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A review of transparent solar photovoltaic technologies

Alaa A.F. Husain[a,*], Wan Zuha W. Hasan[a,b], Suhaidi Shafie[a,b], Mohd N. Hamidon[b], Shyam Sudhir Pandey[c]

[a] Department of electronic engineering, University Putra Malaysia, Serdang 43400, Malaysia
[b] Institute of Advanced Technology, University Putra Malaysia, Serdang 43400, Malaysia
[c] Department of Biological Functions Engineering, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka 808-0196, Japan

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ABSTRACT

Energy is essential for economic development and growth. With the rapid growth of development and the drive to expand the economy, society demands more electricity. Coupled with the realisation that unsustainable energy production can have a detrimental effect on our environment. Solar energy is the most prolific method of energy capture in nature. The economic drive to make solar cells more cost effective and efficient has driven developments in many different deposition technologies, including dipping, plating, thick film deposition and thin film deposition. Typically, in order for solar energy to work efficiently and supply energy to a building, a very large amount of space is required, in the form of rooftops or land, in order to install solar panels; these solar panel space requirements are a large impediment to practical usage. This drawback drove researchers to come up with transparent solar cells (TSCs), which solves the problem by turning any sheet of glass into a photovoltaic solar cell. These cells provide power by absorbing and utilising unwanted light energy through windows in buildings and automobiles, which leads to an efficient use of architectural space. There are approximately nine transparent photovoltaic (TPV) technologies under development, and studies regarding these technologies aim to achieve high transparency along with electrical performance that is compatible with solar panels that are sold in the market. The main objective of this review paper is to state all the latest reported technologies from the year 2007 onwards on transparent photovoltaic technologies with at least 20% average transmission. This includes demonstrating the process used in each technology (including the materials and the methods) and explaining its advantages and disadvantages from a performance, aesthetic and financial perspective. Therefore, this study provides a crucial review on the latest developments in the field of TSCs.

1. Introduction

In recent years, the floodgates of research focusing on clean renewable energy have been opened by scientists who consider solar energy to be the most abundant source of energy that can satisfy society's demands, which stem from continual economic development [1–4]. Solar energy is at least utilised in 4 different ways in our daily lives, and this ranges from heating water to producing electricity. Photovoltaic (PV) technologies are at the top of the list of applications that use solar power, and forecast reports for the world's solar photovoltaic electricity supplies state that in the next 12 years, PV technologies will deliver approximately 345 GW and 1081 GW by 2020 and 2030, respectively [5]. A photovoltaic cell is a device that converts sunlight into electricity using semiconductor materials. Semiconductor materials enable electron flow when photons from sunlight are absorbed and eject electrons, leaving a hole that is filled by surrounding electrons. This phenomenon of electron flow by photon absorption is called the photovoltaic effect. The PV's cell directs the electrons in one direction, which forms a current [5,6]; the amount of current is proportional to the number of absorbed photons, which means that PV solar cells are a variable current source. There are approximately 24 models of solar cell technologies that are made from different types of materials and methods [7]. This review paper is primarily interested in transparent solar cells. However, in order to understand the concept of transparent solar cells, it is important to explain the evolution of solar cells starting from the silicon type. The following is a short background on solar cell technologies.

The challenges that face photovoltaic cells are cost, efficiency, and operating lifetime [8]. Researchers are now focusing on finding materials that will overcome these challenges. Silicon was the first material that exhibited good efficiency [9]. It is used in monocrystalline PV cells, which are at least 6% more efficient but also more expensive than

* Correspondence to: Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
E-mail address: alaa.a.f.husain@gmail.com (A.A.F. Husain).

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Nomenclature

TSC	transparent solar cell
TPV	transparent photo voltaic
NT-TiO2	Nanotube titanium dioxide
TDSSC	transparent dye synthesis solar cell
DSSC	Dye synthesised solar cell
EPD	Electrophoretic deposition
TFSC	Thin film solar cell
TLSC	Transparent luminescent solar concentrator
QD	Quantum dot
CE	Counter electrode
Pt	Platinum
η	efficiency (%)
T	transparency (%)
P0	PV rated power (kW)
P	instantaneous AC power (W)
Pmax	maximum power output (W) of panel at standard test conditions
AVT	average transmission
PSC	Polymer Solar Cells
FTO	Fluorine doped tin oxide
ITO	Indium-doped tin oxide
TPV	Thin film Photovoltaic

polycrystalline PV cells [10–12]. Monocrystalline cells are more electrically efficient, as they have a perfect crystal structure, whereas polycrystalline cells have a less perfect molecular structure that impedes electron flow but are slightly cheaper to make. However, due to the high cost of silicon, the market requires new materials and processes that can give an equivalent efficiency, while at the same time reducing costs [2]. Therefore, researchers came up with thin film PV cells (TFPV). Thin films reduce the amount of semiconductor material used to manufacture amorphous solar cells, which reduce the cost by more than half [13,14]. In addition, there is the third-generation solar cell, which includes concentrators and organic solar cells [15] such as dye-sensitized solar cells (DSSC) [16,17]. Most solar cell applications are terrestrial [3,18]. One of the main challenges that most of these applications face is the surface area needed to produce enough electricity in the solar panel; the larger the surface area is, the more sunlight a PV can harness. Hence, the idea of transparent photovoltaic (TPV) cells came to solve this challenge of effectively utilising space. This review focuses on technologies related to TPV and their merits. However, before going through transparent solar cell (TSC) technologies, it is essential to understand the concept of the solar cell and dye-sensitized solar cells (DSSC), presented in sections A and B, because they are 2 main structures used to build most PV models.

1.1. Photovoltaic principles

The semiconductor material in a PV cell absorbs light (photons), and this displaces electrons to form pairs of electrons and holes, which are guided in one direction, creating a current. The semiconductor is doped to be a p-n junction with a potential difference, which will drive current flow vertically through the cell in one direction, so it can be harvested as electricity. The diffusion length is one of the important factors that affect the efficiency of the solar cell. Photons must have energy (hv) equal to or more than the energy band gap (E_{gap}) of the semiconducting material [4,19]. In summary, a photovoltaic cell is a device that converts sunlight into electricity using semiconductor materials; it has the same working principle as a semiconducting diode. The semiconductor material, such as silicon, has the property to eject electrons when sunlight is absorbed; the PV's cell then directs the electrons in one direction, which forms a current, as illustrated in Fig. 1 [5,20,21].

1.2. Dye-Sensitized Solar Cells (DSSC): Operational Principal

Since O'Regan and Grätzell reported the fabrication of DSSC in 1991, with efficiencies of 7 − 8%, it became a promising energy generating device [22–24]. DSSC is convenient to fabricate, low cost, and has a high power-to-conversion efficiency. These properties attract scientists' and researchers' attention [25]. An ideal DSSC contains a combination of dye-sensitized transparent conducting substrate, semiconductor film (such as titanium dioxide (TiO_2), zinc oxide (ZnO), tin dioxide (SnO_2), Niobium pentoxide (Nb_2O_5)), electrolyte and counter electrode (CE) [26–30]. The elements of DSSC are clear in Fig. 2 [31]. The heart of the DSSC is the mesoporous oxide containing TiO_2 nanoparticles as a roadway for the electrons to cross from the cathode to the anode, the diameter size of the particles range between 10 and 30 nm, while the thickness of the film is 10 μm approximately, and it is doped with a dye for absorbing the photons. The TiO_2 layer is deposited on a glass coated with transparent conducting oxide (TCO) or fluorine-doped tin oxide (FTO); these are the commonly used substrates [22–33]. The dye knocks out electrons from the photons to the conduction band [19] which result in oxidation of the dye. The dye recovers the lost electrons from the electrolyte; this operation is called iodide/triiodide redox system Eq. (1). The I^- loses electrons to the dye and forms $3I^3$ triiodide. The Triiodide returns to be iodide by gaining electron from the cathode, which is covered with platinum as a catalyst, then the electrons flow from the semiconductor side to the counter electrode side forming a flow of current [31]. The components of DSSC are discussed in more detail below:

$$I^- + \quad 2 \quad e^- = 3 \quad I^- \tag{1}$$

1.3. Semiconductors

Around 80% of solar cells in the world are made using silicon-based materials [34]. The markets favour cost reduction in the material and manufacturing process. Therefore, alternative cheaper materials are required. Semiconducting metals with a wide band gap, able to act by photosynthesis through the use of an organic dye to produce pairs of electrons-holes, has become a good alternative to the conventional inorganic semiconductor-based solar cells. [35] Such semiconductors include titanium dioxide (TiO_2) [36], zinc oxide (ZnO) [37–39] and tin dioxide (SnO_2) [40–42] which are very useful for solar energy applications [43,44]. Semiconductors are crystalline solids, they are neither metals nor insulators, their proprieties are determined at low

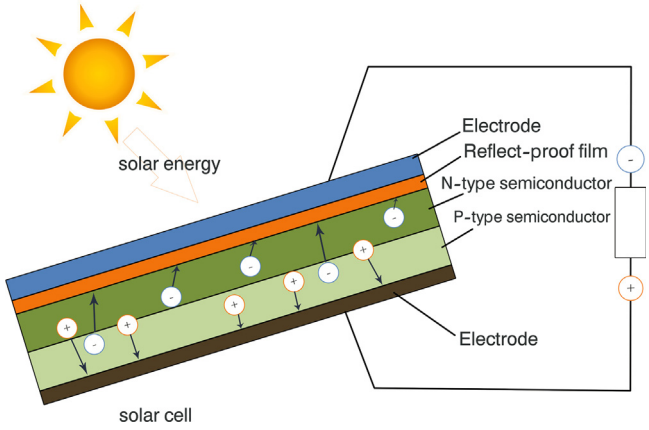

Fig. 1. Si Solar Cell [20].

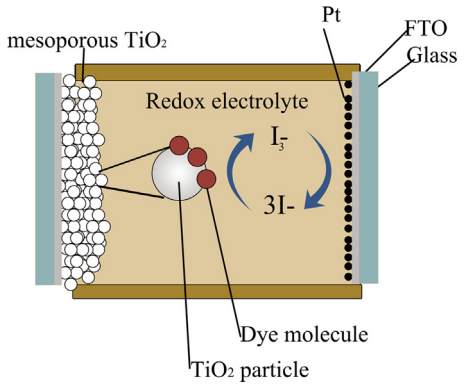

Fig. 2. Schematic overview of a dye-sensitized solar cell operational principle. [31].

temperature by impurities or dopants [45].

1.3.1. Electrolyte

The electrolytes main task in the solar cell is to regenerate the oxidized dye using the iodide species I-, which act as the donor electron in the electrolyte). The electrolyte in the solar cell especially in DSSC contains I-/I3- redox immersed in an organic liquid solvent. The process of oxidization results in producing I3- ions. I3- accepts electrons from an external source to regenerate I- [46–48].

1.3.2. Dye

Increasing the band gap of the semiconductor material is one of the most desired properties in DSSC, which brings up the importance of the dye as an essential part of DSSC. Dye synthesis can satisfy this by increasing the excitation process efficiency and expanding the range of the wavelength of excitation [49]. This helps in absorbing the photons of sunlight and produce electrons and holes. The dye is bonded chemically to the porous surface of the semiconductor. The DSSC's efficiency depends on the properties of the dye material, such as high absorbing and good transforming of photons into the final device [50]. However, the dye must meet some conditions to be valid for DSSC use, such as the absorption spectrum must cover the whole visible region including near- infrared (NIR) region, the dye must have anchoring groups in order to bind it to the semiconductor surface, the photosensitised must have a higher level of energy in the excited state level than the conduction band in the n-type semiconductor, and a more positive oxidized state than the redox potential of the electrolyte, and it should also be stable [31].

Counter electrode (CE)

The Counter electrode (CE) plays a big role in increasing the performance of the DSSC. A thin film of the electrode material such as Platinum (Pt) can act as the catalytic layer on the CE side. Pt is used as the counter electrode in DSSC due to its high electrochemical activity, high conductivity, electrocatalytic aptitude, and long-term stability, although it's a very expensive material [51,52]. The conductive oxide glass such as fluorine-doped tin oxide (FTO), and indium-doped tin oxide (ITO) are coated with Pt thin film. [46]. Alternative materials such as carbon-based materials, and conducting polymers have been investigated to replace Pt; due to its high cost, low corrosion-resistance and low availability. However, none was equivalent in conductivity to Pt [53,54].

Transparency is a physical property that allows light to pass through without interrupting it. The core of this research is transparent solar cell (TSC) and its use in many applications that require optically transparent solar cells, such as car windows. What makes a material transparent is the arrangement of atoms and electrons in it. When an electron has an energy gap equal to a photon energy it absorbs the photon and moves to a higher energy level, in this case, little light passes through that material, which makes that material opaque [55]. In a transparent material the energy gap of the electron is higher than the photons, so the electrons will not be able to use the photons' energy, and light will pass through, which will make the material translucent. This is the main characteristic of the solar cell, which is to absorb light. So, researchers are trying to increase the transparency without affecting the performance of the cell. To achieve that, a synthesised transparent material is required, in order to fabricate the layers of the solar cell [56]. There are multiple layers that are combined together for fabricating the solar cell, as explained before. The main struggle is to find a transparent conducting material for the counter electrode [57]. The key to reaching a transparent paste is to control the factors that affect transparency such as:

1. The Shape of synthesis nanocrystals.
2. The process of producing the paste
3. Absorbing the NIR and UV light and letting the visible light pass through
4. The Thickness of the deposited paste

2. Implementation of transparent solar cell technologies

Sun light is available for free everywhere, but the guarantee of using this light for solar power is restricted to solar farms and rooftop panels. Recently, transparent solar cells caught the attention of scientists due to their variety of possible applications in our daily lives. Transparent solar cells are already in use for these applications in some countries, while others are for the far future, once their efficiency is improved. Transparent solar cells can transform crowded cities from exclusively power consumers into power plants. Building integrated photovoltaics, also known as BIPV, is the nearest application for transparent solar cells. If all the buildings with 90% glass on their surface used transparent solar cells printed on the surface of the glass, the solar cells have the potential to power more than 40% of that building's energy consumption.

Another application of transparent solar cells is in automobile and electronic devices. If these applications used TSC in their glass surfaces, people could have cars that do not need fuel or devices that can be self-charged from the sun. Solar-powered vehicles are a desired application of TSC, with cars, air planes, trains, and boats potentially being powered with solar energy. TSC has the potential to power all the electronic devices that we use in our daily lives, from tablets, MP3 players, cell phones, and e-readers, to laptops and other portable devices.

Transparent solar materials and semi-transparent materials started to be developed in the past few years. Some companies have implemented transparent solar cells with reasonable efficiency but not enough to compete with silicon solar panels. However, this invention has a high potential of turning every glass surface in the advanced world into a solar panel. Researchers are now working to improve the efficiency of TSC without sacrificing transparency; this is expected to be achieved in the next 5 years.

3. Transparent solar cell technologies

There are approximately nine technologies that apply to the fabrication of transparent solar cells, and they are a focal point of current research due to market demand and the potential applications of transparent solar cells (TSC). The centres of research that report some success with TSC are in Japan, Germany, the USA, and India. It should be noted that 90% of these technologies use an FTO or ITO conductor on glass, which has a layer with almost 10 Ω/sq resistance, using a thin film with a thickness of less than 20 nm [58,59]. Combined with intrinsic optical losses of the glass itself, these layers reduce the transparency by approximately 15–20% before the deposition of any other materials. Thus, the best transparency achieved currently is less than 80% [60,61], The technologies that achieved more than 20%

transmittance with at least 1% efficiency are elaborated in chronological order below.

3.1. Thin film photovoltaics (TPVs)

Thin film photovoltaics (TPVs) are one of the most prolific technologies in TSC and achieved via different methods. Some of these methods depend on the fabrication of the material and pastes to accomplish transparency, and others depend on the deposition method of pastes on FTO glass. In this section, categorisation will be based on the deposition methods, and in each method, the fabrication of pastes and the type of material will be clarified.

TPV is basically a thin film that has a thickness ranging from a few nanometres to tens of micrometres of active material deposited on glass in different ways [62,63]. Thin film technology reduces the cost of solar cells by conserving the materials used in fabricating the cell; it is easy to deposit thin films on many different substrates, from rigid to flexible and from insulators to metals, which allows for new applications [13,64–66]. By reducing the thickness of the film, the transparency increases in some materials, such as titanium dioxide. Thin film solar cell TFSC is fabricated by combining material layers that are usually used to make solar cells, but as thin films, which reduces the cost of the solar cell's materials, by depositing the optimal amount of material that allows the solar cell to function properly. [67–70] The properties of these materials are different from each other, and the overall performance of the cell is affected by each layer. The interaction between these layers is important due to the variety in their crystal structures [62]. There are many ways to deposit thin films on a substrate, such as chemical bath deposition (CBD) technique [71–73], physical vapour deposition (PVD) technique or sputtering [74–77], electro deposition [78–81], screen-printing [82–85], pulsed laser deposition (PLD) [86–88], and spray and atomic layer deposition (ALD) [89–91].

Transparent thin film solar cells mostly depend upon the thickness of the film, the material used, the process of fabrication and the deposition method. Screen printed thin films are the first reported transparent thin films; other thin film deposition methods will be further explained in subsequent sections.

Screen printing is the preferred method for depositing thin films and is widely used in thin film applications; it provides an easy way to control the thickness and the position of the film. Screen printing depends on the quality of the paste used to make the layer of the thin film [92–95]. With most DSSC, titanium dioxide nanoparticles (commercially known as P25) are used for making the paste for screen printing [96]. After depositing the desired quantity of paste into the frame, the paste is swiped at a constant velocity using a squeegee across the surface of the screen. The paste will eventually flow from the screen to the substrate surface. While the squeegee passes above the screen, the left part of the screen is separated from the substrate, and only a thin film of the paste is deposited and dried. Fig. 3 shows an example of screen printing a polymer film on a substrate [97,98].

Transparency is controlled by screen printing through a screen made from a mesh stretched over a frame, and its properties (mesh count, mesh opening, thread diameter, open surface and fabrication thickness) control the thickness and porosity of the film. Transparency is also controlled by the pressure and speed applied on the squeegee [85,99–101]. In 2007, researchers reported a transparent solar cell by experimenting with 3 commercially available TiO_2 nanoparticle pastes called P25, ST21, and ST41 [102]. Each of the pastes was printed on FTO glass, using a fabric of 83 μm thickness, and the results showed that P25 was the most transparent and that ST21 was hazy, while ST41 was totally white and opaque. The resulting thickness of P25 TiO_2 as a screen-printed thin film was 17 μm, the light transmission obtained was 60%, and the efficiency of the DSSC at the end of the fabrication of P25 TiO_2 thin film was 9.2% [102].

In 2008, another study from Korea reviewed different types of TDSSC. One of the reviewed methods used a bilayer TiO_2 DSSC in order to improve photocurrent density in the TSC. The material used was nanocrystalline with a wide band gap. This material improved the performance of DSSC through increasing the amount of dye per unit volume of the nanocrystalline film. The film was made of small particles that increased the surface area of the film and allowed for more dye absorption [103] [103]. Nevertheless, the smaller particles did not mean better performance due to the recombination of electrons, which requires a balance when choosing the design. The study reported efficiencies of approximately 7.8% and 8.4% for 6 μm and 12 μm thick nanocrystalline films, respectively, while both films had an average transmission range of 20–23% over a wavelength of 400–700 nm. However, this result is not satisfying, which led to the addition of a light-scattering layer. The bilayer contains a light-scattering layer [104] and a nanocrystalline semi-transparent TiO_2 layer and/or sub micrometer-sized particles with nanocrystalline TiO_2; adding the scattering particles led to an 18% improvement in light scattering efficiency. The diagrams of light-scattering layers on top of TiO_2 nanocrystalline particles are shown in Fig. 4. Light-scattering particles can gain more photons because they capture incident light. Transparency is controlled by engineering the particle size, film thickness, structure of the semiconductor oxide material and dye colour, which can contain different colours to absorb more light at different wavelengths [105]. Further research and experimentation must be done to improve from previous methods.

3.2. Near-Infrared transparent solar cell

As mentioned before, the main function for a solar cell is to absorb photonic energy, while the main characteristic of transparency is to let photons pass through, which makes it hard to encompass both features in one material. Most research is directed towards making thin layers to achieve some amount of transparency and focus on absorbing the visible spectrum; this results in producing cells with an average transparency of less than 30% in order to maintain reasonable efficiency. In 2011, Richard Lupnt's research group took a different direction by changing the molecules of the dye in order to absorb ultraviolet and near-infrared (NIR) wavelengths (650– 850 nm), instead on focusing on the active layer's thickness to achieve a transparent solar cell. A heterojunction organic PV (OPV) is transparent to visible light with a transmission of more than 65% and will absorb in the near-infrared spectrum with an efficiency of 1.3 ± 0.1%. The OPV contains chloroaluminium phthalocyanine (ClAlPc) as a molecular organic donor and C_{60} as a molecular acceptor [106].

The anode of the cell is coated with indium-tin oxide (ITO), ClAlPc, C_{60}, bathocuproine (BCP) and MoO_3, while the cathode is coated with Ag via thermal evaporation. The transparent NIR mirror is grown separately on a quartz substrate and is called a distributed Bragg reflector (DBR). TiO_2 and SiO_2 layers are sputtered to a selected thickness to produce a stop band of approximately 88 nm. On the other side of the quartz, a broadband antireflection (BBAR) layer is coated. The schematic of the OPV is shown in Fig. 5; the main objective of this TSC model is to allow for visible light to pass through and absorb ultraviolet and near-infrared NIR wavelengths [106].

3.3. Polymer solar cell (PSC)

In 2012, a research team from the University of California

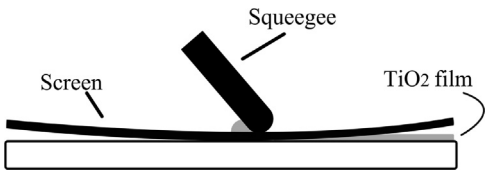

Fig. 3. Schematic diagrams of screen-printing polymer film [97].

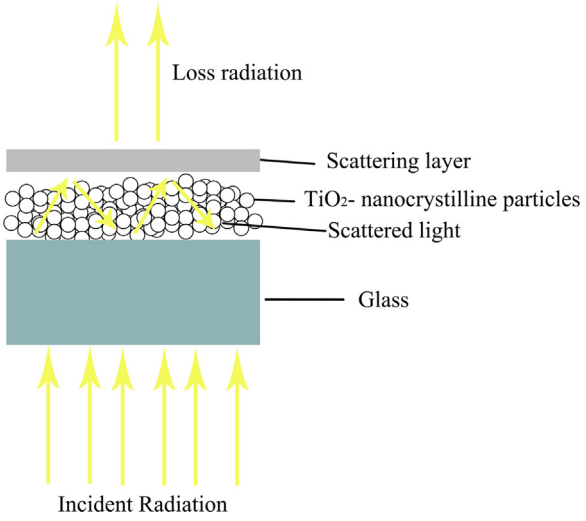

Fig. 4. Schematic diagrams of light-scattering layer on top of TiO_2 nanocrystalline particles [105].

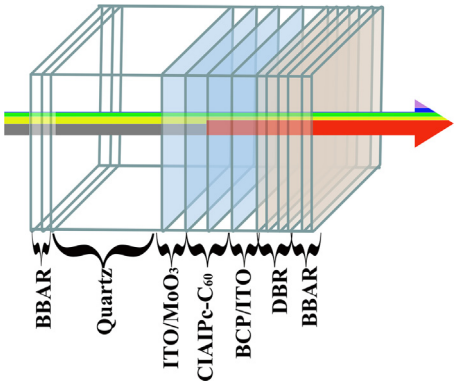

Fig. 5. Transparent OPV [106].

investigated the possibility of producing TSC using solution processing. To obtain an ideal TPV, the absorbing materials must harvest all the light in the ultraviolet (UV) and near infrared (NIR) regions and allow for visible light to pass through. There are some materials with these properties, such as carbon nanotubes and graphene, which are transparent conducting materials. It is inefficient to only use these materials to build a TPV. Thus, it is suggested to combine a transparent polymer solar cell with a transparent conducting material, such as silver nanowires (AgNWs) combined with a transparent polymeric PV cell, which is non-transparent for UV and NIR light but transparent to visible light [107–110].

There are three reported TPV technologies that employ polymers to absorb within the NIR spectrum. They are different in terms of their combined materials. For instance, the first study reported a TPV combining a polymeric material, which is sensitive to NIR light and is highly transparent to visible light, with a conductor made of AgNW.

Visibly transparent polymer solar cells (PSCs) are another TPV technology that involves a polymer that can harvest near-infrared light and allow visible light to pass. The visible electrode is coated with a silver nanowire metal oxide through a mild solution process. The efficiency is 4%, and the transparency at 550 nm wavelength is 66% [109].

Fig. 6 shows the design of the transparent PSC. It includes 2 transparent electrodes that have active materials sandwiched between them, which are sensitive to UV and NIR light. The active material has a polymer heterojunction as an electron donor and PCBM as an electron acceptor; the combination makes PBDTT-DPP: PCBM. This photoactive material has 68% AVT in the visible region. However, it strongly absorbs light in the UV and NIR regions. ITO is the electrode anode substrate coated with PEDOT: PSS as a modification and is placed at the bottom of the PV cell. The electrode placed on the top must be chosen well because organic materials are sensitive and might not survive the deposition process. To solve this problem, AgNW is spray coated on top of the active material, while a TiO_2 sol-gel solution is used to connect and confirm the adhesion of AgNW to the photoactive layer. The previous step is performed using mild processing [109].

A study reported an efficiency of 7.56% and an average transmission of 25%. This TPV contains a low band gap polymer (PBDTTT-C-T) based on thieno [3,4-b] thiophene (TT) and benzo [1,2-b: 4,5-b′] dithio-phene (BDT) alternating units with $PC_{71}BM$ as an active material. The substrate used is ITO glass with spin-coated ZnO sol–gel, and above that was a C_{60}-based self-assembled monolayer. The MoO_3 and Ag anode was thermally evaporated. PBDTTT-C-T: PC71BM bulk-heterojunction (BHJ) is a promising polymer material that gives a high efficiency of 7.6% in the visible light spectrum [108]. In another study, an alternative way was presented, which used a PTB7: PC71BM polymer as well and reported a 30% transmittance and 5.6% efficiency. The structure of the solar cell combines 5 layers that harvest a region in the light spectrum to cover the whole wavelength (to see architecture of the cell, refer to [107]). The side effect of the five layers is lack of periodicity [107].

3.4. Transparent luminescent solar concentrator (TLSC)

Michigan State University has reported another approach in 2014 called TLSC, which is based on organic salts, and these take a totally different direction to realise a solar cell design with a different structure, which combines efficiency with transparency. NIR fluorescent transparent dyes are used in order to capture UV and NIR light, convert them into visible light, and then guide it to the edge of the glass where the solar cell is placed. TLSC is developed from luminophore blends of canine and cyanine salts and has synthesised cyanine salt-host blends with quantum yields, combined with spectrally selective NIR harvesting. The solution is drop cast on a glass substrate. The transparency exhibited by TLSC is 86%, and the efficiency is 0.4% [111].

3.5. Perovskite solar cell

Researchers focus on improving the semi-transparent nature of organic solar cells by utilising an absorbing material that has a lower band gap than the photons, which means it will allow for visible light through and absorb near infrared light. [112] By improving the transparency, efficiency is affected. This led to trying to find a transparent material that improves the efficiency of the cell, such as methyl ammonium lead halide perovskite. [113] Most of the highly efficient

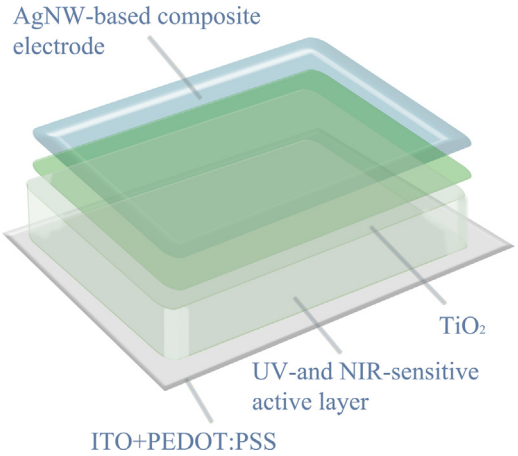

Fig. 6. Transparent PSC.

perovskite solar cells are made out of a sandwich of a metal oxide material, such as TiO_2 or Al_2O_3, and organic transport materials. Perovskites are abundant organic materials that have good electric properties suitable for solar cells, such as a high absorption coefficient, high carrier mobility, direct band gap, and high stability.[112,113] Most solar cells with perovskite crystal structure can achieve a power conversion efficiency of over 13%, which makes perovskite a good alternative to DSSC [114–116].

Semi-transparent perovskite was achieved in 2014 by the University of Antioquia, Spain, with 6.4% PCE – 29% AVT and 7.3% PCE – 22% AVT, using perovskite evaporation deposition, which is a robust process that enables the continuous deposition of layers with low thickness (less than 40 nm). This strategy implemented an ultra-thin gold electrode with 6 nm thickness capped with an LiF layer for protection and to reduce energy loss. The reduction in thickness in this method caused an increase in transmission. In addition to protection, the LiF layer also modifies the electric field circulation inside the cell. The methyl ammonium lead halide is between the electron-blocking material and the hole-blocking material. The electron-blocking material contains two layers with 95 nm thickness [112].

The semi-transparent single-junction perovskite solar cell is composed of several layers, namely, (in increasing order from the bottom): poly (3,4-ethylenedioxythiophene): poly (styrenesulfonic acid) (PEDOT: PSS), which is spin-coated onto an ITO covered glass substrate with a thickness of 75 nm, and poly [N,N0-bis(4- butylphenyl)-N,N0-bis (phenyl) benzidine] (polyTPD), which is deposited with a thickness of 20 nm. In a high vacuum chamber, the CH_3-NH_3PbI_3 layers are deposited using the co-evaporation of the two starting materials, PbI_2 and CH_3NH_3I. Consequently, using the meniscus coating, the hole-blocking material is deposited with a thickness of 20 nm. From a chlorobenzene solution, the hole-blocking material, [6,6]-phenyl C61-butyric acid methylester ($PCBM_{60}$) Solenne BV, is deposited. The order of the layers is represented in Fig. 7 [112]. A 2014 study from Stanford University reported a tandem solar cell design with semi-transparent perovskite (1.7–1.8 eV band gap) on the top and opaque electrode perovskite (1.1 eV band gap). The semi-transparent device on the top of the tandem solar cell combined a mesoporous titanium dioxide (TiO_2) layer infiltrated with perovskite and is contacted from one side by electron-selective and hole-selective (2,2 ´,7,7 ´-tetrakis(N,N ´-di-p-methoxyphenylamine) – 9,9 ´-spirobifuorene, spiroOMeTAD). For compatibility with these existing electron and hole selective contacts, $MAPbI_3$ perovskite was used. The front electrode is fluorine-doped tin oxide (FTO) coated glass. AgNW is deposited on the spiroOMeTAD or perovskite, and the semi-transparent solar cell is finalised by depositing two lithium fluoride (LiF) anti-reflective (AR) coats onto the glass surface and on top of the AgNW electrode for better transmission through the cell. The semi-transparent perovskite solar cell achieved a peak transmission of 77% approximately 800 nm and an efficiency of 12.7% [117]. The architecture of the semi-transparent solar cell is the same as the one reported by Burschka et al. [118].

3.6. Electrophoretic deposition (EPD)

Electrophoretic deposition is another method for obtaining thin films. This method can be easily applied in two steps to deposit a thin film on FTO glass [119]. First, particles are deposited on glass by applying direct voltage across two electrodes, which creates an electric field. One of the electrodes acts as a cathode and the other as an anode, and they are immersed in a solvent that contains the particles. The cells are separated by a small distance; Fig. 9 below demonstrates the EPD components [120–122]. In the second step, the synthesised particles will gather and deposit on one of the electrodes, forming a thin layer of titanium dioxide [123].

In 2015, Xi'an Technological University, China, suggested using EPD for the production of TSC using TiO_2 nanotubes. A nanotube structure is one of the shapes of TiO_2 that has good catalytic properties. These properties fit very well with solar cell applications due to the ability to construct layers that possess a high surface area with low thickness. In addition, there is the tubular nature of the grown oxide, which is aligned in a way that is beneficial for transparency reasons [124,125]. Transparency is accomplished by controlling the thickness of the tube wall, the length of the tubes, and the inner diameter of the tubes. Fig. 8 below shows the shape of the nanotubes [126,127].

TiO_2 nanotubes can be synthesised in many ways; the most reliable way is anodisation, which is a process in which TiO_2 tubes grow on conducting glass by anodising it in an electrolyte containing fluoride at high positive potentials [128,129]. The structure of nanotubes can be controlled by controlling some electrochemical factors, such as anodisation time, applied potential, sweep rate of the potential ramp and temperature [130–132].

The anodisation voltage and solution properties such as the concentration of HF, the pH and the water in the electrolyte affect the structure of the layers and the morphology. [133] One of the challenges that affect solar cell efficiency is the loss of electrons caused by recombination. TiO2 nanotubes overcome that through providing a short, quicker and direct path for the electrons to be delivered, as it is known that the longer the electrons spend on the film, the higher the probability of recombination happening [134]. The deposition of the TiO2 nanotubes film is carried out after the formation of the TiO2 nanotubes powder, which is prepared through anodisation and ultrasonic oscillation [135]. First, by rapid anodisation, the TiO_2 NT-bundle powder is synthesised from Ti foil in the electrolyte [136]. Through ultrasonic oscillation assistance, the TiO_2 tubes are disaggregated into individual tubes [137]. The TiO_2 thin film is then deposited on the glass through electrophoretic deposition (EPD). EPD is a simple method, it requires two electrodes FTO glass for the electrophoretic cell, and the thickness of the film can be controlled through varying the voltage from (20–80 V). The electrodes are connected to the voltage source and immersed in the solution, that contains the TiO_2 nanotubes, with 22 mm distant between them Fig. 9. [138] The thin film deposition rate is controlled by varying the concentration of the solution and the voltage. Jin Zhang and his colleagues have reported in 2015 a transparent DSSC with average transmittance of 55% and an efficiency of 7.1%. The thin film was fabricated using EPD and had 5 μm thickness [124,125,135,139,136,140,141]. However, more tests and studies are required to support this study for real applications in TDSSC.

3.6.1. Dip-coater

A research study on thin films in 2015 (Hamedan University of Technology, Iran) reported using coral-like TiO_2 nanostructure as a photoanode and transparent polyaniline (PANI) films as counter electrodes (CEs) to make a thin film. TiO_2 and PANI were chosen due to their matched energy band gap levels (TiO_2 (3.2 eV) and PANI (2.8 eV)). TiO_2 paste was chemically synthesised using a sol-gel method, and PANI-based CEs were prepared by a facile in situ polymerisation [30], but the deposition of the TiO_2 thin film was done using a dip-coater. The transmittance of the thin film obtained out of this report was ~70%, and the DSSC was bifacial with an efficiency of 8.22% [142].

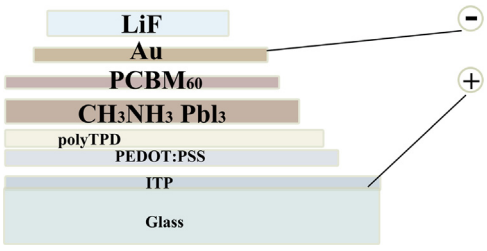

Fig. 7. Perovskite solar cell layers [112].

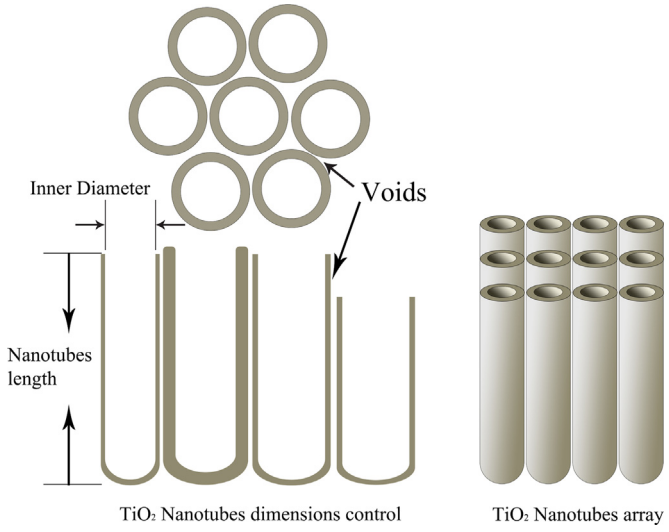

Fig. 8. Illustration of TiO_2 nanotubes [122].

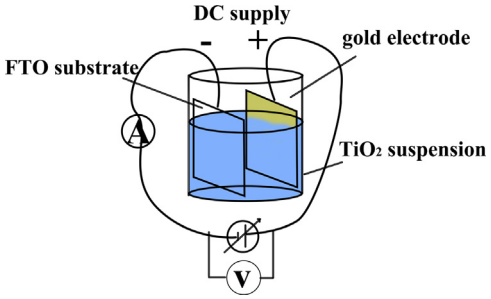

Fig. 9. Schematic of the electrophoretic deposition (EPD) setup [122].

3.6.2. Sputtering deposition

Sputtering deposition is another method to deposit nanotube thin films; a thin titanium nanotube layer is deposited on fluorine doped tin oxide FTO using sputtering. The process includes two main steps: fabrication of thin films of TiO_2 nanotubes by anodisation and sputtering and then an oxygen annealing process at 459 °C on the nanotube arrays. Finally, the remaining Ti islands are oxidized until they become transparent [143]. However, further experimentation must be done to validate the above approach towards TSC, as no specific conclusion was drawn from this particular source.

3.6.3. Quantum dot (QD) solar cell

QDs have recently garnered attention due to their outstanding optoelectronic properties. By carefully cutting QDs in different sizes, their absorption spectrum changes, which makes them suitable for solar cell applications. There are several fabrication techniques employed for QD-based solar cells [119,144–147]. Here, we focus on transparent or semi-transparent QD-sensitized solar cells. Xiaoliang Zhang (Uppsala University, Sweden) in 2016 reported 2 models of TSC using QD. The first model uses PbS QD, which has a tuneable band gap, e.g., in the infrared range. This makes PbS QD a perfect light absorber for solar cell applications. Some heterojunction PbS QD solar cells were reported to have a 9% power conversion efficiency [148]. Additionally, PbS QD has an interesting property of multi excitation generation, in which one photon excites more than one hole-electron pair, crossing the Shockley–Queisser restriction for a single-junction solar cell [148,149].

In addition, PbS QD has a transparent property that can be used in semi-transparent heterojunction solar cells. A semi-transparent solar cell (SCQDSCs) is fabricated on transparent FTO glass, combining TiO_2 film as an electron transporting layer (ETL) and an MoO_3 film as a hole transporting layer (HTL) [151]. First, TiO_2 film is deposited as an electrode; then, a PbS QD thin film is deposited on the TiO_2 film as a light absorber, which has a band gap energy of 1.3 eV, by the spin-cast method [152,153]. To increase the mobility of the charge carrier inside the QD, the bifunctional ligand 3-mercaptopropionic acid (MPA) is treated. Finally, a thin film of 10 nm Au is thermally evaporated on the QD layer; Fig. 10 shows the design of the cell. By changing the thickness of the QDs, the PCE varies from 2.04% to 3.88%, and AVT ranges from 32.1% to 22.7%. In summary, a semi-transparent solar cell is fabricated using PbS QDs, achieving 3.88% PCE and 22% AVT [150]. The second model reported a 5.4% efficiency and an average visible transmittance of 24.1% [151]. The architecture and the materials used to build this device help to decrease the optical loss, which eventually increases the efficiency. This device is suitable for applications with low transmittance requirements [151,153].

Fig. 10. Quantum dot (QD) solar cell [151].

4. Discussion

The transparent solar cell is a highly desirable invention, applicable to more than 5 applications used in our daily lives, such as buildings, car windows, trains, cell phones, laptops, etc. However, the process for realising this technology is faced with a group of four obstacles and challenges, starting from synthesising the transparent material to be used in building the TSC to the design of a new TSC structure, while at the same time maintaining high efficiency. The main obstacle is the selection of materials that allow for the transmission of the visible wavelength of the absorbed light, while at the same time allowing for the absorption of photons that lie in the invisible section of the wavelength. It is difficult to find such materials because the main characteristic of a solar cell is to absorb light and not let it through. The second obstacle is the fabrication process used to prepare the materials needed to build the TSC, which must have high transmission with good efficiency. The third obstacle is the architecture of the TSC and the substrate used to protect the cell. The final challenge is the cost of the fabrication and materials, which must result in building a cheaper solar cell.

To overcome the challenges highlighted above, there has been ongoing research studies in more than ten directions; some are focused on finding alternative materials that can obtain an acceptable transparency for specific applications, while others are focused on UV absorption and near infrared radiation NIR while transmitting visible light. Moreover, research was engaged in finding new structures that would be translucent yet supply a good amount of electricity. In general, 80% of the solutions are still under development or at the pre-commercializing stage.

Transparent solar cells are built using different ways deposition methods of the active material. Table 1 below summarises each transparent solar cell based on the method of fabrication. Screen-printing DSSC, electrophoretic deposition (EPD) and dip-coating are all methods of depositing a thin film of TiO_2 on FTO/ITO glass. With screen printing, the transparency is controlled by the screen mesh design. Table 1 shows a 60% transmission reported by [102] with 9.2% efficiency using TiO_2 as a photoanode. On the other hand, the electrophoretic method is a difficult process to control, as the structure of the TiO_2 nanotube requires a separate procedure for it to be synthesised, which adds more steps to the manufacturing process; additionally, the factors that control thickness are not precisely understood. However, one study reported a 55% transmission with 7.1% efficiency. Overall, there have not been many reports published using an electrophoretic technique for depositing thin films [124]. Using a dip-coater to deposit coral-like TiO_2 nanostructure as a photoanode and transparent polyaniline (PANI) film as a counter electrode (CE) [142] to fabricate TSC, an approximately 70% transmission was achieved, with 8.22% efficiency. Coral-like TiO_2 is prepared using sol-gel chemical methods, which increases the complexity and fabrication cost.

In contrast, near-infrared OPV [106] followed a different direction to fabricate a TSC through design, which focused on absorbing the UV and NIR light spectrum and transmitting visible light through the structure. This method achieved approximately 55% transparency and more than 1% efficiency; the low V_{oc} in Table 1 is due to the low absorption of light in the visible region. Transparent luminescent solar cells [111] use a different structure, in which the solar cells are placed on a frame, and NIR fluorescent transparent dyes are pasted on the active area. This meant that fluorescent paste would absorb NIR light and direct it to the edge of the glass, where it is converted to electricity. This method achieved high transparency, which exceeds 86%, but very low efficiency of less than 1%. The transparent luminescent solar cell procedure is still under experimentation and has a very high potential to achieve 10% efficiency. Polymer solar cells have the heterojunction structure of an NIR polymer material and PCBM. Some researchers have achieved 66% transmission with 4.2% efficiency from this design [108].

Quantum dot semi-transparent solar cells were fabricated using PbS QD [140] and MoO_3 in [151], achieving 3.88% PCE, 22% AVT and 5.4% PCE, 24.1% AVT, respectively. This type of solar cell is suitable for applications that require low transparency, such as tandem solar cells. The discovery of perovskite materials opens a big avenue of potential development for PV cells in general and especially for TPV. A new semi-transparent perovskite achieved 6.4% PCE and 29% AVT; the perovskite was applied using evaporation deposition [144]. Tandem semi-transparent perovskite [117] used a semi-transparent device in a tandem solar cell. The idea of the device is that the top solar cell is semi-transparent, and the bottom is an opaque solar cell. In this way, the top cell absorbs light in the UV and NIR regions, and the bottom absorbs whatever passes through the top cell from the light wave. The top cell achieved 77% transmission peak at 800 nm wavelength and 12.7% efficiency. In summary, TPV can be achieved in many ways; however, most of these methods are still under development at the laboratory bench scale. It is noticeable that most photoanode materials are made from TiO_2 due to its good photocatalytic properties and its suitable band gap [118].

The complexity of the manufacturing process is reduced by using screen printing as a deposition method for thin films because this method can be applied at room temperature and does not need a highly decontaminated environment for building a TSC, compared with silicon-based PVs, which need a special environment with a specific temperature. In addition, the manufacturing process is environmentally friendly. However, in regard to other thin film deposition methods such as EPD and dip-coating, the environment is contaminated, and chemical reactions increase the complexity of the manufacturing process; in addition, the EPD method needs more adjustment and standardisation to suit large-scale manufacturing. The DSSC design is very simple, whereby a lab-scale PV cell can be built within 24 h (Table 2). Transparent luminescent solar concentrators (TLSC) increased the design complexity, whereby the number of elements included in the device building is more than twice the elements used to build DSSCs. Similarly, transparent perovskite solar cells have a complicated production process, despite their high efficiency, as the process involves depositing many layers via complex techniques. Finally, the complexity of the manufacturing of polymer solar cells is decreased using a roll-to-roll technique, which makes it easy to mass-produce transparent polymer solar cells.

In general, when comparing all these technologies in terms of maturity and closeness to market, 80% of these technologies are still under development and need more improvements in order to be compatible with market PVs. In addition, these studies are limited to transparent solar cells, not transparent solar panels. The only available technology that provides solar panels is the semi-transparent solar cell, which can provide 20–40% AVT, with an efficiency that is not more than 8%. However, some of these technologies are closer than other technologies to the market, such as polymer [109], perovskite [112], and transparent luminescent solar [111] concentrator (TLSC). These technologies can be found in developed countries around the world, such as Heliatek in Germany, one of the leading companies in the world in the manufacture of organic solar films. Heliatek released in a press conference in 2014 that they have reached a new 7% efficiency of 40% transparent solar cells of perovskite solar panels [154]. Moreover, at Michigan State

Table 1
comparisons between different TPV based on process.

Name of Solar Cell	Year	T%[a] (%)	J_{sc}[b] (mA cm^{-2})	V_{oc}[c] (V)	FF[d]	Ƞ%[e] **(%)**
Screen printing DSSC [102]	2007	60%	16.25	0.779	0.73	9.2%
Near-Infrared OPV [106]	2011	55 ± 3%	4.7 ± 0.3	0.62 ± 0.02	0.55 ± 0.03	1.7 ± 0.1%.
Polymer Solar cell [108]	2012	66%	9.3	0.77	56.2	4.02%
Transparent luminescent solar **concentrator (TLSC)** [111]	2014	86 ± 1%	1.2 ± 0.1	0.5 ± 0.01	0.66 ± 0.02	0.4 ± 0.03%
Perovskite [112]	2014	30%	10.30	1.074	57.9	6.4%
Tandem Semi-transparent Perovskite [117]	2014	77% peak[f]	17.5	1.025	0.71	12.7%
Electrophoretic Technique [124]	2015	55%	14.83	0.68	0.71	7.1%
Dip-coater [142]	2015	~70%	16.17	0.738	0.688	8.22%
Quantum Dot Solar cell [150]	2016	22.74%	12.83	0.58	0.52	3.88%
Quantum Dot Solar cell [151]	2016	24%	0.56	18.2	0.53	5.4%

[a] Transmission rate percentage of the light through the solar cell.
[b] Current short circuit in one cm^2 active area of the solar cell.
[c] Voltage open circuit in one cm^2 active area of solar cell.
[d] Fill factor which equal to the maximum power divided by the theoretical power.
[e] The efficiency percentage of the solar cell.
[f] The peak of the transmission at 800 nm wave length.

Table 2
Advantages and disadvantages of TDC technologies.

Name of Solar Cell	Advantages	Drawbacks
Screen printing DSSC [102]	1. law complexity in terms of manufacturing process and final design. Can be produced at industrial scale. 2. Materials used to build the solar cell are organics like titanium and abundant. 3. Cost of manufacturing is almost half price of silicon based solar cell. 4. Efficient usage of architectural space. 5. Manufacturing process is environmentally friendly 6. Have a homogeneous appearance 7. Shading and high temperatures do not have any major effect on performance.	1. Low reliability, live time quality, and power output dropping rate need to be tested and improved. 2. Not practical for large-scale deployments where higher-cost and higher-efficiency cells are essential. 3. Liquid electrolyte is not stable at variable temperatures.
Near-Infrared OPV [106]	1. Organic semiconductor, environmentally friendly. 2. High transmission more than 55%.	1. The architecture of the device is more complex compared with DSSC. 2. Low efficiency not more than 1.7%. 3. Low supporting resources. 4. Not ready for Industrial manufacturing.
Polymer Solar cell [108]	1. Flexibility. 2. Low material cost compared with silicon. 3. Environmentally friendly. 4. Flexible and lightweight. 5. Low band gap. 6. Easy manufacturing for industrial request using Roll-To-Roll technique.	1. Low efficiency 2. Low stability 3. Short operational lifespan.
Transparent luminescent solar concentrator (TLSC) [111]	1. Improve energy harvesting efficiency. 2. Increase electronic device autonomy. 3. Reduce the traditional PV module cost.	1. In case in complexity and manufacturing stamps. 2. Low efficiency less than 1%.
Perovskite [112]	1. Close to the market. 2. Environmentally friendly. 3. Can be made flexible in shape. 4. Doesn't require high temperature processes. 5. Uniform perovskite layers 6. High efficiency	1. Low transmission 2. Most material used are scarce elements like tellurium (as rare as gold), indium, and gallium. 3. Liquid electrolyte has the temperature stability problems. 4. Expensive compounds 5. Highly volatile 6. Low stability. Rapid degradation
Electrophoretic Technique [124]	1. The transparency can be increased with the use of nanotubes without affecting the efficiency. 2. Manufacturing cost reduce with the reduction in the waste of active material used.	1. Complicated process that includes chemicals and need to be standardized for transparent solar cell. 2. The its difficult to control the homogeneity. 3. It can be used for laboratory scale however mass-production is complicated. 4. Reports supported this process are few compare to other process.
Quantum Dot Solar cell [150,151]	1. Capable of absorbing photovoltaic waves from infrared region of the spectrum. 2. Low complexity in manufacturing and installing. 3. Better stability than DSSC.	4. Low transmission 5. Quantum dots are inorganic

University, USA, the Lunt team is optimistic to reach a 10% efficiency from TLSC while maintaining an average transmission of more than 70% by enhancing and configurating materials to build a careful design of TPV. It is expected for this technology to be ready for small applications such as electronic devices in the coming 5 years [155]. These developed countries and others such as China, Japan, and Switzerland are leading the research on transparent solar cells, and great improvements are expected to happen in the coming 10 years that will help solve the problems facing the world with regards to transparent solar cells.

Efficiency and transparency are not the only parameters that decide which technology would be better to implement; cost is an important factor that markets care about. The cost of each technology is divided into 3 types. The first cost is that of the materials used to produce the solar cell. The second cost is that of the process of manufacturing the solar cell, and the third cost is that of system instalment. For the third cost, the cost of system instalment is difficult to estimate at this stage because this technology has not yet reached a level of maturity. However, this cost varies based on applications and the efficiency required for supplying these applications with energy; it can be expected that TSC would be economical in regard to instalment and installation spaces via architectural layout design optimisation. Some technologies such as TLSC reduce the installation cost by easily coating existing glass by depositing the active layer on one of the inner surfaces of double-paned windows, along with standard low-emittance or solar-control coatings. Moreover, the cost of the materials is economical compared with the cost of silicon. Most of the materials used to make the active layers in TDC are cheap and abundant, such as titanium and perovskite. Furthermore, the cost of TDC in general is considerably lowered by using thin photoactive TiO_2 layers and by decreasing the number of production steps. For example, producing TDC using screen printing does not need highly complex machines that are normally used in the fabrication of conventional systems. Moreover, using existing glass and window frames reduces the manufacturing cost by almost 50% compared with a conventional PV system. As seen in Table 2, the cost of TSC manufacturing can be more economical compared to traditional solar systems.

The idea of combining transparency and energy generation is unique, and this widens the market potential. The future for this technology is very wide, starting from electronics to skyscrapers. These applications that gather energy from a free source and renewable one will deliver important benefits, including accessibility and better use of space. Current work in this technology is concerned with the scale of the solar cell; however, it is projected that in the coming 10 years, this technology would scale up to the transparent solar panel size. The idea is challenging, but the benefits are significant. For example, if this technology reaches its potential application and replaces most of the windows in a skyscraper, it is possible to supply a quarter of the energy

demand of that building. Table 2 shows the advantages of these technologies.

Nevertheless, these technologies still have challenges and disadvantages that researchers are trying to overcome. One of these challenges is stability. Most organic solar cells degrade when exposed to oxygen or water vapour. This is one of the reasons that organic solar cells in the market do not have a lifetime warranty such as silicon PVs. In addition, electrolytes are affected by temperature changes, as they may freeze at low temperatures, and the sealing of the panels becomes a difficult task when the liquid expands at higher temperatures. Another major challenge that most of these technologies are facing is the low efficiency. The idea of TSC is very unique; however, it is very challenging to combine high transparency with high efficiency, and most of these technologies have low efficiency. To apply TSC and produce it for the market, its efficiency must be compatible with traditional solar cell efficiency. This implies that most of these technologies are not yet ready to be commercialized. Although most of the material used to build TSCs are abundant, this is not the case for perovskite solar cells, which use scarce elements such as tellurium (as rare as gold), indium, and gallium for the active layers in TSC. Lastly, despite the complexity of manufacturing, the TSC is reduced in some solar cells such as DSSC; however, it has been increased in others, such as TLSC, which added more steps to the manufacturing process. In summary, all the methods listed in Table 2 lack sufficient research, while supporting reports on each method and testing of the transparent solar cell have been done in few places only. Moreover, all these technologies must be tested under different conditions, such as snow, dirt on the window, and temperature changes. Further experimentation must be done in different weather conditions and environmental impacts to increase the possibility for TSC to be compatible with traditional PVs.

5. Conclusion

Transparent solar cells are very challenging devices to fabricate and have the potential to be used for a large number of applications. The challenge lies in the fact that transparency intrinsically conflicts with the concept of photonic absorption. The photovoltaic principle is to absorb photons and convert these to power, while transparency means to let through as many photons as possible. However, TPV is a very desirable technology, especially for architects, as well as equipment and automotive designers. Nevertheless, in regard to defining the required transparency, this varies by application. For example, a 50% optical transmission in some buildings could be desirable; on the other hand, mobile screen applications would require more than 80% transmission. This paper has reviewed nine technologies towards TSCs that have achieved transmissions of more than 20% through different attempts and methods that have been developed to achieve high transparency with the maximum possible efficiency, comparing their advantages and disadvantages. After analysing these methods, it can be concluded that the main directions were either to reduce the thickness of the component of the solar cell using thin film methods with different deposition techniques or to use transparent absorbing materials that absorb light in the infrared and UV regions, such as polymers, perovskites, QD, and TLSC. All the applications used transparent substrates, such as ITO, FTO glass or polymer. The highest transparency reported was 86% with a TLSC technology, but this was less than 1% efficient. On the other hand, the highest efficiency to transparency ratio was 8.2%:70% using a nanotube thin film of TiO_2 for transparent DSSC. TPV is not yet commercially available and is still under research. It is expected that this research will result in the integration of TPV in most electrical applications. Soon, mobile devices will self-charge, and skyscrapers will have zero net energy consumption without needing additional roof space for solar panels.

Acknowledgments

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