Recent Advances in Solar Cells

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Abstract

This chapter outlines the recent technologies in solar cells and their advancements in supporting various industries to achieve greater efficiency and compatibility. For example, the agrivoltaic technology is discussed. This technology integrates food, energy and sometimes water security. Other topics focus on more novel and sustainable cell manufacturing technologies that will push the utilization of PV technology further, such as tandem cells as well as innovative metallic transparent substrates.

1 Introduction

Photovoltaic technologies can be augmented and incorporated into a multitude of applications, helping to improve the overall performance. The following sections illustrate some of the recent developments in PV technologies. Considering the manufacturing vantage point, redesigning the production of PV would yield ultimate advantages, such as using flexible metallic substrates instead of the brittle glass-based substrates. In addition, employing perovskite/silicon solar cells aids in the maximum utilization of incident solar radiation due to bandgap differences between the different cells. PV technologies can also be used in agrivoltaic setups, where bifacial solar panels can be used to shade crops and also absorb irradiance from both panel faces.

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2 Tandem Silicon/Perovskite Solar Cells

Tandem cells refer to the combination of various solar cells assembled on top of each other. Generally, the upper cell has a high bandgap such as perovskite cells, which converts part of the solar spectrum into electricity, and the rest (infrared) goes through to the bottom cell which is a low bandgap cell such as silicon solar cells. The bottom cell could be a bifacial cell that benefits from the diffused light that falls on the back side of the cell (Akhil et al. 2021; Jošt et al. 2020). Tandem solar cells can be connected either in series or individually, but series-connected cells are easier to manufacture (Tandem Cells 2022). A typical tandem cell is shown in Fig. 1.

There are many types of tandem solar cells, and this includes organic tandem cells: the cheapest and the lowest efficiency of all types with a range of 10–15%. The second type is the inorganic tandem cells, and this form of tandem cell is commercially available and is manufactured from III-V group materials, used in multi-junction cells and has the highest efficiency with 44.4% for the 3-junction cell and 46% for the 4-junction cell. These cells are mainly used in space applications due to their high efficiency and competitive cost. Hybrid tandem cells made of perovskite solar cells have proven to have higher efficiency and reduced cost (What are tandem cells Introduction to solar technology 2022; Yan and Saunders 2014).

2.1 Manufacturing

The deposition process flow and steps of a tandem cell layers are illustrated in Fig. 2. The figure concentrates on the

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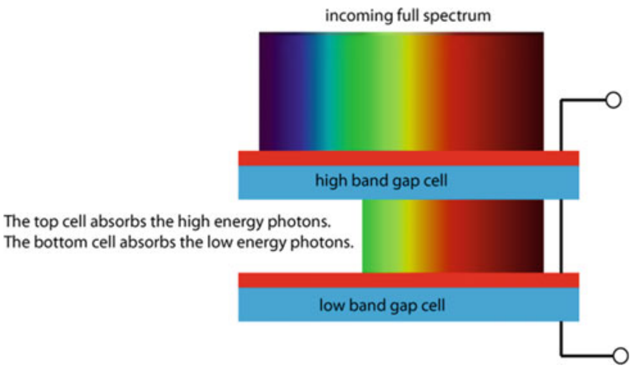

Fig. 1 Series-connected tandem solar cell (Tandem Cells 2022)

manufacturing steps of perovskite tandem and perovskite/Si cells.

The fabrication of perovskite/Si tandem cells is initiated with the deposition of a clear recombination layer on the Si cell (A1) (no reflector or solid metal electrode), and in the second step (A2) the perovskite film is deposited on the previous layer without damaging it or the c-Si cell. In step (A3) a clear and conductive sputter buffer layer is deposited on the perovskite cell. The buffer layer serves as a protection layer, since it protects the perovskite layer in step (A4) when sputter deposition of the transparent electrode occurs on the front side. This electrode is characterized by its high transparency and small sheet resistance. Finally, to reduce the resistance of the conductor, metal gridlines are added (A5) (Leijtens et al. 2018).

In the case of perovskite tandem cells, the process starts with step (B1), where a buffer layer deposited on a wide-bandgap front cell to avoid damage, and after that step (B2) a recombination layer is deposited via sputtering on the top of the buffer layer to protect underlying cell. The rear cell with the small bandgap is deposited through (step B3). Finally, in step (B4) a reflective metal electrode is utilized to connect the rear cell and increase the light path length (Leijtens et al. 2018).

A recent study at the University of Arizona established a new manufacturing technique regarding tandem perovskite cells which reduces the reflection loss and extends the pathway of the long-wavelength light inside the silicon. The researchers claim that this technique could lead to a 30% efficient perovskite tandem cells. The perovskite layer is deposited with the help of nitrogen blading over a textured silicon substrate with pyramids of 1 µm in height. The existence of the pyramids on the perovskite layer helps in reducing the reflectance. The resulting perovskite layer had thickness of 3–10 µm which is shown in Fig. 3.

The process of blade coating was used to planarize the texture of the silicon layer by filling between the pyramids. Meanwhile the N_2 knife-aided process was used to investigate the capability of the cell to planarize sub-micrometer-textured wafers and coat the poly [bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA). The knife helps to remove the solvent vapor (Chen et al. 2020; Deng et al. 2019; New manufacturing technique for 26%–efficient tandem perovskite solar cell 2022) (Fig. 4).

2.2 Efficiency

The efficiency varies based on the type of the tandem cell, and the highest achieved efficiency for perovskite/CIGS tandem cell was 24.2 and 25.5% for all perovskite tandem cells (Best Research-Cell Efficiency Chart 2022). Similarly, for the perovskite/Si tandem cells an efficiency of 29.15% was achieved in 2020 (Al-Ashouri et al. 1979), then improved by the research center of Helmholtz Zentrum Berlin für Materialien und Energie (HZB) to 29.8% in 2021 (HZB sets new 29.8% efficiency record for perovskite–silicon tandem solar cells 2022).

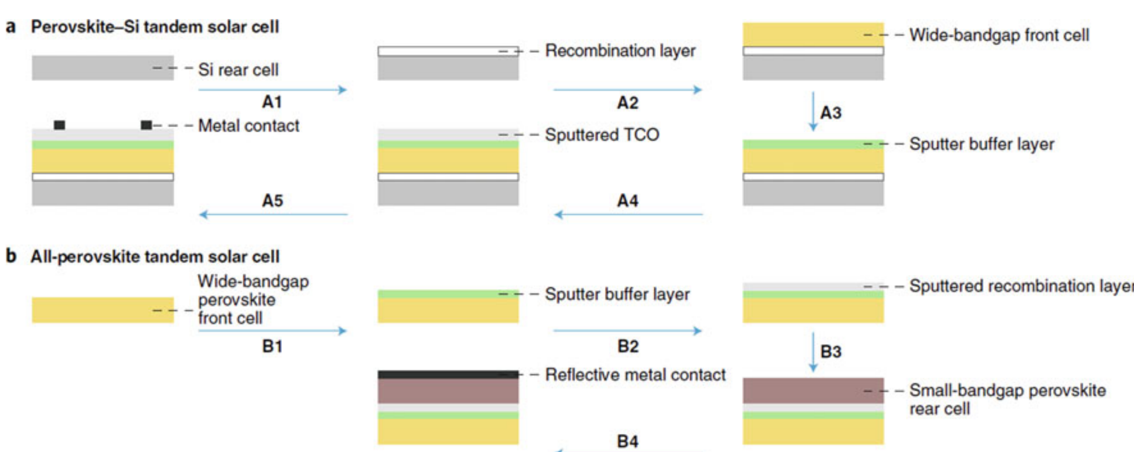

Fig. 2 Typical tandem process flow (Leijtens et al. 2018)

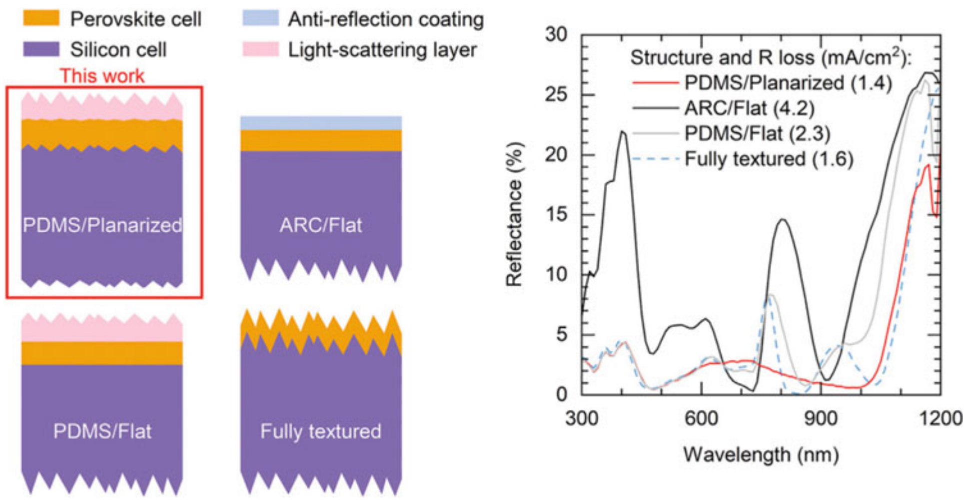

Fig. 3 Architectures of various perovskite/Si tandem cells (Chen et al. 2020)

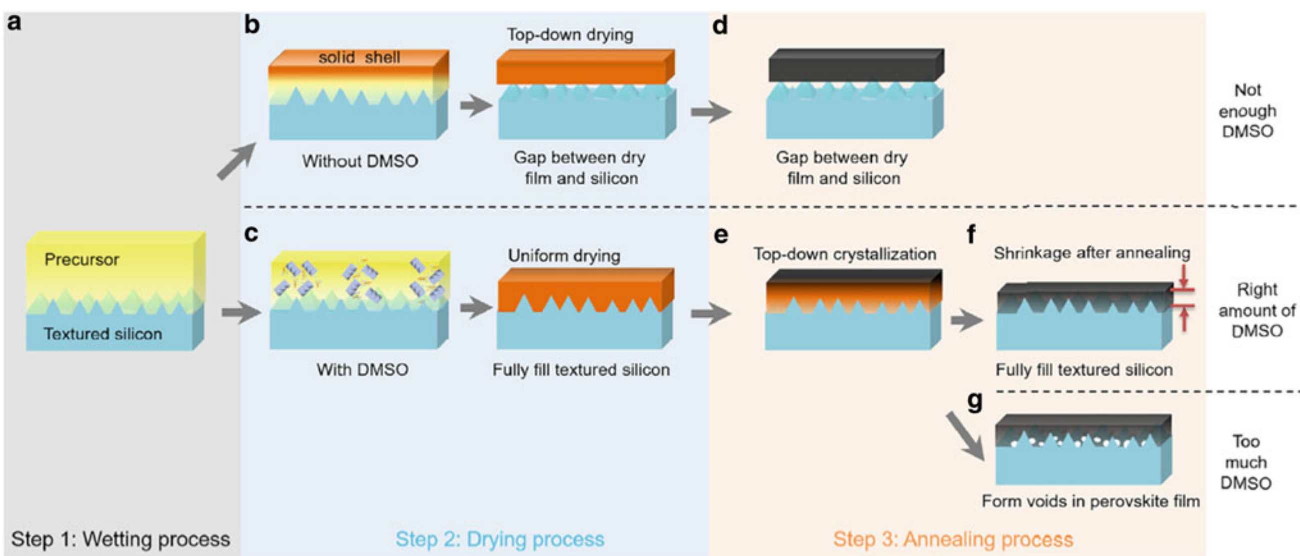

Fig. 4 Various perovskite film formation techniques (Chen et al. 2020)

2.3 Challenges

The commercialization of tandem cells is prevented by numerous challenges in both the architecture and the fabrication aspects.

2.3.1 Transparent Electrodes

Transparent electrodes are the most important components of a solar cell. A great performing electrode must have both high transparency and conductivity. Various materials were used as an electrode for the perovskite cells such as silver (Ag) nanowire, carbon nanotube, graphene and transparent conductive oxides (TCOs) (Rahmany and Etgar 2020). TCOs such as indium transparent oxide (ITO) have proven to improve the device lifetime and provide high transparency and conductivity (Jung and Guo 2012). However, to achieve that, high treatment temperature (over 300°C) is essential throughout and after the sputtering process (Balasundaraprabhu et al. 2009; Jung and Guo 2012). Yet perovskite materials can't survive under this high temperature (Afroz et al. 2020).

2.3.2 Scalability

Presently, efficiency tests for 1 cm^2 cells are laboratory tests only. Although, there are many studies that investigate cells with areas exceeding 10 cm^2 (Afroz et al. 2020). The main issue is the reduction of the lateral conductivity of the TCO-based electrode when compared to other metal electrodes. This effect increases significantly with the increase of the device area (Akhil et al. 2021).

2.3.3 Stability

Tandem solar cells must endure at least 25 years to compete with single-junction silicon. To do so, the instability issues associated with perovskite cells need to be addressed. Since methylammonium is a volatile (unstable) cation, encapsulation was introduced to prevent it from escaping at high temperatures. Formamidinium, on the other hand, demonstrated improved thermal stability as well as higher efficiency (Eperon et al. 2014).

2.3.4 Tin, Lead and Bromide

It has been found that perovskite cells based on tin have short lifetimes, and this is attributed to the fact that the oxidation of tin from Sn^{+2} to Sn^{+4} is carried easily when the cell is exposed to conditions with oxygen and moisture. However, substituting 50% of the halide with an element other than tin (lead (Pb)) improves the lifetime by 10 to 100% (Noel et al. 2014). Another instability problem within the perovskite tandems is the transfer of ions between the various perovskite layers, especially given the fact that the cations of the perovskite structure sites have been proven to be mobile. For instance, it is quite possible for the bromide ions to diffuse within the cells if the diffusion barrier of the recombination layer is not strong. TCOs have provided a good protection (recombination layer), but it must be investigated whether they are suitable for long operations (Leijtens et al. 2018).

2.4 Environmental Impact and Recycling

The presence of lead and tin in perovskite tandem cells raises environmental issues. It has been found that lead is slightly soluble in water, leading to leak from damaged panels into the environment and groundwater and causing contamination and health hazards. Lead could enter the human body through gastrointestinal and respiratory system causing heavy metal intoxication (Babayigit et al. 2016). In addition, it has been found that chronic exposure to tin is as poisonous as lead and may cause serious damages to the human body (Tin and inorganic tin compounds 2022).

Lead is a valuable material both environmentally and economically, and thus it should be recovered from the waste of perovskites solar cells. Recently, a study developed an economical recycling technique utilizing carboxylic acid cation-exchange resin as lead adsorbent and using thermal detachment to expose perovskite films. Firstly, organic solvents, such as dimethylformamide (DMF), are employed to dissolve the lead. To remove the lead from the organic solvent, it is adsorbed by resin-regeneration process via HNO_3, then followed by precipitation of PbI_2 by pouring NaI into Pb $(NO_3)_2$ containing solution. Figure 5 shows the steps of recycling Pb from that is used in PV cells (Chen et al. 2021).

2.5 Characterization

2.5.1 Morphological, Structural and Compositional Characterization

The characteristics of perovskite cells are vital to identify shunt paths to coarse surfaces of CIGS cells or phase impurities over bandgap modification (Jošt et al. 2019).

Several techniques are used to assess the quality of the layers of the perovskite tandem cells: scanning electron microscopy (SEM), transmission electron microscopy

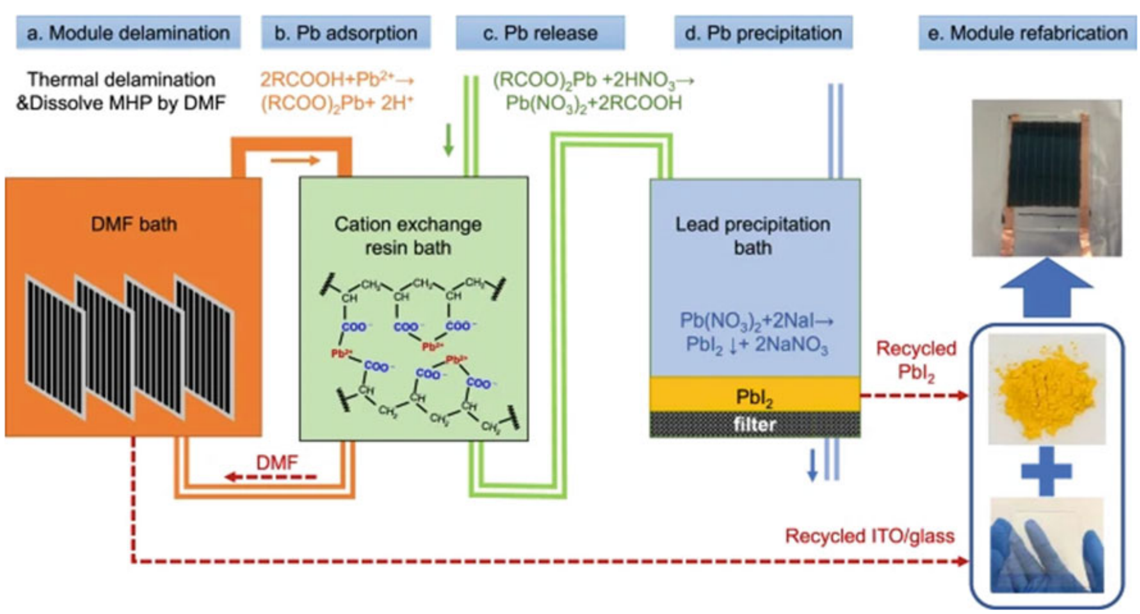

Fig. 5 Flow process and steps for the recycling of perovskite solar modules (Chen et al. 2021)

(TEM), secondary ion mass spectrometry (SIMS) and X-ray diffraction (XRD).

SEM is an electron microscopy mechanism that generates an image of a sample by focusing a beam of electrons on a specific region. The interaction between the beam and the atoms of the samples reveals information on the surface topography and morphology. SEM also provides top and cross-sectional views of the tandem cell that allow the calculation of grain sizes and layers' thicknesses (Jošt et al. 2020).

TEM is similar to SEM with the exception that electrons are transmitted through the sample rather than being scattered or diffracted. This phenomenon can produce images with higher resolution and allows for a more accurate calculation of the layer thicknesses as compared to SEM (Jošt et al. 2020).

SIMS is used to investigate the chemical conformation of samples. SIMS uses a primary beam of ions (Ar^+, Ga^+ or Cs^+), to collect and analyze the ejected secondary ions.

XRD is employed to study the crystal structure and crystallinity of atoms. It is also utilized to identify the crystalline phases and orientation (Jošt et al. 2020).

2.5.2 Optical Characterization

For perovskite tandem cells, reflection R (%) and transmission T (%) measurements are the main optical characterization using photospectrometer that measures the reflection and transmission of a material as a function of wavelength. The equation $A = 1 - R - T$ can be utilized to calculate the absorption A (%) which in return can help in the optimization of the tandem cells (Jošt et al. 2020).

2.5.3 Radiative Characterization

Radiative characterization helps measure the charge carrier dynamics and recombination at the layers interfaces. In addition, it displays loss mechanisms in a device and provides information on electronic properties of an absorber. To determine the radiative behavior of a PV cell, photoluminescence (PL) is used, where light is emitted from any form of matter after the absorption of photons (Jošt et al. 2020).

2.5.4 External Quantum Efficiency Spectra

Quantum efficiency is the ratio of the charges collected by a solar cell to the number of photons of a specific energy applied on the cell. This method helps in determining the bandgap of the solar cell as well as absorption losses (Jošt et al. 2020).

2.5.5 Current–Voltage Characterization

It is the most common and used characterization technique for most solar cells. It provides information on the overall efficiency of the device. The efficiency depends on the short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and fill factor (FF). Both current and voltage are measured under 1.5 air mass (AM) illumination. All these values are required for the plot of the *I-V* curves (Jošt et al. 2020).

2.5.6 Stability Characterization

Stability characterization is important as it studies the degradation of solar cells due to its interaction with air, moisture and oxygen. Perovskite materials are known to be the most degradable solar cells. Hence, numerous research explored the ideas of stacking and encapsulating cells. Researchers summarized several routes to enhance the stability of the perovskite cells (Jošt et al. 2020):

1. Bulk and surface passivation of perovskite films can enhance the stability of the solar cells by reducing the ionic defects.
2. Applying contact and charge extraction layers enhances the stability and prevents degradation.
3. Proper encapsulation through transparent glass/transparent glass substrates and sealed using curable UV glue.

All the characterization methods will be explained in detail in Chap. Characterization Techniques for Photovoltaics Manufacturing (Characterization techniques for Photovoltaics manufacturing).

3 Bifacial Solar Photovoltaics

The strive to enhance solar radiation utilization within solar photovoltaic panels has resulted in many innovative techniques to reduce reflection, enhance absorption, permit better solar tracking or allow more routes for radiation to interact with the cells. Bifacial solar panels belong to the latter school of thought. They can be thought of as double-sided solar panels capable of generating electricity from either/both sides (front and rear), unlike their conventional counterparts that can only generate from one side. They are usually monocrystalline to achieve the highest possible efficiency, despite being more expensive than polycrystalline ones.

In conventional solar panels light is absorbed by cells with a portion of incident light passing through and being forever wasted. In the case of using bifacial panels, there is still ample chance that the transmitted portion of light to be reabsorbed by rear cells, when it is reflected back by the ground or another material. This reflection effect is called albedo and is a function of the reflecting surface material properties. Generally lighter-color materials will lead to more reflected sunlight than darker materials, and rougher surfaces tend to absorb more than reflect. On the other hand, care must be taken in installing the panels in array form to ensure minimal adverse interference effects of cast shadows.

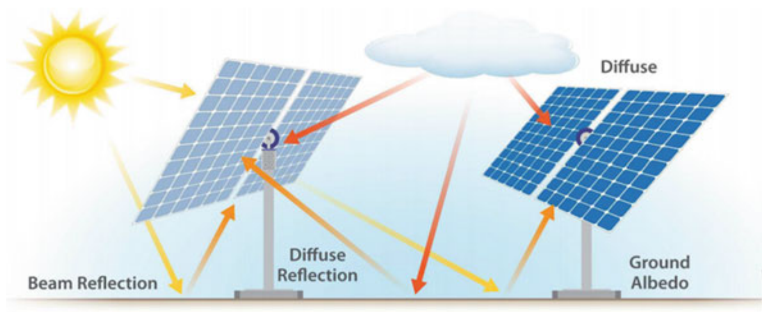

Fig. 6 Bifacial solar panels' working principle (Deline et al. 2019)

Therefore, small junction boxes, narrow rail supports and vertical supports at the very end of the steel structure are utilized to reduce the shaded area on the rear panels. This type of solar panels comes in different designs: framed and frameless. Also, a number could consist of dual-glass sheets and others of clear back sheets. Figure 6 shows a schematic of how bifacial panels work.

There are several factors that affect the power generation of bifacial solar panels such as mounting height, the further a bifacial module from the ground or a surface the higher chance reflected or diffused light will reach the back of the module. Also, the number of modules in series, and the diffused irradiance fraction which is the ration between the diffused horizontal irradiance (DHI) and the global horizontal irradiance (GHI). Moreover, the albedo of the ground surface is another important factor, a surface covered with snow or ice most likely will reflect more light than soil, or a surface painted with white or silver color will reflect more light than a surface painted with darker colors. Table 1 shows the albedo values for various surfaces:

Table 1 Albedo values for various materials (Stein et al. 2021)

Material	Albedo
Grass	0.15–0.26
Snow	0.55–0.98
Black soil	0.08–0.13
Clay soil	0.16–0.23
Sand	0.21–0.60
Asphalt pavement (new)	0.09
Asphalt pavement (weathered)	0.18

The efficiency of a bifacial solar panel is measured as the ratio of incident luminous power to generated power, and it is measured for front and rear independently. Another important term is the bifaciality factor, which is the ratio of the rear efficiency in relation to the front efficiency when subjected to same irradiance. Due to the existence of another generation source in this type of solar panels, recent researches show that bifacial provides energy yield higher than monofacial by 25 to 30% just from the rear (Dullweber and Schmidt 2016; Sun et al. 2018; Kopecek and Libal 2018) (Fig. 7).

There are two different types of bifacial solar cells: p-type technology that includes the passivated emitter and rear cell (PERC) and the n-type technology that includes passivated emitter rear totally diffused (PERT) and heterojunction with thin layer (HJT). There are many works on other types of p and n-type technologies, but they are still under development and not commercialized yet, such as passivated emitter rear locally diffused (PERL), interdigitated back contact (IBC) and tunnel oxide passivated contact (TOPCon). Table 2 shows a comparison between the different types, and as seen in Fig. 8.

3.1 PERC

It could be used for both concepts: monofacial and bifacial. It is more efficient than traditional solar cells delivering more

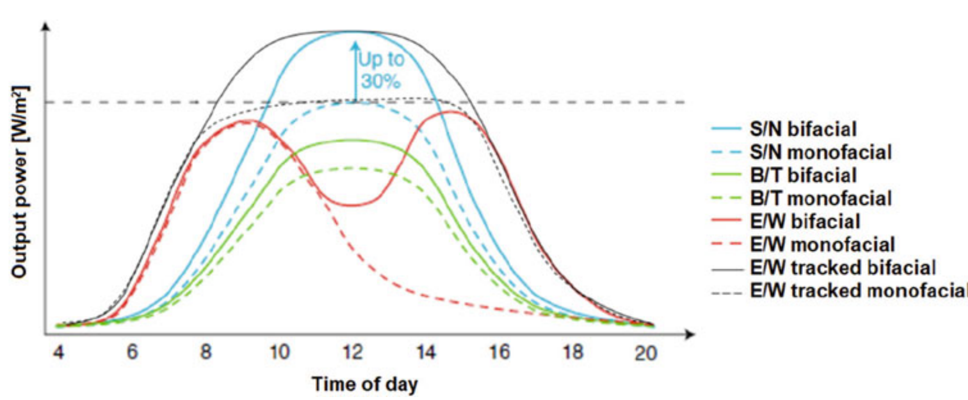

Fig. 7 Comparison of power generation curves for monofacial and bifacial modules (Kopecek and Libal 2018)

Table 2 Comparison between the different types in terms of efficiency and bifaciality (Bifacial solar cells 2022)

Type	Solar cell efficiency (%)	Bifaciality (%)
PERC	21.2	70–80
PERT	22	80–90
PERL	19.8	80–90
HJT	24.7	95–100
IBC	23.2	70–80
TOPCon	22.5	85–90

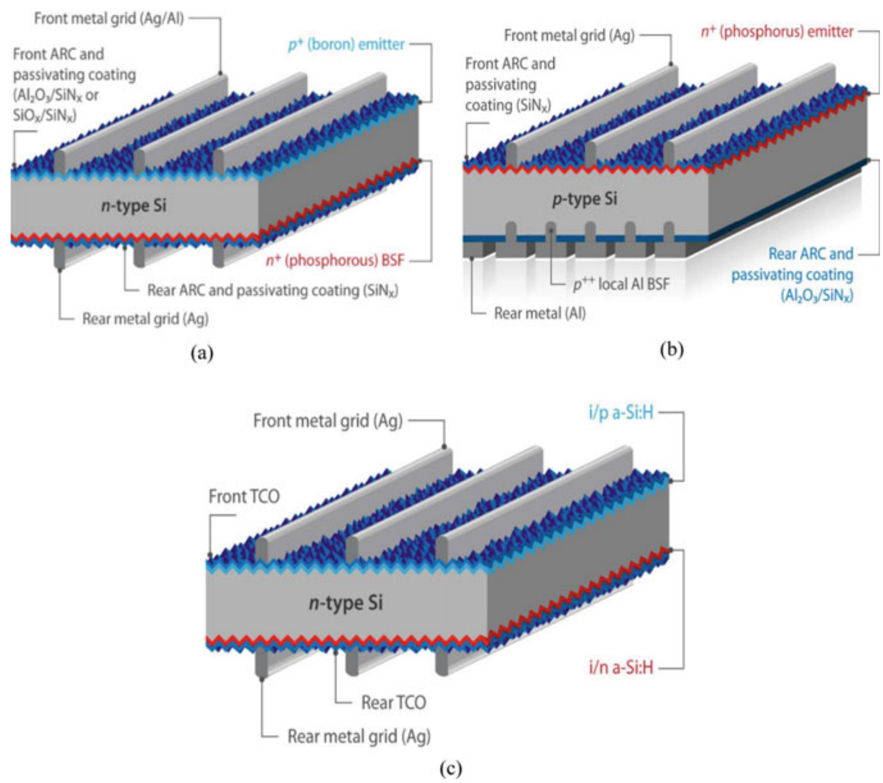

Fig. 8 Architecture of the different types of bifacial solar cells: **a** PERC, **b** PERT and **c** HJT (Stein et al. 2021)

than 6% higher, in low light and high-temperature conditions. The main difference between this type and a typical monocrystalline solar cell is the existence of a back surface passivation which provides three benefits that boost the efficiency of these cells such as reflection of light back through the cell, reduced electron recombination and reduced heat absorption. The manufacturing processes are similar to the traditional solar cells. Therefore, shifting into this type will not cause a significant increase in the manufacturing costs.

3.2 PERT

Similar to the PERC cells, it can be used as monofacial and bifacial solar cells. The difference between these two types is that PERT back surface is totally diffused whether by boron (p-type) or phosphors (n-type), but this requires additional processes, high-temperature POCL and BBr_3 diffusion, which in return results in a more expensive manufacturing process than PERC. On the other hand, this type of cells displays no light-induced degradation (LID) unlike PERC cells.

3.3 PERL

This type of solar cells combines the advantages of both PERC and PERT, where both front and rear monocrystalline cells are passivated; however, the rear cell is locally diffused at the metal contacts to minimize recombination rates yet maintaining electrical contact. This type has many benefits: higher efficiency and energy yield, low process times on the manufacturing process, different configurations on the rear side could be used (transparent back sheet or glass layer) and similar costs to PERC cells.

3.4 HJT

The heterojunction cells are a new technology, and they have the potential to be the successor to the PERC cells. The novelty of these cell lies in the simple manufacturing process as it requires less steps and lower temperatures. Also, it is compatible with thin wafers allowing for a more facile production and a higher bifaciality potential (Stein et al. 2021).

3.5 IBC

It is one of the HJT configurations with a potential higher efficiency, however accompanied with higher production costs and difficulty in the production processes. This type has several advantages such as lower shading losses, easier connections (no space required between the cells) and lower series resistance.

3.6 TOPCon

Compared to the new technologies such as HJT and IBE, TOPCon can be upgraded from the current PERC and PERT lines. Therefore, the manufactures will only need to upgrade their existing production lines (lower capital investment). To upgrade n-PERT into n-TOPCon, only additional ultrathin silicon dioxide (SiO_2) to act as a passivation layer between the rear Si surface and the rear contact and a doped poly-Si layer is required to produce a high conductivity layer.

The National Renewable Energy Laboratory (NREL) in 2018 stated that the manufacturing costs of both monofacial and bifacial are relatively close, and this difference is expected to be reduced with coming years with the recent advances in the manufacturing process. Figure 9 illustrates the difference in the manufacturing costs between monofacial and bifacial and its different types (Woodhouse et al. 2019). It can be observed that there is a trade-off between the cost and the efficiency. Nevertheless, the energy yield difference is much higher.

Currently, the monofacial technology is dominating the market share; although there is a reduction in the manufacturing process and many efforts to reduce the usage of aluminum, bifacial cells require only 25% of the aluminum needed for the monofacial type (Photovoltaic Equipment International Technology Roadmap for Photovoltaic (ITRPV) 2019 Results 2019). Figure 10 demonstrates the difference in the amounts of aluminum needed to produce monofacial and bifacial cells.

According to the International Technology Roadmap for Photovoltaic (ITRPV), the shift has already begun. Attitudes are shifting in favor of bifacial technology, it is expected that it will lead the market by the end of 2030 by 70% of the

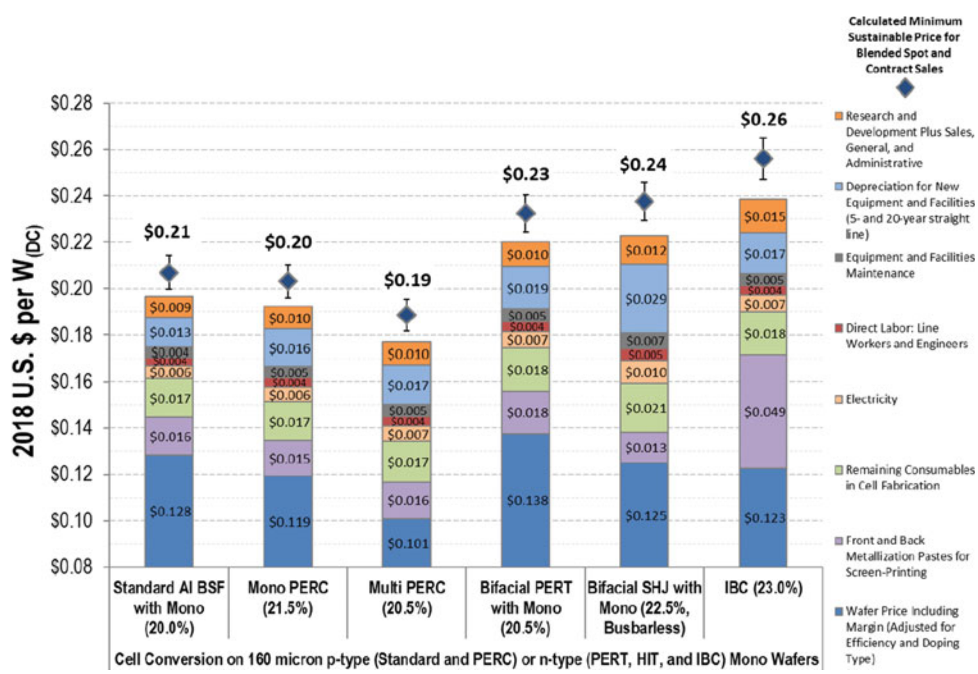

Fig. 9 Modeled costs and minimum sustainable prices for Al-BSF, PERC, PERT, SHJ and IBC cell technologies (Woodhouse et al. 2019)

market share, which gives an indication on how rapid this technology, and its manufacturing processes are developing (Photovoltaic Equipment International Technology Roadmap for Photovoltaic (ITRPV) 2019 Results 2019). Figure 11 illustrates the expected worldwide market share of the two technologies for the next 10 years.

Bifacial solar panels are still under development. Nevertheless, several large-scale projects were implemented in many countries around the world due it is higher power output by 30% and lower LCOE by 2–6% approximately (Gu et al. 2020). Table 3 illustrates many of these projects with their capacity and the manufacturer.

Due to many advantages, there are several applications for these solar panels that put them ahead of monofacial solar panels. Applications such as: being employed into building integrated photovoltaics (BIPV), agrivoltaics, space stations, large-scale power plants and noise barriers. Table 4 provides the pros and cons of this technology compared with monofacial solar panels.

4 Semi-transparent Bifacial

Semi-transparent solar cells are a new type of solar cells that are able to generate electricity from light and visible light transparency. Unlike the conventional solar cells (opaque rear), the back contact acts as a conductive layer instead of a back reflector. Currently, the only commercially available semi-transparent bifacial cells is thin-film silicon technology, and other types such as perovskite and organic transparent cells are still under research and development. The pressing issue with this technology is the need to improve the efficiency while maintaining the targeted transparency (Gao et al. 2017).

Such type of technologies could be used in several applications such as smart energy buildings (architecture), agriculture, automobiles and many other applications, where it can replace regular windows to give an aesthetically pleasing look for buildings, provide passive solar heating, and electricity.

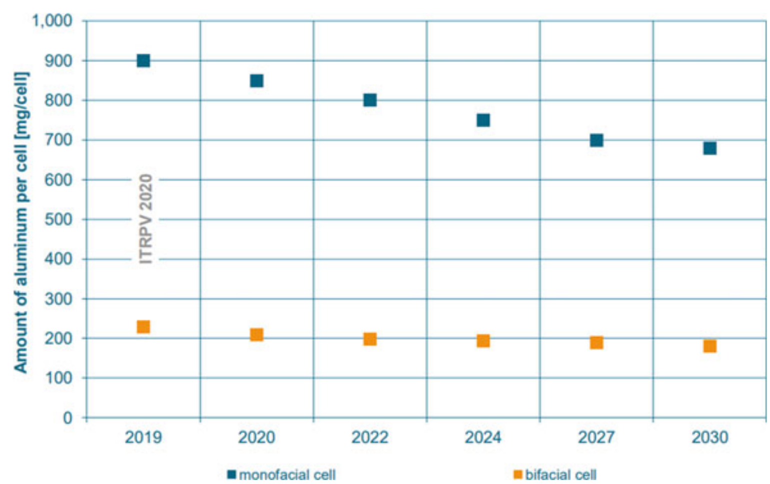

Fig. 10 Amount of aluminum per cell required for monofacial (blue) and bifacial (yellow) PERC (Photovoltaic Equipment International Technology Roadmap for Photovoltaic (ITRPV) 2019 Results 2019)

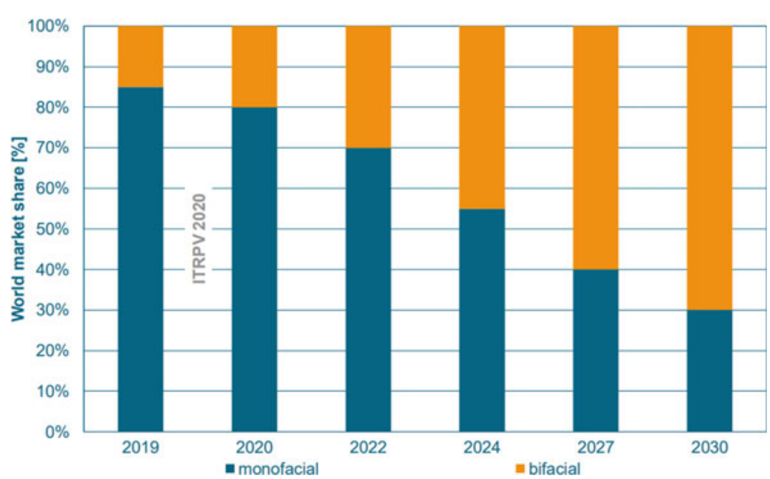

Fig. 11 Worldwide market shares for bifacial technology (Photovoltaic Equipment International Technology Roadmap for Photovoltaic (ITRPV) 2019 Results 2019)

Table 3 Global large-scale bifacial power plants (Greece launches the largest bifacial solar farm in Europe 2022, LONGi and Enel to Build Mexico's Largest Bifacial Photovoltaic Power Plant 2022, LONGi will supply 224MW of bifacial PERC modules for the largest 'bifacial + tracking' project in the United States 2022, Robins Air Force Base Solar 170MW 2022, Taygete I Energy Project 2022, Taygete II Energy Project 2022, Trina Solar ships 600W+ series Vertex modules for a 850 MWp PV project , one of the largest in Brazil 2022)

Year	Country	Installed capacity (MW_p)	Manufacturer
2019	Georgia, USA	224	LONGi solar
2019	Traxscara, Mexico	220	LONGi solar
2021	Taygete I & II, Texas, USA	592	7X energy
2021	Robins air force base in Georgia, USA	170	Georgia power
2022	Kozani, Greece	204	Jinko solar
2022	Juazeiro, Brazil	850	Trina solar

Table 4 Advantages and the disadvantages of bifacial solar cells compared with monofacial

Advantages	Disadvantages
Better performance (higher efficiency)	High installation costs
More durable (UV resistance and prevents moisture permeability)	
Esthetically pleasing	High initial cost
Reduced potential-induced degradation (PID)	
Works well in diffused light	
Lack of aluminum frames	Less flexibility
Longer warranties (up to 30 years)	

In the case of passive solar heating as shown in Fig. 12, the energy during the day is stored in high thermal mass products and items inside the building in order to emit this energy during night to keep the heat inside when it is needed especially for certain types of crops that can't stand coolness, or during winter for houses and buildings.

For greenhouse applications, certain wavelengths of light are allowed to go through this type of solar cells and are absorbed by the plants for photosynthesis. Which in return helps in increasing the productivity of the crops. Figure 13 demonstrates a prototype of the combination of semi-transparent cells and greenhouse building.

There are two different types of transparent cells: partially transparent, which has better power output and efficiency but less light transmission; it still enables some sunlight to flow

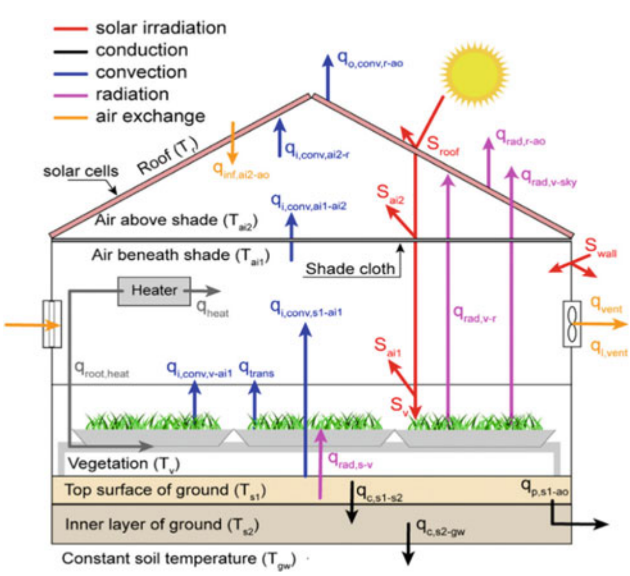

Fig. 12 Schematic diagram of the energy fluxes for OSC greenhouse with shades (Ravishankar et al. 2020)

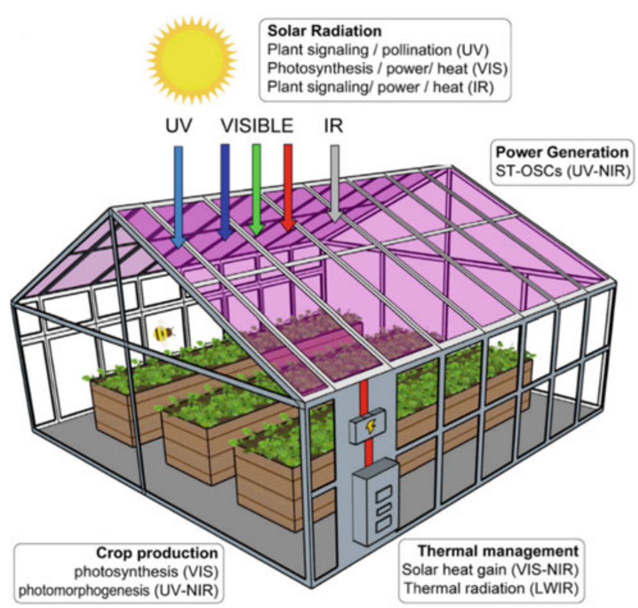

Fig. 13 Depiction of an OSC-integrated greenhouse indicating spectral use of sunlight (Ravishankar et al. 2021)

through the cells. Fully transparent cells, on the other hand, offer a very high level of light transparency but with a very poor efficiency.

5 Semi-transparent Organic Solar Cells (ST-OSC)

This type of solar cells utilizes organic materials in the active region due to its facile and cheap fabrication process, flexibility and lightness. Recently, organic solar cells (OSC) have achieved efficiencies over 18% (Liu et al. 2020). Semi-transparent OSCs, on the other hand, have reported efficiencies in the range of 8.1 and 10.2%, with an average visible transmittance (AVT) ranging between 23 and 36% (Jiang et al. 2020).

In a recent research, a comparison study between two organic solar cells, the first cell being an opaque organic cell that consists of (FTO/ZnO/P3HT:PCBM/MoO_3/Ag), where Ag is used as a top electrode that has a thickness of 100 nm. The other is a semi-transparent that replaced the opaque Ag with transparent top contact MoO_3/Ag/MoO_3 (dielectric/metal/dielectric), and the inner and outer MoO_3 layers are set to be 10 and 30 nm, respectively (Çetinkaya et al. 2021).

The researchers selected 6 nm as an optimal thickness for the Ag, since it provided the highest current density and average visible transmissivity of 63.30 mA/cm^2 and 38.52%, respectively, as shown in Fig. 14. The schematic of the semi-transparent organic solar cell in this comparison is illustrated in Fig. 15. The reflectance and absorption in the visible light region increase as the thickness of the Ag layer increases up to 16 nm.

From the obtained results it can be observed that there is a slight reduction in the efficiency of the semi-transparent cell (12.5%), but this could be negligible in the case of windows and greenhouses applications.

6 Semi-transparent Perovskite Solar Cells (ST-PSC)

Third-generation solar cells are the most recently developed cells, and only within 11 years the efficiencies were raised significantly, especially for perovskite cells. Perovskite solar cells started with only 3.9% in 2009 and improved up to 25.5% by 2020 (Best Research-Cell Efficiency Chart 2022). Therefore, there is a potential that perovskite semi-transparent cells could achieve high efficiencies with good transmissivity. Currently, the average achieved visible transparency is between 20 and 30% with a power conversion efficiency (PCE) of 8 to 12% (Zhao et al. 2017).

Similar to the ST-OSC, the Ag (opaque layer) of a perovskite cell was replaced with softly deposited MoO_3/Ag/WO_3 (MAW) and MoO_3/Ag/MoO_3 (MAM), Ag thickness was selected to be 12 nm, and then both cells were tested and compared with traditional perovskite cell with Ag as a rear electrode (Liang et al. 2020). The structure of the semi-transparent used in this study is shown in Fig. 16.

Conventional TCOs can are not recommended as rear transparent electrodes due to the high amount of energy and temperature associated with the deposition process. These high temperatures will certainly damage the perovskite and transport layers (Fu 2015).

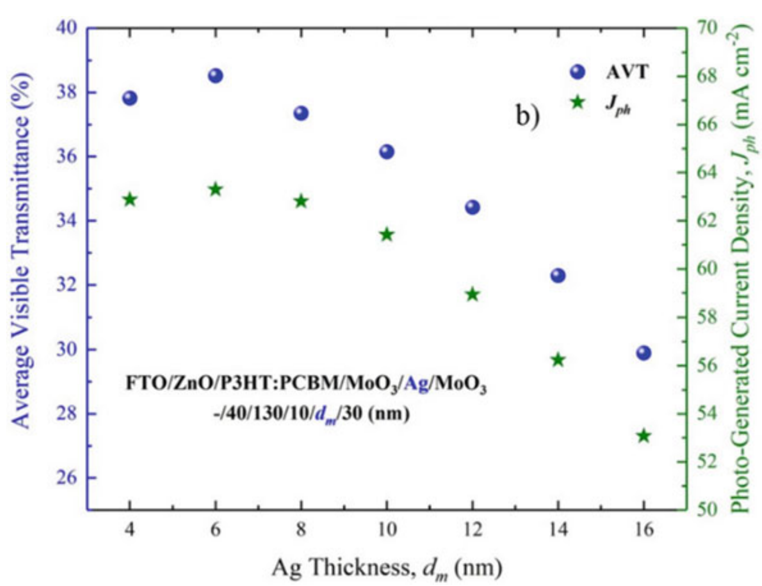

Fig. 14 Variation of the AVT and J_{ph} with respect to the Ag layer thickness for the ST-OSC (Çetinkaya et al. 2021)

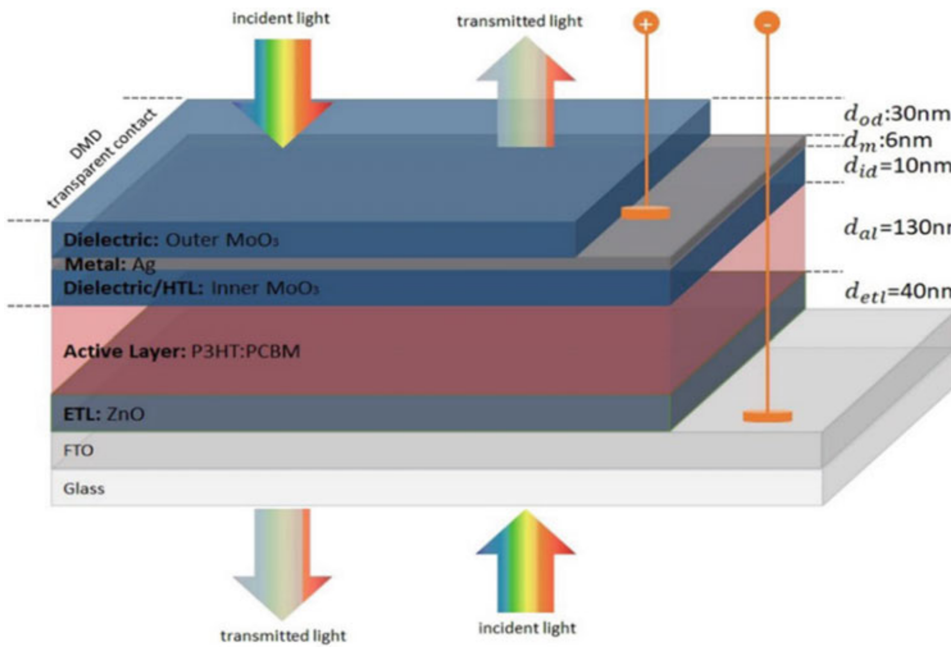

Fig. 15 Structure of FTO/ZnO/P3HT:PCBM/MoO_3/Ag/MoO_3 (–/40/130/10/6/30 nm) ST-OSC (Çetinkaya et al. 2021)

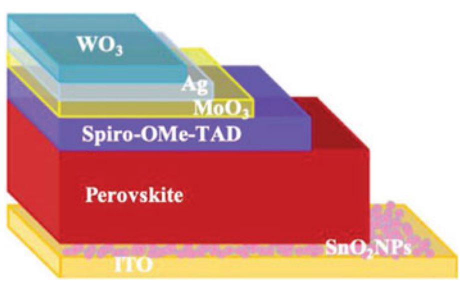

Fig. 16 Structure of (ITO/SnO_2NP_s/perovskite/Spiro-OMe-TAD/MoO_3/Ag/WO_3) ST-PSC (Liang et al. 2020)

The obtained results for the tested cells are illustrated in Table 5. It can be observed that there is a potential to get higher efficiencies from ST-PSC, but this wouldn't occur without a loss in the AVT.

The transmissivity of both MAW and MAM PSC with wavelengths in the range between 400 and 1200 nm was 21.56 and 17.63%, respectively. The AVT of these cells was found to be 10.17 and 6.11%, which is much lower than the ST-OSC, but with huge increase in terms the PCE.

Several researchers studied different rear transparent electrodes for perovskite cells. In Table 6, different works

Table 5 Performance of PSCs with various electrodes (Liang et al. 2020)

Cell	J_{sc} [mA cm^{-2}]	V_{oc} [V]	FF (%)	Power conversion efficiency (%)
ITO-MAW	22.8	1.03	66.0	15.4
ITO-MAM	21.5	1.06	62.4	14.22
Opaque cell	23.7	1.02	71.6	17.3

Table 6 Performance for recent PSCs based on different rear transparent electrodes (Giuliano et al. 2019; Kim et al. 2016; Kim and Tatsuma 2017; Lee et al. 2021; Ying et al. 2019; Zhao et al. 2017)

Rear transparent electrode	AVT (%)	PCE (%)
Bep/Ag/MoO_3	17.80	9.73
MoO_3/Au/ MoO_3	14.98	13.13
MoO_3/Ag/ZnS	7.42	13.30
ZrAcac/PEI/Ag/Ta_2O_5	12.47	13.40
SnO_x/Ag/SnO_x	17.00	11.20
MoO_3/Au/Cu/MoO_3	5.00	12.50

are shown with different results in terms of transmissivity of the layer and the PCE.

7 Agrivoltaic Applications: Large-scale Projects in Arid Areas

PVs offer an efficient way of harnessing solar energy than the natural photosynthetic processes. Additionally, establishing PVs in open areas reduces the installation costs. However, the use of land areas for large-scale PV modules has raised concerns associated with the loss of agricultural lands to increase the profits out of power production from PVs (Weselek et al. 2019). The International Energy Agency (IEA) estimated that in 2050, 16% (6000 TWh) of the global power will be generated from PV, to fulfill societies' requirements. To supply the total demand of PVs, large surface areas are required due to the diffusion of solar energy. Due to the increasing number of people living in densely populated areas and mountainous regions, the land competition in these regions has become more intense (Dinesh and Pearce 2021). Agrivoltaic systems, also known as agrophotovoltaics, serve as a way for the development of PV without affecting food production; in fact, these systems have shown to benefit land productivity. Goetzberger and Zastrow were the first to introduce this technology a few decades ago. They proposed increasing the solar collectors' heights to 2 m above the ground to minimize the effects of excessive shading and noted that the current generation of these systems only requires about a third of the radiation coming from the sun. The technology has already been implemented in commercial and small-scale projects. According to calculations, the implementation of this approach could raise farms' profits by up to 30% (Weselek et al. 2019). Figure 17 shows a timeline for the implementation of agrivoltaics between 2010 and 2021 (Trommsdorff 2021). In 2011, Dupraz and colleagues used the land equivalent ratio to evaluate the productivity of intercropping systems using a dual-use agrivoltaic system. Their simulations showed that the system can increase the overall land productivity by about 70% (Weselek et al. 2019).

Agrivoltaics are even more attractive for deployment in semi-arid and arid areas that suffer from extreme solar radiation that affects crop production and leads to water losses. Due to efficient water use for irrigation and PV cleaning, high crop yield with reducing solar radiation by solar panels, less soil evaporation and high power generation that adds to the profits of farming, agrivoltaics is the best choice to increase food production with simultaneous electricity production (Mamun et al. 2022; Weselek et al. 2019).

8 Agrivoltaic Case Studies

8.1 India

The Indian economy is considered to be supported by the agricultural sector. According to the most recent study, which was performed in 2011, 70% of the residents were employed in agriculture. According to a survey carried out by the nation's Labor Bureau in 2015–2016, almost 47% of the workforce was engaged in jobs pertaining to agriculture. About 18% of the nation's greenhouse gas (GHG) emissions are attributable to the country's extensive agricultural industry and its Gross Domestic Product (GDP) contribution. The use of antiquated and undependable farming methods is the main cause of this. Furthermore, overuse of government-funded fertilizers led to the destruction of farms. The IPCC Report from 2019 states that land degradation increases GHG emissions and decreases carbon capture rate, which in turn accelerates climate change. Therefore, for India to attain a greater development rate and give its expanding population a place to work, self-sustaining and growth-driven agriculture is crucial (Mahto et al. 2021).

Numerous studies on solar energy and Indian agriculture have previously been published, providing a variety of uses for the technology that can generate Climate Smart Agriculture (CSA). An irrigation system powered by solar energy for sustainable agriculture in India was investigated by the authors of Chel and Kaushik (2011); Kanna et al. 2020). A plant for crop and grain dying driven by solar energy was also planned for Rajasthan. The same study highlighted the use of solar energy for air and water heating. Additionally, in the rural parts of the Kaudikasa village in India, drinkable water was obtained, and sewage was treated using a solar-powered system. These examples show how solar

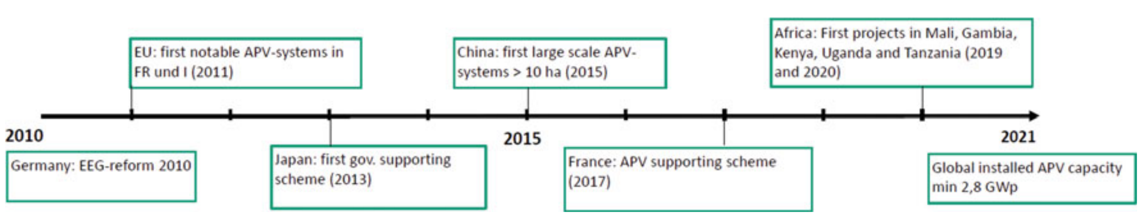

Fig. 17 Timeline for the implementation of agrivoltaics between 2010 and 2021 (Trommsdorff 2021)

panels can be used to support and improve agriculture activities in India (Mahto et al. 2021).

The solar radiation reaching India is enough to generate 500,000 TWh annually. Approximately 10% of the power production is taken into consideration when calculating production. The development of solar manufacturing techniques and enhancements to the maximum power point tracker will inevitably result in a rise in energy production. Figure 18 displays the predicted potential of solar energy for India as a whole according to the National Institute of Solar Energy (NISE) (Mahto et al. 2021).

Agrivoltaics, according to Worringham, might speed up India's implementation of renewable energy by dispersing it throughout the nation. He points out that studies conducted in other countries have revealed that some crops can withstand light shadowing and that, in times of intense heat, some may even profit from reduced temperatures and better soil moisture. He adds that India has already begun to identify the specific techniques, crops and conditions that work best with nearly 20 projects utilizing a variety of panel structures under way. Various policy barriers must be resolved if the agrivoltaics industry is to realize its full potential (Gupta 2021). Jain Irrigation Systems Limited (JISL) and Abellon Energy are both recognized as the originators of agrivoltaics in India. With the first pilots commencing in 2012 and crops being cultivated also underneath the solar structures, JISL has given agriculture greater importance. Table 7 shows the applied agrivoltaic pilot projects in India (Pulipaka and Peparthy 2021).

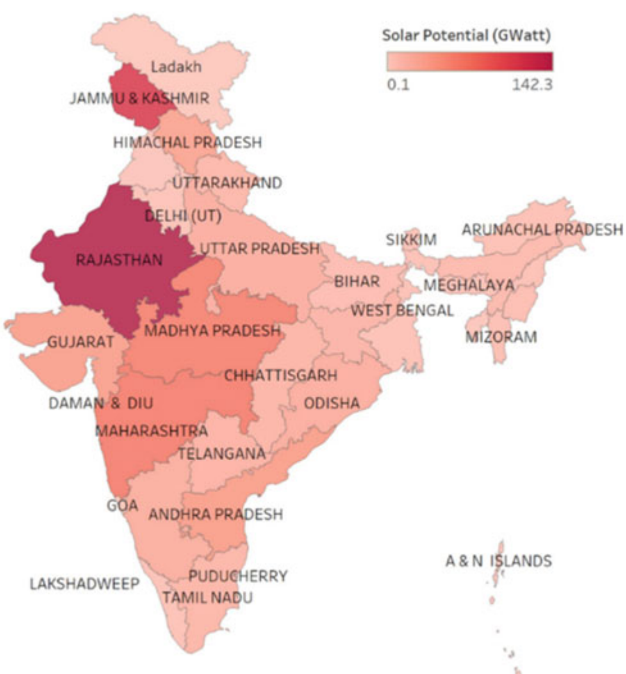

Fig. 18 Potential for producing power in India, according to the National Institute of Solar Energy (NISE) (Mahto et al. 2021)

8.2 Africa

The International Renewable Energy Agency (IRENA) estimates that by 2040, the potential for renewable energy in Africa will be 1,000 times more than its anticipated electricity demand. By then, renewable energy in Southern and Eastern Africa could increase from a fifth in 2016 to 63%. Figure 19 shows the potential for solar energy to meet the demand in Africa (Edmond 2022).

In East Africa, the distribution of electricity is not equitable, with about twice many more urban than rural towns receiving electricity, despite the fact that these latter areas are generally distant geographically. Owing to the absence of electricity, the majority of rural homes must use biomass for heating and cooking which has negative effects on human health, forest degradation and climate change (Randle-Boggis et al. 2021).

The agriculture industry contributes between 24 and 44 percent of the GDP in East African countries, supporting the income of 80 percent of the population. More than 100,000 people are now employed in sub-Saharan Africa's solar energy sector, which is developing to address electricity concerns. However, this growth calls for creative business approaches to penetrate emerging markets. Specifically in rural areas without current new infrastructure, agrivoltaics will also create new, specialized job opportunities for agrivoltaic manufacturing, application and maintenance. These jobs will increase wages and improve food security while addressing rural unemployment (Randle-Boggis et al. 2021).

Recently, a collaboration between the Universities of Sheffield, York and Teesside in the UK, the Stockholm Environment Institute, World Agroforestry, the Centre for Research in Energy and Energy Conservation and the African Centre for Technology Studies has led to the launch of the first agrivoltaic system in East Africa in Insinya, Kenya, at the beginning of 2022 (Best Research-Cell Efficiency Chart 2022).

Adoption of agrivoltaics in Mali might be quite advantageous. Owing to its geographical location, Mali has among the highest amounts of yearly radiation in Africa, with an average of 2,200 kWh/m^2 annually (Cheo et al. 2022).

For rural communities in Mali and Gambia, arable land is becoming increasingly scarce which will pose serious issues related to climate change. APV-MaGa is a research and development (R&D) project that intends to create agrophotovoltaic systems that offer local residents with food, water and electricity while boosting the agriculture sector's tolerance to climate change. It is established to ensure that the communities' crop yields are profitable and that the

Table 7 Applied agrivoltaic pilot projects in India (Pulipaka and Peparthy 2021)

Project	Year of commission	Capacity (kWp)	Location	Project type
Amrol distributed solar power	2016	1000	Gujarat, Amrol	Commercial
1 MW GSECL STPS solar	2016	1054	Gujarat, Sikka	Commercial
1 MW Agri base solar power plant	2016	1054	Panandhro	Commercial
N/A	2017	105	Rajasthan, Jodhpur	Research
N/A	2017	10	Noida	Research
N/A	2020	200	Agra	Research
N/A	2017	7.2	Gujarat, Junagadh	Research
Solar-agri electric model	2012	3000 (~1000 kWp with agriculture)	Modasa Taluka	Commercial
Clean solar private limited	2016	36.6 MW (~400 kW with agrivoltaics)	Gingurthy Village	Commercial/partially research
AgroPV model plants by Jain irrigation	2014	14.4 (banana pilot), 9.6 (rice pilot) and 50.4 (cotton pilot)	Jalgaon	Research
N/A	N/A	100	Haryana, near Gurgaon	Research
Cochin international airport limited (CIAL)	2015	12,000 (partially with agriculture) Total in 2020: more than 26,000	Kerala	Commercial
Krishi vigyan kendra ujwa solar farm	2021	110	Delhi	Research
Residential agri-PV rooftop	2019	3	Delhi	Commercial

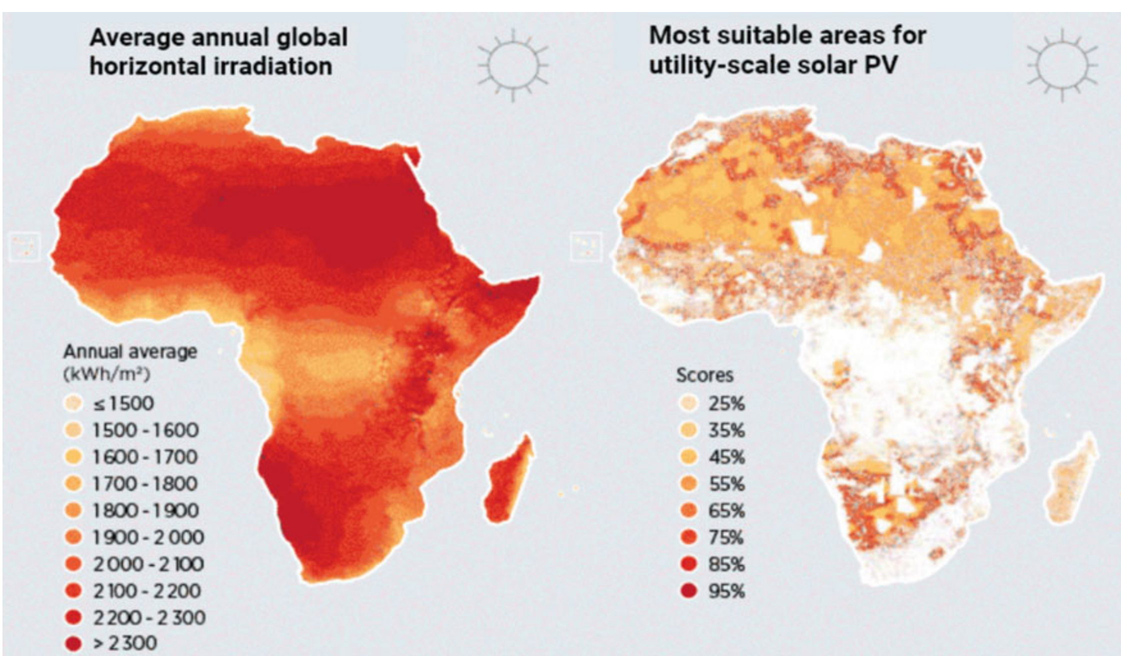

Fig. 19 Solar energy potential in Africa (Edmond 2022)

Fig. 20 Location of University of Djilali Bounaama in North Algeria (Trommsdorff 2021)

electricity produced is used as efficiently as possible. The project is expected to end in 2023 (United Nations University 2022).

Many agricultural crops grown under agrivoltaics are predicted to increase yields in dry, hot and sunny climate regions like Mali because the partial shading prevents extreme solar radiation, heat and extreme weather conditions from affecting them and benefits the quality of the crop. Rainwater might also be collected directly from the PV panels for irrigation or other uses in farming (Cheo et al. 2022).

In Algeria, WATERMED4.0 project was installed in April 2021 through partnership with European research centers and agencies for the purposes of employing new irrigation techniques to conserve nutrients and water. It is located in the University of Djilali Bounaama in North Algeria as shown in Fig. 20 for conducting experiments by the research laboratory of agricultural production and sustainable development. The pilot project aims at increasing the productivity of crops by 25% (Trommsdorff 2021).

8.3 Agrivoltaics Projects in Europe

In Europe, several enormous agrivoltaics projects were implemented in in many countries: Spain, Greece, France, Germany and Netherlands. BayWa is a German company that has undertaken several agrivoltaics projects across Germany and Netherlands, focusing on different types of crops such as wheat, blackberries, strawberries, blueberries, red currants, raspberries, celery and potato.

BayWa has built one of the largest agrivoltaics plants across Europe in Babberich and other four test projects across the Netherlands. The project's size was expanded last year to 2.7 MW_p in capacity to cover up to 3.2 hectares using 10,250 solar panels that deliver power to nearly 1250 households (Benefits of Agrivoltaics and 5 real–life examples of successful implementations 2022).

They proved that during hot days, the temperature beneath the solar panels was lower by two to five degrees. This leads to a huge reduction in the evaporation rates, which in return reduces water demand. In addition, during night, the heat got retained better than plastic covering that is used to protect the crops from the cold, in turn decreasing the utilization of plastic in farms (Benefits of Agrivoltaics and 5 real–life examples of successful implementations 2022).

Endesa & Enel are planning to implement the Carmona solar plant project in Spain, with a capacity of 100 MW_p covering up to 100 hectares to be combined with 3 hectares of aromatic plants: sage, rosemary, oregano and coriander in addition to beekeeping. They say that beekeeping helps in improving the productivity of the crops by increasing the degree of pollination (Benefits of Agrivoltaics and 5 real–life examples of successful implementations 2022; The place where bees, crops and photovoltaic panels coexist 2022).

Sun'Agri has installed 84 kW_p in the wine-growing area in Piolenc, France, to test the performance of the agrivoltaics where over 600 m^2, and 280 solar panels were used at 4.2 height (Benefits of Agrivoltaics and 5 real–life examples of successful implementations 2022; Viticulture results–Sun' Agri 2022). This combination provided several benefits:

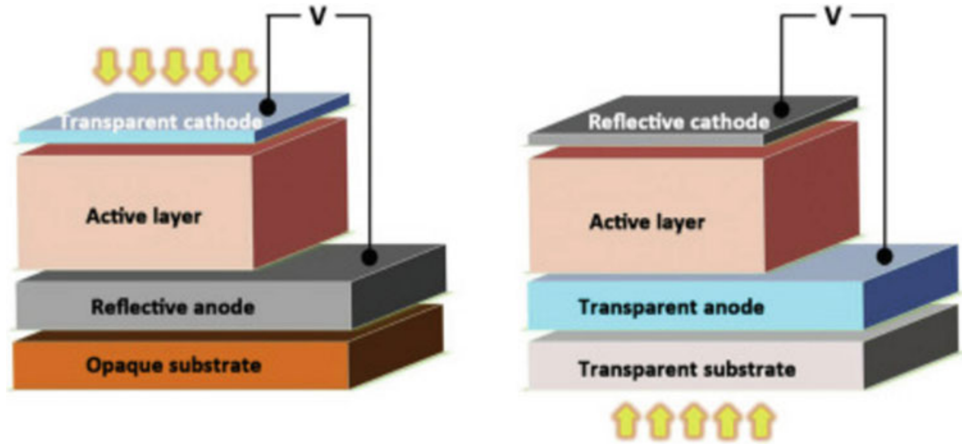

Fig. 21 Architecture of a flexible solar cell with two electrodes and an active layer (Elsevier, Open Access) (Li et al. 2021)

limiting excess solar radiation and high heat, reducing water demand by 12 to 34%, improving water comfort while limiting irrigation, pooling additional protection solutions and leading to a better aromatic balance of the wine produced (Viticulture results–Sun' Agri 2022).

Enel implemented many projects around Greece (Pezouliotika, Polysitos I and Polysitos II, Pezouliotika, Herodasos and Sounio), these power plants were not designed for the purpose of agrivoltaics specifically, but Enel utilized sheep to guarantee that plants don't intervene with the operation of the solar panels. In addition, with the help of the sheep, the vegetation was kept under control and prevented the spread of fire by providing a natural firebreak. Also, it saves the needed fuel to use mechanical machines for cutting (Benefits of Agrivoltaics and 5 real–life examples of successful implementations 2022).

9 Flexible Solar Cells

Manufacturing flexible solar cells presents an expansion to the conventional applications of photovoltaics. Flexible solar cells can be applied in buildings, vehicles, garments and many more applications. Thin-film solar cells are characterized by their lightweight and flexibility, especially when compared to classical crystalline silicon first-generation solar cells (Zhang et al. 2022). Thin-film solar cells are effortlessly folded into different forms and dimensions based on the required application. These flexible thin-film solar cells present novel energy generation solutions for various outdoor and indoor applications in which weight resilience is essential. Thus, flexible thin-film solar cells can be manufactured on opaque or transparent substrates. Generally, manufacturing flexible photovoltaics is similar to that of the thin-film second-generation solar cells. Thin-film solar cells are constructed through the deposition of several functional layers above a flexible substrate by utilizing methods including spin coating, printing and vacuum deposition. The flexible substrate offers substantial mechanical support and an overall environmental shield of the solar cell. Figure 21 illustrates the different materials employed to construct a flexible thin-film solar cell; the figure on the right represents the solar cell structured on a transparent substrate; and the figure on the left shows the structure of solar cell on an opaque substrate. To construct a flexible solar cell, two electrodes are integrated to obtain photoelectric charge carriers. In order to for the semiconductor layer to absorb light, one of the electrodes needs to be transparent, and once light is absorbed it is converted to energy through the photovoltaic effect. The main element of flexible solar cells is the active material which plays an essential role in the power conversion efficiency, where this material can either be inorganic, organic or an inorganic–organic semiconductor. Examples of inorganic semiconductors include cadmium telluride, amorphous silicon and copper indium gallium diselenide. Amorphous silicon is primary applicant of flexible photovoltaics owing to their flexible manufacturing processes. Organic semiconductors are classified based on the molecule size, and they contain donor and acceptor compounds. Metal halide perovskite is among the popular types of hybrid semiconductors employed in flexible solar cells. Figure 22 reveals the efficiency of the most recent flexible solar cells along with their materials. Due to the recent swift advancements in material systems, the commercialization of flexible solar cells in many products is anticipated (Li et al. 2021).

9.1 Substrate Types for Flexible Solar Cells

Flexible substrates are of great importance for developing flexible photovoltaics. Substrates are an essential part of the electrode that have great effects on the electrode itself and the overall solar cell performance (Zhang et al. 2022).

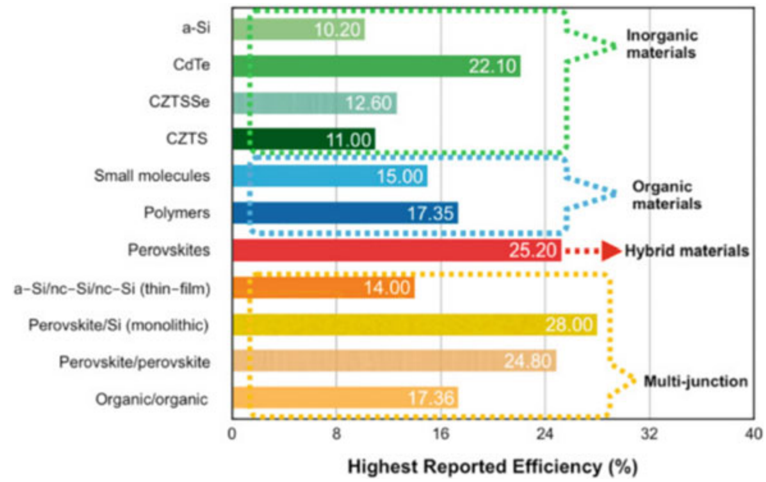

Fig. 22 Documented records of the reported efficiencies of different active layers applied in flexible solar cells (Elsevier, Open Access) (Li et al. 2021)

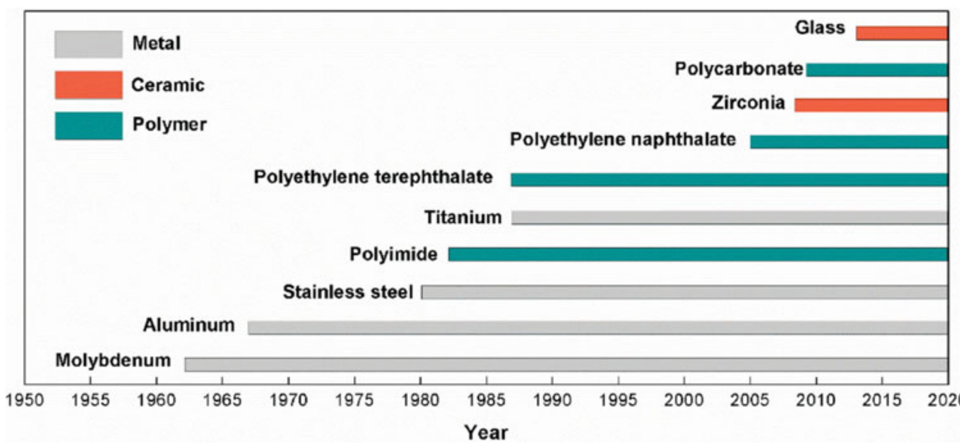

Fig. 23 Depiction of the most utilized substrate material for flexible solar cells organized in a chronological order (Elsevier, Open Access) (Li et al. 2021)

Figure 23 demonstrates the most commonly used flexible substrates classified based on the utilized material. Metal, ceramic and plastic materials are common substrates for flexible cells (Li et al. 2021).

9.2 Metal Substrates

Thin metals that are less than 125 µm foils that can be utilized as flexible substrates for creating flexible solar cells (Wong and Salleo 2009). The high flexibility of the metal substrate is a result of the metal's high ductility. Metal substrates have high thermal stability and chemical erosion resistance (Zhang et al. 2020). Stainless steel metals are the most popular type of metal substrates as they are both cost-effective and have great chemical and thermal stability (Williams et al. 1980). Other than stainless steel metals, aluminum alloy metals and titanium metals have been presented as flexible electrodes for fabrication of flexible solar cells. Titanium metals have been utilized precisely for the fabrication of perovskite solar cells (Kim et al. 2015; Xiao et al. 2016). Titanium metal substrates in perovskite solar cells allow for to attainment of a PCE of around 13.07% (Wang et al. 2015). Despite these advantages, the high costs of titanium metal substrates limited their wide commercialization. Metal foils in general are associated with high optical reflectance of the visible light spectrum, while the solar cell's top electrode must be optically transparent to allow the transmittance of light to the active materials (Yun 2017).

9.3 Ceramic Substrates

Ceramic substrates are usually made from glass, and they have high thermal stability and chemical erosion resistance. Unlike metal foils, glass does not possess high ductility, and this in return adversely impacts the flexibility resulting in a smaller bending radius (Wong and Salleo 2009). To compensate for their low ductility, the thickness of glass should be thinner than 100 µm to exhibit high flexibility. A perovskite solar cell fabricated on a glass substrate has a power conversion efficiency of 18.1% (Dou et al. 2017). Other than glass substrates, zirconia ribbon ceramics can also be utilized as flexible substrates for solar cells (Ishizuka et al. 2010).

9.4 Plastic Substrates

Plastics or polymers are cost-effective and lightweight materials that are widely utilized as flexible substrates for flexible solar cells. The most popular types of plastic substrates are polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) because of their high transparency, mechanical robustness, cost-effectiveness and lightweight (Zardetto et al. 2011). It was recently shown that PEN substrates in perovskite solar cells produce a power conversion efficiency up to 19.1% (Yoon et al. 2016). On the other hand, plastic substrates have low thermal stability, lower than 250°C, even though the fabrication processes of solar cells are associated with high temperatures (Zardetto et al. 2011). However, colorless polyimide (cPI) substrates have high thermal stability and resistance and light transmittance (Yi et al. 2020). Moreover, due to the low density of plastic substrates, they have high oxygen and water permeability (Jung et al. 2019). These negative consequences of plastic substrates adversely affect the lifespan of the solar cell (Yi et al. 2020). Nevertheless, this issue can be solved by coating the barrier of the layers of the plastic substrates (Li et al. 2020).

9.5 Electrode Materials for Flexible Solar Cells

After selecting the substrate, the rest of the electrode will be developed on the selected substrate. A flexible solar cell comprises a conducting electrode, an active material and a reflective electrode. Transparent solar cells are made up of only transparent electrodes.

9.5.1 Thin-film Metals

Thick metal layers made up of Al, Mg or Ag with thicknesses higher than 100 nm and high electrical conductivity have been employed as the reflecting electrodes in solar cells. However, when the metal's thickness is thinned down to thinner than 20 nm, the metal film becomes semi-transparent (Wang et al. 2013). Much research has been conducted to enhance the performance, transparency and conductivity of these ultrathin films (Chen et al. 2012).

Metal grids are made up of thin metal lines (~ 1 μm) which act as the front contacts in inorganic solar cells (Yu et al. 2013). Metal meshes are thin-film electrodes comprised of networked structured metal lines. Metal meshes or grids possess defined and organized geometry forms that can be accurately controlled via the fabrication process. Metal meshes can be created by photolithography, nanoimprint lithography, thermal evaporation, electroplating, inkjet printing and spin coating.

9.5.2 Transparent Conducting Oxide

TCO is the most common material for flexible solar cells electrodes. Tin-doped indium oxide (ITO) is the most utilized electrode material for solar cells (Xue and Forrest 2004). Several studies have been facilitated to alter the surfaces of ITO via UV ozone, and chemical and oxygen plasma (Li et al. 2005). There are several factors that inhibit the popularity of the ITO electrode (Sandström et al. 2012). These factors include the restricted global supply of indium and the high utilization of ITO (Gupta et al. 2013). However, new alternatives for ITO have been found, such as ZnO-based compounds (Liu et al. 2013; Park et al. 2011).

9.5.3 Metal Nanowires

Various structures of metal nanowires including gold, silver, copper and nickel have been presented as transparent electrodes for flexible solar cells. Until recently, silver nanowires are the most popular metal nanowire because of its positive optoelectronic characteristics and its low costs. Moreover, silver nanowires possess high thermal resistance and significantly high aspect ratio that is much higher than 10,000 (Huo et al. 2008). Copper nanowires are associated with lower costs than silver nanowires; however, they bear low thermal stability and resistance (Bobinger et al. 2017). The synthesis process of metal nanowires is facilitated in a wet-chemical solutional process. For instance, the polyol process is the most widely utilized synthesis process of metal nanowires (Chen et al. 2006). While for copper nanowires, the hydrothermal process is preferable to carry out the metal synthesis.

The aspect ratio of metal nanowires, which represents the length to diameter ratio of the nanowire, has displayed positive impact on the conductivity and transparency of the nanowire (Kim and Tatsuma 2017; Lee et al. 2021). Metal nanowires come in various sizes with different dimensions. For example, the average length of a silver nanowire is between 0.5 and 220 μm, and the average diameter is between 13 and 150 nm (Sannicolo et al. 2016). Due to the small diameter of metal nanowires, the electrodes' chemical, thermal and electrical stability is negatively impacted (Lu et al. 2015). To overcome this challenge, it is necessary to integrate these metallic nanowires with other nanomaterials including conductive polymers, polystyrene sulfonate, metal oxides, graphene, carbon nanotubes, graphene oxide and metals. This integration presents several other improvements in the performance of the electrode (Kim et al. 2020).

9.5.4 Nanocarbons

Carbon nanotubes and graphene have received the attention of many researchers over the years because of their enhanced electrical, optical and mechanical characteristics. Hence, these novel carbon materials can be applied as flexible electrodes in flexible solar cells (Zhang et al. 2005). Carbon nanotubes are classified based on their structure either into single-wall nanotubes or into multi-wall nanotubes based on the number of layers. Both of these categories have been integrated in optoelectronics posing as transparent electrodes. Single-wall nanotubes are much more transparent and conductive than multi-wall nanotubes due to the variances in the optical transmittance based on identical current density (Biris et al. 2008). Consequently, single-wall nanotubes are more preferable as electrodes for substituting the ITO transparent electrodes. Graphene produces high conductivity and utilizes organic polymers and metal oxides for altering its interface. Single-wall nanotubes and graphene electrodes can be synthesized and deposited by the means of chemical vapor deposition techniques (de Arco et al. 2010).

9.5.5 Conducting Polymers

Conducting polymers such as PEDOT:PSS are presented as an interlayer in organic optoelectronics. The presence of such polymers aids in smoothing the surfaces roughness of conductive layer and improving the hole interactions rates between the transport material and the hole (Po et al. 2011). PEDOT:PSS polymer electrodes are widely known for their cost-effectiveness and their enhanced optical characteristics. Polymer electrodes are associated with low electrical conductivities; however, these electrical conductivities can be enhanced through chemical doping (Hsiao et al. 2009). Additionally, high boiling point temperature solvents can improve the electrical conductivity of polymers (Nickel et al. 2010).

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