

# Transparent photovoltaic technologies: current trends towards upscaling

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**Abstract.** The world energy scenario is now living significant contributions coming from the photovoltaic field: new organic/inorganic hybrid materials have emerged in recent years, and in some cases these emerging strategies have exceeded the performance of traditional crystalline silicon. The next step concerns the integration of these technologies in smart buildings, in order to maximize the active surface capable of producing electricity and to contain the costs of air conditioning without affecting the amount of light needed. This review focuses on some of the most recent strategies developed to this purpose. Following an initial background on solar cells and figures of merit to characterize a transparent photovoltaic panel, the manuscript deals with a thorough analysis of wavelength-selective and non-wavelength selective devices, mentioning the main outcomes in the recent years. This distinction is proposed for both solar cells and solar concentrators, two areas in rapid evolution in academia and company worlds. A newly proposed case study and the example of a pre-industrial reality that has just started to scale-up this technology conclude this review, leaving to the reader a rich background on this highly-in-vogue field.

**Keywords:** Solar energy; Transparent photovoltaics; Energy consumption; Building-integrated photovoltaics; Financial analysis; Transparent solar cell.

## List of abbreviations:

AgNWs = silver nanowires

AVT = average visible light transmittance

BIPV = building-integrated photovoltaic

CIGS = copper indium gallium diselenide

COP = coefficient of performance

DSSC = dye-sensitized solar cell  
 EER = energy efficiency ratio  
 EPD = electrophoretic deposition  
 ETL = electrons transporting layer  
 FTO = fluorine-doped tin oxide  
 HTL = holes transporting layer  
 ITO = indium-doped tin oxide  
 LSC = luminescent solar concentrator  
 MPPT = maximum power point tracking system  
 NIR = near-infrared  
 NPV = net present value  
 OPV = organic photovoltaic  
 PBDTT-DPP = poly(2,6'-4,8-bis(5-ethylhexylthienyl)benzo[1,2-*b*;3,4-*b*]dithiophene-*alt*-5-dibutyloctyl-3,6-bis(5-bromothiophen-2-yl)pyrrolo[3,4-*c*]pyrrole-1,4-dione)  
 PBT = payback time  
 PCBM = [6,6]-phenyl-C<sub>61</sub>-butyric acid methyl ester  
 PCE = power conversion efficiency  
 PEDOT:PSS = poly(3,4-ethylenedioxythiophene):poly(styrenesulfonic acid)  
 PIPV = product-integrated photovoltaic  
 polyTPD = poly(N,N'-bis-4-butylphenyl-N,N'-bisphenyl)benzidine  
 PSC = polymer solar cell  
 PV = photovoltaic  
 PVGIS = Photovoltaic Geographical Information System  
 PVSC = perovskite solar cell  
 QD = quantum dot  
 SSC = scattering solar concentrator  
 TCO = transparent conducting oxide  
 TFPV = thin film photovoltaic  
 TLSC = transparent luminescent solar concentrator  
 TPV = transparent photovoltaic  
 TSC = transparent solar cell  
 UV = ultraviolet

## 1. Introduction

The demand for novel sustainable energy sources has become one of the most challenging topics addressed by worldwide researches in the last years [1,2], which stems from the increasing development of a consumerist world. Industrialization and rapid growth of global population have catalysed a search for practical renewable energy sources with the huge aim of fossil fuels replacement [3,4]. However, pushing global energy consumption far from fossil fuels demands for novel and not expensive technologies for the conversion of sustainable sources [5,6].

Due to its accessibility, cleanliness and abundance, solar energy has emerged as the most promising choice for the plan of a concretely sustainable world [7,8,9]; it is utilised in different ways, such as for heating water, producing electricity through photovoltaic (PV) technologies, etc. [10,11,12,13,14]. PVs can fulfil this demand many times over if adopted over a wide scale [15,16,17,18,19]. As an example, a PV installation covering around 20% of a region like Nevada can provide energy to the whole United States [20]. However, currently the installed PV plants only satisfy around 1% of the global energy demand [20]. Moreover, a really important barrier to the further growth of a solar energy scenario and the large-scale installation of PV technologies is given by the relatively weak energy density of sun irradiation in comparison to the energy demand [21,22]. Given that such a small portion of the global energy requirement can be satisfied by the nowadays installed PV plants, mainly in isolated and particularly sunny regions, it is required to boost the solar energy-related infrastructure if the real aim of the society is that of convert enough light to compensate for a relevant amount of non-renewable energy consumption.

This issue drove researchers to design new PV concepts, like transparent solar cells (TSCs), that can solve the problem by turning any sheet of glass (or, in general, a transparent substrate) into a PV device. The resulting solar cells are able to provide power by capturing and making use of light through windows in buildings and vehicles, leading to a truly efficient use of architectural spaces, also ensuring definitively better aesthetic features. Several transparent PV (TPV) technologies are investigated in this review as the most representative of the state of art; their main aim is that of achieving important transparency together with an electrical response compatible with that of PV modules currently sold in the global market. Furthermore, keeping in mind the extreme potential applications of TPV technologies in modern buildings, semi-TSCs are also mentioned as a relevant example, since they contribute to the often-mentioned building-integrated PVs (BIPVs) [23,24,25]. In this framework, with the aim of analyzing these promising technologies also from a financial point of view, a case study based on a generic building with offices in Europe is proposed as a precious and concrete example. The present findings show that

these integrated systems would be able to generate electricity and also lower lighting and cooling energy demand. As a further success story, the case of an Italian start-up which has invested 2.25 M€ in TPV technology for BIPV application is reported as a clear signal of the high potential of this market.

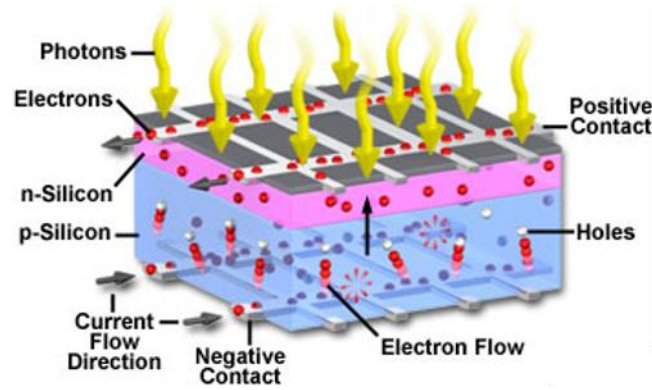
## **2. Background**

In the case the reader is not an expert in PV technologies, this section briefly summarizes the principle behind the PV effect. Furthermore, the main classes of PV cells are described, with particular attention to the emerging strategies based on hybrid, abundant and low-impact materials.

### **2.1. The structure and working principle of a photovoltaic cell**

TPV technologies have recently caught the attention of scientists given their unique feature of transforming common products, such as windows and electronic devices, into power generators without altering how they normally appear or work. However, in order to properly examine the TPV technology, the operational principle of the most used PV cells needs to be described [26,27,28,29,30], together with a short background on the evolution that this technology experienced over the years leading to different kinds of solar cells.

A PV cell is a device able to convert solar light into electricity by means of semiconductors, e.g. crystalline solids, the properties of which are achieved under normal conditions by the use of dopants and impurities [31,32,33,34,35]. The semiconductor present in a PV cell captures sunlight (photons), and this allows electrons to form electrons and holes couples, that are then guided in one direction, thus allowing current generation. The semiconductor is doped to behave as a p-n junction bearing a voltage difference, that will drive current flowing through the device in one direction, so that it can be harvested as electricity. This phenomenon of electrons flow as a consequence of photons absorption represents the PV effect and is clearly shown in **Figure 1**. The diffusion length is among the main factors affecting the power conversion efficiency (PCE) of the PV device [36,37,38,39,40].



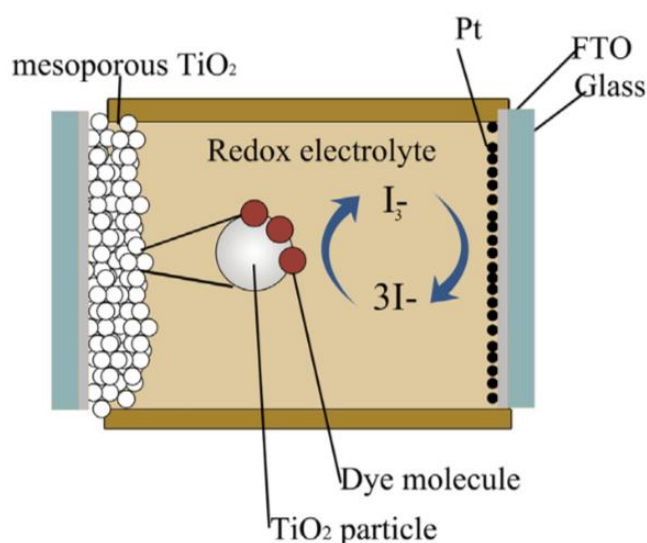
**Figure 1.** Schematic representation of a solar cell. Adapted and reprinted from [41].

## 2.2. The technological evolution of photovoltaic cells

The challenges that PV cells face concern cost, PCE and operating lifetime [42,43,44]. The scientific community is now focusing on developing suitable materials and fabrication processes that will improve the exploitation of the PV technology [45,46,47,48,49]. Silicon had been the first semiconductor that showed good PCE, obeying to the structure and operational principle described in Section 2.1 [31]. It is used for the fabrication of monocrystalline PV devices, that are at least 6% more performant, but also costlier than polycrystalline PV counterparts. Monocrystalline Si solar cells shows to be more electrically efficient, since they possess a defects-free crystal structure, while polycrystalline devices, based on multiple small silicon crystals, show lower performance, but are slightly cheaper to be produced [50,51]. Researchers have also proposed alternative materials and processing technologies that can lead to a similar PCE, and this led to the second generation of PVs, mainly populated by thin film PV (TFPV) cells [31]. Thin films possess the feature of reducing the quantity of semiconductor used for the preparation of PV cells, also reducing – in several cases – the cost by more than one half. Last, but not least, third generation solar cells emerged when hybrid and highly abundant materials were chosen as principal components of PV cells [52,53,54]; among the most known technologies, dye-sensitized solar cells (DSSCs) [55,56,57,58,59] and perovskite solar cells (PVSCs) [60,61,62,63,64] must be mentioned. A little background on DSSCs is given in the following section, since these cells, together with the standard silicon-based ones, are representing the main technology used to build PV modules/panels in both conventional and unconventional fields [65,66,67,68,69]. The current energy scenario is also pushing the PV community to try the integration of solar cells with batteries and supercapacitors, in order to concretely achieve smart cities and companies [70,71,72,73,74,75,76,77,78,79,80].

### 2.2.1. The structure and working principle of a dye-sensitized solar cell

Since the scientists O'Regan and Grätzel reported the fabrication of the first DSSC in 1991 [81], with PCE of 7-8%, this regenerative photoelectrochemical device became a promising solar energy converter [82,83,84,85]. DSSC is truly easy to being assembled, at low cost, and shows a high PCE [86,87,88,89,90], exceeding 14% at lab-scale level. These properties rapidly attracted scientists' and researcher's attention [91,92,93,94,95]. A well-designed DSSC possesses a combination of a dye-sensitized semiconductor anode (such as  $\text{TiO}_2$ ,  $\text{ZnO}$ ,  $\text{SnO}_2$ ,  $\text{Nb}_2\text{O}_5$ ), an electrolyte and a counter electrode [96,97,98,99,100]. The components of a DSSC are illustrated in **Figure 2**.



**Figure 2.** Schematic representation of a DSSC. Adapted and reprinted with permission from [31].

The core of a DSSC is the mesoporous semiconductor layer based on  $\text{TiO}_2$  nanoparticles as a path for the electrons to cross from the excited dye molecules to the current collector [101,102,103]; the diameter of the nanoparticles ranges between 10 and 30 nm, while the layer thickness is around 10  $\mu\text{m}$  [104,105,106,107,108]. The semiconductor layer is deposited on a substrate previously coated with a transparent conducting oxide (TCO) [109,110,111,112,113], such as the fluorine-doped tin oxide (FTO) [114,115,116,117,118]. After being excited by sunlight, the dye molecules inject electrons in the conduction band of the semiconductor and are then regenerated by electron donation from the redox shuttle present in the electrolyte [119,120,121,122,123]. The electrolyte in these solar cells contains the  $\text{I}^-/\text{I}_3^-$  species dissolved in an organic solvent, but quasi-solid and solid counterparts were also proposed [124,125,126,127,128]. The process of redox shuttle oxidation leads to the production of an excess of  $\text{I}_3^-$  ions, which are then regenerated by the electrons coming from the cathode, that is commonly

made of a thin layer of platinum [129,130,131,132,133]. Other compounds like carbon-based nanostructures and conducting polymers have been widely studied to replace Pt given its important cost, weak corrosion-resistance and scarce abundance [134,135,136,137,138].

Of note, integration of DSSCs into portable products is leading to a new field called product-integrated PV (PIPV) [139,140,141,142,143]. This further pushed the research community towards the development of suitable cell components [144,145,146,147,148].

### 3. Review of main transparent photovoltaics technologies

The core of this review is the analysis of the state of the art of TPVs and its use for many applications, particularly regarding windows in buildings. Transparency is the physical property of allowing the transmission of light through a material. What makes a material transparent is the intrinsic arrangement of its atoms and electrons. When the incident photons have a sufficient energy to make the electrons of the semiconducting material move to a higher energy state level, light passes through that material, making it opaque (**Figure 3A**). The principal feature of a solar cell is that of absorbing light, and now the scientific community is trying to boost the transparency of PV devices without reducing too much their efficiency.

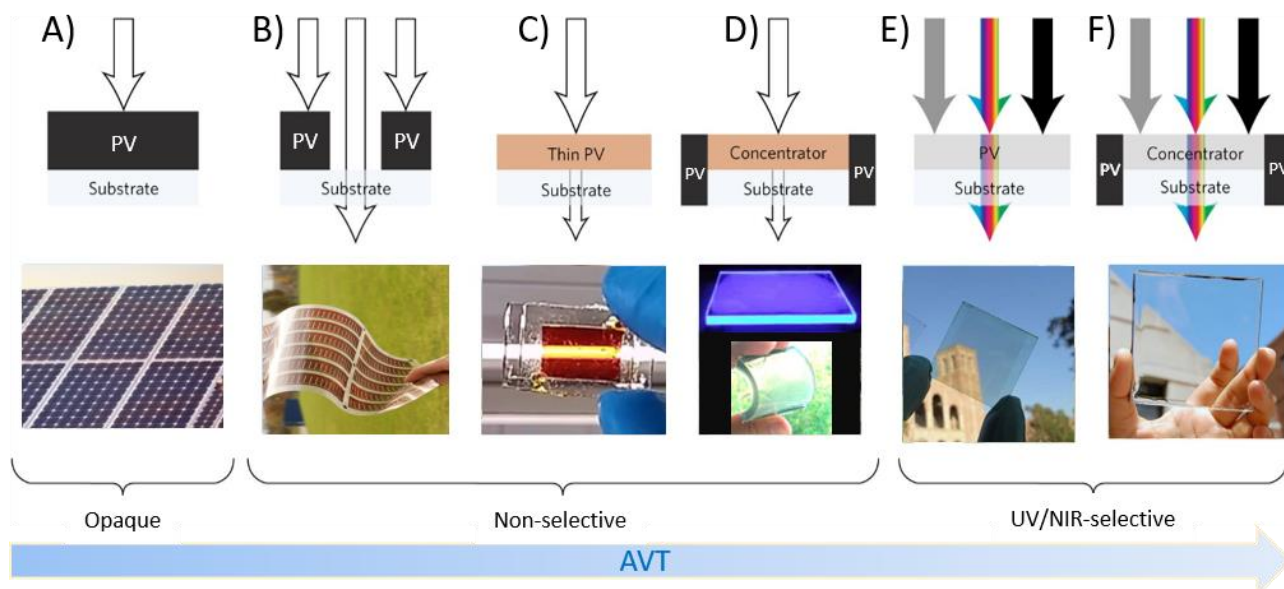
Considering this ambitious goal, the development of TPVs is carried out keeping in mind these two factors:

- *Average visible light transmittance (AVT)*, which is determined by selecting the average of device transparency in the visible portion of the spectrum (400-700 nm) based on the spectrally-dependent response of the human eye [149].
- *PCE*, which is intended as the ratio of energy output from the PV device with respect to the energy input from the sun. Besides reflecting the efficiency of the PV device itself, the PCE is function of the spectrum and intensity of the incident solar light and the temperature of the solar cell. As a consequence, the conditions under which PCE is determined have to be carefully checked with the aim of precisely comparing the efficiency of a cell to another [150].

The main aim of realizing a technology able to have a high AVT without affecting its PCE led to two main categories of TPVs [20]:

- *Wavelength-selective technologies*, which make use of photoactive compounds that preferentially harvest ultraviolet (UV) and near-infrared (NIR) radiation, while selectively transmitting the visible wavelengths (**Figure 3E-F**). These devices have already shown AVT values of 50-90%.

- *Non-wavelength-selective technologies*, which generate electricity from a wide absorption of sunlight (of course, visible portion included) and reach AVT through segmenting opaque devices (**Figure 3B**) or making use of a really thin or small amount of photoactive material (**Figure 3C-D**). They show AVT values included between 0 and 50% and are relevant for uses in colored windows and decorative outdoor architectures.



**Figure 3.** Trend of AVT property according to different classes of PV technologies, with a diagram and a digital picture of each example. **A)** A traditional opaque PV device where full spectrum sunlight (indicated by white arrows) is not transmitted. **B)** Spatially segmented PV device, where opaque modules on a transparent substrate are spaced to partially allow transmission of all wavelengths: increasing the distance among modules boosts transmission sacrificing performance, since this lowers the active area of the combined module. **C)** A non-wavelength-selective TFPV device, where the thickness of the absorbing film(s) is modulated to equilibrate AVT and PCE, since raising the thickness improves PCE at the cost of partial transmission (narrow white arrows) and color rendering. **D)** Diagram of a non-wavelength-selective solar concentrator, colored luminescent solar concentrator (LSC) and a scattering solar concentrator (SSC): light is collected by harvesting, re-emitting, and waveguiding photons from a sensitizer or by scattering impinging photons toward the edges of a substrate, to be then collected by edge-mounted PV cells. **E)** A wavelength-selective TPV device. **F)** A wavelength-selective LSC; wavelength-selective TPV technologies preferentially absorb UV (grey arrows) and NIR (black arrows) light, while allowing the transmission of visible light (colored arrows). Scheme inspired from [20], but containing digital pictures updated in 2020 from authors' archive.

There are a few technologies that can be exploited to develop TPV products, and they represent a milestone of present research efforts due to the market demand and their potential uses. The research centers that publish and patent some success stories with TPV are mainly located in Japan, USA, Germany and India. The forthcoming sections detail the development and performance issues of TPV technologies, including TSCs, LSCs and SSCs; a particular focus will be given to



those technologies that demonstrated the ability to target a transmittance higher than 20% and with a PCE higher than 1%, by highlighting their structures and fabrication processes.

### 3.1. Transparent solar cells technologies

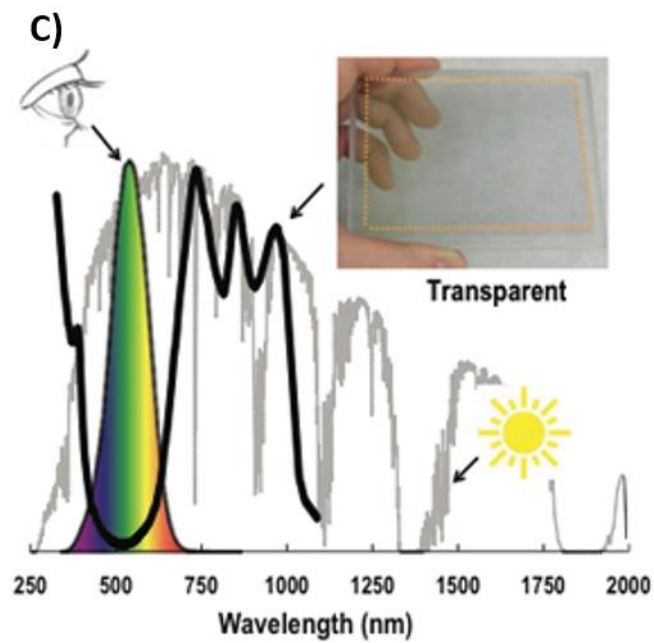
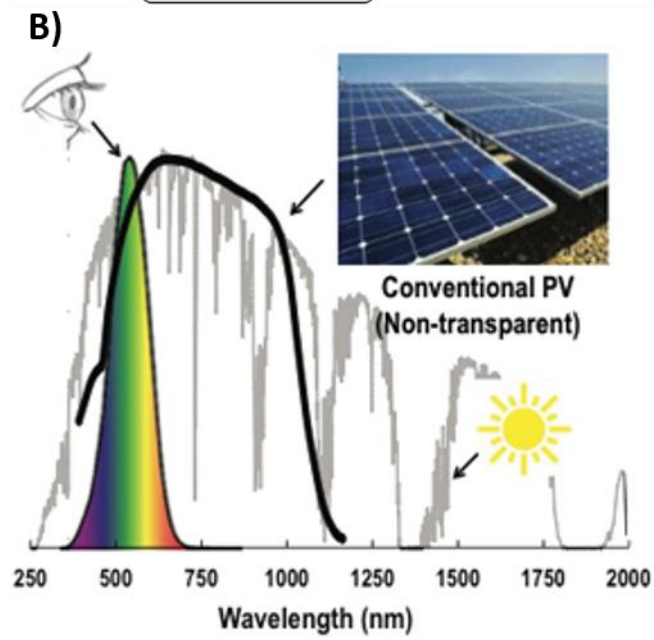
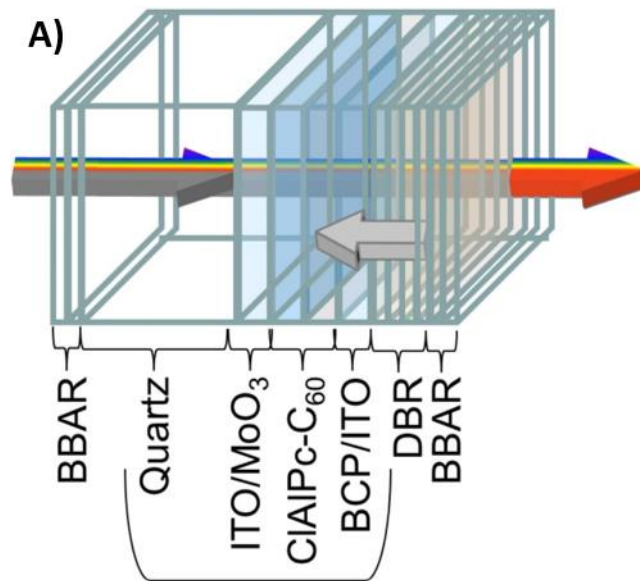
Research efforts on TSCs largely focused on strategies to segment opaque solar cells, lowering the thickness of otherwise opaque photoactive thin films, or on exploiting UV/NIR wavelength-selective photoactive compounds to reach visible light transmission. In these paragraphs, different approaches to TSC technologies are examined according to the two main categories of wavelength and non-wavelength selective technologies mentioned above. However, the materials that will be mentioned are not strictly related to a single type of TPV concept; conversely, a material used for a wavelength-selective solar cell can often be applied for a non-wavelength-selective device according to a different fabrication method. Consequently, the analysis of the technologies described below should be done by taking into account the whole fabrication process and cell geometry, without simply focusing on the single photoactive material.

It should also be emphasized that current research is very active with the challenging aim of using emerging concepts in the fields of nanomaterials [151,152,153,154,155,156,157], photocatalysis [158,159,160], design of sensitizers [161,162,163,164,165], electrochromics [166,167,168,169,170], semiconductors [171,172,173], polymers [174,175,176,177,178,179,180] and smart materials [181,182,183,184,185,186,187,188] for the preparation of new PV-compatible compounds [189,190,191,192,193,194,195,196].

#### 3.1.1. Wavelength-selective thin film solar cells

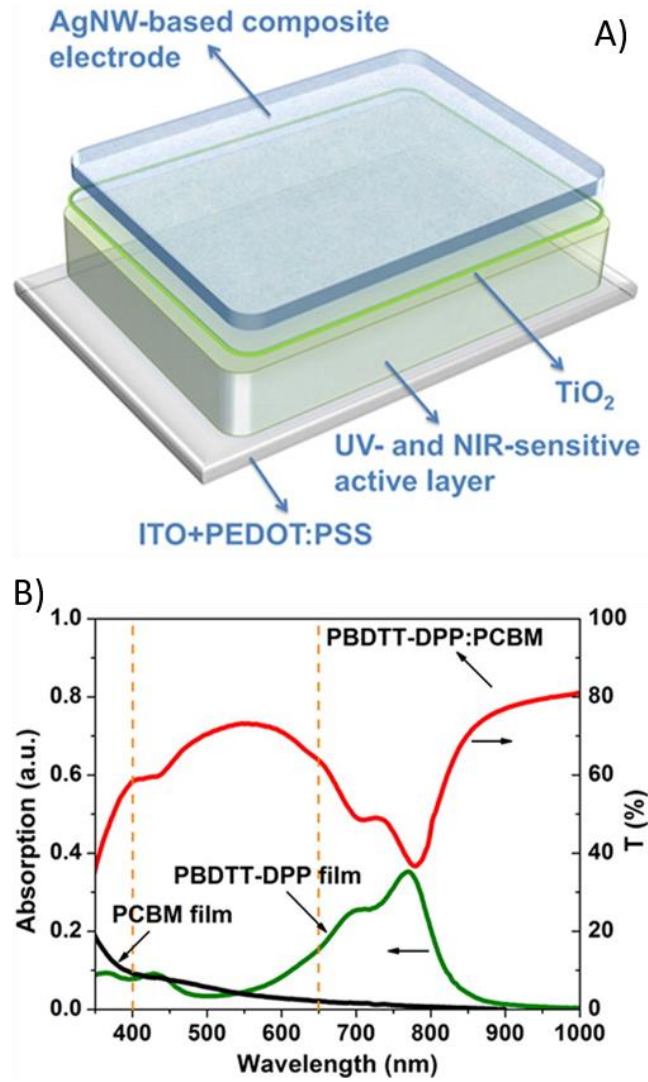
Technologies transparent to human eye recently came to the attention of the scientific community by exploiting compounds that selectively absorb UV and/or NIR light (**Figure 3E**) [197,198]. These active materials are typically small organic molecules, nanotubes, polymers and salts [199,200,201]. From a chemical point of view, these kinds of solar cells base their principles on the fact that optical absorption in semiconductors (both organic and molecular ones) takes place in different molecular orbitals ( $S_1$ ,  $S_2$ , ...,  $S_n$ ) from the ground state ( $S_0$ ). Consequently, the energy gap between  $S_1$  and  $S_2$  levels can be purposely used to permit the transmission of visible light and UV/NIR-selective absorption through a precise control of the molecular skeleton. By tailoring the band-gap and the discontinuity of states, research groups demonstrated the possibility to specifically tune the solar absorption outside the visible portion and into the NIR wavelengths.

In 2011, Lunt *et al.* followed the aforementioned criteria by designing dye molecules able to absorb UV and NIR (650-850 nm) wavelengths [202]. Their concept was based on a heterojunction organic PV (OPV) cell able to absorb sunlight in the NIR spectrum, showing an AVT of 65% and a PCE of  $1.3 \pm 0.1\%$ . The cell contained chloro-aluminium phthalocyanine as a molecular organic donor and  $C_{60}$  as an acceptor. The cell anode was coated with indium-doped tin oxide (ITO), ClAlPc,  $C_{60}$ , bathocuproine and  $MoO_3$ , while the cathodic side contained a Ag layer deposited by thermal evaporation. The growth of the transparent NIR mirror was carried out separately onto a quartz substrate and constituted a distributed Bragg reflector.  $TiO_2$  and  $SiO_2$  films were sputtered to obtain a precise thickness useful to generate a stop band of around 88 nm. At the opposite part of the quartz, a broadband antireflection film was deposited. The overall scheme of the cell is shown in **Figure 4A**; the principal aim of the presented TSC geometry was to permit visible wavelengths to pass through and harvest UV and NIR portions. To demonstrate the operation of the TSC, its absorptive response was measured and then compared with that of a conventional solar cell (**Figure 4BC**), and the absorptive response (black curve) was superimposed on the solar spectrum (grey curve). In a conventional cell, the wavelengths at which absorption was relatively high included the visible part of the spectrum; conversely, the transparent cell absorbed well in the NIR and the UV portion of sunlight, but in the visible region the absorption dropped off, approaching zero.



**Figure 4.** **A)** Scheme of a TSC. **B)** Spectral response of a conventional Si-based solar cell and of **C)** a TSC. Adapted and reprinted with permission from [202,203].

In 2012, Chen *et al.* checked the opportunity to produce TSCs by means of a solution processing technique [204]. With the goal of achieving an ideal TPV cell, the harvesting compound must absorb all the radiation in both UV and NIR portions and let visible light pass through the device (see **Figure 5A**). Some materials with these properties exist, like graphene and carbon nanotubes, that are both transparent and characterized by a proper conductivity; however, it is not efficient to simply adopt these compounds to fabricate a TPV device. Therefore, the suggestion coming from these authors was that of combining a transparent polymer solar cell (PSC) with a transparent conducting compound, like silver nanowires (AgNWs), thus creating a transparent PSC able to harvest both UV and NIR portions (sometimes these kinds of solar cells are referred as “semitransparent”). This photoactive layer consisted of a bulk heterojunction mixture based on the NIR wavelengths-sensitive polymer poly(2,6'-4,8-bis(5-ethylhexylthienyl)benzo[1,2-*b*;3,4-*b'*]dithiophene-*alt*-5-dibutyloctyl-3,6-bis(5-bromothiophen-2-yl)pyrrolo[3,4-*c*]pyrrole-1,4-dione) (PBDTT-DPP, bearing strong absorption between 650 and 850 nm) as the electron donor and [6,6]-phenyl-C<sub>61</sub>-butyric acid methyl ester (PCBM, working below 400 nm) as electron acceptor. The PBDTT-DPP:PCBM photosensitive substrate showed a maximum AVT of 73% at ≈550 nm, with a 68% values over the whole visible spectrum (400-650 nm), remaining successfully active also in the NIR portion (650-850 nm), as shown in **Figure 5B**. As regards the highly efficient transparent top cathode to be placed on the top of the photosensitive layer, a spray-coated AgNWs-laden composite was processed using alcoholic solvents compatible with standard PSC compounds.



**Figure 5.** A) Schematic representation of a transparent solution-processed PSC. B) Absorption spectra of PBDTT-DPP and PCBM and transmission spectrum of the PBDTT-DPP:PCBM bulk heterojunction photosensitive layer; the dashed lines highlight the visible portion of the spectrum. Adapted and reprinted with permission from [204].

Another TSC technology that has recently gathered attention due to the impressive optoelectronic properties is based on quantum dots (QDs) [205]. In this field, transparent and semi-transparent QDs-sensitized solar cells are emerging as leading technologies. Zhang *et al.* published two TSCs concepts based on QDs [206]. The first approach was based on PbS QDs with a tuneable band-gap, leading to an excellent light absorber for PV cell applications and achieving 9% PCE. Additionally, these QDs were transparent and showed an intriguing feature of multi-exciton generation, where a photon produced more than one electron-hole pair. The PbS QDs-based solar cell was fabricated onto a FTO glass, matching a TiO<sub>2</sub> film as an electrons transporting layer (ETL) and a MoO<sub>3</sub> film as holes transporting layer (HTL); moreover, the difunctional ligand 3-mercaptopropionic acid was added to boost the charge carriers mobility within the QDs film.

Through modifying the thickness of the QDs layer, the PCE varied passing from 2.04% to 3.88%, and the AVT ranged from 32.1% to 22.7%. The second device proposed by Zhang *et al.* achieved a 5.4% PCE and an AVT equal to 24.1%. The materials and the architecture chosen to fabricate this cell helped to lower optical losses, which eventually increased the PCE, making it adapt for uses characterized by low transmittance requirements.

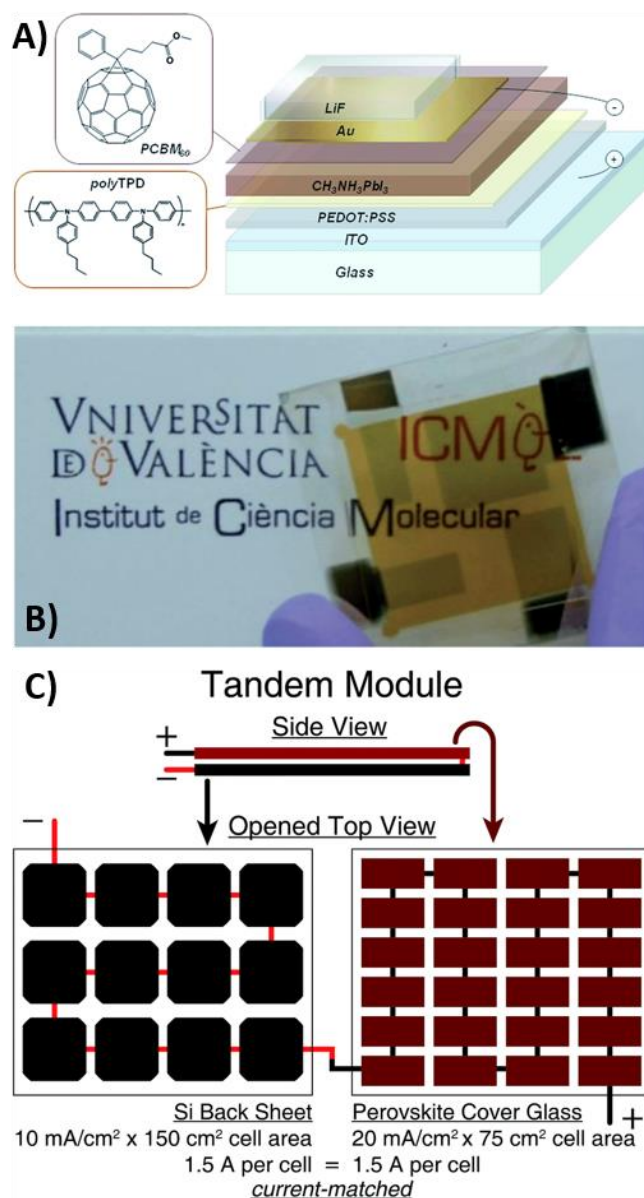
### 3.1.2. Non-wavelength-selective solar cells, spatially segmented photovoltaics

Spatial segmentation is the process based on the dispersion of opaque PV devices across transparent substrates. This strategy leads to various levels of neutral optical transmission through the space present between difference PV cells. Increasing these areas leads to the improvement of transmission and worsening of performance, since this approach lowers the photosensitive area [20].

Due to the fact that the scientific community focuses on the improvement of the semi-transparent nature of hybrid PV devices by utilizing a harvesting material bearing a band-gap lower than photons, the resulting strategy will permit visible radiation to pass through smart windows while absorbing NIR photons. However, the improvement of transparency makes PCE inevitably affected. As a consequence, big efforts towards the research of a potentially transparent material that improves cell PCE are spent, e.g. methyl ammonium lead halide in the form of perovskite [207,208,209,210,211]. Most of the highly efficient PVSCs are typically fabricated sandwiching a metal oxide material, the perovskite, and charge transporting materials [212,213,214,215,216]. Synthesized perovskites are hybrid materials that show good electric and optical properties [217,218,219,220,221,222], valid for PV devices application, like high carriers mobility and absorption coefficient, direct band-gap and suitable structural stability [223,224,225,226,227]. Most PV devices fabricated with perovskite crystals demonstrate the ability of targeting a PCE higher than 25% [228].

A semi-transparent perovskite was demonstrated by Roldán-Carmona *et al.*, with 6.4% PCE and 29% AVT, by choosing a perovskite evaporation deposition, that is a robust strategy enabling the progressive deposition of layers at low thickness (lower than 40 nm) [229]. This approach used an ultra-thin gold electrode (6 nm) capped with a LiF film with the aim of reducing energy losses. The thickness reduction caused a transmittance increase. Further, the LiF layer modified the circulation of the electric field within the device. The device was composed of several layers (see **Figure 6AB**), namely poly(3,4-ethylenedioxythiophene):poly(styrenesulfonic acid) (PEDOT:PSS), poly(N,N'-bis-4-butylphenyl-N,N'-bisphenyl)benzidine (polyTPD),  $\text{CH}_3\text{NH}_3\text{PbI}_3$ , PCBM<sub>60</sub>, Au and LiF. One year later, Bailie *et al.* published a tandem PV device where a

transparent AgNWs electrode was deposited on the top of PVSCs to achieve semi-transparent devices. These latter were placed into a mechanically-stacked tandem architecture onto copper indium gallium diselenide (CIGS) and low-quality multicrystalline silicon [230]. The 12.7% efficient semi-transparent PVSC combined with the 17.0% efficient CIGS cell led to a 18.6% PCE in the tandem device, the scheme of which is shown in **Figure 6C**.



**Figure 6.** **A)** Scheme of a semitransparent PVSC (also showing the chemical structures of the organic holes and electrons blocking materials) and **B)** digital picture of the device. **C)** A perovskite/silicon (or CIGS) module with a simplified geometry and current density to show how current-matching at the module level can occur with a mechanically-stacked tandem. Here the filtered silicon produces half of the photocurrent density of the perovskite, so the silicon devices are twice as large to target the current of the perovskite unit. Adapted and reprinted with permission from [229,230].

### 3.1.3. *Non-wavelength-selective solar cells, thin film photovoltaics*

TFPV is among the most successful technologies for TSCs and comprehends several fabrication strategies. Part of these processes are function of materials and pastes preparation to achieve transparency requirements, while others approaches are based on the deposition of active materials onto FTO glasses. In this part of the review, the deposition strategies are highlighted and – for each of them – the preparation of pastes and active materials will be detailed.

TFPV is based on thin-film materials bearing thicknesses from a few nanometres up to tens of micrometres of photoactive compound deposited on glass by several approaches [31]. Indeed, it is rather simple to deposit thin layers on several substrates, both flexible and rigid, as well as insulators or metals. Through lowering the film thickness, transparency lowers. TFPV devices can be prepared by these frequently-mentioned technologies: screen-printing, electrophoretic deposition (EPD), dip-coating and sputtering.

Screen-printing is among the best method for the deposition of thin films and is largely applied in the PV field [231,232]; indeed, it provides a simple way to tailor the geometry and the thickness of the final film. The success of a screen printing process depends on the quality of the initial paste. In the case of DSSCs [233,234,235,236,237],  $\text{TiO}_2$  nanoparticles are used for preparing the paste to fabricate photoanodes. The transparency is function of the screen printing technical features, e.g. made through a screen based on a mesh stretched over a frame; characteristics such as mesh opening and count, thread diameter, fabrication thickness and open surface are at the basis of the resulting film thickness and porosity. Moreover, the transparency can be controlled by the speed and pressure applied on the squeegee. **Figure 7A** highlights a typical screen printing process for  $\text{TiO}_2$  paste deposition onto a conductive substrate.

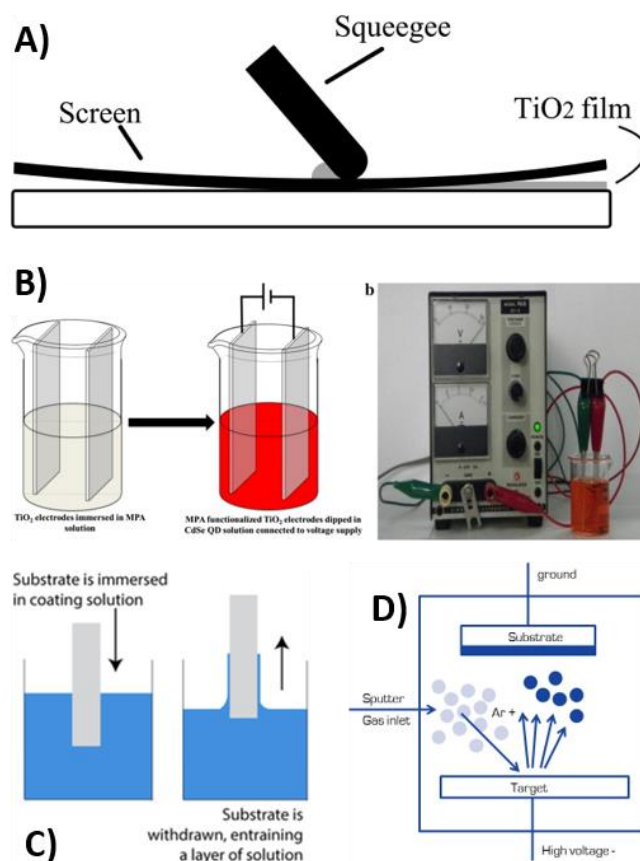
EPD is an alternative strategy to obtain thin films and it is possibly to carry out this process in two steps [238,239]. The deposition of a thin film onto a FTO glass starts with particles spreading onto the glass by applying a direct voltage between two electrodes, thus creating an electric field. In this setup, one electrode behaves as a cathode, the other as an anode, and both of them are immersed into a solvent containing the particles. The second processing step is based on the gathering and deposition of synthesised particles onto one of the electrodes, with the resulting formation of a thin layer. The process is shown in **Figure 7B**.

A dip-coater (**Figure 7C**) is an instrument used to ensure high precision in the deposition process, the latter including five steps: i) Immersion: the substrate is placed into the solution of the coating compound; ii) Start-up: the substrate starts to be pulled up; iii) Deposition: the deposition of the thin layer on the substrate takes place, while it is pulled up at a constant speed;



iv) Drainage: the excess of liquid will drain from the surface; v) Evaporation: the solvent evaporates leaving the liquid phase, thus allowing to the obtainment of a thin layer [240,241].

Sputtering is another strategy to deposit thin films for PVs, based on a process where microscopic particles of a solid material are ejected from a target material when it is bombarded by energetic particles of a plasma or gas (see **Figure 7D**) [242,243]. A thin titanium nanotubes layer or a Pt counter electrode can indeed be deposited on FTO by sputtering.



**Figure 7.** Schemes of processes for thin-film depositions: **A)** Screen-printing; **B)** EPD (with digital picture of the setup); **C)** Dip-coating; **D)** Sputtering. Adapted and reprinted with permission from [31,244,245,246].

### 3.2. Solar concentrator technologies

Solar concentrators are based on photoactive species or scattering effects to harvest the incident radiation normal to a substrate surface and redirect it at the edges, allowing it to be absorbed by a standard PV unit [247,248]. This paragraph describes the current work behind luminescent solar and scattering concentrators according to the same classification previously used for TSCs, based on wavelength and non-wavelength-selective technologies.

### 3.2.1. Non-wavelength-selective and colorful luminescent solar concentrators

A LSC is based on a substrate coated or embedded with an organic dye bearing the function of redirecting the incident radiation towards the edges by means of a photoluminescence phenomenon[249]. Its operating principle lies on the process here described: a part of sunlight is harvested by a luminescent species or luminophore incorporated into a transparent waveguide. The harvested sunlight is subsequently re-emitted at a different wavelength in an isotropical way, i.e. in all directions within the waveguide. Given the presence of a refraction index difference among the ambient environment and the waveguide, the re-emitted photons are quite all blocked by total internal reflection, leading to their redirection towards the waveguide edges. Here, they are converted to electrical power in a PV unit mounted at the edge. Overall, the system power efficiency,  $\eta_{LSC}$ , can be calculated by this equation:

$$\eta_{LSC} = \eta_{opt} \cdot \eta^*$$

where  $\eta_{opt}$  is the optical efficiency and represents the ratio between the number of photons transported out of the LSC edge and the impinging photons on the active area in spite of  $\eta^*$ , which represents the PCE of the edge-mounted PV unit under a monochromatic irradiation coming from the luminescent emitter [17]. Moreover, the optical efficiency is defined according to:

$$\eta_{opt} = (1 - R_f) \cdot \eta_{abs} \cdot \eta_{pl} \cdot \eta_{trap} \cdot \eta_{ra}$$

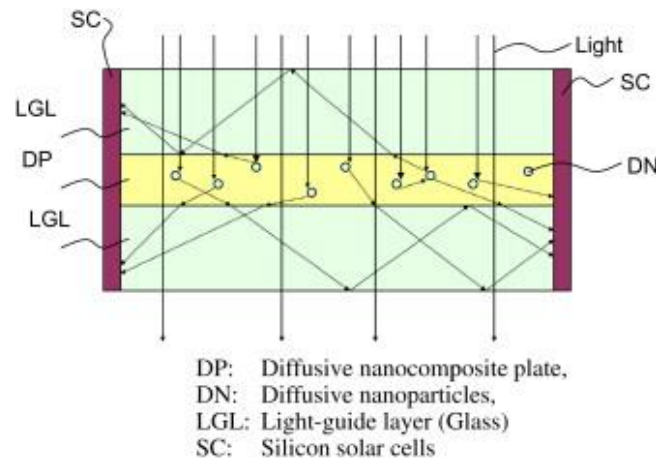
where  $R_f$  is the front-face reflection,  $\eta_{abs}$  is the absorption efficiency,  $\eta_{pl}$  is the luminescent efficiency,  $\eta_{trap}$  is the waveguiding efficiency, and  $\eta_{ra}$  is the efficiency of suppressing reabsorption.

The operating mechanism previously described is the same for non-wavelength and wavelength selective LSCs. The main difference between the two technologies is the different transmission of the visible region of the solar spectrum linked to the wavelength selective properties of the device. In fact, the non-wavelength-selective LSCs show colorful optical transmission because of the discrete visible harvesting.

### 3.2.2. Non-wavelength-selective scattering solar concentrators

SSCs are based on a uniform distribution of diffusive nanoparticles into a nanocomposite plate, the latter being sandwiched among two glass plates (**Figure 8**). When the impinging radiation from the sun passes through the first glass plate, the portion directed onto the nanocomposite is scattered in an irregular way by the embedded nanoparticles, being later transmitted in all the directions within the plate. Part of the radiation goes through the diffusive nanocomposite plate and penetrates the glass plate. The latter behaves as a second light-guiding substrate, due to its

refraction index differs from that of the diffusive nanocomposite plate. Part of the radiation is refracted at the moment it penetrates the diffusive nanocomposite plate, and the refracted photons later undergo a total internal reflection phenomenon occurring at the boundary of the glass plate. Some radiation at the end arrives at the silicon PV unit mounted at the device edges, where the sunlight is converted to electricity [250]. The intensity of the scattering and efficiency of the transmission strongly depend on the wavelength of the impinging radiation.



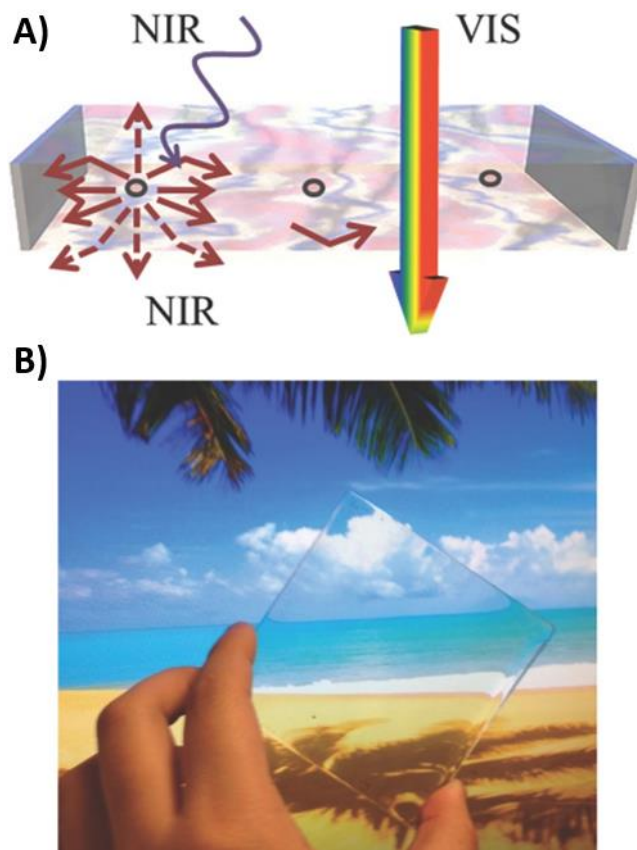
**Figure 8.** Scheme of light guided to PV devices through a radiation diffusive layer and light-guide layer. Adapted and reprinted with permission from [250].

Unfortunately, the principal challenge for a scattering concentrator is given by the significant optical losses, especially at area scales above a few inches. This is caused by the multiple scattering events of the waveguided photons, that can lead to important losses via outcoupling from the cell. As a consequence, this type of technology has registered PCE values of approximately 5% with AVT of 50-60%.

### 3.2.3. Wavelength-selective and transparent solar concentrators

The use of non-wavelength-selective LSCs is usually constrained by the absorption of the chromophore and relative emission in the visible wavelengths, that causes a wide degree of colored tinting. To overcome these hurdles, Zhao *et al.* reported another approach in 2014, called transparent LSC (TLSC) [251]. This technology harnesses the structured harvesting of sensitizing chromophores to fabricate LSC architectures able to selectively absorb NIR light by waveguiding deeper-NIR luminophore emission to highly performance segmented PV devices. TLSC can avoid the visual impact and lower the quantity of costly photovoltaic materials necessary when widening the light absorption within the NIR range. The device was realized using NIR fluorescent transparent molecules, in particular cyanines, phthalocyanines and squaraine sensitizers, with the

aim of capturing NIR wavelengths, convert them into visible photons, and subsequently guide them towards the glass edge (where the PV unit was placed) (**Figure 9**). The transparency exhibited by this TLSC was 86%, with a PCE of 0.4%.



**Figure 9.** A) Schematic of a TLSC; B) Digital picture of a transparent LSC architecture incorporating the cyanine derivative 1-(6-(2,5-dioxopyrrolidin-1-yloxy)-6-oxohexyl)-3,3-dimethyl-2-((E)-2-((E)-3-((E)-2-(1,3,3-trimethylindolin-2-ylidene)ethylidene)cyclohex-1-enyl)vinyl)-3H-indolium chloride as luminophore. Adapted and reprinted with permission from [251].

TLSC can be fabricated also in order to harvest the UV radiation using hexanuclear metal halide in spite of the NIR fluorescent dyes. Also, advanced materials coming from raw sources or design of composites represent a concrete possibility for the next generation of TLSC [252,253,254,255,256,257].

### 3.3. Overview of the transparent photovoltaic technologies analysed

In order to provide a summarized view of all the examined TPV technologies, **Table 1** displays the comparison between them underling the main electrical and optical aspects according to which they can be classified.

According to what reported above, transparent solar technologies are highly desirable inventions, and can find applications in several environments and daily circumstances, such as in buildings, trains, autovehicles windows, smartphones, laptops, etc. Unfortunately, the processes behind the fabrication of these technologies still face a few obstacles and challenges that the research community is called to overcome:

- The complex choice of compounds that permit the visible wavelengths transmission, and simultaneously allow the harvesting of photons lying in the “invisible” portion of sunlight.
- The scalability of the manufacturing approach adopted for materials preparation behind TPV technologies.
- The most suitable TPV units architecture and the choice of the substrate to be used for device protection.
- The fabrication cost, which must lead to rather cheap products.

To overwhelm the challenges listed in this paragraph, currently active investigations are covering several directions, as listed in **Table 1**. Many among these strategies focus on the search for alternative/unconventional materials able to lead to acceptable transparency levels for particular uses, while different research groups are working on UV or NIR radiation harvesting while transmitting the visible portion of sunlight. However, generally, when the technologies presented above are compared watching at maturity and market closeness, around 80% of them show to be still in the academic investigation phase, needing major improvements so as to become suitable for the PV global market. In such a scenario, investments by multinational companies are urgently required.

**Table 1.** Comparison among several TPV technologies based on different fabrication processes. *T* denotes the transmission rate percentage of the radiation through the PV unit. Adapted and reprinted with permission from [31].

<b>TPV</b>	<b>T (%)</b>	<b><math>J_{sc}</math> (mA cm<sup>-2</sup>)</b>	<b><math>V_{oc}</math> (V)</b>	<b>FF</b>	<b>PCE (%)</b>	<b>Ref.</b>
Screen-printed DSSC	60	16.25	0.779	0.73	9.2	[258]
NIR OPV	55±3	4.7±0.3	0.62±0.02	0.55±0.03	1.7±0.1	[202]
PSC	66	9.3	0.77	56.2	4.02	[259]
TLSC	86±1	1.2±0.1	0.5±0.01	0.66±0.02	0.4±0.03	[251]
PVSC	30	10.30	1.074	57.9	6.4	[229]
Tandem PVSC	77 peak	17.5	1.025	0.71	12.7	[230]

EPD-produced DSSC	55	14.83	0.68	0.71	7.1	[260]
Dip-coated DSSC	$\approx 70$	16.17	0.738	0.688	8.22	[261]
QDs solar cell	22.74	12.83	0.58	0.52	3.88	[262]
QDs solar cell	24	0.56	18.2	0.53	5.4	[206]

#### 4. Case study: feasibility analysis of transparent solar cell building integration

Although the vast majority of literature and patent studies are based on experimental or optical approaches, it is important to construct scenarios where transparent technologies are placed in particular environments, in order to study their impact on the overall costs of the building, on the quality of the illuminance and on the payback time (PBT).

The aim of this newly proposed case study is to quantify the capability of semi-TSCs applied to facade and to assess financial effects of the investment. Solar cells are applied as movable blinds to improve building energy performance. The analysis is conducted for each orientation of the building and for three window sizes. The prototype office developed has a square plan of 36 m<sup>2</sup> and is 3.1 m-high. Three window sizes were set during the analysis: 6 m<sup>2</sup>, 12 m<sup>2</sup> and 18 m<sup>2</sup>. The window is located on the wall adjacent to the external environment, while the other surfaces of the office are considered to be adjoining to conditioned rooms and are, therefore, not subjected to the inter-zonal heat flow. **Figure 10** shows the prototype office room examined. Influences from surrounding buildings, vegetation or other obstructions are disregarded in the simulation.



**Figure 10.** Digital scheme of the office room designed for the proposed case study.

#### 4.1 Optical and thermal characteristics of the building

The thermal transmittance of opaque surfaces meets the minimum requirement set in the national standards [263] and the visible reflection factors are assumed equal to 50%, 20% and 70% for walls, floor and ceiling, respectively. In order to evaluate thermal and optical properties of the window with and without transparent PV shutters, the software WINDOW 7.7 was used. The reference window was designed with double glass and an air gap in the middle. Optical and thermal characteristics for the glazed surface are summarized in **Table 2**.

**Table 2.** Optical and thermal characteristics of transparent elements.

	Transparent glass	PV blinds	TG + PV blinds
Thermal transmittance ( $\text{W m}^{-2} \text{K}^{-1}$ )	2.67	1.0	1.93
Visible transmittance	0.8	0.6	0.5
SHGC	0.62	0.42	0.51

Blinds are realized with two semi-transparent PV panels, with each area equal to 0.5 transparent glass area. Movable blinds are used as nocturnal insulation shutter during heating period, their effect is considered by applying a reduced thermal transmittance of window and shutter. Moreover, they are used as solar shading when the incident sunlight on the surface at the given hour is higher than  $300 \text{ W m}^{-2}$  [264]. When shutters are open, they are supposed to be normal to the facade surface.

#### 4.2 Semi-transparent solar cells and panels configuration

For this analysis it is assumed to install screen-printed DSSCs with an AVT factor of 60% and a PCE equal to 8.7%. The PCE is referred to a single prototype cell, but larger DSSCs are required for large-scale marketing. PV parameters were recalculated according to the relative percentage changes reported by Sygkridoua *et al.* [265].

Each module ( $10 \text{ cm} \times 30 \text{ cm}$ ) is realized by connecting 10 cells in series ( $1 \text{ cm} \times 28 \text{ cm}$ ). The active area of a module is supposed to be 60% of the total area. Taking into account the cell up-scaling and the lower active area of each module, the total PCE is 7.5%. Panels are connected to an inverter provided with maximum power point tracking system (MPPT).

### 4.3 Simulation method and conditions

The prototype office is located in Turin (45.070 N, 7.687 E). Weather data, hourly and average monthly solar irradiance are evaluated on a vertical surface for different orientations employing the Photovoltaic Geographical Information System (PVGIS) [266].

The building is occupied every weekday for 10 h, from 8:00 AM to 6:00 PM. The lighting characteristics of the room comply with the requirements imposed by national standards [267]: the maintained illuminance required is 500 lux on the visual task plans and 200 lux in the surrounding areas, respectively. The lighting system chosen for the simulation consists of flat LED panels (electric power of 70 W and luminous efficiency of 113 lm W<sup>-1</sup>). The Relux simulation software was used to establish the natural and artificial lighting characteristics inside the building and the electricity load required.

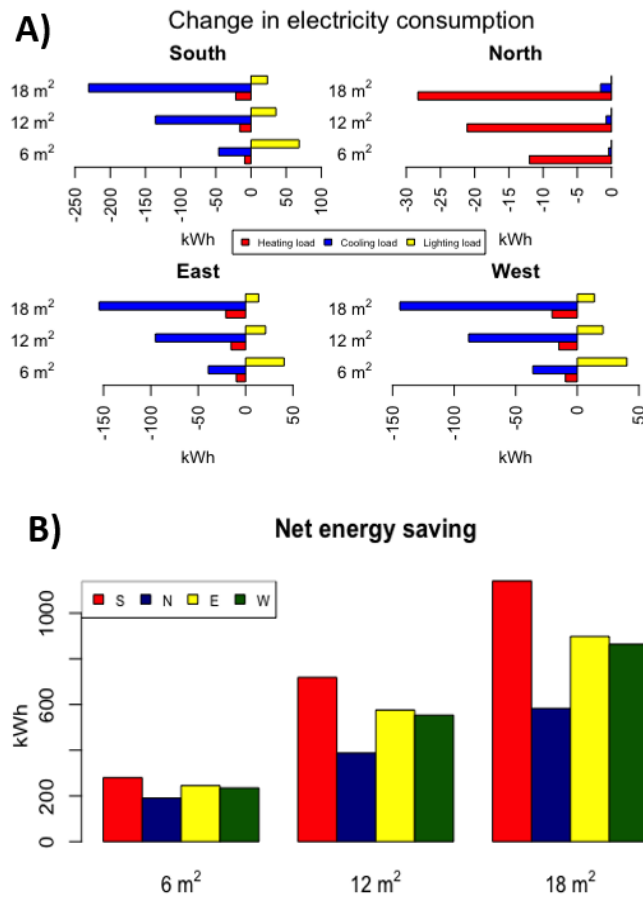
Criteria for assessing the building thermal performance are provided by national standards [268]. Heating, cooling and ventilation are activated intermittently, only during office occupation. The set point temperatures are 20 °C for heating and 26 °C for cooling. The air-conditioning unit is powered by a heat pump with an average coefficient of performance (COP) for heating equal to 3.6 and an average energy efficiency ratio (EER) for cooling of 3.2.

The amount of energy generated by solar cells contributes to the reduction of purchased electricity. The energy is produced by the irradiance incident on the photoelectrode. The amount of power produced by the counter electrode is not accounted, underestimating the energy produced. Losses downstream of the PV system such as the inverter, the MPPT and other components are not accounted.

### 4.4 Outcome of the simulation study

In the economic feasibility analysis of the system it is necessary to evaluate the change of electricity consumption for lighting, heating and cooling, the electricity generation and the investment cost. Results are presented in form of tables and figures: **Figure 11A** shows the change in the energy requirement for heating, cooling and lighting when the PV system is installed, while **Table 3** lists the amount of electricity produced by the PV system. **Figure 11B** presents the net energy saving.





**Figure 11. A)** Change in electricity consumption when movable blinds are installed; **B)** Net energy saving: sum of the PV energy generation and difference in total energy consumption.

**Table 3.** Total amount of energy produced per year by PV panels (values expressed in kWh year<sup>-1</sup>).

	6 m <sup>2</sup>	12 m <sup>2</sup>	18 m <sup>2</sup>
South	293.4	602.3	911.1
North	178.1	365.6	553.2
East	237.1	486.6	736.2
West	229.6	471.2	712.9

The thermal energy requirements for heating is lower when blinds are installed (from 2% for the smallest window to 9% for the biggest one) since the overall heat transmission coefficient is lower when shutters are closed during the heating season for nocturnal insulation. When the office window is placed towards south, east and west, the cooling load is also reduced (12÷16%) as a result of lower solar heat gain during cooling season when solar shading is in use. Contrariwise, the lighting energy consumption is higher due to lower light transmission coefficient of semi-

transparent solar panels. The rise is more appreciable when the transparent element is facing south (21÷23%) compared to the increment of load at east and west orientation (12÷14%). Instead, when the window is facing north, the effect on cooling and lighting loads is negligible. In fact, blinds are never used as solar shading due to the low incident irradiance on this wall.

The electric power generation is not sufficient to satisfy all the energy needs of the building, but it can still guarantee an energy saving. With a larger window, not only the effect of the screen is enhanced, but also the electricity production of PV panels, clearly, increases. It can provide about 25% of the total load with 6 m<sup>2</sup> PV area. If the transparent surface is higher, the percentage contribution rises remarkably (50% when the area of the window is 12 m<sup>2</sup> and 65% if the size is 18 m<sup>2</sup>).

The net energy saving is the balance between the generated electric power and the variation of heating, cooling and lighting energy consumption and it depends on the orientation of the building and on window size. For each area, the highest energy saving occurs with the transparent element south-oriented, while the worst direction is toward north.

The investment cost for the installation of semi-transparent PV panels is 130 € m<sup>-2</sup> [269]. To assess the economic effect throughout the life of the plant, the net present value (NPV) and the discounted PBT are calculated. **Table 4** and **Table 5** show these results. Both PBT and NPV are more desirable when the window is placed toward south and with the largest size. The higher investment cost is balanced by higher energy saving and higher power generation.

The worst scenario occurs with the glazed surface north-oriented. In this case, both net energy saving and energy generation are low and the initial investment cost is balanced by energy saving after more than 7 years.

**Table 4.** Net present value after 20 years (values expressed in €).

	South	North	East	West
<b>6 m<sup>2</sup></b>	1037	570	868	813
<b>12 m<sup>2</sup></b>	2891	1157	2145	2027
<b>18 m<sup>2</sup></b>	4654	1733	3383	3204

**Table 5.** PBT (values expressed in years).

	South	North	East	West
<b>6 m<sup>2</sup></b>	4.75	7.1	5.4	5.7
<b>12 m<sup>2</sup></b>	3.75	7.25	4.75	4.9
<b>18 m<sup>2</sup></b>	3.6	7.25	4.6	4.75

## 5. A success story of building-integrated photovoltaics: Glass-to-Power

BIPV represents the most concrete final destination for the commercial use of TPVs. **Table 6** shows the electrical and optical features of the four principal PV technologies used in the BIPV scenario. Crystalline silicon modules, bearing the highest PCE, have been found not to be aesthetically appealing. They do not offer any chance of color selection given their intrinsically band-like absorption spectrum. As an alternative, amorphous silicon is optically more homogeneous and visually more comfortable. These aspects make it more suitable for integration as solar windows in new-generation buildings, but it has a really low PCE with respect to its crystalline counterpart. As a possible solution to these issues, PSCs and PVSCs are really emerging as cost-effective choices. They can be printed at high-speed by adopting high-throughput fabrication processes and show relatively high PCE. Moreover, the predicted energy PBT for both organic and perovskite-based PV devices are rapidly decreasing thanks to novel findings in modules fabrication and choice of charge carriers transporting materials, rendering them excellent candidates for power-generating windows.

**Table 6.** The comparison of electrical and optical features of various kinds of PV cells. Adapted and reprinted with permission from [149].

PV material	Thickness (μm)	Harvesting properties	Charge mobility (cm <sup>2</sup> V <sup>-2</sup> s <sup>-1</sup> )	Certified PCE (%)
Crystalline Si	300	Broad band Abs. coeff = 10 <sup>3</sup>	10 <sup>3</sup>	26.1
Amorphous Si	1	Broad band Abs. coeff = 10 <sup>4</sup>	10 <sup>-1</sup>	14.0
Perovskite	0.3	Broad band Abs. coeff = 10 <sup>5</sup>	10 <sup>1</sup>	25.2
Polymer	0.1	Confined band absorption Abs. coeff = 10 <sup>5-6</sup>	10 <sup>-3</sup>	12.3

In this respect, the Italian company Glass-to-Power has raised 2.25 M€ via crowdfunding to advance its R&D aimed at setup an industrial production line for TSCs [270]. Glass to Power utilizes the LSC technology and aims to reach a PCE of 5%. Photons are guided by total internal reflection to the window edges, and are then transformed into electricity by traditional solar units

mounted along the slab perimeter. The technology behind their LSC panels uses nanoparticles as chromophores, thus decoupling the absorption processes and the emission of light, even in areas of hundreds of square centimeters.

The quality of light transmitted by Glass to Power panels is located in group 1A (UNI 10380 certification), i.e. the group with the highest quality, therefore suitable for lighting houses and offices (**Figure 11A**). Right now, the company declares that it managed to reach PCE values up to 3.2% with a degree of transparency in the visible spectrum of around 80%. Noteworthy, the optical conversion efficiency of the blue/UV fraction of the solar spectrum reaches values exceeding 10% and “ray-tracing” simulations have shown that these performances are also conserved for large-scale units.

Plastic panels behind Glass to Power products are made of high quality Plexiglass (**Figure 11B**), and the nanoparticles used for light-management are made of inorganic materials such as silicon, thus guaranteeing stability under sunlight without any risk of photodegradation of organic components.

The reference market for Glass to Power is that of BIPV for large commercial and residential glass buildings, and its technology also suits in the case of architectural, historical or landscape constraints, contributing to the energy sustainability of existing buildings also where traditional PV cannot be installed. The product is expected to be marketed in 2019 [271].



**Figure 11.** **A)** The Glass to Power strategy for LSCs to be integrated in smart building; **B)** Photograph of a Glass to Power panel made of Plexiglass. Adapted and reprinted with permission from [270].

It is conceivable that many other spin-off/company realities like this one will be born in the near future, building themselves on the innovation promoted by chemistry and materials science, and with particular inspiration to what the scientific community is studying in the fields of unconventional PV [272,273,274,275,276,277,278]. Besides this, polymer science and technology is making great steps ahead targeting the replacement of oil-derived compounds [279,280,281,282,283], designing new objects by 3D printing [284,285,286,287,288], entering in the Li-ion battery market to achieve lightweight storage pack units [289,290,291,292] and, last but not least, offering novel biomedical devices bearing high compatibility with human organisms and long-term stability [293,294,295,296]. On the other hand, chemical sciences are re-starting to explore inorganic materials, especially for those applications where stability under radiation and thermal aging are concrete problems for organic matrix systems [297,298,299,300,301]. In this scenario, new semiconductor nanostructures and composite materials containing different inorganic compounds are emerging and providing important responses in the fields of energy and environment [302,303,304,305,306,307].

The transition from micro to nano has pervaded the sciences in the past twenty years, but only today are we started enjoying nanotechnologies [308,309,310,311,312]. Among these, the PV field counts several applications and the scientific community is working towards new integrations with systems for CO<sub>2</sub> reduction and decontamination of waste water [313,314,315,316,317]. Furthermore, nanoscience field includes a new generation of sensors, where highly responsive nanostructures are able to monitor traces of chemical species at a very low concentration [318,319,320,321,322]. In any case, the field of nanoscience will remain closely linked to that of the sustainability of materials and processes. The novel PV technologies (and the energy field in general) must be based on abundant materials [323,324,325,326,327], not impacting on the ecosystem and, possibly, reusable at the end of their life [328,329,330,331]. To this end, the training of new generations of scientists is important and some recent publications are showing interesting advanced to this purpose [332,333,334,335,336].

In summary, scientists today can make use of cutting edge, advanced synthesis techniques. Among the salient aspects, a nanomaterial developed for a certain application can also be used for other purposes: PV includes several compounds capable of interacting with sunlight or transporting charges that are used or can be used even in other (also very different) fields [337,338,339,340]. To this purpose, chemical synthesis remains a cornerstone of the technological development, for which the ability to design molecules to meet today's energy needs is priceless [341,342,343,344].

## **6. Conclusions**

Highly transparent PVs represents a valid possibility to substantially offset fossils fuel consumption worldwide. Their effective commercialization and widespread adoption require the mutual optimization of PCE and AVT. The challenge is given by the intrinsic conflict between transparency and light harvesting concepts.

This manuscript has reviewed several technologies for TPVs, all of them having achieved transmission levels higher than 20%. They were classified according to different approaches to reach high transparency levels along with the highest possible PCE, also highlighting the big challenges that need to be faced in order to turn them into realisable technologies. Among transparent, segmented and thin-film solar cells it emerged that the former are the most credible towards a truly efficiency transparent PV concept, and will surely be of interest of several companies in the near future. As an alternative, solar concentrators could offer valid performances,

e.g. PCE = 5% and AVT = 50-60%, simplifying the window fabrication and installation in several circumstances.

In order to provide a practical application of TPVs, a case study simulating a real office in Europe has been proposed and analyzed in terms of energy, environmental and financial issues. The electric power generation is not sufficient to satisfy all the energy needs of the building, but it can still guarantee an energy saving; the overall PBT is 3.6 years with South exposition.

A comparison between optical and electrical properties offered by amorphous silicon panels and recently emerged semi-transparent technologies has also been proposed, such as PSCs and PVSCs, highlighting the valuable impact that TPVs can have in the BIPVs market. Focusing on this consideration, the case of a start-up company in Italy, i.e. Glass to Power, which has recently crowdfunded 2.25 M€ to advance its plans for the set-up of an industrial production line of LSCs to be used in windows applications for buildings, has been reported.

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