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2021

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## Review

# State-of-the-Art Review on the Energy Performance of Semi-Transparent Building Integrated Photovoltaic across a Range of Different Climatic and Environmental Conditions

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**Abstract:** Semi-transparent Building Integrated Photovoltaics provide a fresh approach to the renewable energy sector, combining the potential of energy generation with aesthetically pleasing, multi-functional building components. Employing a range of technologies, they can be integrated into the envelope of the building in different ways, for instance, as a key element of the roofing or façade in urban areas. Energy performance, measured by their ability to produce electrical power, at the same time as delivering thermal and optical efficiencies, is not only impacted by the system properties, but also by a variety of climatic and environmental factors. The analytical framework laid out in this paper can be employed to critically analyse the most efficient solution for a specific location; however, it is not always possible to mitigate energy losses, using commercially available materials. For this reason, a brief overview of new concept devices is provided, outlining the way in which they mitigate energy losses and providing innovative solutions for a sustainable energy future.

**Keywords:** BIPV; energy performance; semi-transparent solar cells; OPV; power; thermal; optical performance; soiling; shading; retrofitting



**Citation:** Khalifeeh, R.; Alrashidi, H.; Sellami, N.; Mallick, T.; Issa, W. State-of-the-Art Review on the Energy Performance of Semi-Transparent Building Integrated Photovoltaic across a Range of Different Climatic and Environmental Conditions. *Energies* **2021**, *14*, 3412. <https://doi.org/10.3390/en14123412>

Academic Editor: Chi-Ming Lai

Received: 12 May 2021

Accepted: 1 June 2021

Published: 9 June 2021

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## 1. Introduction

In 2015, the United Nations General Assembly adopted a series of Sustainable Development Goals (SDGs), including the requirement to protect the planet's environment [1]. SDG 7 specifically highlighted the importance of 'ensuring access to affordable, reliable, sustainable and modern energy for all [2]'. According to [3], sustainable energy is derived from the natural flows of energy originating with bioenergy, direct solar energy, geothermal energy, wind and ocean energy (tide and wave). Photovoltaic systems, which can be seamlessly integrated in the built environment, are particularly significant in meeting the rising demands for energy resulting from the accelerating rate of urbanization, in a sustainable way. It is worth mentioning that the solar systems can be divided in photovoltaic (PV) and solar thermal (ST) systems. Building Integrated Photovoltaics (BIPV) and Building Integrated Solar Thermal (BIST) are PV or ST panels integrated into the building envelope, combining the energy generation with other functions [4]. Several research projects have been discussed in [4], in particular, for integration of solar energy systems in heritage sites and buildings, in addition to proposing a framework for reviewing these projects.

The energy performance of semi-transparent Building Integrated Photovoltaics (BIPV), in a variety of climatic and environmental conditions, is the subject of interest in this review.

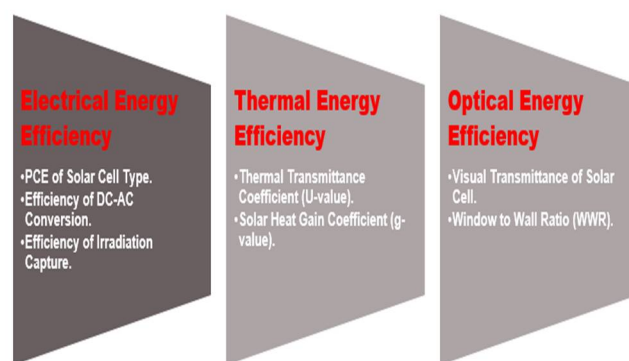
### 1.1. Advantages of BIPV

Semi-transparent Building Integrated Photovoltaics (BIPV) offer a fresh approach to generating renewable energy, potentially delivering ‘costs competitive with fossil fuels [5]’. In this case, PV modules are integrated into the design of the building, offering a multi-functional solution, which combines the function that the building construction element would normally perform, as well as generating solar power. In addition, semi-transparent BIPV also offer the possibility of conserving energy, reducing the amount consumed to achieve ‘thermal comfort’, in addition to offering aesthetically pleasing lighting effects [6]. Integration of the PV-system has several advantages, including the ability to maximise the power generation capacity, through utilising more of the surface area of the building in urban environments, where there are many skyscrapers [7]. BIPV modules can potentially be installed into any part of the building envelope, providing opportunities for solar electric architects to design energy efficient, aesthetically pleasing buildings [8].

### 1.2. Framework for Analysing Energy Performance

The basic BIPV technology and applications have been extensively studied in the literature [9]. In recent years, research efforts focus on novel designs to increase the efficiency both at the system level and also at the PV cell level. All are supported and validated by simulation and experimental work. Another important point that affects the power output is the grid integration of renewable energy sources when the BIPV system is considered as a whole. The purpose of this approach is to minimize the loss of electricity on electronic components, transformers, and long distribution lines by altering the configurations of the distribution systems.

There are a wide range of semi-transparent BIPV systems, which can be classified according to the technology employed, the application-type and the way in which the system is configured [9–11]. There is a strong correlation between this classification and the energy performance of the BIPV-system. Solar electric architects need to take this into account in the design process Figure 1 presents a methodology framework, aimed at facilitating understanding of the most energy efficient solution for each location [12]. It details the key factors impacting energy production and conservation, ensuring that all are taken into consideration, in creating the most efficient solution.



**Figure 1.** Framework for analysing the energy performance of semi-transparent BIPV.

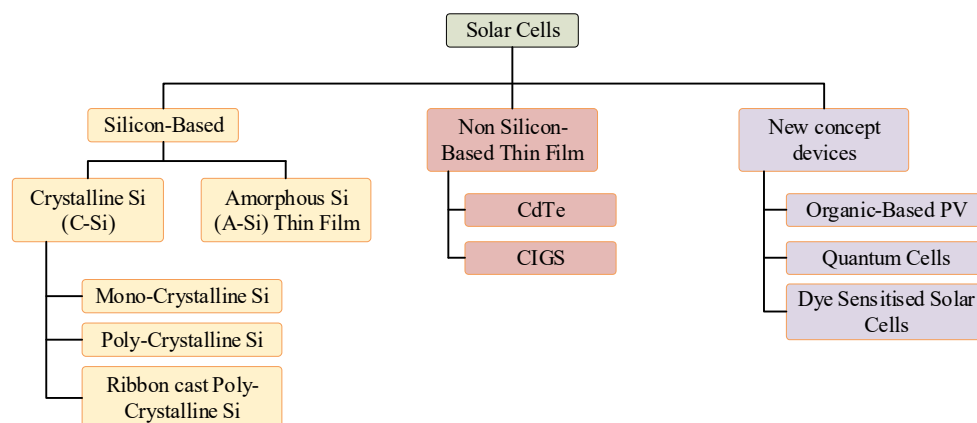
## 2. Power Performance

The first aspect of this framework concerns the way in which the electrical output or power performance of the BIPV system may be critically evaluated.

### 2.1. PCE of Different Technologies

The power conversion efficiency (PCE) is defined as the ability of a solar cell to convert light to electricity, and it can be calculated using the equations in [13]. PCE of the specific technology employed in the BIPV system is assumed to be the most accurate predictor of its potential for generating electrical power. According to [14], energy conversion efficiency

is ‘the useful energy output divided by the energy input’, which in the case of solar cells is the percentage of the sun’s energy the PV cell is capable of converting to electrical power. In [15], collated information outlining the ‘conversion efficiency’ of a wide variety of different PV technologies, i.e., Silicon-based crystalline, thin-film and ‘new concept devices’. These are described below, with specific information about the PCE for each set out in Figure 2.



**Figure 2.** PV Technologies [11].

#### 2.1.1. Silicon-Based Crystalline Solar Cells

There are two types of Silicon-based crystalline solar cells—monocrystalline and polycrystalline. Currently, the highest efficiencies are achieved by using monocrystalline silicon, which has a higher PCE value than the poly-crystalline cells [10]. Semi-transparency of the normally opaque, silicon-based PV cells can be achieved by changing the amount of space between modules to allow the transmittance of light, but this does have an impact on overall efficiency. Their efficiency is also sensitive to environmental factors.

#### 2.1.2. Thin-Film Solar Cells

Silicon-based thin-film cells comprise a very thin layer of amorphous silicon (a-Si), which is vacuum-deposited along with ‘transparent conductive oxides’, creating ‘a semiconductor on a glass substrate’. Although the modules are tinted, ‘20% light transmission’ is achieved due to the ‘ultra-thin’ nature of the product [16]. Non-silicon-based thin-film cells use semiconductors such as Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Copper Indium Diselenide (CInSe<sub>2</sub>) and Copper Indium Gallium Selenide (CIGS). In this case, the solar cells are manufactured by vapour-deposition on conductive glass, with the solar cells being subdivided into ‘thin linear cells, broken up by metallic or transparent lines [11]. Laser ablation can be used to achieve semi-transparency, by removing layers to allow light through. While non-silicon PV modules are generally more economic to produce, achieving semi-transparency results in a product with lower energy efficiency and a limited degree of transparency [17].

#### 2.1.3. Coloured BIPV Technologies

The turning point in the acceptance of BIPV applications has been the development of hidden coloured BIPV modules. This module typology, which includes several different technologies, can hide the PV cells behind coloured patterns which hinder the perception of the original material of the cells [18]. In this way, the modules appear very similar to standard construction materials. This solution appears appropriate also for architecturally sensitive areas, i.e., historical centres, vernacular and historic buildings and natural and cultural landscapes, thanks to the aesthetical and technological advances related to low-rate reflection, mimetic appearance, compact shape and geometric flexibility, enabling a flexible integration of large sets of unexploited vertical and horizontal envelope surfaces [19,20].

However, multilevel integration aspects should be considered like technical, aesthetic and energy aspects [18].

#### 2.1.4. New Concept Devices

Emerging technologies, known as ‘new concept devices’, could be instrumental in transforming the sector. These cells often still employ ‘thin-film’ technology, but the cost is reduced by using new materials such as ‘solar inks, nanotubes, organic dyes, conductive plastics, etc. [6]’. Developers are seeking to create products, which are lower cost but still offer high levels of efficiency and are effective at addressing current limitations.

#### 2.2. Efficiency of DC-AC Conversion Process

The efficiency of a solar array is also impacted by the compatibility of the different components, which make up the system. This includes the Power Conditioning System (PCS) which refers to devices that use power electronics technologies to convert electric power from one form to another as DC-DC and DC-AC converters [21]. PCS requires the input power to be around 30–50% of the rated power of the PCS to achieve anticipated rates of 94.5% in the DC-AC conversion process. Incompatibility may result in a reduction of around 8% in electrical energy performance [22]. Losses can be avoided by ensuring that system design supports maximum efficiency.

#### 2.3. Efficiency of Irradiation Capture

Irradiation capture is the ability to capture the optical energy which is impacted by both environmental factors and by the design of the electrical system and has a significant impact on energy efficiency. Calculation equations can be found in [23]. Basically, the PCS has a minimum voltage at which it operates, meaning that a minimum intensity of irradiation is required for the system to automatically turn on. Where the solar radiation intensity is below this level, the system remains inactive, failing to generate any solar energy. This irradiation capture inefficiency may undermine the power performance of the solar array in a variety of meteorological and installation conditions. Authors in [22] discovered that, depending on the orientation of the system, somewhere between 4.6% and 15.7% of the annual irradiation may not be used for power generation, due to low levels of irradiation failing to trigger the standby function on the PCS. Figure 3 shows different oriented solar cells systems. Four different arrays were installed on horizontal (HR 0°), south-inclined (SI 30°), south vertical (SV 90°), and west vertical (WV 90°) directions, respectively on a building in Daejeon in Korea. PEC is used by the authors as a figure for power conditioning system (PCS) conversion efficiency-corrected performance which take into account the PCS stand-by power, converters efficiencies, module temperature and dust and soiling. Each array consisted of 12 transparent-Si BIPV modules connected in 6 series  $\times$  2 parallel and had an installed capacity of 0.528 kWp. The evaluation of evaluate the system loss and capture loss is conducted based on the monitored data. The 8.3% loss is caused by the PCS conversion losses.

The combined effect of losses associated with the impact of the Power Conditioning System standby-mode on irradiation capture and DC-AC conversion inefficiencies could be significant [24]. Lee et al. [22] demonstrated that an overall performance ratio of no greater than 75% could be anticipated (Figure 3), with capture losses of around 17% and system losses of around 8%, not being out of the question. Optimising the system design to ensure efficiency in the DC-AC conversion process and thereby maximising irradiation capture is likely to have a significant impact on the electrical power performance of the system.

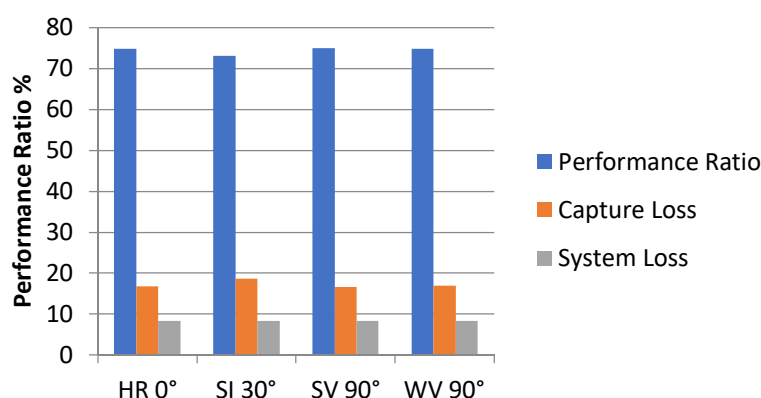


Figure 3. PCS Performance ratio of four different Solar Arrays [22].

### 3. Thermal Performance

In addition to generating electrical power, semi-transparent BIPV are also useful in contributing to thermal comfort and reducing the energy demands for regulating the internal temperature of the building [25]. Similar to electrical power performance, the thermal performance of a semi-transparent BIPV system is not only impacted by external factors but also by the inherent features of the semi-transparent BIPV module employed. According to [26], thermal energy performance is related to both the ‘thermophysical properties of the materials’ and the ‘transmission and absorption coefficients’ of the transparent material, in other words, the thermal efficiency of the glazing components, the degree of transparency of the solar cell-type and, potentially, the manner in which transparency is achieved.

As noted previously, the semi-transparency of ‘crystalline silicon PV arrays is created by the transparent glazing surrounding the opaque solar cells, whereas thin-film technologies achieve semi-transparency by using laser ablation to remove layers of the substrate. For this reason, assessing the thermal performance of semi-transparent BIPV is a relatively complex matter, with standard methods designed for conventional glazing potentially producing erroneous results [27,28]. Both the U-value, which measures heat transmission through the BIPV-module and can be calculated using the equations in [29], and the ‘solar heat gain coefficient’ (SHGC), also known as the g-value, which measures the amount of heat transmitted into the building due to solar radiation, need to be taken into account [26]. SHGC can be calculated using the equations in [30].

It would, therefore, seem important to examine both the impact of the solar cell-type and the type of glazing on the thermal performance of the PV module. Most of the research on the thermal performance of semi-transparent BIPV has involved solar cells employing thin film technologies, such as amorphous silicon (a-Si) and cadmium telluride (CdTe).

#### 3.1. Solar Heat Gain (g-Value)

The solar heat gain coefficient (g-value) has been linked to the thickness of the semiconductor film in the photovoltaic cell. Chae et al. [31] carried out an evaluation of thin film semi-transparent a-Si solar cells, which employed different thickness of amorphous silicon. They found that while the thermal transmittance (U-value) was similar, cells with a lower g-value (SHGC), demonstrated strong correlation between the thickness of a-Si layers and energy conservation in lower latitudes. In another study, Martin-Chivelet et al. [27] concluded that the degree of transparency of PV modules had ‘no appreciable influence’ on thermal transmittance (U-value), whereas differences associated with SHGC (g-value) were noted.

#### 3.2. Thermal Transmittance (U-Value)

Another study, carried out by Al Rashidi et al. [29], examined the performance of thin-film CdTe cells, compared to a conventional single-glazed window. They found that the U-value of the BIPV window was half of that of the single glazed unit and that the SHGC



(g-value) was over 70% lower, meaning that the thermal performance of the CdTe was much better than that of the regular glazing. Different glazing structures, for a crystalline silicon (c-Si) BIPV cell, were also investigated by Ghosh et al. [32]. They found that the BIPV vacuum system was most effective in delivering ‘thermal comfort’, with values up to 39% above the BIPV double-glazed system. In all these cases, the results obtained were location-dependent, with different results being obtained under different climatic conditions and at different latitudes, underlining the need for bespoke location-specific solutions.

Figure 4 shows the overall heat transfer coefficient (U-value) of a CdTe BIPV window and a single glazed window when they are tested indoor under sun simulator showing the different temperature figures, while the outdoor test is shown in Figure 5. It is worth mentioning here that the sample transparency was 25% and was tested in Penryn, UK in indoor and outdoor setups. The indoor simulator was set at  $1000 \text{ W/m}^2$  constant solar exposure for eight hours. The maximum solar heat gain for the CdTe BIPV window was found as 20% which was 73% lower than a 72.8% transparent single glazing. CdTe BIPV had an average U-value of  $2.7 \text{ W/m}^2\text{K}$  in the indoor and outdoor experiments. This average is lower than that of the single glazing that showed  $5.7 \text{ W/m}^2\text{K}$  in the indoor experiment and  $5.6 \text{ W/m}^2\text{K}$  in the outdoor experiment.

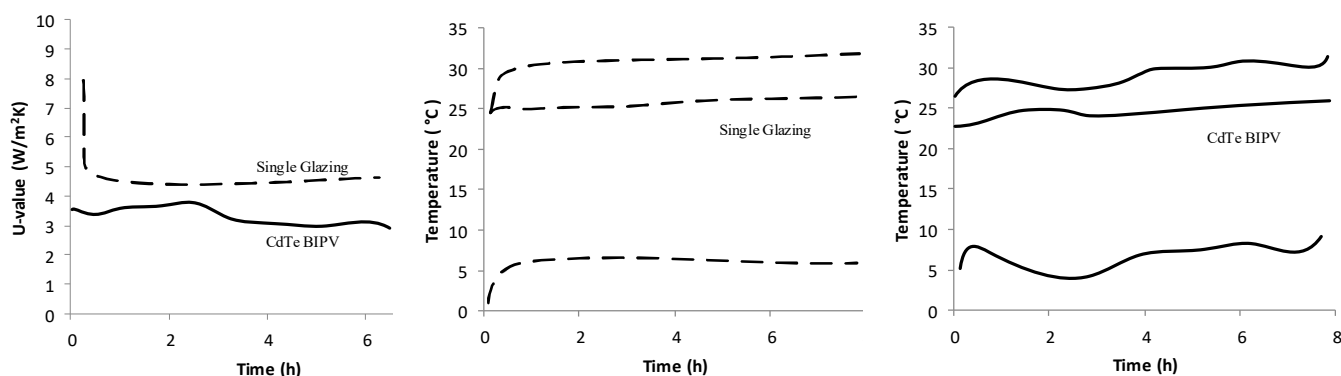


Figure 4. Overall heat transfer coefficient (U-value) of a CdTe BIPV window and a single glazed window—Indoor test [29].

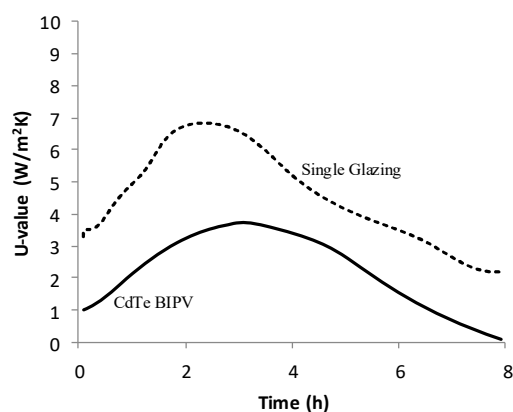


Figure 5. Diurnal variation of thermal transmittance (U-value) of a CdTe BIPV window and a single glazed window—Outdoor test [29].

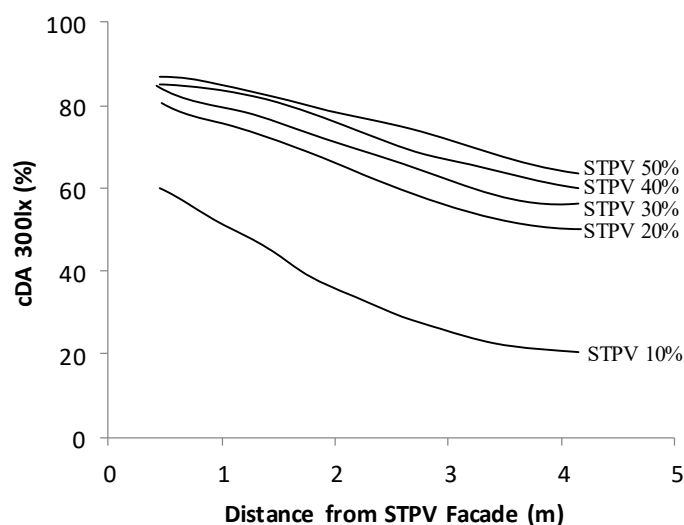
#### 4. Optical Performance

Semi-transparent BIPV also improve the visual comfort of a building by reducing unwanted solar glare. In contrast to the way thermal energy performance is calculated, optical performance is exclusively linked to the degree of transparency of the semi-transparent BIPV module. For this reason, optimising lighting-energy conservation is related to the relationship between the average visible transmittance (AVT) and the window to wall ratio (WWR). AVT is an optical property that indicates the fraction of visible light transmitted through the window while WWR is the ratio between the glazed surface and the gross

façade area [33], higher outputs being achieved where more transparent BIPV are used over a larger WWR.

Even so, the way in which transparency is achieved has a huge bearing on the outcome. Thin-film technologies, which have not been customised, currently offer visible transmittances of around 5%, on the ‘orange-brown spectrum’, which fail to meet the required ‘daylighting performance’, resulting in ‘severe visual discomfort [34]. Where laser ablation has been used to increase transparency, higher levels of visible transmittance can be achieved, allowing optical performance to be optimised. This, however, results in lower levels of power generation for the area of glazing. Using silicon laminates provides a third option, offering higher rates of PCE, but creating transparency by using a ‘patterned array of opaque solar cells’ diminishes the overall visual effect [34]. While standard semi-transparent BIPV-technology has its limitations, there are emerging technologies, which show promise.

Despite these limitations, there has been a considerable amount of research carried out to investigate the optical performance of standard semi-transparent BIPV windows in terms of Continuous Daylight Autonomy (cDA) [35] and the spatial Daylight Autonomy (sDA) [36]. A simulation carried out by [37] examined the daylight performance of perimeter office façades utilizing semi-transparent photovoltaic-windows. They investigated three façade configurations, incorporating Si-based opaque spaced cells and thin film technologies, in a way that ensured sufficient daylight ‘within the perimeter zone’ throughout the year. The three-façade system comprised an opaque lower section, extending 0.8 m upwards to correspond with ‘work-plane height’; a middle section which maximises external viewing (to 2.0 m above the floor) and a third section, designed to allow sunlight to enter the room, while minimising glare. Windows with five ‘effective visible transmittance’ values (Figure 6), ranging from 10–50%, were chosen, one set having an outer glass layer only, the other being an insulated double-glazed unit (IGU). Visible effective transmittances (VET) ranged from 6–50%. Three different configurations were studied: one utilising only PV-film, another utilising only Si-based technology and the last combining both. The optimum configuration according to the simulation was achieved using a 30% VET Semi-transparent PV (STPV) module ‘integrated as the outer glass layer of a double glazed low-e window. VET higher than 30% would have resulted in poor power output and unacceptably high solar gains. This study would seem to suggest that standard technologies can be combined in a way that optimises their power, thermal and optical performance.



**Figure 6.** Spatial Daylight Autonomy for a BIPV façade with various visible effective transmittances (10% to 50%) [37].



Another interesting study combined the use of semi-transparent BIPV windows and daylight dimming systems [38]. Researchers assumed that using less electricity for lighting could reduce the cooling load, resulting in a daylight-dimming system being incorporated along with three different types of BIPV solar cells, ranging in transparency from 10–40%. A light sensitive cell controlled the electric lighting system, maintaining it at 323 lux in rooms orientated towards the four points of the compass. The research demonstrated lighting energy savings ranging from 3–14%, with the highest levels associated with increased window-transparency. The greatest impact was achieved with the east-facing window, although the system design did not compensate for excessive direct sunlight entering early in the day. In addition to the reduction in energy-consumption associated with the lighting system, ‘peak cooling demands’ were reduced by up to 26%, resulting in overall energy savings in the range of 12–20%, emphasising the close link between optical and thermal energy performance.

## 5. Climatic and Environmental Effects

This framework can be employed to investigate the potential energy efficiency in a specific location, by understanding the way in which electrical, thermal and optical performance is affected by different climatic and environmental conditions.

### 5.1. Climatic Effect on PCE

The electrical energy performance of a semi-transparent BIPV system is affected by the installation environment, with climatic, geographical and environmental effects being observed. According to [39], the PCE-value of the solar cell decreases with elevated operating temperature, compromising the efficiency of the system. Indeed, Popovici et al. in [40] documented a reduction of around 0.45% for every degree of increase in temperature over the optimum value of 25 °C. The reduction in PCE is described by the following Equation (1), where  $\eta$  is the cell/electrical efficiency value;  $\beta$  is the temperature coefficient, and  $T$  is temperature [41]. The subscript  $c$  denotes a cell,  $ref$  denotes reference value at reference conditions, and  $T$  denotes a referenced tilted plane.

$$\eta_c = \eta_{Tref} \left[ 1 - \beta_{ref} (T_c - T_{ref}) \right] \quad (1)$$

Even in temperate zones, where climatic conditions are closer to ideal, the solar cell itself generates heat as a result of electrical resistance of the solar cells, which amounts to the difference between the solar energy absorbed and the electrical energy produced [42].

Researchers have found that the temperature of PV modules changes slowly, however, with a ‘time lag’ between the incidence of ‘solar radiation’ and the rise in PV module temperature. This varies with the solar cell type and the type of glazing used. Yoon et al. [43] stated that surface temperature not only affects PCE but also may impact ‘indoor cooling and heating energy consumption’, as well. Crystalline silicon cells are rather more prone to reductions in efficiency than non-crystalline solar cells, with relative reductions in efficiency of 0.45% and 0.2%, per 1 °C rise in temperature.

### 5.2. Environmental Effect on Irradiation Capture

The ambient temperature of the environment and solar irradiation are not the only climatic factors which affect energy efficiency. The position of the sun and amount of direct solar radiation are significant, as are the effects of soiling and shading.

#### 5.2.1. Effect of Angle of Orientation and Inclination

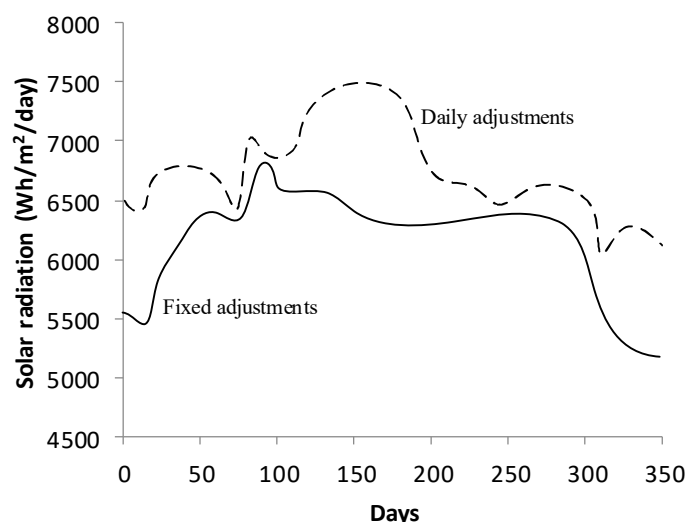
The position of the sun and the amount of direct solar energy are defined by the solar altitude angle ( $h$ ) and the solar azimuth angle ( $A$ ). The solar altitude ( $h$ ) is the angle between the horizontal surface of the earth and the direct line to the sun, in contrast to the solar zenith angle ( $\theta_z$ ), which is the angle between the vertical line and the line to the sun. In the Northern Hemisphere, the solar azimuth angle ( $A$ ) is the angle of the incident

beam of radiation from the south. These angles define the physical position of the sun, a particular time in the day, and determine the optimum angle of orientation ( $\alpha$ ) or the tilt ( $\beta$ ) of the solar installation.

It should be noted, however, that some authors [44] use the term, ‘azimuth angle of the BIPV’, which rather confusingly actually refers to the angle of orientation ( $\alpha$ ) in relation to the azimuth, rather than the solar azimuth angle ( $A$ ). Furthermore, direct solar radiation is only one component of the overall incident solar radiation, with diffuse and reflected radiation also playing a part [45]. In some situations, the impact of these two additional components can be significant.

A study carried out by [44] examined the optimum angle of orientation in relation to the azimuth and inclination of BIPV panels in an urban environment. In general, it was found that the optimum angle of inclination ( $\beta$ ) for a solar panel was equivalent to the latitude of the location. This was confirmed by a computer simulation, focusing on twenty different locations in the northern hemisphere, with significant discrepancies increasing somewhat non-uniformly with latitude [46].

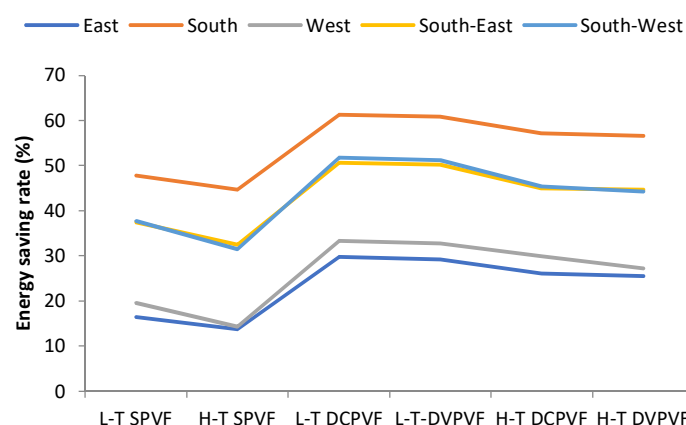
Further research on optimum tilt angle ( $\beta$ ) was carried out by [45], who demonstrated differences between fixed and adjusted tilt angle in Jeddah, Saudi Arabia (latitude:  $21.5^\circ$  N, longitude:  $39.17^\circ$  E). The test has four samples with different tilt angle adjustment and configuration observed on a monthly, seasonally, half-yearly and yearly basis. They compared the effect of adjusting the tilt angle daily, as opposed to keeping the solar module in a fixed position, finding that the electrical output was just over 7% less when no adjustments were made as shown in Figure 7.



**Figure 7.** Daily solar radiation on fixed and daily adjusted surfaces [45].

Obviously, for the vast majority of BIPV installations, it is not possible to adjust the angle of orientation or inclination of the panel as the module would generally form a fixed part of the structure. In this situation, it is necessary to determine optimum configuration, within these constraints.

According to [47], the optimal angle of orientation, in relation to the azimuth, was a value of  $0^\circ$ , when the panel is south-facing in the northern hemisphere and north-facing in the southern hemisphere. The variation in energy-saving rates for different solar azimuth angles was examined more closely through research carried out on semi-transparent thin-film façades installed on an office building in the Tianjin city, China, cold-zone [48]. The highest energy-saving rates of over 60% were achieved by the south-facing DSF (Double-skin Façade) as compared to just under 14% saving with SSF (Single-skin Façade, facing east) as shown in Figure 8. L-T denotes to low transmittance, H-T to high transmittance, SPVF to single photovoltaic façade, DPVF to double photovoltaic façade, DCPVF to double closed photovoltaic façade and DVPVF to double ventilated photovoltaic façade.



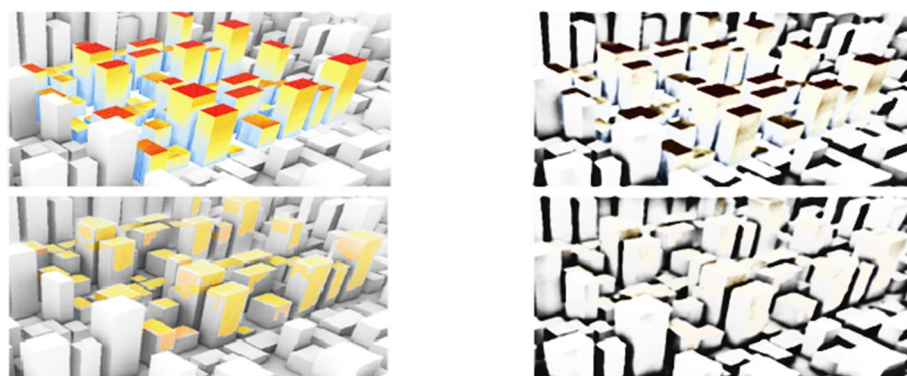
**Figure 8.** Energy saving rates of Photovoltaic façade (PVF) at different orientations in China cold-zone [48].

South-east and south-west facing façades performed similarly, with energy savings of around 50% for DSF and west facing façades performing around 4% better than east-facing, at best. In general, energy-saving rates are therefore found to be much more sensitive to the angle of orientation than any other factor, with the comprehensive heat-gain coefficient (CHGC) demonstrating greater sensitivity than visible light transmittance (VLT). Interestingly, VLT is a much more significant factor than CHGC for the poorly performing east-facing façade. Hence, both the angle of inclination and the angle of orientation are very important in determining the energy efficiency of semi-transparent BIPV; however, in urban settings the impact of shading by adjacent buildings may result in assumptions needing to be revised [44].

### 5.2.2. Effects of Shading

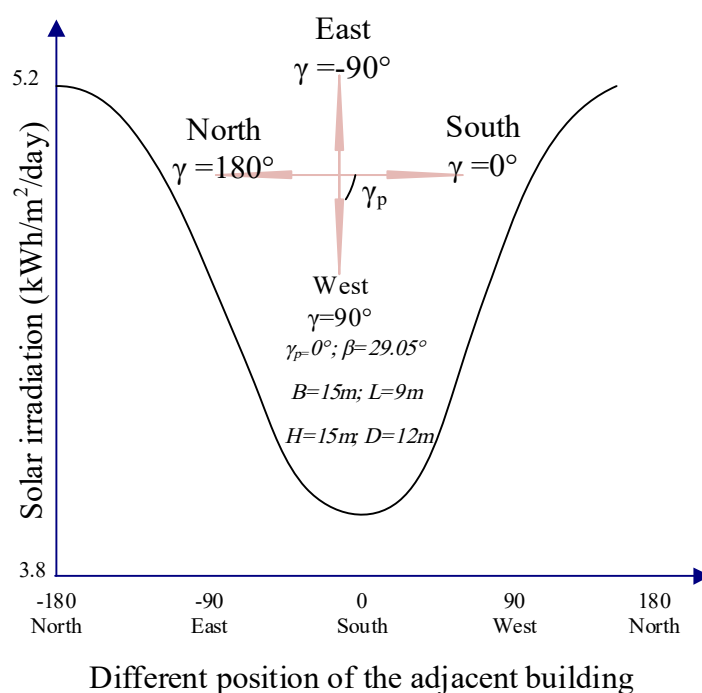
While BIPV modules installed on high-rise commercial or residential buildings offer very significant energy-saving potential, this can be dramatically affected by the proximity of nearby buildings. A striking example from the Norwegian city of Trondheim cited a BIPV system retrofitted on a seven-story office building, with BIPV-façades integrated into south- and west-facing façades. The system was orientated for optimum energy performance; however, a year after its commission, a newly-erected, twenty-one storey hotel caused the south-facing panels to be partially obscured, impacting the ‘solar production and energy performance of the system’ [49]. Determining the effect of partial shading on BIPV performance is a complicated matter, due to the ‘non-uniform and dynamic conditions’, which occur over time, impacting both urban planning and the retrofitting of BIPV on existing buildings [50]. Two types of adverse shadow-effects have been observed, including shading due to the sun being ‘trapped behind an adjacent building’ and the ‘sky blocking effect’, which causes ‘diffuse irradiation’ and ‘horizontal brightening’, from that ‘portion of the sky to become zero’ [44].

A Python-based tool was used to analyse the amount of solar radiation falling on building surfaces in Tehran, Iran, determining the most optimal surfaces for BIPV installation, taking into account the shading from surrounding buildings. The heat map analysis is shown in Figure 9, which shows different potential of PV installation according to the heat concentration and distribution.



**Figure 9.** Radiation analysis, meshing and calculation of average annual radiation (upper) defining the installation boundary based on thresholds (lower) [50].

In [46], the BIPV panels are integrated into the roof of a sample building in Delhi, India. The adjacent building is situated in the south direction to investigate the impact of shadow. Figure 10 presents the influence of different positions of the adjacent building on solar irradiation received by south-faced BIPV panel for the duration in September 2017. It can be noticed from Figure 10 that the irradiation values are most adversely influenced by the adjacent building situated in the south direction as for this location the shadow effect is maximum.



**Figure 10.** Variation of monthly average daily irradiation with different positions of the adjacent building (width of the adjacent building,  $B = 15$  m, length of the adjacent building,  $L = 9$  m, relative height of the adjacent building,  $H = 15$  m, horizontal distance of the adjacent building from BIPV panel,  $D = 12$  m) at inclination angle of BIPV panel,  $\phi = 28.70^\circ$ , when the BIPV panel is south facing, September 2017 [51].

In a rather more detailed study, Yadav et al. [44] examined the influence of shading, 'caused by different plan orientations of an adjacent building' on the optimum angle of orientation, in relation to the azimuth and the angle of inclination of the BIPV module. The test was conducted on 15 May 2018, for an optimally tilted semi-transparent BIPV two-storied single room system with consideration of periodic nature of insolation parameters

evaluated for the warmest day of the year. The BIPV system is integrated as the south facing roof top of a two-storied sample building in Delhi, India. The optimum inclination angle was exactly the same as the latitude of the location in Delhi, India, when there were no shadow effects. The optimum inclination angle decreased, with an increase in shading and increased as the 'shadow effect', caused by sky-blocking, decreased. Furthermore, if the adjacent building was situated in a south-facing position, there was a much greater impact on level of irradiation on the panel than in any other orientation.

Therefore, the effects of shading also have an impact on the energy performance, significantly affecting the irradiation capture of the BIPV system. Capture-losses are also similarly observed with soiling.

### 5.2.3. Effect of Soiling on Irradiation Capture

Soiling of the BIPV panel with dust or accretion with snow or ice may cause the BIPV module to become temporarily shaded. Borrebæk et al. [10] carried out research on the 'challenges, strategies and opportunities' created by the formation of ice and snow on the external surface of semi-transparent BIPV in cold climate regions. Unlike the rather more predictable energy losses detailed above, losses associated with accumulations of ice and snow in winter are less predictable, creating major discrepancies in the 'estimated annual specific yield' and actual output values, as exemplified by a study in Norway [49]. In addition to the 'lower incident light intensity' on the module in arctic and sub-arctic regions, the occurrence of ice and snow in many different forms can impact the efficiency of the solar panel in different ways [10]. In some cases, the solar module can be completely covered rendering it completely ineffective in producing electricity due to the passage of solar radiation being blocked; in other cases, coverage can be minimal or partial, resulting in less significant losses of output. Mitigation strategies for the complex differences between ice and snow are also not a simple matter, with an 'application-based approach', employing a bespoke range of active and passive measures, being suggested by the study. Even 'application-based approaches' require evaluation to ensure that the benefits achieved from removing the snow or ice do not outweigh the energy output of the chosen solution. A great deal of further research would be needed to yield overall viable solutions and to understand how energy output could be maximised.

The effects of soiling due to the accumulation of dust and other contaminants, which 'adversely affect the optical performance', are somewhat more predictable [52]. While 'dust' may be generated by pollution in urban centres, more significant effects were noted in arid or semi-arid regions, where wind direction and precipitation (or lack of it) had an impact on dust accumulation [53]. Seasonal variations in the thickness of the dust layer affect energy performance in a linear fashion, with larger grains proving more significant, in addition to wind speeds and the level of humidity in the atmosphere [54,55]. Losses of efficiency, resulting from impaired irradiation capture, of around 20% were reported in Kuwait, California, Saudi Arabia and Mexico, at certain times of the year [56–59].

In [52], the authors investigated the energy yield losses caused by dust deposition on photovoltaic modules and the results of experimental research conducted in Poland. The locations in the order of increasing latitude, as shown in Figure 11 are Hong Kong, China; Abu Dhabi, UAE; Riyadh, Saudi Arabia; Dhahran, Saudi Arabia; Gran Canaria, Spain; Arava Valley, Israel (blue bars) and Gdansk, Poland, (green bar).

Rather surprisingly, highly polluted urban environments like Gdansk in Northern Poland (Latitude 52°) could yield losses as great as arid desert regions in the Middle East (Abu Dhabi UAE, Latitude 24.7). Reference [52] concluded that even at an optimum angle, the effects of the elements were not sufficient to clean the photovoltaic modules and that frequent cleaning was important to maintain maximum system output.

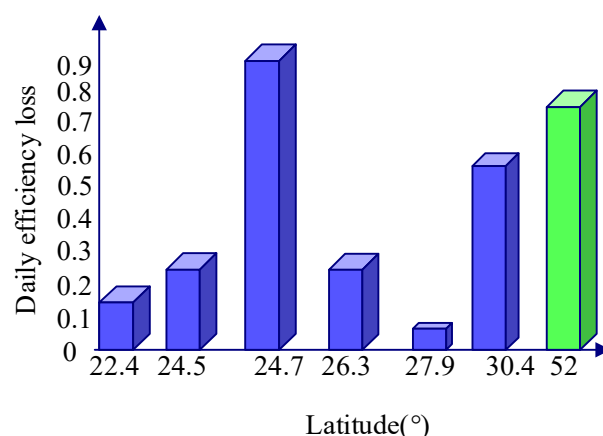


Figure 11. Maximum daily efficiency loss for various latitudes [52].

#### 5.2.4. Effect Is Retrofitting

Retrofitting BIPV into existing buildings is of significant interest in countries where there are limitations placed on construction of new buildings in highly developed urban centres, which already have many high-rise structures. Hong Kong provides a good example of this, although roof mounted BIPV modules were estimated to produce almost 87% more energy than BIPV façades, due in part to the impact of shading in a densely populated city [60,61]. Electricity production has also been estimated for a range of member states of the International Energy Agency as shown in Table 1. While figures look very promising in some locations, it is not clear to what degree various environmental factors have been taken into account in these calculations.

#### 5.3. Climatic Effect on Thermal and Optical Efficiency

Further studies compared the energy performance of semi-transparent BIPV in different climatic zones. The first analysed the energy savings delivered by a range of semi-transparent BIPV façades (up to 10% VLT) in the tropical climate of Singapore. Figure 12 shows the results of an experiment where six commercially available semi-transparent BIPV windows, four single-glazed and two double-glazed, are studied in Singapore. Moreover, selected results of semi-transparent BIPVs were also compared against commonly used window types such as single-glazing, doubled-glazing and low-emissivity windows. Modules 1 to 6 have different transparency, U-value, efficiency and technology. Modules 1, 5 and 6 are amorphous silicon while modules 2, 3 and 4 are micromorph silicon. In general, energy savings were greater with higher WWR-values, ranging from <5% to approximately 33%.

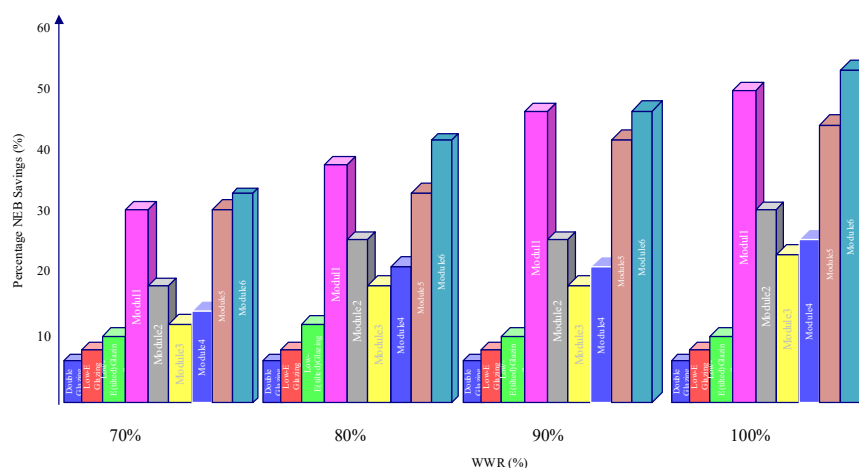


Figure 12. Percentage of total NEB (Net Energy Benefit) savings for different window types [62].



**Table 1.** The potential electricity generation capacity of BIPV for selected countries of the International Energy Agency [63].

Country	Expected Roof Area (km <sup>2</sup> )	Expected Facades Area (km <sup>2</sup> )	Expected Roof Energy (TWh/year)	Expected Facades Energy (TWh/year)	Total Expected Energy (TWh/year)	Actual Consumption (TWh/year)	Expected Demand Ratio (%)
United States	10,096.26	3876.10	1662.3	418.3	2080.6	3602.6	57.8
United Kingdom	914.67	343.00	83.2	22.1	105.4	343.5	30.7
Canada	963.54	361.33	118.7	33.05	151.7	495.3	30.6
Denmark	87.98	32.99	7.7	2.1	10.8	34.4	31.6
Finland	127.31	32.99	11.7	3.1	14.8	76.5	19.4
Germany	1295.92	485.97	128.3	31.7	160.0	531.6	30.1
Italy	763.53	362.39	103.1	23.8	126.9	282.01	45.0
Japan	966.38	97.26	117.4	29.4	146.8	1012.9	14.5
Netherlands	259.36	168.31	25.6	6.2	31.8	99.06	32.2
Spain	448.82	81.04	70.7	15.7	86.4	180.17	48.0

The study demonstrated that in climatic conditions, with elevated outdoor temperatures, the best energy savings were, in general, delivered by a-Si double-glazed BIPV modules, which had the lowest thermal transmittance (U-values) and SHGC (g-values). Higher levels of VLT were also evident in the best-performing modules, particularly Module 1, which was not double-glazed. These findings emphasise the importance of understanding the interaction between power, thermal and optical energy performance, under specific climatic conditions [62].

## 6. Emerging Technology

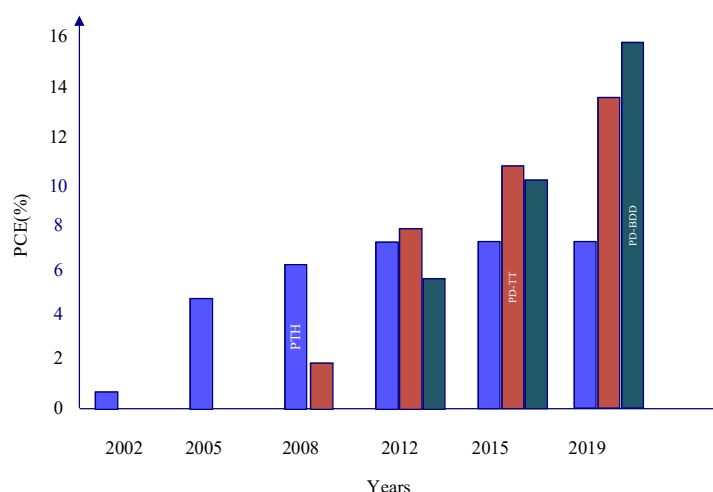
It is clear that there are limitations to the existing BIPV systems, which compromise overall energy efficiency. Researchers are currently seeking to develop technologies, which maintain high levels of power conversion at elevated temperatures and offer greater efficiency in the irradiation capture process. New concept devices include Organic-Based PV, Solar Concentrator Systems, Quantum Dot Cells and Dye Sensitised Solar Cells (DSSC) although these are merely indicative of a very broad, highly complex field of research [11].

Organic-Based Photovoltaic (OPV) are solar cells, which generate electricity from sunlight, using organic semiconductors [64]. The introduction of the bulk heterojunction (BHJ) cells, which comprise an optically active layer which is ‘composed of an interpenetrating network of electron donor and acceptor-materials’, increased the PCE to 7.4% [64,65]. Recent advances claim PCEs of 16.4%, for non-transparent cells; however, despite the advantage of being cheap to manufacture, light weight and flexible, these cells currently yield a PCE of no more than 10.8%, for semi-transparent OPV cells, with a visible transparency of around 50%. This technology offers potential for further advances [66].

Regardless of the advances which have been made in this field, OPV still have one significant limitation: their photostability is adversely affected by high temperatures, meaning that they might be overall less useful in hotter climatic zones.

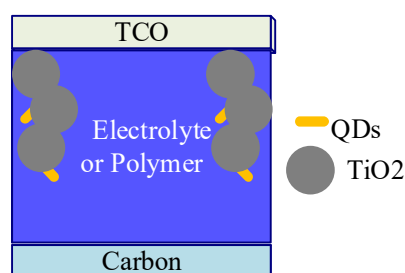
Solar convertor technology has been applied to OPV to ‘improve the operational stability’, by introducing a luminescent solar concentrator (LSC), capable of converting damaging short-wavelength photons, which release a lot of heat during the photoelectric conversion, into long wave-length photons. In addition to being more stable, the OPV-LSC cells offer possibilities for ‘harvesting both direct and diffuse light’, optimising them for use in a wide-range of locations [66]. Indeed, solar convertor technology represents a very promising, albeit emerging technology, for semi-transparent BIPV applications, being less sensitive to the angle of system orientation and losses in efficiency associated with shadowing-effects than first- and second-generation technologies. Furthermore, triple-glazed units containing the LSC deliver a high-level of thermal-energy performance, by reducing the heating effects of solar radiation, while still facilitating the passage of ‘natural light for internal illumination’. Recent technological breakthroughs have resulted in improved ‘solar-collection and concentration processes’, although further work is needed

to facilitate improvements in the optical-electrical conversion process [67]. The literature interest distribution over different technologies for the recent year as shown in Figure 13.



**Figure 13.** Research progress with regard to the efficiency enhancement for different kinds of OPV systems (Polythiophene (PTh), Poly electron-donating unit-thieno-thiophene (PD-TT) and Benzo-dithiophene-dione (PD-BDD)) from 2001–2019 [65].

Quantum Dot Solar Cells (QDSC) employ nanotechnology, where the structure is shown in Figure 14, increasing the output of electrons by three times, over first- or second-generation materials. Whereas one electron would normally be expected to be produced from one photon of light entering the cell, three are produced in the quantum dot solar cell, reducing the amount of energy wasted through heat [68,69].



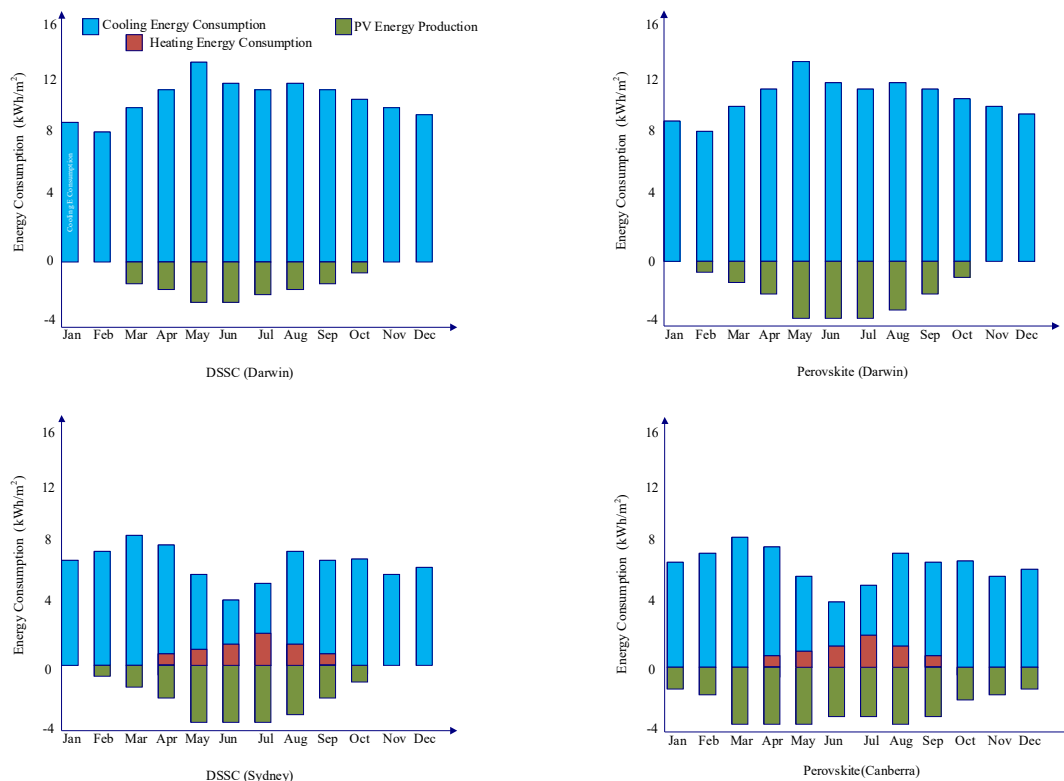
**Figure 14.** The structure of quantum dot sensitized solar cells, ultrathin film of colloidal QDs is sandwiched between two contacts for the extraction of photogenerated electrons and holes [69].

It is estimated that QDSC have the potential to convert around 65% of the sun's energy into electricity, using radiation in the infrared spectrum in addition to the visible spectrum, assuming that production can be scaled up to a commercial level [69]. Some very cutting-edge research has involved combining the use of this technology with the high-efficiency semi-conductor perovskite, which has demonstrated very high PCE-levels in other applications [70].

No examination of new concept designs in solar technology would be complete, however, without taking a much closer look at Perovskite, one of the most recent success stories in this field. In December 2020, researchers at Oxford PV celebrated a new record with a perovskite solar cell, which was shown to 'convert 29.5% of solar energy into electricity [71]. Perovskite-sensitised solar cells 'emerged from the field of dye-sensitised solar cells (DSSCs)'. Their anticipated future development is discussed in [72] like solid-state DSSCs (ssDSSCs), Extremely thin absorbers (ETAs) cells, Meso-superstructured Solar Cell (MSSC) and others perovskite-based cells.

The potential energy savings offered by using Perovskite-based technology was clearly illustrated in a study carried out by Yang et al. [47]. The following graphs highlight the advantages offered by Perovskite cells over DSSC in different climatic zones in Australia.

Solar energy output of Perovskite cells, as opposed to energy consumption, was much more favourable in all locations, and increases in output, over those achieved using a-Si cells were evident in Figure 15.



**Figure 15.** DSSC and Perovskite solar cell for Darwin (hot, humid climate), Australia [47]. Each set of bars represents the monthly value of heating (orange) and cooling (blue) energy consumption and PV production (green) for the four models.

## 7. Conclusions

BIPV technology is a promising addition to the existent technologies for renewable and sustainable energy. In this paper, we have provided a wide review on all aspects that might be considered when targeting the energy performance of Semi-Transparent Building Integrated Photovoltaic across a range of different climatic and environmental conditions. Several studies in the literature addressed mainly the aesthetic and mechanical designs, and others tackled the integration aspects and the energy efficiency when it is integrated in a building. The location oriented has been laid out properly by the proposed framework in this paper, which is useful for establishing the most energy efficient configuration of a location-specific semi-transparent BIPV system, in addition to identifying avenues for further research aimed at reducing overall energy losses and increasing output. Specifically, this includes developing solar technology, which can deliver higher PCEs, maximise irradiation capture and not only reduce the adverse effect of heat on the PV cells but also recycle the heat produced in the generation of solar power for other purposes. These are important if a sustainable energy future is to be achieved.

**Author Contributions:** Conceptualization, W.I. and R.K.; methodology, H.A.; resources, R.K. and N.S.; writing—original draft preparation, R.K. and N.S.; writing—review and editing, W.I., R.K., H.A. and T.M.; supervision, W.I., T.M.; project administration, H.A.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

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

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