Energy Performance

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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.

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

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1. Introduction

According to [1], 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. 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 [2]. Several research projects have been discussed in [2], 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.

In this case, PV modules are integrated into the design of the building, offering a multifunctional 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 [3]. 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 [4]. 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 [5].

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 [6][7][8]. There is a strong correlation between this classification and the energy performance of the BIPV-system. 1presents a methodology framework, aimed at facilitating understanding of the most energy efficient solution for each location [9]. It details the key factors impacting energy production and conservation, ensuring that all are taken into consideration, in creating the most efficient solution.

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.

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 [10]. 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 [11], 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. These are described below, with specific information about the PCE for each set out in **Figure 1**.

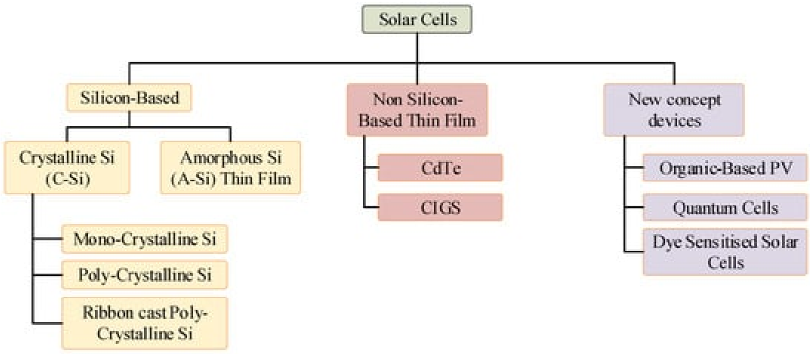

Figure 1. PV Technologies [8].

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 [7]. 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.

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 semi-conductor on a glass substrate’. 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 [8]. 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 [12].

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 [13]. 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 [14][15]. However, multilevel integration aspects should be considered like technical, aesthetic and energy aspects [13].

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. [3]’. Developers are seeking to create products, which are lower cost but still offer high levels of efficiency and are effective at addressing current limitations.

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 [16]. 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 [17]. Losses can be avoided by ensuring that system design supports maximum efficiency.

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. Authors in [17] 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 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. The evaluation of evaluate the system loss and capture loss is conducted based on the monitored data.

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 [18]. Lee et al. [17] demonstrated that an overall performance ratio of no greater than 75% could be anticipated (**Figure 2**), 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.

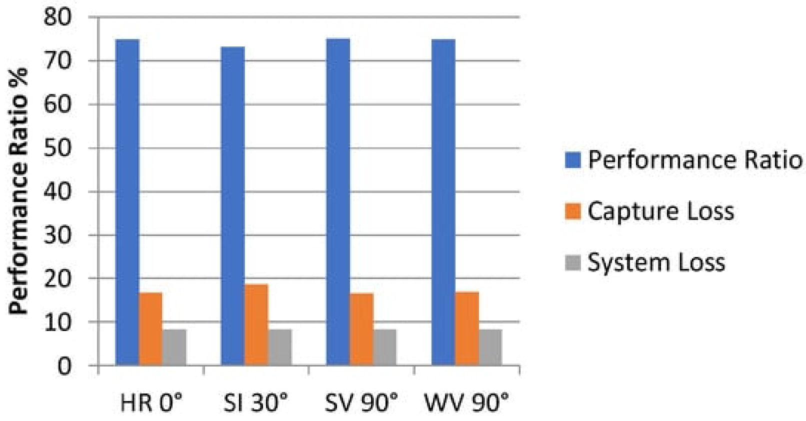

Figure 2. PCS Performance ratio of four different Solar Arrays [17].

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 [19]. 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 [20], 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 [21][22]. Both the U-value, which measures heat transmission through the BIPV-module and can be calculated using the equations in [23], 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 [20]. SHGC can be calculated using the equations in [24].

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).

The solar heat gain coefficient (g-value) has been linked to the thickness of the semi-conductor film in the photovoltaic cell. [25] 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. [21] 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.

[23], 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. 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 3 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 4**. 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 W/m2constant solar exposure for eight hours. This average is lower than that of the single glazing that showed 5.7 W/m2K in the indoor experiment and 5.6 W/m2K in the outdoor experiment.

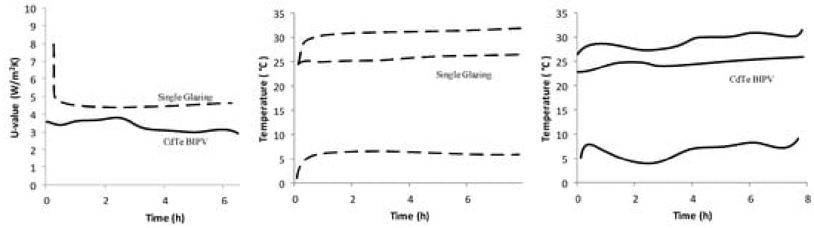

Figure 3. Overall heat transfer coefficient (U-value) of a CdTe BIPV window and a single glazed window–Indoor test [23].

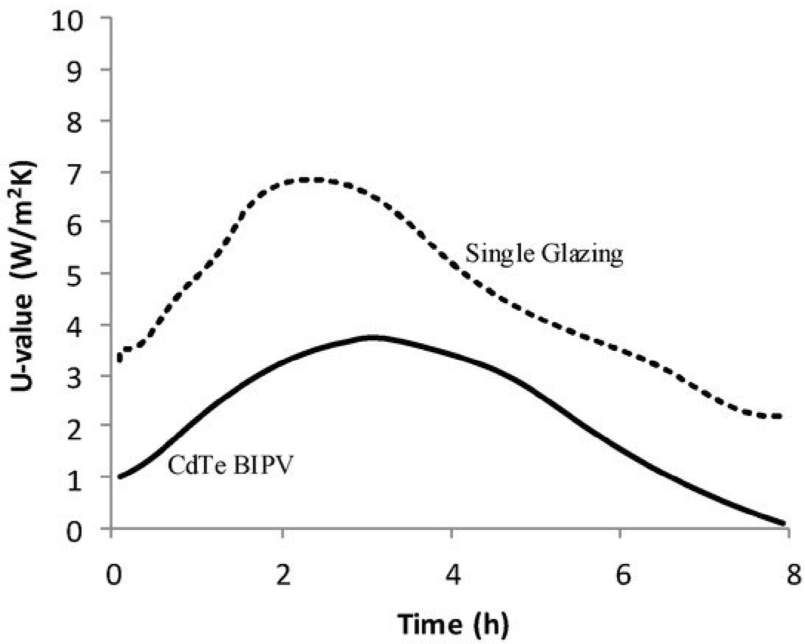

Figure 4. Diurnal variation of thermal transmittance (U-value) of a CdTe BIPV window and a single glazed window–Outdoor test [23].

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

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 [27]. 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) A simulation carried out by [28] 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. VET higher than 30% would have resulted in poor power output and unacceptably high solar gains.

Another interesting study combined the use of semi-transparent BIPV windows and daylight dimming systems [29]. 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%. The research demonstrated lighting energy savings ranging from 3–14%, with the highest levels associated with increased window-transparency. 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.

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