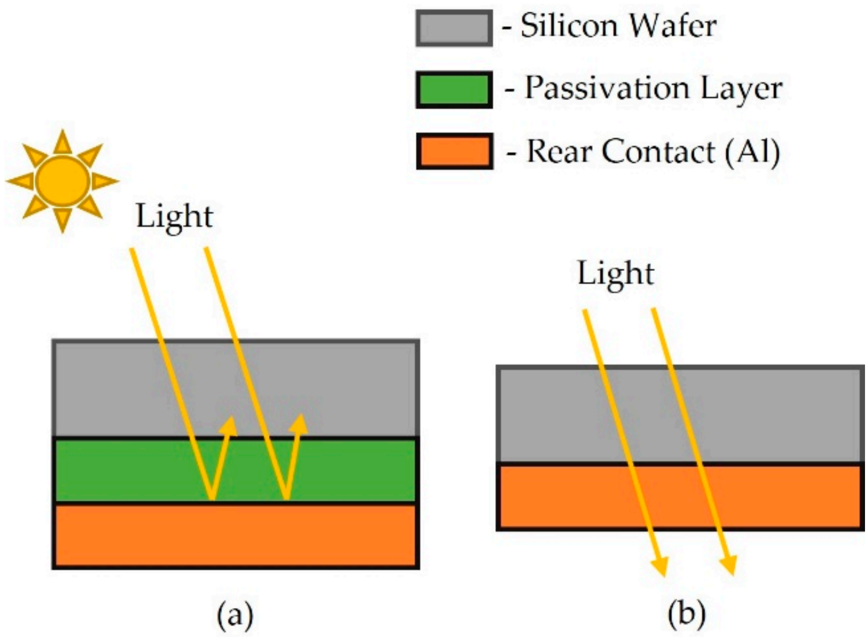

Figure 1. Difference between (**a**) PERC and (**b**) Al-BSF solar design.

The first PERC solar cell was published in the year 1989, at an efficiency of 22.8% by [19]. The schematic of this PERC cells is presented in Figure 2. The structural design of PERC solar cell consists of:

- Front contact (Ag)
- Antireflection coating (ARC) layer
- Emitter
- Si-Wafer
- Passivated oxide layer
- SiNx Capping layer and
- Rear Contact

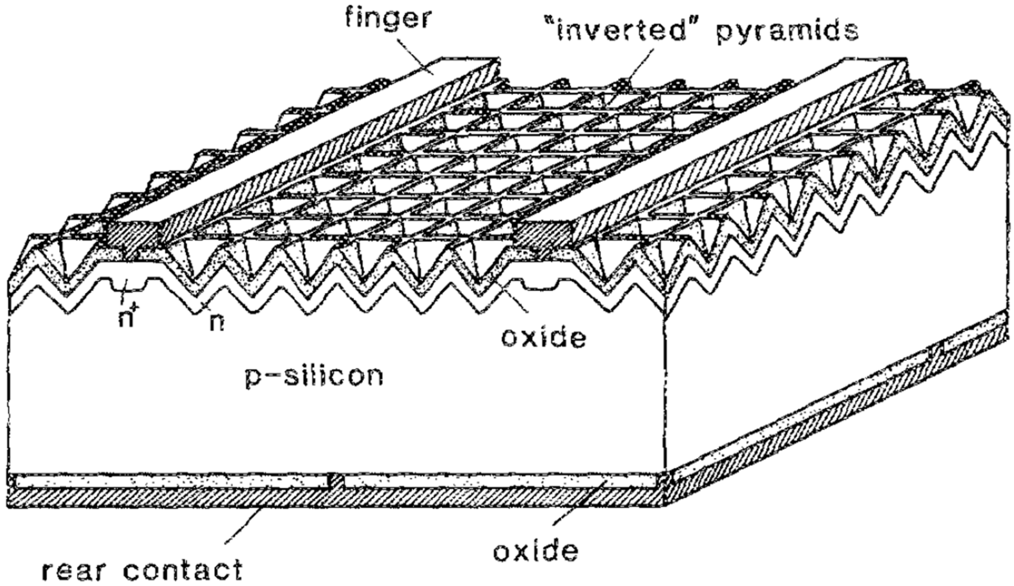

Figure 2. Structure of the first PERC cell. Reprinted/adapted with permission from Ref. [19]. 1989, AIP publishing.

The major difference of the PERC cell that boosted the efficiency is due to the addition of the rear passivating oxide layer as compared to the Al-BSF solar cell. This Passivated layer helps in absorbing more light. Normally, the Si-wafer layer absorbs light up to 1180 nm wavelength range, and the light higher than this wavelength is passed through this layer, as shown in Figure 1 for the Al-BSF cell. The passivated layer in PERC cell helps in absorbing this light and is thereby able to improve the efficiency of the cell. A comprehensive review on the development of these PERC design solar cell is presented in [23]. In [26], a comparative study of different methods in PERC cells and their performance parameters is provided. For further improving the efficiency of these cells, different combinations of SiNx and AlOx layers are used, and a study on these types is provided in [27]. An analysis using the simulation model based on 2D Sentaurus Device simulations of the PERC in comparison to the industrial PERC cell is provided in [28] and the analysis of the losses in these cells are presented in [29].

The Bifacial solar cell structure technology can be used for PERC solar cells that can further improve the efficiency. These cells, which are also known as the PERC+ solar cell, were introduced in 2015 at ISFH and Solar World. Due to their bifacial nature, these PERC+ solar cells can increase the efficiency by up to 25% [20]. A simplified structure of PERC cell and bifacial PERC cell is presented in Figure 3.

2.2. Passive Emitter and Rear Locally Diffused (PERL) Solar Cell

The PERL solar cell is one of the configurations of the PERC solar cell. The performance of the PERC cells was limited by the fact that the rear contact areas with aluminum comes directly in contact with the silicon, which results in a high recombination rate at these areas. This recombination rate can be reduced by a diffused layer underneath the metal contact area that can help to passivate the contact surface. This gave birth to the PERL solar cells in 1992, which has a P^+ passivation layer underneath the rear metal contact area that helps to lower the recombination rate, thereby improving the efficiency [30]. An improved cell with 24% conversion efficiency was proposed by [31] in 1996. The basic structure of the PERL cell is shown in Figure 4.

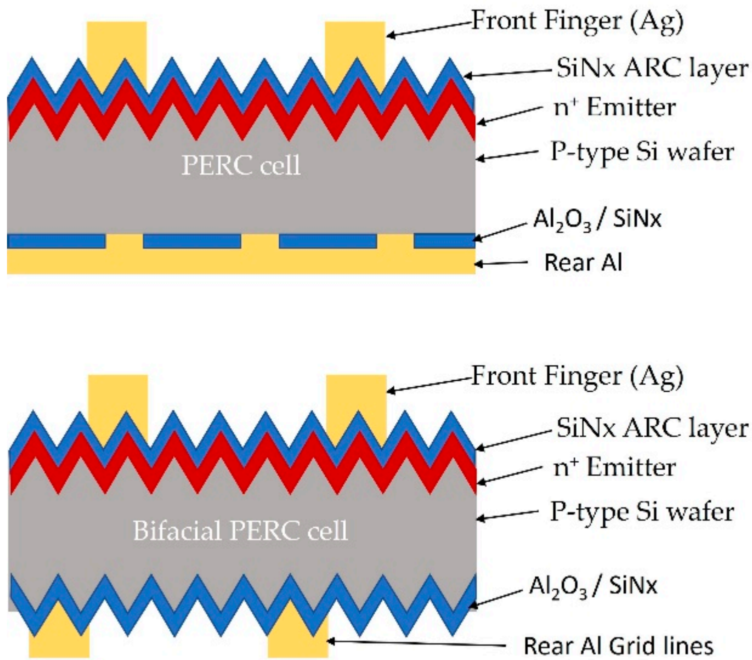

Figure 3. Simplified Schematic diagram of the PERC cell and Bifacial PERC.

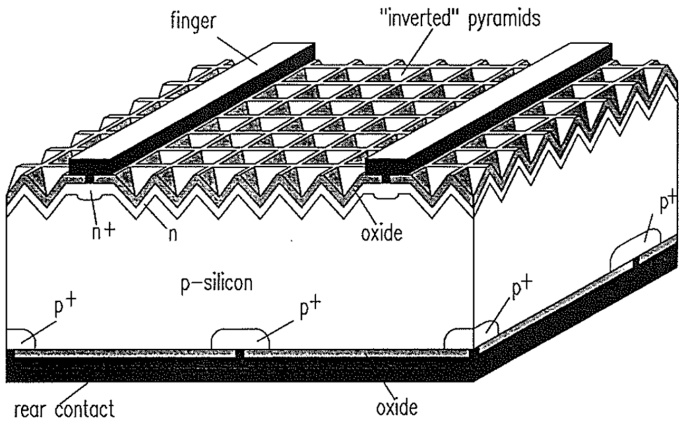

Figure 4. Structure of first PERL cell Reprinted/adapted with permission from Ref. [30]. 1992, Wang, Aihua.

When these solar cells were introduced, one of the major hurdles was to develop a technique to diffuse this passivated layer underneath the rear metal contact area without damaging the surface. Though the authors in [30] proposed to use boron tribromide (BBr_3) liquid to diffuse this passivated layer, researchers tried to find different methods that further optimize the efficiency of these cells [21]. A novel co-diffusion process was proposed in [32] using Aluminum doping paste. Moreover, the process flow of both the PERC and PERL cells that were produced at their ExcelTon^{TM}-Cell-III production line were presented and proved the fact that the PERL cells achieved higher efficiency than the PERC cells. Additionally, the concept of bifacial cell structure can be implemented for the PERL solar cells that can further boost the efficiency [33]. Further research on these solar cells led to the development of passivated emitter and rear totally diffused (PERT) solar cells which worked very well for high resistivity cells [30]. These cells have proven to be one of the most efficient solar cells with an efficiency of 24.5% [21]. An overview on these PERT solar cells, fabrication procedures, and the promising techniques that can reduce the cost of these solar cells are presented in [34]. Similar to the other cells in the PERC family, the bifacial structure technology can also be implemented for these PERT cells. Effective passivation techniques of P^+ and n^+ emitters for the industrial bifacial p-PERT solar cells is presented in [35].

2.3. Heterojunction with Intrinsic Thin-Layer (HIT) Solar Cell

HIT solar cell is another type of silicon wafer-based cells which has achieved the energy conversion efficiency of up to 26% [11]. These cells were first reported and published in the year 2000. In these cells, a very thin-layer of intrinsic a-Si is inserted between the p-type a-Si as n-type c-Si [36], as shown in Figure 5. These solar cells use crystalline silicon (c-Si) wafers for the light absorption and the carrier transportation, and the amorphous silicon (a-Si) layers for the purpose of passivation and for the junction formation, the top grid electrode is made of a transparent conductive oxide (TCO) layer that acts as an anti-reflection (AR) layer in combination with a metal grid [37,38]. A HIT solar cell is common and most promising structurer due to its lower manufacturing costs and higher conversion rate. These cells grabbed the attention of industries because of the requirement of temperatures below 200 °C for the complete fabrication process and a relatively lower cost. Due to this low temperature process and symmetrical structure, thin silicon wafers (~70 µm) can be used to fabricate these cells [39].

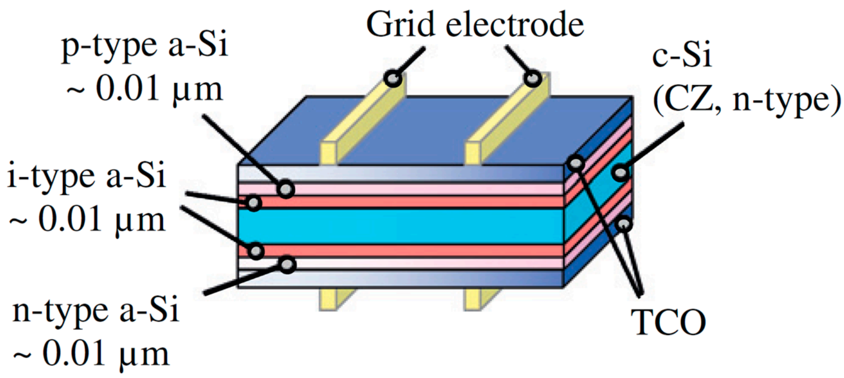

Figure 5. Structure of the HIT cell. Reprinted/adapted with permission from Ref. [40]. 2011, Elsevier.

For improving the efficiency of these solar cells, concepts on improving the a-Si/c-Si heterojunctions (HJ), improving the grid electrode to suppress resistance loss, and methods in reducing the absorption rate in the a-Si and TCO layers are studied in [39,41]. It is presented in [42] that, using a high-quality TCO film can improve the efficiency of the c-Si based HIT solar cells. Additionally, the concept of bifacial structure can be implemented for the HIT cells, and it is seen from [40] that bifacial HIT solar cell produced 10.9% more power than the single-sided HIT cell.

At present, the highest efficiency for a single-junction silicon based solar cell is the HJ solar cell with interdigitated back contacts (IBC) with a conversion efficiency of 26.7% [11]. The concept of IBC for solar cell was first proposed in 1977 by Michael D. Lammert and Richard J. Schwartz [43]. The advantage of this back contact structure is that all of the collection regions and the contacts for the holes and electrons are formed on the rear side of the solar cell [44]. Though several groups worked on the HJ-IBC structures solar cells, Kaneka Corporation was able to achieve, so far, the highest efficiency cell in 2017 [44]. The cross-section schematic diagram of this HJ-IBC cell structure is presented in Figure 6. The topmost layer is the a-Si passivation layer with an AR layer where the generated carriers due to the incident light, are collected by the a-Si layer and the grid electrodes. A review of these HIT solar modules, manufacturing technologies, and loss characteristics with research ideas on improving the reliability is published in [45].

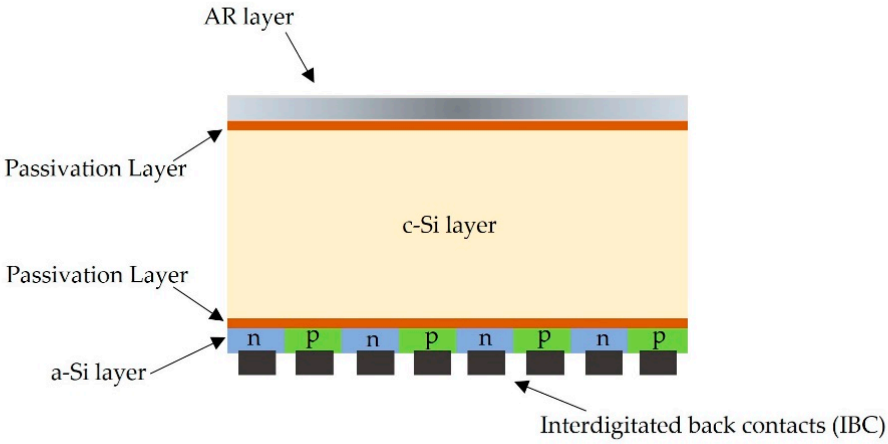

Figure 6. Cross-section of an HJ-IBC solar cell.

2.4. Tunnel Oxide Passivated Contact (TOPCon) Solar Cell

TOPCon solar cells have demonstrated to be one of the efficient cells and gained the significance interest from researchers and the industry. In these cell designs, an ultra-thin tunnel oxide is inserted followed by a highly doped p-type or n-type poly silicon layer that is connected to the metal contacts at the end [46], as shown in Figure 7. These solar cell structures stand as the second highest efficient silicon based single-junction solar cells, with an efficiency of 26.1% achieved very recently in October 2022 by JinkoSolar. They surpassed their previous record of 25.7%, achieved in April 2022 [22].

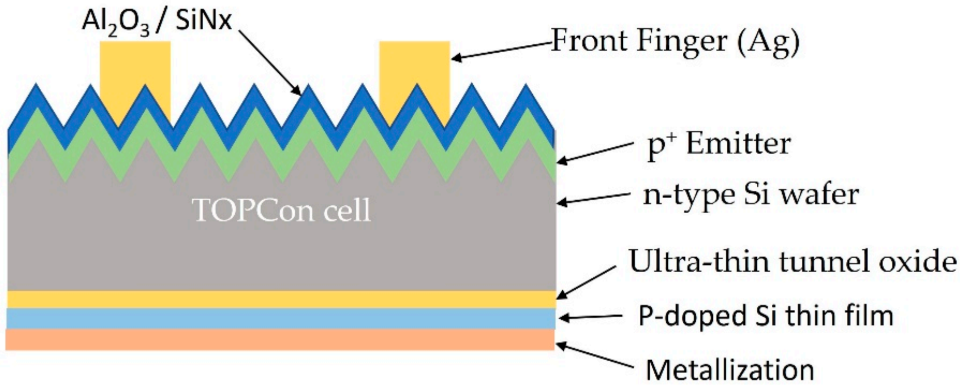

Figure 7. Schematic diagram of TOPCon solar cell.

The top surface of the TOPCon cell is passivated by a stack of Al_2O_3 and SiN_x [47] or constructs with a boron emitter [46]. The effect of boron doping on the efficiency of n-type TOPCon solar cell is studied in [48]. For reducing the surface recombination velocity, the effects of tunnel oxide layer thickness, impact of surface recombination, and doping of tunnel oxide were studied using the software tool Automat FOR Simulation of HETero-structures (AFORS-HET) developed by HZB (Hahn-Meitner-Institute Berlin) in [49], and using the same software, it was proposed in [50] that by optimizing the parameters such as doping concentration, tunnel oxide thickness, interface-states density, and the pinhole density through the oxide layer it is possible to achieve the theoretical maximum efficiency for the TOPCon cell. The process flow for the fabrication of these cells were presented in [46] and the effects of the process techniques were presented in [47]. Mass production of these cells via lean process flow was proposed in [51] and experimental results of the produced cells were presented. The concept of bifacial structure technology can also be implemented for TOPCon [51,52]. Figure 8 shows a double-sided structure for the cells that is presented in [53] with an analysis on the cell characteristics.

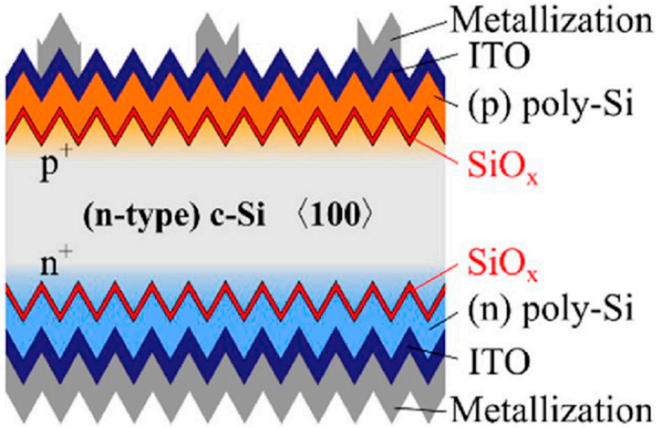

Figure 8. Double-sided structure of TOPCon solar cell. Reprinted/adapted with permission from Ref. [53]. 2020, Elsevier.

3. Integration Methods and Techniques for Better Efficiency

Though the present research on solar cell architecture has proved that the conversion efficiency of about 27% can be achieved, these are mostly related to the laboratory test and were under a confined environment. For better utilizing these highly efficient solar panels, there is a need for better integration of these panels. Moreover, efficiency limiting factors, like irregular sunlight due to shade or panel orientation, module temperatures, etc., need to be addressed. Additionally, space constraints are another drawback of the solar PV systems that limits the installation of solar panels in a tight space and optimizing these solar panels in a limited space can significantly boost the usage of these panels. This section provides an overview of the available integration methods and techniques that can be employed for the solar PV system that can address the efficiency limiting factors and also different integration methods to save land space.

3.1. Building Integrrated Photovoltaics (BIPV)

BIPV refers to the integration of PV into the building envelope, as shown in Figure 9. In BIPV, the PV modules are used to replace conventional building materials. These also help in avoiding the maintaining of additional or backup power source for building. The overall cost of BIPV system is much lower when compared to the traditional PV system as dedicated space and mounting requirements are avoided [54]. Despite these advantages, there are a few concerns for BIPV systems:

1. Providing adequate ventilation: As the conversion efficiency of PV panels is directly affected by their operating temperature, if suitable ventilation is not provided for BIPV systems, their performance efficiency is reduced. To overcome these issues, suitable ventilation needs to be provided in these panels.
2. Planning of site and orientation: At the design phase, orientation and installation of PV panels is to be chosen such that they receive maximum exposure to the sun and will not be shaded by any nearby obstructions. Suitable orientation to the sunlight can improve the system efficiency to as high as 50–70% compared to traditional vertical facade systems. Additionally, measures are to be taken so that PV panels do not get affected by the ice/dust settlements or dry environments.
3. The most widely used modules in BIPV systems are of thin film type as they perform better in low light conditions and at high temperatures [55,56]. Thin film technologies based on CdTe, CIGS and a-Si have been developed in the recent past [57]. The tunable color properties of Dye Sensitized Solar Cells (DSSCs) along with semi-transparent nature makes them best alternative for BIPV applications. These can be employed for replacing the building envelopes besides generating electric energy for operating the entire building [58]. Despite their lower efficiency of 12% when compared to other thin film solar cells, DSSCs are widely employed because of their low cost and low

toxicity with ease of production. Besides, DSSCs have sandwiched glass structure which makes them bulky, and flexible DSSCs can be employed as an alternative [14]. Since the PV modules in BIPV systems are installed in different orientations, there is a higher chance of them being shaded by nearby building or trees. In [59], an efficient and cost-effective configuration of PV-DC building module (PV-DCBM) has been proposed, which includes a centralized inverter.

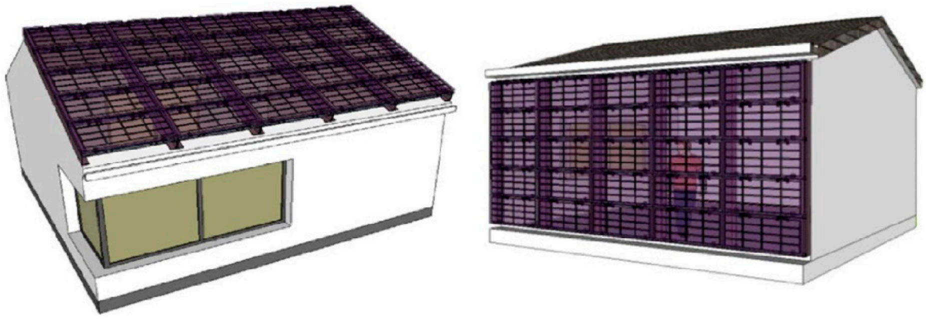

Figure 9. Architectural representation of BIPV. Reprinted/adapted with permission from Ref. [56]. 2016, Elsevier.

3.2. Floating Solar Photovoltaic (FPV) Systems

FPV systems is one of the emerging technologies where the solar PV panels are placed directly on the surface of the water body, as represented in Figure 10. These have been gaining much importance in the recent past [60,61]. A recent survey by Technavio suggests that the market share of FPV systems is expected to rise by USD 775.85 million from 2021 to 2026, and the market's growth momentum will accelerate at a compound annual growth rate (CAGR) of 16.89% [62]. Unlike the conventional land based solar farms which require large amount of land surface, a FPV system can address the issues of land conversation and water [63]. Besides they offer convenient energy conversion at a higher efficiency up to 13% higher than land-based PV due to the lower temperature underneath the panels [64]. Additionally, the FPV systems do not contribute to the global warming. These systems will help in reducing the evaporation of water reservoirs thereby protecting water resources [65]. In [66], it is observed that, even though tracking mechanisms increase the cost of FPV systems, a single axis tracking mechanism to these systems can increase the electric power generation annually by 11%.

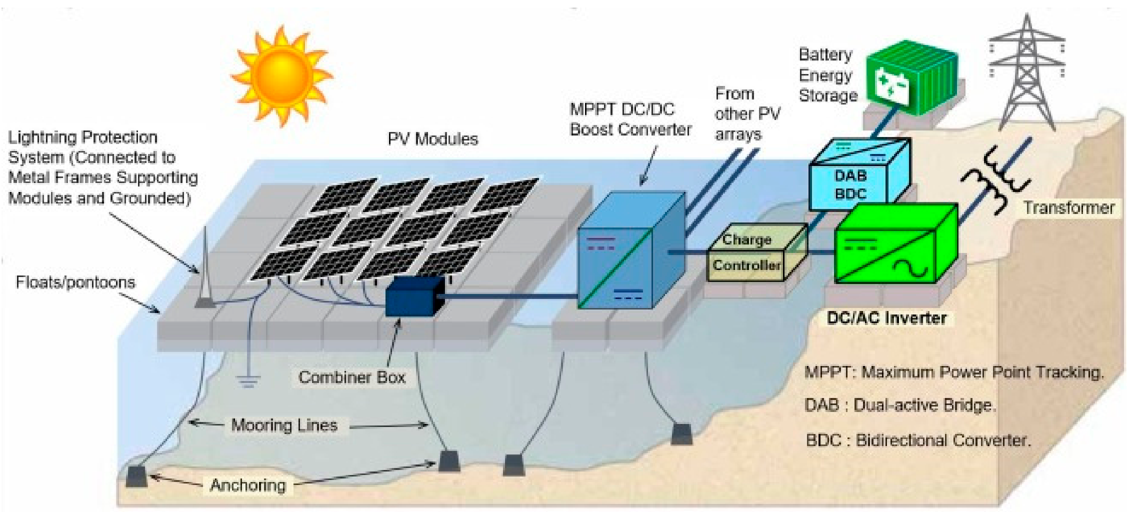

Figure 10. Architectural representation of FPV system. Reprinted/adapted with permission from Ref. [60]. 2022, Elsevier.

Though these FPV system help to conserve the water and land, there are certain limitations that need to be considered for reliable operation of these systems. One disadvantage of these FPV systems are the adverse effects of sea water. Though there are not many studies on the effect of sea water on the FPV, the sea salt accumulation on the PV modules can be treated as dust or as partial shading conditions [67]. Moreover, these FPV systems are to be designed to withstand the corrosion from the water and high waves/tides [68]. Due to these factors, the initial cost of an FPV system is very high in comparison to a conventional land PV system. Addressing these factors can help to build better and more efficient FPV systems.

3.3. Agrivoltaics

In the recent past, agrivoltaics has been on the rise. The term was first used by French Scientists led by Christophe Duprax. Agrivoltaics means utilizing the land for food crops and also installing PV panels thereby maximizing the usage of land. A conceptual representation of agrivoltaics is shown in Figure 11. The research in [69] indicates that the increase in global land productivity can be from 35–73%. In the InSPIRE project [70], funded by the National Renewable Energy Laboratory (NREL) and the US Department of Energy (DoE), the researchers found that the five central elements that lead to agrivoltaics success were the climate, configurations, crop selection, compatibility, and collaboration. In the work mentioned by [71], the authors mentioned that if shade tolerant crops are utilized for agrivoltaics, the economic value of the farms will be increased by 30% when compared to that of conventional agriculture.

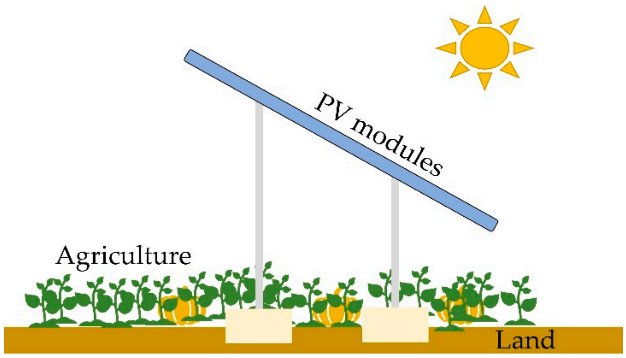

Figure 11. Conceptual representation of Agrivoltaics.

In the extensive review work mentioned in [72], the authors found that cultivating the crops underneath the PV panels may reduce the yield, but the land productivity can be increased by nearly 70%. It not only improves the economic value of farming but also improves rural electrification where main grids are not available. The study on agrivoltaics was extended deeper with using of normal, bifacial, and transparent solar panels by the research study mentioned in [73], and it was found that the performance of agrivoltaics had no significant difference. The authors in their work [74] have quoted that agrivoltaics systems can provide optimum energy conversion by extending agricultural land and can also be used to protect crops from UV-B radiation.

3.4. Panel Orientation and Tilt Angle

PV panels installed at a particular tilt angle can provide maximum yield. This optimal tilt angle depends on the latitude of the location at which the PV panels are installed and the weather at the location [75]. Poor selection of tilt angle and inter row spacing for installation area of PV panels will incur high financial losses to the investors of PV systems [76]. The impacts of the panel orientation and the elevation will affect the performance of the solar system [77]. The position of the sun changes in the sky every minute, day, month, and the year, so there is a need for solar tracking system that can trac the movement of the sun and adjust the panel orientation and the tilt angle to extract the maximum power from the solar panels [78]. Further, in urban locations, the partial shading due to blocking of PV panels because of nearby buildings and sky has to be taken into consideration for determining the optimal tilt angle. A two-axis solar tracking system which can offer varying tilt angle for different methods based on the seasons can offer higher total solar radiation which ultimately results in higher gain in the daily generated power of a PV panel [79].

The authors in [80] have demonstrated in their research, based in Cairo, Egypt, that the south facing monocrystalline silicon-based PV panels with a tilt angle of 20–30 degrees can yield maximum PV energy. In [81], research conducted in Mumbai, India, revealed that the for a fixed tilt orientation of the PV panels, the optimal tilt angle which gave the best performance overall the year was the latitude of that place (19 degrees). Based on the climatic data provided by the National Renewable Energy Laboratory (NREL), optimized solar panel orientation and its performance were studied in [82].

Apart from the tilt angle, which is considered as the angle of inclination of PV panels from a horizontal surface, another angle that is commonly employed during the large PV installations is the azimuth angle, which is referred to as the angle of PV modules relative to the direction due south if the PV installation is in the northern hemisphere and the panels should face north if the installation is in the southern hemisphere [77]. In their research on a low voltage distribution grid [83], the authors observed that a small deviation of azimuth angle from the south has reduced grid losses but at the cost of higher reduction in energy output whereas a change in tilt angle was more effective with lower grid losses. In [84], the authors have suggested that for large consumers or large PV systems, an east/west oriented PV installation can have more benefits.

3.5. PV Panels Cleaning

Dust accumulated on the surface of the PV panel will reduce the amount of sunlight incident on the panel, which in turn reduces the output of the panel, thereby reducing its efficiency. In [85], the authors have observed that due to opaque particles, in particular moss, there can be reduction of nearly 86% in power output of PV panel. Additionally, they have quoted that the rainwater can clean the dust and sand, but moss needs proper cleaning. In [86], the authors have observed that the average degradation rate on the optical efficiency of the PV panels can be up to 7% per month in a desert type of environment due to sand and dust accumulation on the PV panels. In the study mentioned on the performance of PV panels in Saudi Arabia, where sandstorms are frequent [87], the authors have concluded that the decrease in performance of PV modules due to dust accumulation can be improved by regular cleaning of PV panels. According to the research conducted in [88], the authors observed that, despite having the same mass distribution, the impact of smaller dust particles is greater than that of larger dust particles on the output of the PV panel. The authors observed that for particles less than 75 µm, the decrease in short circuit current was 49.01% when compared to that of larger particles of 600 µm to 850 µm creating a decrease of 15.68%. The authors in their work [89] have mentioned that the output of the PV modules decrease linearly with the decrease in the diameter of the dust particle. Additionally, in the research mentioned in [90], it has been observed that finer (smallest) particles block more sunlight than the larger particles and hence result in decreases in the efficiency of PV panels. The choice of the cleaning technologies to be employed should depend on the properties of dust and their characteristics in the area where the PV modules are installed.

Several practices are being implemented to clean the PV panels. A few of them include manual cleaning of the panels, piezo electric actuators, electric curtain system, self-cleaning mechanism using nano-films and robotic systems. These have been extensively discussed in the article of [91]. An Infrared based solar panels cleaning system using a robotic arm that is driven by Pulse-Width Modulation (PWM) based motor to drive the robotic arm and a DC geared motor to move the robotic arm from one panel to the other is proposed in [92]. A novel approach on harvesting the rainwater and using it to clean the solar panels is proposed in [93] to boost the performance of the solar panels and the effect of humidity on the dust particles is studied in [94].

4. Discussion

As the solar PV system is growing with the latest technologies and methods that can boost the conversion efficiency and the better integration, there is room for further research development and consideration of some constraints that need to be taken care of for better, safer, and more reliable operation of the system. This section highlights some of the advanced technologies that can be implemented for the better operation and utilization of the solar PV systems. Moreover, issues and aspects related to the growing technologies, and advanced monitoring and controlling systems are also highlighted.

4.1. Artificial Intelligence (AI) Based Solar Tracking for Orientation

Many researchers have published work on optimizing the panel orientation, panel tilt angle for better and energy conversion [95,96]. Adaptive technologies that are based on the Internet-of-Things (IoT) devices, web-based monitoring and control system are developed for solar monitoring [97]. Non-linear controllers based on AI, Machine learning (ML) or the Deep Learning (DL) algorithm have proven to be more effective in the closed loop control applications [98]. They are very fast in processing, better in optimizing the parameters and can boost the performance of the connected system. Based on the historical data that can be gathered over time is used to train the supervised machine learning algorithm models.

These supervised learning algorithms can be used to optimize the solar tracking and can be implemented to control the panel orientation, panel tilt angle and the azimuth angle. They will be able to track the best possible orientation for the better conversion efficiency very quickly based on the present conditions and be able to boost the efficiencies of the installed system, thereby reducing the total cost of the PV system by limiting the required number of panels.

4.2. AI Based Solar Cleaning

The effect of dust particles on the solar panels and the research for cleaning methods are discussed in the Section 3. For better conversion rates, especially in a dessert area or windy areas where the solar panels are more prone to dust particles, it is utmost required to employ a mechanism that helps to clean this dust accumulated on the solar panels. Though various methods using autonomous cleaning robots and automatic wipers [99–102] were proposed to clean the solar panels by researchers, they are mostly predefined to operate at a certain time intervals. Enhancing the control algorithms of these proposed cleaning system can help in better cleaning of the panel and helps in optimizing the cleaning duty.

Based on the output parameters, like the voltage or current parameters and considering the solar irradiance levels and the temperature, the machine learning algorithms based on the reinforcement learning can be implemented for tracking the affected solar panel [91]. These machine learning algorithms can help in determining the cause of the changes in the output parameters, whether it is because of the dust particles or because of the change in irradiance or temperature and can take the right action as to whether to clean the panels or not. This helps in optimizing the cleaning system and responds very quickly to the change in parameters and helps boost the efficiency of the solar PV system.

4.3. Cybersecurity Issues

From the previous discussion, it is seen that panel orientation and tilt angles play an important role in the performance of the solar PV model. For a large solar PV system, it can significantly affect the overall power production and can impact the connected loads. The control algorithms that are employed to control the panel orientation receive data for the temperature, irradiance levels, weather conditions, sun angle, etc., using the IoT devices to determine the optimal position. These data can be controlled and monitored remotely [97] through wired or wireless communication lines [103]. Any communication lines are prone to cyber intrusions that can give the system access to the attackers [104,105]. These attackers can manipulate the data received by the control algorithm or be able to adjust the panel orientation that can affect the overall production. Necessary means that can identify, detect, and mitigate the cyber-attacks are to be implemented for the safe and reliable operation of these systems.

4.4. Protection of Solar Cells

Apart from providing security and protection against dust or cybersecurity issues, protection of solar panels against certain weather elements like hailstorms, snow or rain is also an important factor to consider for better and reliable operation. For areas like Texas, where they had a large hailstorm [106], using necessary protective means can help to protect the panels from destruction and help to maintain steady and stable power conversions. Though there is not much literature available on protection of these solar panels, predicting the weather conditions and using protective measures like using protective covers, building a wire gauge, or using methacrylate material, which is known for its resistance to hail, can help to protect these panels [107]. Moreover, tilting the panel to a direction opposite to the impact of hail can also prevent the damage. Thus, implementing a protective means that can forecast the weather conditions and taking the necessary protective means is required for reducing the maintenance and operation cost of these panels.

5. Conclusions

This paper provides a comprehensive review of the available single-junction silicon solar cell architectures that have an energy conversion efficiency of at least 25% and different integration methods and the possible approaches that help to maintain these efficiencies. The conclusions that can be drawn from this paper are as follows.

1. Though there are solar cell architectures that can achieve the efficiencies close to their theoretical SQ-limit, those efficiencies are only confined to the laboratory environment.
2. For better utilization of the highly efficient solar cells and to overcome the drawbacks of the solar PV system, different integration methods and techniques are reviewed.
3. An extensive bibliography on the existing solar cell structures, and other applications that can help to maintain the efficiency of the solar panels, are presented.
4. Some recommendations on the future research on the solar PV systems that can help in achieving better efficiency are proposed.

This article would serve as a guideline for understanding the highly efficient solar cell architectures, methods that can improve the efficiency of the installed solar panels, and for further investigation of the technologies to better control and for safe, reliable operation. Thus, this work benefits the readers, researchers, and engineers who work in the field of solar PV systems.

Author Contributions: Conceptualization, S.N.V. and M.H.A.; resources, M.H.A.; writing—original draft preparation, S.N.V.; writing—review and editing, M.H.A.; supervision, M.H.A.; project administration, M.H.A.; funding acquisition, M.H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are pleased to acknowledge the financial support from the Electrical and Computer Engineering department of the University of Memphis to complete this work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Becquerel, A.E. Memoire Sur Les Effects d'Electriques Produits Sous l'Influence Des Rayons Solaires. *Comptes Rendus De L'academie Des Sci.* **1839**, *9*, 561–567. Available online: https://www.scirp.org/(S(i43dyn45teexjx455qlt3d2q))/reference/ReferencesPapers.aspx?ReferenceID=447678 (accessed on 27 October 2022).
2. Fritts, C.E. On a New Form of Selenium Cell, and Some Electrical Discoveries Made by Its Use. *Am. J. Sci.* **1883**, *s3-26*, 465–472. [CrossRef]
3. Weston, E. Apparatus for Utilizing Solar Radiant Energy. U.S. Patent 389124A, 4 September 1888.
4. Oh, R.S. Light-Sensitive Electric Device. U.S. Patent 2402662A, 27 May 1941.
5. Ohl, R. Light-Sensitive Electric Device Including Silicon. U.S. Patent 2, 443,542, 15 June 1948.
6. Chapin, D.M.; Fuller, C.S.; Pearson, G.L. A New Silicon P-n Junction Photocell for Converting Solar Radiation into Electrical Power. *J. Appl. Phys.* **2004**, *25*, 676. [CrossRef]
7. Bube, R.H. *Photovoltaic Materials*; World Scientific: Singapore, 1998. [CrossRef]
8. Jackson, E.D. Areas for Improvement of the Semiconductor Solar Energy Converter | Europeana. Available online: https://www.europeana.eu/en/item/9200146/150083F0081EB9B335C182FD5FFDE41058399DB4 (accessed on 27 October 2022).
9. Chiu, P.T.; Law, D.C.; Woo, R.L.; Singer, S.B.; Bhusari, D.; Hong, W.D.; Zakaria, A.; Boisvert, J.; Mesropian, S.; King, R.R.; et al. 35.8% Space and 38.8% Terrestrial 5J Direct Bonded Cells. In Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference, PVSC, Denver, CO, USA, 8–13 June 2014; pp. 11–13. [CrossRef]
10. Geisz, J.F.; France, R.M.; Schulte, K.L.; Steiner, M.A.; Norman, A.G.; Guthrey, H.L.; Young, M.R.; Song, T.; Moriarty, T. Six-Junction III–V Solar Cells with 47.1% Conversion Efficiency under 143 Suns Concentration. *Nat. Energy* **2020**, *5*, 326–335. [CrossRef]
11. Green, M.A.; Dunlop, E.D.; Hohl-Ebinger, J.; Yoshita, M.; Kopidakis, N.; Bothe, K.; Hinken, D.; Rauer, M.; Hao, X. Solar cell efficiency tables (Version 60). *Prog. Photovolt. Res. Appl.* **2022**, *30*, 687–701. [CrossRef]
12. Solar Photovoltaic Cell Basics | Department of Energy. Available online: https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics (accessed on 27 October 2022).
13. Chen, L.X. Organic Solar Cells: Recent Progress and Challenges. *ACS Energy Lett.* **2019**, *4*, 2537–2539. [CrossRef]
14. Sharma, K.; Sharma, V.; Sharma, S.S. Dye-Sensitized Solar Cells: Fundamentals and Current Status. *Nanoscale Res. Lett.* **2018**, *13*, 381. [CrossRef] [PubMed]
15. Singh, R.; Alapatt, G.F.; Lakhtakia, A. Making Solar Cells a Reality in Every Home: Opportunities and Challenges for Photovoltaic Device Design. *IEEE J. Electron Devices Soc.* **2013**, *1*, 129–144. [CrossRef]
16. Green, M.A. The Path to 25% Silicon Solar Cell Efficiency: History of Silicon Cell Evolution. *Prog. Photovolt.* **2009**, *17*, 183–189. [CrossRef]
17. Rühle, S. Tabulated values of the Shockley–Queisser limit for single junction solar cells. *Sol. Energy* **2016**, *130*, 139–147. [CrossRef]
18. Luque, A.; Martí, A. Theoretical Limits of Photovoltaic Conversion and New-Generation Solar Cells. In *Handbook of Photovoltaic Science and Engineering*; John Wiley & Sons: Hoboken, NJ, USA, 2011; pp. 130–168. [CrossRef]
19. Blakers, A.W.; Wang, A.; Milne, A.M.; Zhao, J.; Green, M.A. 22.8% efficient silicon solar cell. *Appl. Phys. Lett.* **1989**, *55*, 1363–1365. [CrossRef]
20. Dullweber, T.; Schulte-Huxel, H.; Blankemeyer, S.; Hannebauer, H.; Schimanke, S.; Baumann, U.; Witteck, R.; Peibst, R.; Köntges, M.; Brendel, R.; et al. Present status and future perspectives of bifacial PERC+ solar cells and modules. *Jpn. J. Appl. Phys.* **2018**, *57*, 08RA01. [CrossRef]
21. Zhao, J.; Wang, A.; Green, M.A. High-efficiency PERL and PERT silicon solar cells on FZ and MCZ substrates. *Sol. Energy Mater. Sol. Cells* **2001**, *65*, 429–435. [CrossRef]
22. JinkoSolar Achieves 26.1% Efficiency for n-Type TOPCon Solar Cell—Pv Magazine International. Available online: https://www.pv-magazine.com/2022/10/13/jinkosolar-achieves-26-1-efficiency-for-n-type-topcon-solar-cell/ (accessed on 22 October 2022).
23. Blakers, A. Development of the PERC Solar Cell. *IEEE J. Photovolt.* **2019**, *9*, 629–635. [CrossRef]
24. Lin, Y.-H.; Li, L.-Y.; Chen, S.-Y.; Hsu, S.-P.; Chen, Y.-S.; Cheng, T.-H.; Chen, C.-P.; Yu, P. New designed electrode patterns on rear side of bifacial PERC solar cells. In Proceedings of the Conference Record of the IEEE Photovoltaic Specialists Conference, Chicago, IL, USA, 16–21 June 2019; pp. 1124–1126. [CrossRef]
25. Dullweber, T.; Schmidt, J. Industrial Silicon Solar Cells Applying the Passivated Emitter and Rear Cell (PERC) Concept—A Review. *IEEE J. Photovolt.* **2016**, *6*, 1366–1381. [CrossRef]
26. Kashyap, S.; Madan, J.; Pandey, R.; Sharma, R. Comprehensive Study on the Recent Development of PERC Solar Cell. In Proceedings of the Conference Record of the IEEE Photovoltaic Specialists Conference, Calgary, AB, Canada, 15 June–21 August 2020; pp. 2542–2546. [CrossRef]
27. Lv, Y.; Zhuang, Y.F.; Wang, W.J.; Wei, W.W.; Sheng, J.; Zhang, S.; Shen, W.Z. Towards high-efficiency industrial p-type mono-like Si PERC solar cells. *Sol. Energy Mater. Sol. Cells* **2020**, *204*, 110202. [CrossRef]
28. Weber, T.; Fischer, G.; Oehlke, A.; Kusterer, C.; Strauch, K.; Schiepe, R.; Mühlbauer, M.; Müller, M.; Wolny, F.; Köhler, R.; et al. High Volume Pilot Production of High Efficiency PERC Solar Cells-Analysis Based on Device Simulation. *Energy Procedia* **2013**, *38*, 474–481. [CrossRef]
29. Saint-Cast, P.; Werner, S.; Greulich, J.; Jäger, U.; Lohmüller, E.; Höffler, H.; Preu, R. Analysis of the losses of industrial-type PERC solar cells. *Phys. Status Solidi A* **2017**, *214*, 1600708. [CrossRef]
30. Wang, A. High Efficiency PERC and PERL Silicon Solar Cells. Ph.D. Thesis, UNSW, Sydney, Australia, 1992. [CrossRef]

31. Zhao, J.; Wang, A.; Altermatt, P.; Wenham, S.; Green, M. 24% efficient perl silicon solar cell: Recent improvements in high efficiency silicon cell research. *Sol. Energy Mater. Sol. Cells* **1996**, *41–42*, 87–99. [CrossRef]
32. Lin, Y.-S.; Hung, J.-Y.; Ku, C.-H.; Wang, J.-C.; Chen, T.-C.; Yu, J.; Lee, S.-L.; Guo, T.-W.; Wen, C.-C. ANovel Co-Diffusion Process for P-type PERL Solar Cells by Using Aluminum Doping Paste. In Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018—A Joint Conference of 45th IEEE PVSC, 28th PVSEC and 34th EU PVSEC, Waikoloa, HI, USA, 10–15 June 2018; pp. 1526–1529. [CrossRef]
33. Luo, W.; Chen, N.; Shanmugam, V.; Yan, X.; Duttagupta, S.; Wang, Y.; Aberle, A.G.; Khoo, Y.S. Investigation of Potential-Induced Degradation in Bifacial n-PERL Modules. *IEEE J. Photovolt.* **2020**, *10*, 935–939. [CrossRef]
34. Rehman, A.U.; Nadeem, M.; Usman, M. Passivated Emitter and Rear Totally Diffused: PERT Solar Cell-An Overview. *Silicon* **2022**, 1–11. [CrossRef]
35. Huang, H.; Modanese, C.; Sun, S.; von Gastrow, G.; Wang, J.; Pasanen, T.P.; Li, S.; Wang, L.; Bao, Y.; Zhu, Z.; et al. Effective passivation of p+ and n+ emitters using SiO2/Al2O3/SiNx stacks: Surface passivation mechanisms and application to industrial p-PERT bifacial Si solar cells. *Sol. Energy Mater. Sol. Cells* **2018**, *186*, 356–364. [CrossRef]
36. Taguchii, M.; Kawamoto, K.; Tsuge, S.; Baba, T.; Sakata, H.; Morizane, M.; Uchihashi, K.; Nakamura, N.; Kiyama, S.; Oota, O. HIT TM Cells-High-Efficiency Crystalline Si Cells with Novel Structure. *Prog. Photovolt. Res. Appl.* **2000**, *8*, 503–513. [CrossRef]
37. Zeman, M.; Zhang, D. Heterojunction Silicon Based Solar Cells. In *Engineering Materials*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 13–43. [CrossRef]
38. Sawada, T.; Terada, N.; Tsuge, S.; Baba, T.; Takahama, T.; Wakisaka, K.; Tsuda, S.; Nakano, S. High-efficiency a-Si/c-Si heterojunction solar cell. In Proceedings of the Conference Record of the IEEE Photovoltaic Specialists Conference, Waikoloa, HI, USA, 5–9 December 1994; Volume 2, pp. 1219–1226. [CrossRef]
39. Tsunomura, Y.; Yoshimine, Y.; Taguchi, M.; Baba, T.; Kinoshita, T.; Kanno, H.; Sakata, H.; Maruyama, E.; Tanaka, M. Twenty-two percent efficiency HIT solar cell. *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 670–673. [CrossRef]
40. Mishima, T.; Taguchi, M.; Sakata, H.; Maruyama, E. Development status of high-efficiency HIT solar cells. *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 18–21. [CrossRef]
41. Taguchi, M.; Yano, A.; Tohoda, S.; Matsuyama, K.; Nakamura, Y.; Nishiwaki, T.; Fujita, K.; Maruyama, E. 24.7% Record Efficiency HIT Solar Cell on Thin Silicon Wafer. *IEEE J. Photovolt.* **2013**, *4*, 96–99. [CrossRef]
42. Park, H.; Lee, Y.-J.; Park, J.; Kim, Y.; Yi, J.; Lee, Y.; Kim, S.; Park, C.-K.; Lim, K.-J. Front and Back TCO Research Review of a-Si/c-Si Heterojunction with Intrinsic Thin Layer (HIT) Solar Cell. *Trans. Electr. Electron. Mater.* **2018**, *19*, 165–172. [CrossRef]
43. Lammert, M.; Schwartz, R. The interdigitated back contact solar cell: A silicon solar cell for use in concentrated sunlight. *IEEE Trans. Electron Devices* **1977**, *24*, 337–342. [CrossRef]
44. Yoshikawa, K.; Kawasaki, H.; Yoshida, W.; Irie, T.; Konishi, K.; Nakano, K.; Uto, T.; Adachi, D.; Kanematsu, M.; Uzu, H.; et al. Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. *Nat. Energy* **2017**, *2*, 17032. [CrossRef]
45. Park, H.S.; Jeong, J.S.; Park, C.K.; Shin, W.S.; Kang, J.Y.; Kim, Y.K.; Park, N.C.; Nam, S.-H.; Yi, J. HIT PV Module Performance Research for an Improvement of Long-Term Reliability: A Review. *Curr. Photovolt. Res.* **2017**, *5*, 47–54. [CrossRef]
46. Yousuf, H.; Quddamah Khokhar, M.; Chowdhury, S.; Phong Pham, D.; Kim, Y.; Ju, M.; Cho, Y.; Cho, E.-C.; Yi, J. A Review on TOPCon Solar Cell Technology. *Curr. Photovolt. Res.* **2021**, *9*, 75–83. [CrossRef]
47. Feldmann, F.; Steinhauser, B.; Arya, V.; Buechler, A.; Feldmann, F.; Steinhauser, B.; Arya, V.; Büchler, A.; Brand, A.A.; Kluska, S.; et al. Evaluation of TOPCon Technology on Large Area Solar Cells. In Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands, 25–29 September 2017.
48. Wang, Q.; Wu, W.; Li, Y.; Yuan, L.; Yang, S.; Sun, Y.; Yang, S.; Zhang, Q.; Cao, Y.; Qu, H.; et al. Impact of boron doping on electrical performance and efficiency of n-TOPCon solar cell. *Sol. Energy* **2021**, *227*, 273–291. [CrossRef]
49. Anand, N.; Kale, P. Optimization of TOPCon Structured Solar Cell Using AFORS-HET. *Trans. Electr. Electron. Mater.* **2020**, *22*, 160–166. [CrossRef]
50. Zeng, Y.; Tong, H.; Quan, C.; Cai, L.; Yang, Z.; Chen, K.; Yuan, Z.; Wu, C.-H.; Yan, B.; Gao, P.; et al. Theoretical exploration towards high-efficiency tunnel oxide passivated carrier-selective contacts (TOPCon) solar cells. *Sol. Energy* **2017**, *155*, 654–660. [CrossRef]
51. Chen, Y.; Chen, D.; Liu, C.; Wang, Z.; Zou, Y.; He, Y.; Wang, Y.; Yuan, L.; Gong, J.; Lin, W.; et al. Mass production of industrial tunnel oxide passivated contacts (i-TOPCon) silicon solar cells with average efficiency over 23% and modules over 345 W. *Prog. Photovolt. Res. Appl.* **2019**, *27*, 827–834. [CrossRef]
52. Ghosh, D.K.; Bose, S.; Das, G.; Acharyya, S.; Nandi, A.; Mukhopadhyay, S.; Sengupta, A. Fundamentals, present status and future perspective of TOPCon solar cells: A comprehensive review. *Surf. Interfaces* **2022**, *30*, 101917. [CrossRef]
53. Lozac'H, M.; Nunomura, S.; Matsubara, K. Double-sided TOPCon solar cells on textured wafer with ALD SiOx layer. *Sol. Energy Mater. Sol. Cells* **2019**, *207*, 110357. [CrossRef]
54. Building Integrated Photovoltaics (BIPV) | WBDG—Whole Building Design Guide. Available online: https://www.wbdg.org/resources/building-integrated-photovoltaics-bipv (accessed on 27 October 2022).
55. Everything You Need to Know About The BIPV System | Solar Labs. Available online: https://thesolarlabs.com/ros/bipv-system/ (accessed on 27 October 2022).
56. Shukla, A.K.; Sudhakar, K.; Baredar, P. A comprehensive review on design of building integrated photovoltaic system. *Energy Build.* **2016**, *128*, 99–110. [CrossRef]

57. Biyik, E.; Araz, M.; Hepbasli, A.; Shahrestani, M.; Yao, R.; Shao, L.; Essah, E.; Oliveira, A.C.; del Caño, T.; Rico, E.; et al. A key review of building integrated photovoltaic (BIPV) systems. *Eng. Sci. Technol. Int. J.* **2017**, *20*, 833–858. [CrossRef]
58. Yeoh, M.-E.; Chan, K.-Y. A Review on Semitransparent Solar Cells for Real-Life Applications Based on Dye-Sensitized Technology. *IEEE J. Photovolt.* **2021**, *11*, 354–361. [CrossRef]
59. Liu, B.; Duan, S.; Cai, T. Photovoltaic DC-Building-Module-Based BIPV System—Concept and Design Considerations. *IEEE Trans. Power Electron.* **2011**, *26*, 1418–1429. [CrossRef]
60. Uddin, M.N.; Biswas, M.; Nuruddin, S. Techno-economic impacts of floating PV power generation for remote coastal regions. *Sustain. Energy Technol. Assess.* **2022**, *51*, 101930. [CrossRef]
61. Hooper, T.; Armstrong, A.; Vlaswinkel, B. Environmental impacts and benefits of marine floating solar. *Sol. Energy* **2020**, *219*, 11–14. [CrossRef]
62. Floating Solar Panels Market | Size, Share, Growth, Trends | Industry Analysis | Forecast 2026. Available online: https://www.technavio.com/report/floating-solar-panels-market-industry-analysis (accessed on 27 October 2022).
63. Sahu, A.; Yadav, N.; Sudhakar, K. Floating photovoltaic power plant: A review. *Renew. Sustain. Energy Rev.* **2016**, *66*, 815–824. [CrossRef]
64. Golroodbari, S.Z.; Van Sark, W. Simulation of performance differences between offshore and land-based photovoltaic systems. *Prog. Photovolt. Res. Appl.* **2020**, *28*, 873–886. [CrossRef]
65. Mittal, D.; Saxena, B.K.; Rao, K.V.S. Floating Solar Photovoltaic Systems: An Overview and Their Feasibility at Kota in Rajasthan. Proceedings of IEEE International Conference on Circuit, Power and Computing Technologies, ICCPCT 2017, Kollam, India, 20–21 April 2017. [CrossRef]
66. Ravichandran, N.; Panneerselvam, B. Floating photovoltaic system for Indian artificial reservoirs—An effective approach to reduce evaporation and carbon emission. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 7951–7968. [CrossRef]
67. Setiawan, F.; Dewi, T.; Yusi, S. Sea Salt Deposition Effect on Output and Efficiency Losses of the Photovoltaic System; a case study in Palembang, Indonesia. *J. Phys. Conf. Ser.* **2019**, *1167*, 012028. [CrossRef]
68. Why Conventional Floating Solar Will Fail in the Ocean, Says SINN Power | Solar Builder. Available online: https://solarbuildermag.com/news/why-conventional-floating-solar-will-fail-in-the-ocean-says-sinn-power/ (accessed on 13 December 2022).
69. What Is Agrivoltaics? How Can Solar Energy and Agriculture Work Together? Available online: https://metsolar.eu/blog/what-is-agrivoltaics-how-can-solar-energy-and-agriculture-work-together/ (accessed on 14 December 2022).
70. Growing Plants, Power, and Partnerships Through Agrivoltaics | News | NREL. Available online: https://www.nrel.gov/news/program/2022/growing-plants-power-and-partnerships.html (accessed on 14 December 2022).
71. Dinesh, H.; Pearce, J.M. The potential of agrivoltaic systems. *Renew. Sustain. Energy Rev.* **2016**, *54*, 299–308. [CrossRef]
72. Weselek, A.; Ehmann, A.; Zikeli, S.; Lewandowski, I.; Schindele, S.; Högy, P. Agrophotovoltaic systems: Applications, challenges, and opportunities. A review. *Agron. Sustain. Dev.* **2019**, *39*, 35. [CrossRef]
73. Cho, J.; Park, S.M.; Reum Park, A.; Lee, O.C.; Nam, G.; Ra, I.-H. Application of Photovoltaic Systems for Agriculture: A Study on the Relationship between Power Generation and Farming for the Improvement of Photovoltaic Applications in Agriculture. *Energies* **2020**, *13*, 4815. [CrossRef]
74. Coşgun, A.E. The potential of Agrivoltaic systems in TURKEY. *Energy Rep.* **2021**, *7*, 105–111. [CrossRef]
75. Gharakhani Siraki, A.; Pillay, P. Study of optimum tilt angles for solar panels in different latitudes for urban applications. *Sol. Energy* **2012**, *86*, 1920–1928. [CrossRef]
76. Shah, S.F.A.; Khan, I.A.; Khan, H.A. Performance Evaluation of Two Similar 100MW Solar PV Plants Located in Environmentally Homogeneous Conditions. *IEEE Access* **2019**, *7*, 161697–161707. [CrossRef]
77. Ebhota, W.S.; Tabakov, P.Y. Impact of Photovoltaic Panel Orientation and Elevation Operating Temperature on Solar Photovoltaic System Performance. *Int. J. Renew. Energy Dev.* **2022**, *11*, 691–699. [CrossRef]
78. N'Tsoukpoe, K.E. Effect of orientation and tilt angles of solar collectors on their performance: Analysis of the relevance of general recommendations in the West and Central African context. *Sci. Afr.* **2022**, *15*, e01069. [CrossRef]
79. Kacira, M.; Simsek, M.; Babur, Y.; Demirkol, S. Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey. *Renew. Energy* **2004**, *29*, 1265–1275. [CrossRef]
80. Hussein, H.M.S.; Ahmad, G.E.; El-Ghetany, H.H. Performance evaluation of photovoltaic modules at different tilt angles and orientations. *Energy Convers. Manag.* **2004**, *45*, 2441–2452. [CrossRef]
81. Singh, R.; Banerjee, R. Impact of Solar Panel Orientation on Large Scale Rooftop Solar Photovoltaic Scenario for Mumbai. *Energy Procedia* **2016**, *90*, 401–411. [CrossRef]
82. Naraghi, M.H.; Atefi, E. Optimum Solar Panel Orientation and Performance: A Climatic Data-Driven Metaheuristic Approach. *Energies* **2022**, *15*, 624. [CrossRef]
83. Dhimish, M.; Silvestre, S. Estimating the impact of azimuth-angle variations on photovoltaic annual energy production. *Clean Energy* **2019**, *3*, 47–58. [CrossRef]
84. Azaioud, H.; Desmet, J.; Vandevelde, L. Benefit Evaluation of PV Orientation for Individual Residential Consumers. *Energies* **2020**, *13*, 5122. [CrossRef]
85. Sulaiman, S.A.; Singh, A.K.; Mokhtar, M.M.M.; Bou-Rabee, M.A. Influence of Dirt Accumulation on Performance of PV Panels. *Energy Procedia* **2014**, *50*, 50–56. [CrossRef]

86. Said, S.A.M. Effects of dust accumulation on performances of thermal and photovoltaic flat-plate collectors. *Appl. Energy* **1990**, *37*, 73–84. [CrossRef]
87. Al Garni, H.Z. The Impact of Soiling on PV Module Performance in Saudi Arabia. *Energies* **2022**, *15*, 8033. [CrossRef]
88. Tripathi, A.K.; Aruna, M.; Venkatesan, E.P.; Abbas, M.; Afzal, A.; Shaik, S.; Linul, E. Quantitative Analysis of Solar Photovoltaic Panel Performance with Size-Varied Dust Pollutants Deposition Using Different Machine Learning Approaches. *Molecules* **2022**, *27*, 7853. [CrossRef] [PubMed]
89. Emre Coşgun, A.; Demir, H.; Meslek Yüksek Okulu, O.; Bölümü, E.; Üniversitesi, A.; Geliş, T. The Experimental Study of Dust Effect on Solar Panel Efficiency. *J. Polytech.* **2022**, 1. [CrossRef]
90. Hussain, A.; Batra, A.; Pachauri, R. An experimental study on effect of dust on power loss in solar photovoltaic module. *Renew. Wind. Water Sol.* **2017**, *4*, 9. [CrossRef]
91. Khadka, N.; Bista, A.; Adhikari, B.; Shrestha, A.; Bista, D.; Adhikary, B. Current Practices of Solar Photovoltaic Panel Cleaning System and Future Prospects of Machine Learning Implementation. *IEEE Access* **2020**, *8*, 135948–135962. [CrossRef]
92. Ghodki, M.K. An infrared based dust mitigation system operated by the robotic arm for performance improvement of the solar panel. *Sol. Energy* **2022**, *244*, 343–361. [CrossRef]
93. Nahar Myyas, R.; Al-Dabbasa, M.; Tostado-Véliz, M.; Jurado, F. A novel solar panel cleaning mechanism to improve performance and harvesting rainwater. *Sol. Energy* **2022**, *237*, 19–28. [CrossRef]
94. Chen, E.; Renner, P.; Lee, K.; Guo, B.; Liang, H. Effects of humidity on dust particle removal during solar panel cleaning. *Surf. Topogr. Metrol. Prop.* **2022**, *10*, 015003. [CrossRef]
95. Jagoda, S.U.M.; Dilanga, W.M.C.; Jarathne, D.S.D.S.; Punchihewa, H.K.G.; Dassanayake, V.P.C.; Karunathilake, H.P. A Device to Determine the Panel Orientation for Best Annual Solar Energy Generation at a Selected Location. *Lect. Notes Civ. Eng.* **2022**, *174*, 151–168. [CrossRef]
96. Shilin, A.A.; Kuznetsova, N.S.; Isaev, I.A. SEMS Positioning Solar Panels. In *Studies in Systems, Decision and Control*; Springer: Berlin/Heidelberg, Germany, 2022; Volume 419, pp. 251–258. [CrossRef]
97. Kassim, M.; Lazim, F. Adaptive photovoltaic solar module based on internet of things and web-based monitoring system. *Int. J. Electr. Comput. Eng. (IJECE)* **2022**, *12*, 924–935. [CrossRef]
98. Ramaneti, K.; Kakani, P.; Prakash, S. Improving Solar Panel Efficiency by Solar Tracking and Tilt Angle Optimization with Deep Learning. In Proceedings of the 5th International Conference on Smart Grid and Smart Cities, ICSGSC 2021, Tokyo, Japan, 18–20 June 2021; pp. 102–106. [CrossRef]
99. Jaiganesh, K.; Bharath Simha Reddy, K.; Shobhitha, B.K.D.; Dhanush Goud, B. Enhancing the efficiency of rooftop solar photovoltaic panel with simple cleaning mechanism. *Mater. Today Proc.* **2021**, *51*, 411–415. [CrossRef]
100. Magdum, V.; Patil, V.; Koli, Y.; Ghatage, G.; Mahadik, S.R.; Magdum, J.J. Solar Panel Cleaning Robot. *Int. Res. J. Mod. Eng. Technol. Sci.* **2022**, *4*, 485–488.
101. Nattharith, P.; Kosum, T. Gmsarn, Development of Mobile Robot System for Monitoring and Cleaning of Solar Panels. *Int. J.* **2022**, *16*, 302–306.
102. Roy, S.; Mandal, M.; Jena, C.; Sinha, P.; Jena, T. Programmable-Logic-Controller Based Robust Automatic Cleaning of Solar Panel for Efficiency Improvement. In Proceedings of the 2021 International Conference in Advances in Power, Signal, and Information Technology, APSIT 2021, Bhubaneswar, India, 8–10 October 2021; pp. 1–4. [CrossRef]
103. Baimel, D.; Tapuchi, S.; Baimel, N. *Smart Grid Communication Technologies- Overview, Research Challenges and Opportunities*; IEEE: Piscataway, NJ, USA, 2016; ISBN 9781509020676.
104. Dumitrache, I.; Dogaru, D.I. Smart Grid Overview: Infrastructure, Cyber-Physical Security and Challenges. In Proceedings of the Proceedings—2015 20th International Conference on Control Systems and Computer Science, CSCS 2015, Bucharest, Romania, 27–29 May 2015; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2015; pp. 693–699.
105. Hossain, M.M.; Peng, C. Cyber–Physical Security for on-Going Smart Grid Initiatives: A Survey. *IET Cyber-Phys. Syst. Theory Appl.* **2020**, *5*, 233–244. [CrossRef]
106. US Department of Commerce, National Weather Service. *Large Hail and Torrential Rain Targets the Southern Texas Panhandle and Northern Rolling Plains (31 May 2022)*; National Weather Service: Lubbock, TX, USA, 2022.
107. Ways To Protect Solar Panels From Hail—Solar Energy Hackers. Available online: https://solarenergyhackers.com/how-to-protect-solar-panels-from-hail/ (accessed on 15 December 2022).