Review of Transparent and Semi-Transparent Building-Integrated Photovoltaics for Fenestration Application Modeling in Building Simulations

Joaquim Romani, Alba Ramos and Jaume Salom

Abstract: Building-integrated photovoltaics (BIPV) have attracted interest due to their capacity to feasibly supply buildings with renewable power generation, helping to achieve net-zero or net-positive energy goals. BIPV systems include many different solutions depending on the application, the PV technology, and the envelope material they substitute. Among BIPV systems, the last two decades have seen a rising interest in transparent and semi-transparent BIPV (T- and ST-BIPV), which add features such as daylighting and solar radiation control. T- and ST-BIPV mainly consist of opaque PV cells embedded in fenestration systems (PV cladding), while most recent research considers semi-transparent PV cells (homogeneous PV glazing) with improved optical properties. The evaluation of T- and ST-BIPV systems in building performance is complex, as it needs to combine optical, thermal, electrical, and daylighting calculations. Therefore, adequate modeling tools are key to the development of these technologies. A literature review is presented on T- and ST-BIPV. First, the types of T- and ST-BIPV technologies present in the literature are summarized, highlighting the current trends. Then, the most common optical, thermal, and electrical models are described, finishing with a summary of the T-and ST-BIPV modeling capabilities of the most common building simulation tools. Regardless of the implemented modeling tools, the main challenges to be considered are the optical model, the inclusion of the PV output in the window energy balance, and the calculation of the cell temperature for the correct assessment of cell efficiency. Modeling research mostly considers conventional PV (Si-based PV and thin-film) technologies, and research studies rarely address the cost evaluation of these T- and ST-BIPV systems.

Keywords: solar energy; building simulation; transparent BIPV; renewable energy; photovoltaic; PV glazing

1. Introduction

Energy consumption in buildings—including offices, homes, and stores—is responsible for about 40% of energy and process-related carbon dioxide (CO₂) emissions [1,2]. Worldwide building energy demand is forecasted to continue growing in the coming decades, mainly because the growth of floor area (2.5% per year) has outweighed the reduction in energy intensity (0.5–1%) since 2010 [3]. Consequently, building greenhouse gas (GHG) emissions must significantly decrease in order to meet the ambitions for a 1.5 °C world or below in 2050 [3,4]. Thus, the challenge is set: to reduce building GHG emissions while the energy demand is predicted to continue growing. In the last few years, this demand has grown by 1.8% per year, and though energy efficiency should come first, it still does not offset service demand growth [3,5].
In Europe, the EU identified in 2010 that the building sector was crucial for achieving EU energy and environmental goals and established a legislative framework that included the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU, each amended in 2018 and 2019, respectively [6]. In December 2019, the EU presented the so-called European Green Deal, aiming to be the first climate-neutral continent by 2050. Reaching this target will require action by all economic sectors, and the EU specifically names building energy efficiency as a key action. For example, all new buildings must be nearly zero-energy buildings (NZEB) from December 2020, and since December 2018, all new public buildings have already needed to be NZEB [7].

Reducing buildings’ environmental impact is a decisive action to stop global warming and make the global economy sustainable. In this context, together with energy efficiency in buildings, on-site renewable energy generation becomes of great relevance. Among all renewable energy technologies, solar-based technologies, and in particular, solar photovoltaics (PV), provide an opportunity for clean energy generation adapted to building designs [8].

The solar resource is the most widely distributed energy resource worldwide, and when it comes to the building integration of solar-based technologies, photovoltaics takes the lead. Building-integrated photovoltaic (BIPV) systems do not only allow on-site clean energy generation but have been proved to lead to substantial energy savings [9]. BIPV systems generate electricity that could be used to meet buildings’ electricity demand. Buildings’ electricity consumption varies depending on the building use, the climate at their location, and the end-supply energy source. However, on average, it represents a quite significant percentage. In the United States and Europe, building electricity consumption makes up about 50% of the final energy usage (and above 70% when considering source-to-site losses) [10], and in China, recent data indicate that electricity accounts for above 55% of the total building energy consumption [11].

BIPV systems are components that are able to generate electricity by integrating photovoltaics (PV) and replacing conventional building components or materials, i.e., in façades, roofs, windows, or skylights [12]. Depending on the technology, BIPV systems can also supply low-temperature heating and reduce thermal demand in the building [13]. BIPV systems have been growing in popularity in the last 20 years. Initially, research focused on opaque BIPV systems, as opaque PV (monocrystalline and multi-crystalline silicon cells) was the first PV technology strongly established in the market. However, thin-film PV cells were rapidly identified as being of interest for BIPV systems since their semi-transparency in the visible range of the solar spectrum—average visible light transmittance (AVT)—allowed for a wide new range of building integration possibilities [14–16]. Nowadays, there are several emerging PV technologies that also present high AVT, and some of them can be produced at a very low cost [17]. Thin-film PV cells and most of the PV emerging technologies are also flexible due to their extremely small thickness of just a few microns, and thus, their integration into curved surfaces is also possible. Therefore, new PV technology development has led to a new trend of semi-transparent and fully transparent BIPV systems (ST- and T-BIPVs) [8,18].

This work focuses on BIPV systems that can be integrated into building windows and skylights, generating electricity, and at the same time, allowing for daylight to enter the interior spaces: transparent and semi-transparent BIPV systems (T- and ST-BIPVs). When addressing the research on these systems, a number of challenges arise. In particular, in the modeling of T- and ST-BIPV systems, daylighting, window optical properties, and electricity production, among other parameters, need to be evaluated at the same time due to their impact on the building energy balance. Modeling is, without any doubt, a key step in the development of T- and ST-BIPVs, allowing for system performance evaluation under different and/or varying scenarios and avoiding the cost of prototyping and tests in the initial steps of the system development. Needless to say, the closer to reality a system model is, the more accurate and reliable its results will be.
The modeling of transparent and semi-transparent BIPV systems is complex; however, it is decisive for the technology’s development. This work presents a review of the modeling of T- and ST-BIPV with the aim of identifying the different approaches and applications implemented, as well as the research gaps. Firstly, the types of T- and ST-BIPV technologies present in the literature are summarized, the current trends are highlighted, and the level of transparency is discussed. Then, the most common optical, thermal, and electrical models are described, followed by a summary of the T- and ST-BIPV modeling capabilities of the most common building simulation tools. Finally, the shortcomings and research gaps are discussed.

2. Types of Transparent and Semi-Transparent BIPV: T-BIPV and ST-BIPV

The literature found on transparent and semi-transparent BIPV systems is not extensive. Most of the publications found refer to semi-transparent BIPV systems, and publications on technologies with high values of average visible light transmittance (AVT) are scarce. In addition, the authors could not find any fully transparent BIPV system in the literature where the modeling of BIPV systems is addressed. It is worth mentioning that typical clear glazing systems in buildings present AVT in the range of 70–80%. Transparent PV for high-end device applications, such as the integration of mobile electronics, are the ones requiring the highest AVT, typically above 80–90% [19]. In fact, for building glazing applications, 100% AVT is not desired; a percentage that optimizes the solar heat gain coefficient (SHGC) and visual comfort is preferred. The desired SHGC, which includes directly transmitted solar heat and absorbed solar radiation that is then reradiated, conducted, or convected into the building, will suffer significant variations according to the building location (latitude and climate) and the percentage of glazed façade, among other factors [20]. Finally, the color rendering index (CRI) is another important parameter for building fenestrations systems. It evaluates the level of perceptible color-tinting of a window, and thus the quality of a lighting system [19].

In the literature, semi-transparent BIPV is usually referred to as a glazing system with inhomogeneous transparency, where the percentage of light that passes through is due to a separation space between encapsulated non-transparent PV cells. These types of ST-BIPV systems are often named PV cell cladding BIPV systems; examples of this technology can be found in references [21–26]. Non-transparent PV cells can be also frame-integrated, allowing for the maximum possible amount of light to pass through the window glass [27]. In this case, the window aperture is transparent, although this area is significantly lower than the overall window area due to the thick frame necessary for the PV cell integration. Gevers et al. [27] presented a prototype of frame-integrated BIPV systems in which the glazing system is used to redirect part of the radiation to the frame, hence also acting as a solar control window. It is worth mentioning that this reference is the only example of this technology found in the literature. Regarding the homogeneous semi-transparency in BIPV systems, often named PV glazing, it is found that it is usually achieved by means of semi-transparent glass-encapsulated thin-film PV cells. An example of a homogeneous semi-transparent module is presented in reference [28].

The following subsection presents the existing literature on the aforementioned T- and ST-BIPV systems in an organized way. The technologies are classified according to the transparency homogeneity, the degree of transparency, and the type of solar PV cells.

2.1. Semi-Transparent and Transparent PV Cells

Before addressing the BIPV system classification, a review of the quality of PV solar cells is presented, identifying those with the potential to be applied in semi-transparent and transparent BIPV systems.

One of the challenges that T- and ST-BIPV systems face is finding PV materials that present good PV conversion efficiencies at a low cost and with a long operating lifetime [29,30], together with transparency and color. In addition, when seeking to maximize the electricity generation per unit area, a larger PV cell surface area and higher PV
efficiency are desired [29]. State-of-the-art, medium/low-cost PV cells with the highest efficiencies are typically non-transparent to the visible range of the solar spectrum (VT), while those that are transparent or semi-transparent usually present low efficiencies and potential low costs [31,32]. The authors of [31,32] have implied so far that a compromised solution between PV conversion efficiency and transparency has been necessary when designing BIPV systems. In fact, there exists a figure-of-merit for T- and ST-BIPV research, the light utilization efficiency (LUE). The LUE is obtained by multiplying the AVT and the PV cell efficiency, and it allows for the evaluation of the performance of these systems for BIPV applications [33,34]. However, despite the importance of this performance parameter for T- and ST-BIPV comparison, it has rarely been evaluated in the T- and ST-BIPV system literature found.

In the last few years, a number of emerging PV cell technologies have appeared, and some of them present promising characteristics for T- and ST-BIPV applications. The current number of different PV technologies has been classified by the Fraunhofer Institute into the following five groups: crystalline silicon (Si) cells, single-junction gallium arsenide (GaAs), multijunction cells, thin-film, and emerging PV technologies [17]. In Table 1, the different PV technologies that are included within each of these groups are presented together with their properties relevant to T- and ST-BIPV applications.

From the information in Table 1, available PV technologies suitable for T-BIPV and ST-BIPV applications can be identified. Basically, we are looking for medium-low-cost technologies with a proven operating lifetime of 20 years or more. Depending on the PV technology transparency properties, it will be suitable for either cell cladding or homogeneous types of applications.

Despite the large number of PV cell technologies presented in Table 1, those based on silicon material (which is the second most common element on Earth [45]) have been dominating global PV production for more than 20 years. As a reference, in 2019, 66% of the worldwide PV production corresponded to single-crystal (c-Si) and Si heterostructures technologies, and 29% to multi-crystalline (m-Si) technology, both summing up to about 95% of the global PV production. The remaining 5% corresponded to thin-film technologies: CdTe, CI(G)S, and a-Si, from major to minor percentages [17].

From the data presented in Table 1, PV technologies presenting low cost and a long-term operating lifetime (more than 20 years) and that are opaque to the visible part of the solar spectrum are: single-crystal (c-Si), multi-crystalline (m-Si), and Si heterostructures (HIT) [17,35]. Therefore, these PV technologies, if applied to BIPV, will lead to a semi-transparent system with non-homogeneous transparency, typically known as cell cladding [14,15].

Multijunction and GaAs solar cells also present a long-term lifespan and, in general terms, higher efficiencies than those of the Si-based technologies, while also being opaque. Their high efficiencies, above 30%, are obtained at the expense of higher manufacturing costs (a few orders of magnitude above other PV technologies; see Table 1). Therefore, these PV technologies are mainly used for spaces or very particular applications where efficiency takes precedence over the cost [36].

PV technologies that are semi-transparent to the visible range of the solar spectrum and have a low cost and long life are mainly the so-called thin-film technologies. In these, the PV cell thickness varies from a few nanometers (nm) to tens of micrometers (µm). Hence, they are much thinner than crystalline Si solar cells, which can use wafers of about 200 µm thick, with the exception of silicon thin-film crystal technology. The thickness of the film, the material used, the process of fabrication, and the deposition method will define the grade of transparency of each different thin-film technology [29]. Moreover, due to the small thickness of these types of PV cells, these technologies are known for being able to make flexible modules (if deposited on flexible substrates), present a homogeneous semi-transparency, and are cheaper than crystalline Si. However, they present lower efficiencies than the latter [18].
Table 1. Classification of PV technologies and properties relevant to BIPV.

<table>
<thead>
<tr>
<th>PV Technology</th>
<th>Best Research—Cell Efficiency (%)</th>
<th>Average Visible Transmittance (AVT)</th>
<th>Cost (€/W)</th>
<th>Operating Lifetime (Years)</th>
<th>Potential ST- and T-BIPV Applications</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline Si</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-crystal (c-Si)</td>
<td>26.1</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>Cell cladding</td>
<td>[17,29,31,35]</td>
</tr>
<tr>
<td>Multi-crystalline (m-Si)</td>
<td>23.3</td>
<td>Opaque</td>
<td>0.40–0.55</td>
<td>&gt;20</td>
<td>Cell cladding</td>
<td>[17,29,31]</td>
</tr>
<tr>
<td>Si heterostructures (HIT)</td>
<td>27.6</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>Cell cladding</td>
<td>[17,29,31]</td>
</tr>
<tr>
<td>Thin-film crystal</td>
<td>21.2</td>
<td>-</td>
<td></td>
<td>&gt;20</td>
<td>Cell cladding</td>
<td>[17,29,31]</td>
</tr>
<tr>
<td>Single-junction GaAs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-crystal Concentrator</td>
<td>27.8</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>-</td>
<td>[17,36]</td>
</tr>
<tr>
<td>Thin-film crystal</td>
<td>29.1</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>-</td>
<td>[17,36,37]</td>
</tr>
<tr>
<td>Multijunction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-junction (concentrator)</td>
<td>35.5</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>-</td>
<td>[17,36]</td>
</tr>
<tr>
<td>Two-junction (non-concentrator)</td>
<td>32.9</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Three-junction (concentrator)</td>
<td>44.4</td>
<td>Opaque</td>
<td>&gt;&gt;30</td>
<td>&gt;20</td>
<td>-</td>
<td>[17,36]</td>
</tr>
<tr>
<td>Three-junction (non-concentrator)</td>
<td>37.9</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Four-junction or more (non-concentrator)</td>
<td>39.2</td>
<td>Opaque</td>
<td></td>
<td>&gt;20</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Thin-film</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIGS</td>
<td>23.4</td>
<td>&lt;30%</td>
<td>-0.55</td>
<td>~20</td>
<td>Homogeneous / cell cladding</td>
<td>[17,18,31]</td>
</tr>
<tr>
<td>CdTe</td>
<td>22.1</td>
<td>~30%</td>
<td>-0.50</td>
<td>&gt;10</td>
<td>Homogeneous / cell cladding</td>
<td>[17,18,31]</td>
</tr>
<tr>
<td>Amorphous Si:H stabilized (a-Si)</td>
<td>14.0</td>
<td>10–25%</td>
<td>-0.35</td>
<td>&gt;20</td>
<td>Homogeneous</td>
<td>[17,18,29,31,38]</td>
</tr>
<tr>
<td>Dye-sensitized cells (DSSC)</td>
<td>12.3</td>
<td>10–50%</td>
<td></td>
<td>-</td>
<td>Homogeneous</td>
<td>[17,29,32,39,40]</td>
</tr>
<tr>
<td>Perovskite cells</td>
<td>25.2</td>
<td>~30%</td>
<td></td>
<td>-</td>
<td>Homogeneous</td>
<td>[17,29,32,39,41]</td>
</tr>
<tr>
<td>Perovskite/Si- and perovskite/CIGS-tandem</td>
<td>29.1/24.2</td>
<td>30–77%</td>
<td>Expected &lt;0.25</td>
<td>-</td>
<td>Homogeneous / cell cladding</td>
<td>[17,29,32,39,42]</td>
</tr>
<tr>
<td>Organic cells (various types) and organic tandem cells</td>
<td>17.4/14.2</td>
<td>20–65%</td>
<td></td>
<td>-</td>
<td>Homogeneous</td>
<td>[17,29,32,39,43]</td>
</tr>
<tr>
<td>Inorganic cells</td>
<td>12.6</td>
<td>20–55%</td>
<td></td>
<td>-</td>
<td>Homogeneous</td>
<td>[17,29,32,39,44]</td>
</tr>
<tr>
<td>Quantum dot (QD) cells</td>
<td>16.6</td>
<td>20–30%</td>
<td></td>
<td>-</td>
<td>-</td>
<td>[17,29,32,39]</td>
</tr>
</tbody>
</table>

1 R&D stage and/or early stages of development.
Among thin-film PV technologies, a broad range of materials and conversion efficiencies can be found: stabilized amorphous silicon (a-Si:H or a-Si), CIGS (copper indium gallium selenide), and CdTe (cadmium telluride) solar cells [17,18]. CIGS cell efficiency and stability are comparable to those of Si solar cells. However, CIGS and CdTe solar cells are slightly more expensive compared to a-Si technology. Regarding CdTe cells’ lifespan, their operating lifetime has been proved to be over 10 years. However, no manufacturer guarantees its lifespan over 20 years [18]. Moreover, while a-Si thin-film solar cells rely on the second most common element on Earth, CdTe and CIGS PV cells use less abundant materials, which is a limiting factor to the industrial scalability. In the particular case of Cd-Te, the toxicity of cadmium adds to the limited availability of the element. [18]. Regarding their AVT, a-Si:H or a-Si are in the range of 10–25%, while CdTe and CIGS can reach 30% [32].

The so-called emerging PV technologies (also called transparent solar cells—TSCs) are promising PV alternatives to ST- and T-BIPV applications given their expected low cost (<EUR 0.25/W) and transparency properties. However, their operating lifetime is still a challenge in some cases [29]. For example, perovskite-based solar cells are most commonly made out of a sandwich-structured metal oxide material, such as TiO$_2$ or Al$_2$O$_3$, and organic transport materials [46,47]. These materials are abundant and also have good properties suitable for solar cells (electric properties, carrier mobility, etc.). However, despite their promising conversion efficiencies (13–25%) and AVT of around 30% (separately), the stability of today’s perovskite-based solar cells ranges from a few days to a few months [32,48]. In addition, perovskite crystal structure can also be combined with silicon (perovskite/Si tandem) and CIGS solar cells (perovskite/CIGS tandem), aiming to reach higher efficiencies and higher AVT, and hence, overcoming some of the challenges of perovskite single-crystal solar cells [49]. Finally, according to Bailie et al. [42], perovskite tandem solar cells’ peak AVT is 77%.

The concept of dye-sensitized solar cells (DSSC) was first presented in the late 1980s. the properties of these types of solar cells make them suitable for BIPV, even though their conversion efficiency has not increased much in the last few years. DSSC, or Grätzel cells, are based on a semiconductor material formed between a photo-sensitized anode and an electrolyte, allowing for electricity conversion with a semi-transparent thin-film material. Their manufacturing process is relatively cheap, and DSSCs present an AVT in the range of 10–50% [29,32,39,50].

In the last few years, research on a number of new organic cells, as well as the concept of organic tandem solar cells, has been published [51–53]. All these organic and organic-tandem solar cells are promising options for BIPV due to their low manufacturing costs, semi-transparency properties (AVT between 20 and 60%), easy integration into other products, and short energy payback times [32,39,43,54]. Moreover, inorganic PV solar cells based on materials other than silicon have been proposed, i.e., carbon-based CsPbI$_2$Br$_2$ solar cells [35]. The advantage of inorganic solar cells is that they present a better match in their band gap energies to the solar spectrum, although a high purity of the materials is required, increasing the cost. Moreover, the absorptivity of inorganic materials is lower than that of organics, meaning thicker (lower-transparency) absorbing layers are needed [54].

The last types of solar cells in Table 1 are quantum dot cells (QDs). These present outstanding optoelectronic properties, which, with a detailed (and thus, expensive) engineering process, may make them suitable for solar cell applications [29]. QD cells are also one of the so-called TSCs and present an AVT between 20 and 30%,. However, their demonstrated maximum PV efficiency is still far below 20% [17,32,39].

Finally, it is worth noting that the maximum AVT values in Table 1 do not correspond to the researched cells’ peak efficiencies. For example, dye-sensitized solar cells (DSSCs) and c-Si-based perovskite cells have shown conversion efficiencies of ~5–7% and over 12%, respectively, at an AVT of 20%; organic- and inorganic-based TPV cells present conversion efficiencies of up to 9.80% and 9.78% (with 38.3 and 9.04% AVT), respectively; QD cells exhibit an AVT in the range of 26–31% for conversion efficiencies between 7.4 and 4.9% [31].
The number of research studies found on ST-BIPV systems, divided according to the aforementioned different PV cell technologies, are presented in Figure 1. About 50% of the research studies have considered thin-film amorphous silicon-based PV cells; while the second and third most common types of PV cells are multi-crystalline (m-Si) and monocrystalline (c-Si), found in 23% and 12% of the studies, respectively. The remaining PV technologies found represent slightly above 10% of the studies. Moreover, none of the so-called emerging PV technologies, according to the Fraunhofer classification [17], have been found in the literature research conducted for this work. However, note that this research is focused on modeling research of ST- and T-BIPV systems; hence, these papers are covered extensively, while only some experimental research has been included in order to better assess the quality of these BIPV systems.

![Figure 1. Numbers and percentages of research studies found on the different PV technologies.](image)

2.2. Semi-Transparent and Transparent BIPV

In the last few years, the number of research publications on ST- and T-BIPV systems have been increasing. Publications found on the topic can be divided into two main groups: cell cladding and homogeneous PV glazing systems. The first ones are glazing systems with no homogeneous transparency, thus allowing the integration of both opaque and semi-transparent PV cells. The second ones are those presenting a homogeneous AVT, typically lower than 80%—as discussed at the beginning of this section—and thus, integrate semi-transparent PV cells. There also exist some ST-BIPV systems that cannot be integrated within these two main groups as frame-integrated systems, which have been briefly mentioned above.

Figure 2 presents the research studies found on ST-BIPV systems classified into these three different types (cell cladding, homogeneous PV glazing, and frame-integrated). Except for one research study, which represents 2%, all studies found are divided almost equally between the cell cladding (46%) and homogeneous PV glazing (52%) types of ST-BIPV systems.
2.2.1. Cell Cladding

Almost half of the research studies found on ST-BIPV systems are the cell cladding type, thus mainly considering opaque PV solar cells. Furthermore, Si-based PV technologies are represented in more than 90% of these studies.

Research on cell cladding systems based on c-Si PV cells has been addressed in [21, 24, 56, 57]. All of these papers present modeling research supported by experimental validation, except [56]. Cell cladding systems based on m-Si PV cells are also found in [26, 58–63]. Again, all of these papers focus on modeling except for [63], in which the electrical and thermal performance of a semi-transparent PV module was investigated, showing a 0.48–0.52% power decrease per 1 °C increase, and that module glass properties affected the PV module temperature, and thus, its electrical performance.

ST-BIPV systems based on c-Si, m-Si, and/or a-Si PV cells have been studied in [64–68]. In [67], experimental research monitoring a greenhouse prototype with a cell cladding system of flexible thin-film (a-Si) modules was conducted, obtaining an annual electricity production of 8.25 kWh per square meter of ground greenhouse surface for a 9.79% cover occupation with the thin-film modules. In [22, 69], modeling research on cell cladding ST-BIPV systems has been conducted. However, the PV technology considered is not described in their work.

Finally, in [70], modeling research on cell cladding ST-BIPV systems considering a number of different PV technologies is presented; modules integrating c-Si, m-Si, a-Si, CdTe, CIGS, and HIT PV cell types were analyzed.

2.2.2. Cell Cladding/Homogeneous PV Glazing

Some studies have also addressed research on both cell cladding and homogeneous PV glazing ST-BIPV systems. Ref. [71] presents a review of architectural approaches for ST-BIPV systems in China. In [72, 73], modeling research with experimental validation has been conducted. The authors of [73] studied the integration of m-Si, a-Si/µc-Si, and organic PV semi-transparent modules, while those of [72] limited their research to m-Si and a-Si PV modules. The authors of [74] conducted modeling research considering various types of PV technologies (c-Si, m-Si, a-Si, CdTe, CIS, and HIT PV semi-transparent modules). Finally, ref. [75] analyzed aspects linked to human comfort when using semi-transparent BIPV elements. PV technologies considered were m-Si, a-Si, and CIS, and the results of their research claim to be a new way to investigate the characteristics of ST-BIPV systems, measuring, for example, human comfort via thermal comfort and lighting conditions.
2.2.3. Homogeneous PV Glazing

A significant number of research papers on homogeneous PV glazing types of ST-BIPV systems were found. With the exception of [76–78]—research works that have studied TiO₂, TCO (ZnO), and organic PV cell technologies, respectively—the rest of the literature found on this topic was based on amorphous silicon thin-films: a-Si, a-Si:H, and/or a-Si/µc-Si. In [77], thin-film cell manufacturing processes for in-built applications are addressed. Their research on TCO films resulted in an excellent transmittance (>82%) in the whole wavelength range of photovoltaic interest, and a stabilized efficiency of >10% was obtained for micro-morph tandem devices. The technology for a Gratzel cell type (Titania) was studied in [76], presenting the potential for the manufacturing of low-cost semi-transparent PV modules and their multiple applications. The research presented in [78] is limited to the modeling of ST-BIPV systems.

The vast majority of the research works found on homogeneous PV glazing systems focus on modeling [28,38,79–89]. However, there are a few research papers based on experimental work. In [90], the shading effect on the performance of two ST-BIPV systems based on a-Si PV was analyzed, and in [91], an experimental study on hydrogenated amorphous silicon (a-Si:H) PV cells (color-stable and semi-transparent) was conducted. In [92], the power output of an a-Si PV building-integrated module was characterized depending on the solar incidence angle; the results indicated that a slope of 30° facing south provided the best annual power performance (about 2.5 times higher than that with the vertical module). In [85], the outdoor performance of a naturally ventilated ST-BIPV façade was evaluated through field monitoring, observing that a reduction of 15.6 °C in the module temperature of the thin-film solar cell only leads to a decrease of 0.29% in the conversion efficiency.

Finally, some research work addressed different calculations regarding ST-BIPV system performance. For example, in [93], generation calculations for the roof and façade integration of a-Si PV modules were conducted, and in [94], case studies based on a generic reference building were conducted to obtain energy and cooling requirements as well as the cost implications when lighting controls were being used. In the first study, a 4000 t CO₂ reduction per MW of PV installed was obtained. The latter research concluded that the integration of these types of systems does not only produce clean energy but also helps to reduce the cooling load and electrical lighting requirements, obtaining overall annual electricity benefits for water/air-cooled systems of about 900/1300 kWh.

2.2.4. Frame-Integrated

A research work that was not able to be classified among the above was found. A highly transparent PV window was studied by Gevers et al. [27], with a Tvis above 75% and filtering about 95% of IR and UV radiation. However, in this case, the PV device was placed at the edges of the frame, and the glazing system reflected and refracted the UV and IR to the edges of the panel. Therefore, the PV production was not on the glazing itself, either with distributed PV modules or with a transparent film, although the glazing system was used to redirect the radiation to the frame. This technology stands out from other frame-integrated BIPV systems [95] in which the frame material is substituted by PV cells exploiting the solar radiation that falls directly on it.

3. Semi-Transparent and Transparent BIPV Modeling for Fenestration Applications

The interest drawn by T- and ST-BIPV for glazing applications has resulted in a significant amount of simulation research. As PV glazing impacts the heating, cooling, and lighting loads, as well as the visual and thermal comfort, its evaluation requires some complex modeling. Therefore, different modeling tools are used depending on the goals and scope of the research. This section summarizes the main models used considering the optical (including daylighting), thermal, and electrical parts. Simulation research articles for T- and ST-BIPVs considered in this section are listed in Table 2. Section 3.1 describes the models that were developed for specific research, mostly by developing a custom
code. Then, Section 3.2 describes the BIPV research done with existing building simulation software, sometimes including complementary developments. Finally, it was found that electric models had common points in most of the research studies, and hence, these are summarized in Section 3.3.

3.1. T- and ST-BIPV Custom Models

The custom models were classified into four groups according to the main purpose of the research: models for the estimation of window parameters; 1D models for cell temperature and efficiency calculation; 2D models to study ventilation and convection effects within air gaps or rooms; other models. The main feature used to group the models was the thermal and energy balance. It was found that the optical models or equations are not usually described, and hence, the following descriptions highlight those that specify them. Finally, as mentioned above, the electric modeling is described in a specific section.

Note that the current section presents a comprehensive review of the modeling of T-and ST-BIPV models. Despite the interest in the topic, there are relatively few studies on modeling the performance and impact of these technologies.

3.1.1. Models for the Estimation of Window Parameters

Some models were designed for obtaining the window characterization parameters (usually the thermal transmittance (U-value) and solar heat gain coefficient (SHGC)), taking into account the PV effect. In this sense, Infield et al. [62] proposed a methodology for estimating the thermal behavior of a photovoltaic–thermal (PVT) double semi-transparent façade. The transmission losses and ventilation gains were described with four parameters (thermal transmittance ($U_{\text{trans}}$), ventilation thermal transmittance ($U_{\text{vent}}$), solar gain ($g_{\text{trans}}$), ventilation solar gain ($g_{\text{vent}}$)), which were calculated by the 1D single-node energy balance, including the electric production on the PV surface. Alternatively, Misara et al. [96] developed a 1D power balance model for a PV window for calculating the U, SHGC, and solar reduction ratio (Fc) values. The model introduces the electrical output and thermal mass in the energy balance. The power balance model was validated and used to identify the heat transfer coefficients and heat transmission coefficients in the cavities in PV windows, highlighting that the normative methods and heat transfer coefficient values used in the calculations of the U, G, and Fc are not applicable to PV windows. The study concluded that the models need to be adjusted to include the internal heat sources of PV modules and the new thermal parameters, such as the internal and external heat transfer coefficient and heat transfer coefficient of insulated glass.

3.1.2. D for Cell Temperature and Efficiency Calculation

One-dimensional models assume heat transfer only in the direction perpendicular to the window surface, and hence, consider the glass panes or material layers as isothermal, as shown in Figure 3. These were implemented for the evaluation of the thermal behavior and PV efficiency of transparent BIPV, focusing on the calculation of the temperature of the cell and the electric output and usually disregarding the visual comfort impact of the system. The number and position of the nodes were determined by the requirements of the research.
Figure 3. One-dimensional model for single- and double-glass semi-transparent PV glazing system [72].

Wah et al. [72] simulated laminated glazing by modeling each layer with a custom 1D model with one node per layer plus inner and outer surface nodes; see Figure 3. The model considers the thermal mass of the layers, solar absorption only in the PV cell layer, PV production included in the energy balance, and PV efficiency calculated with an adaptation of the Evans and Florschuetz correlation [97]. The model was validated by identifying the temperature coefficient, overall heat transfer coefficients, and visible light transmission.

Similarly, Fung and Yang [60] modeled PV cladding using a 1D model with just one node per layer. The PV layer had different equations for the opaque cells and transparent sections. The optical behavior was modeled with Fresnel relations for the incident and refracted components. The PV output was calculated with the constant PV efficiency. The model was validated and used to evaluate the heat gain, finding that the cell efficiency and module thickness had minor influence, while the main contributor was the solar gain. A similar thermal model was validated by Sánchez-Palencia et al. [21], although without detailing the optical calculations, highlighting the need for a critical review of the current standards for the thermal characterization of the BIPV modules, especially by demonstrating that the overall heat transfer coefficient should include the effect of irradiance.

A different approach was used by Delisle [98] for modeling double and triple curtain walls containing PV laminate glazing. Here, the model considered only one node per glazed pane. The results showed that the electric output was maximized with the PV on the outer pane of the window, while installing it in the middle pane reduces the electric yield but also reduces the heating loads. A similar methodology was used by Meraj and Khan [22] on a PV laminate with transparent and opaque back sheets, finding that the semi-transparent module had a lower temperature and better efficiency. This BIPV modeling approach was also implemented and validated to evaluate a building with a PV cladding roof [57], finding a good fit with the room temperature, PV cell temperature, and efficiency. However, as the inverter was not modeled, the efficiency at a low generation did not match, as the real inverter was not working at the maximum operation level.

3.1.3. 2D models to Study Ventilation and Convection Effects within Air Gaps or Rooms

More detailed 2D models were implemented into ST- and T-BIPV windows by including the heat transfer on the vertical axis. These were implemented in order to evaluate the impact of natural and forced convection in the window gaps or rooms. Therefore, the models discretize also the air gaps or parts of the rooms, with a special focus on the modeling of the air dynamics. The 2D approach allows for the accurate calculation of the
temperature profile of the air circulating in the ventilated gaps or in the room, improving the heat transfer, ventilation, and PV efficiency results. An example is shown in Figure 4.

![Figure 4. Two-dimensional model for a ventilated double-sided PV façade [85].](image)

Chow et al. [99] developed a 2D model for a ventilated double-glazed window. The heat transfer axis was the depth and height of the window, with the model considering the thermal mass of the nodes and the PV production. The daylighting calculations were performed in parallel with EnergyPlus. The combined model was used to compare the PV output, heat transmission, daylight, and energy use depending on the orientation and transparency, finding that the optimal transparency was found in the range of 0.45–0.55. A similar modeling approach was developed and validated by Han et al. [80]. The study provides accurate heat transfer coefficients for a see-through glazing system with the integration of ST-BIPV with naturally ventilated air gaps. As a further step, the model was also used to study an open-ended channel air cavity [85] by implementing a finite-difference technique [100]. In the cases studied, the temperature of the cavities was lower with PV. However, the lower temperature had little effect on the PV efficiency. Another application of 2D models for T- and ST-BIPV was to study the room ventilation—hence, air stratification—impact on the window performance [83]. Here, a Fluent Software model was developed and experimentally validated. Room displacement ventilation was found to reduce the average cell temperature and increase the efficiency compared to mixing ventilation.

3.1.4. Other Models

T- and ST-BIPV models were developed for other specific cases. Simple room models were also developed; for example, Robinson et Athienitis [101] made a whole room model to evaluate the impact of PV cladding on the impact of lighting and PV production. The model used the eight-surface room radiosity theory after infinity interreflections [102,103] for daylighting calculations. The PV output was estimated by calculating the nominal operating cell temperature (NOCT) and using the correlation from [97]. This model was experimentally validated and used to discover that the semi-transparent photovoltaic (STPV) façade could improve the overall energy performance compared to opaque PV due to the significant daylighting benefits at even low transparency ratios. The optimal PV area ratio was found to be between 80 and 90% for all façade orientations and PV efficiencies.

Furthermore, neural network methods have also been applied to T-and ST-BIPV modeling. Pérez-Alonso et al. [67] used experimental data from a greenhouse prototype using PV cladding to train a neural network. The inputs to the model were ambient temperature, ambient relative humidity, wind velocity, wind direction, and solar irradiation, and it calculated the PV production, with a maximal instantaneous error below 20 W.
depending on the complexity of the model (note that the maximum PV output was close to 1500 W).

3.2. Modeling T- and ST-BIPV in Building Simulation Tools

T- and ST-BIPV were mostly modeled with EnergyPlus, TRNSYS, and ESP-r, the former being the most frequently used.

3.2.1. EnergyPlus

EnergyPlus [104] is a well-established building energy simulation program to model energy consumption, including heating, cooling, ventilation, lighting, plug, and process load, as well as water usage.

EnergyPlus contains different options for modeling the energy balance of windows. First, a simple window model uses only the thermal transmittance (U-value) and solar heat gain coefficient (SHGC) as input parameters. This model considers the glazing system as an equivalent single layer whose properties (glass-to-glass thermal resistance, thickness, conductivity, solar transmittance, solar reflectance, and visible properties) and angular performance are calculated according to the correlations and weighting factors according to the U and SHGC.

Second, a layer-by-layer approach uses the glazing optical and thermal calculation algorithm from WINDOW [105], which is based on ISO15099 [106]. This is a one-dimensional approach considering the nodes at each glazed pane surface (see Figure 5), and also allowing for the calculation of the air temperature in the ventilated gaps and shadings. Hence, this model accounts for the heat conduction between the glass pane surfaces, long-wave radiation, and convection heat exchange between glass panes and indoor space. In order to calculate the energy balance of the window, the solar balance needs to be calculated beforehand in order to obtain the solar absorptance. The layer-by-layer approach allows for calculating the window transmittance, reflectance, and absorption per layer depending on the angle of incidence [107]. Alternatively, there is a complex fenestration system model using a bidirectional scattering distribution function (BSDF), which allows for introducing a shading calculation, which still uses the ISO15099 [106] model for the energy balance calculation.

EnergyPlus also allows for integrating PV into the building surfaces, including windows. With this, the electricity generated is subtracted from the surface energy balance and the efficiency can be linked to the glazing temperature. In this regard, EnergyPlus allows for introducing the PV efficiency either as user input or using an equivalent one-diode model (four-parameter model) or the Sandia National Laboratory model.
One main implementation of EnergyPlus is to evaluate the ST- and T-BIPV transmittance optimization, window-to-wall ratio, and façade orientation while comparing it to conventional windows. The goal is to optimize the overall energy performance, considering lighting, heating, and cooling energy use. The relevance or consideration of these loads depends on the climatic zone. The following paragraphs describe the cases found in the literature and their main findings.

Miyazaki et al. [87] studied the impact of a double-glazed PV window on the energy consumption of an office building in Tokyo. The results showed that the best savings were achieved with daylighting control strategies. A better PV window configuration was 40% transmittance and a 50% window-to-wall ratio, with energy savings of up to 55% depending on the orientation. Ng et al. [81] compared different commercially available windows (single-glazed clear glass, double-glazed clear glass, double-glazed with low-e glaze, and double-glazed with low-e tinted glass) and semi-transparent BIPV systems (six combinations of thin-film and amorphous silicon modules in a single- or double-glass configuration) in Singapore, finding that all BIPV units outperformed conventional windows by reducing the overall energy use (including heating, cooling, lighting, and PV output). Moreover, high diffuse skylights in Singapore allowed for good performance of the PV systems even in orientations without direct solar gains. A similar study was performed by Olivieri et al. [79] on five semi-transparent PV systems in Spain, but they complemented the EnergyPlus calculations with an evaluation of the visual comfort with COMFEN [108]. The results showed that ST- and T-BIPV achieved energy savings between 18 and 59%, with the best savings found in the cases of the lowest transparency of the ST- and T-BIPV and high window-to-wall ratio configurations. In contrast, Kapsis and Athienitis [73] evaluated a double-glazed ST- and T-BIPV cladding window in an office building in Toronto, finding that the window-to-wall ratios, façade orientation, and lighting power density did not affect the selection of the ST- and T-BIPV optical properties. In addition, Didoné and Wagner [78] compared the performance of semi-transparent thin-film PV with a conventional window in a sample office building. While the energy savings found were between 19 and 43% depending on the climatic conditions, the authors highlighted the limitations of transparent PV window modeling at the moment. The PV production of the window could not be introduced in the window energy balance; hence, the authors’ approach was to modify the reflectance of the window in order to account for the PV effect. The lighting energy consumption was calculated with data obtained from a Daysim [109] model.

Chow et al. [99] focused on optimizing the transparency of a double-glazed ventilated window with PV cladding in Hong Kong. The authors evaluated the PV output, heat transmission, impact on daylighting, and energy consumption using a combination of custom models and EnergyPlus. The former was used for energy balance and the latter for daylighting calculations, finding optimal transparency in the range of 0.45–0.55 for minimizing cooling and lighting consumption. A similar approach and system were evaluated by Wong et al. [58] in residential building roofs. In this case, the semi-transparent system provided few lighting savings, as occupants were absent during the day, and some overheating was found in the summer. The system reduced the heating load, but the optimization of the window heat transmittance (adding transparent insulation) and transparency (through shading) was found to be necessary depending on the climatic conditions.

Validation studies on EnergyPlus models were also found in the literature. Peng et al. [28] developed and experimentally validated a small room in the Hong Kong model with a thin-film PV double-skin façade with four openable windows with interior venetian blinds. Wang et al. [110] also experimentally validated a model with an insulated glazed unit including laminate a-Si. The model was later used for optimization of the air gap depth and rear side glass type of the glazed unit configuration according to the Hong Kong climate. The objective optimization function was the overall annual energy performance. The optimized configuration achieved savings of 25.3% and 10.7% compared to single clear glass and low-e glass windows. This same model was also used by Zhang et al. [38];
here, ST- and T-BIPV achieved savings of 18% and 16% compared to clear single- and double-pane glazing and a performance very similar to low-e glazing.

3.2.2. TRNSYS

TRNSYS [111] is a simulation environment for the transient simulation of systems, including buildings. It contains an extensive library of components (called Types), each programmed to model a specific part of the system. Among these, TRNSYS contains different building models of various levels of detail. For BIPV modeling, the most usual is to implement Type 56 [112], a multi-zone building model that allows for detailed calculations of the building’s thermal behavior. It includes 3D features that allow for also implementing detailed radiation and daylighting calculations. In this regard, Type 56 can use two window models, both of which can use inputs generated by the glazing and window modeling software OPTICS [113] and WINDOW [105] in order to characterize the optical and thermal characteristics of the glazing system. The simplified window model reduces the complex thermal and optical behavior into a two-node model that connects the ambient with the indoor space. Hence, the simplified window model provides limited information on the panes and air gap temperature. On the other side, the complex fenestration model allows for modeling up to six panes, using a bidirectional scattering distribution function (BSDF) optical model and performing the energy balance according to ISO 15099 [106]. However, Type 56 does not implicitly include tools for modeling transparent BIPV, although it includes a feature to add heat gains at the inner and outer surfaces, which was used to simulate greenhouses [24,114].

De Boer et al. [115] used TNSYS Type 56 to model a cell cladding system in façades, roofs, and awnings in the Madrid (Spain) climate. The model optical properties were calculated with the weighted area between the transparent and opaque sections, but it did not specify if the PV output was included in the energy balance. Different transparency levels were studied through the variation of the cell spacing, determining that lower transparency led to higher glazing (hence, cell) temperatures. However, the associated decrease in efficiency was offset by the increase in the active surface. Bambara et Athienitis [24] also used area-weighted optical properties [114] for modeling a cell cladding in a greenhouse, although, in this case, the PV output was included in the window energy balance. The research focus was on the life cycle cost (LCC) of different cell cladding designs in Ontario (Canada), finding that with the current efficiencies of the PV and lighting technologies, the solution is not economically attractive, although reductions of 30% of the LCC were foreseen.

TRNSYS Type 56 was also used to compare ST- and T-BIPV with other window solutions. Bahaj et al. [68] compared thin-film photovoltaics with other emerging glazing technologies, such as electrochromic glazing, holographic optical elements (HOE), and aerogel glazing in the Dubai climate. They concluded that integrated thin-film was the most promising solution for fully glazed high-rise buildings in the Middle East, as a PV solution covering about 40% of the area would yield a net energy gain over the air conditioning loads.

Alternatively, TRNSYS includes different Types (individual models) for PV and PVT modeling. Specifically, the TESS package [116] includes the Types for BIPV modeling (Types 563, 566, 567, 568, and 569) that are designed to work together with Type 56. While these Types are not specifically designed for transparent PV, some authors have used them to model the cell temperature and efficiency [117–119]. This approach was used by Yang et al. [117] in a preliminary study on semi-transparent PV glazing on a double module in Sydney (Australia), showing its capabilities of buffering heat gains and reducing overheating in summer, as well as the reduction of heat loss during winter. Then the authors used the same modeling strategy to compare the thermal loads of single-skin, double-skin (DSF) non-ventilated, and double-skin ventilated semi-transparent PV glazing configurations [118], finding reductions in the heating load with non-ventilated DSF and reductions in the cooling loads with ventilated DSF. Finally, the research was extended
to different climates in Australia [83], identifying the suitable configurations of a semi-transparent PV glazing system for each.

Another modeling approach was performed by Cipriano et al. [120]; they modeled cell cladding using a TRNSYS Type 56 window model for the transparent sections, and coupled it with a custom model for the cell section using the usual equation formulation of non-transparent photovoltaics.

3.2.3. ESP-r

ESP-r [121] is an open-source integrated modeling tool for building simulations that has also been used for transparent BIPV modeling. It allows for assessing the thermal, visual, and acoustic performance of buildings. The software accounts for shading and insolation patterns, explicit radiation view factors, façade-integrated photovoltaic modules, temperature-dependent thermo-physical properties, CFD domains for fluid flow, and electrical distribution systems. ESP-r is based on a finite volume approach algorithm in which windows are modeled as two-layer virtual surfaces, each having effective optical and thermal characteristics. Interestingly, the window model considers the thermal mass by default.

Chow et al. [89] used ESP-r for modeling a thin-film translucent-type (effective transmittance of 0.1) PV double-glazed window. This model was experimentally validated, and later, it was used for the evaluation of the annual thermal load of the electricity generation of the BIPV system compared to common absorptive glazing, concluding that the PV system could reduce the air conditioning consumption by 28% in Hong Kong office buildings. Yoon et al. [88] also used ESP-r to evaluate the solar radiation distribution on a façade incorporating transparent thin-film PV, evaluating the actual orientation of a building vs. the optimal orientation for maximizing the PV production. Finally, Heim et al. [82] evaluated a triple-glazed window with a transparent thin-film layer on the external surface, concluding that the proposed system could protect against overheating while maintaining window transparency. However, the authors pointed out that the electric production was low, and experimental validation was required. Moreover, aspects such as light color and other visual aspects were not evaluated, although these are key for acceptable office work conditions.

3.3. Electrical Modeling of T- and ST-BIPV

While many options were found in the optical and thermal modeling of T- and ST-BIPV, as detailed in the previous sections, the electrical models followed a similar approach in most cases. Almost all models relied on indirect methods (power calculation) with direct power calculation, according to Rus-Casas et al. [122] classification. These methods obtain the power from some atmospheric parameters and information provided by the manufacturers in the datasheets. The operation at a maximum power point is assumed, considering that the PV cells operate at the point of the intensity–voltage (IV) curve that yields the maximum output power. Among these, most of the research studies relied on the correlation of Evans and Florschuetz [97], shown in Equation (1). This is already the most commonly used correlation for PV efficiency; as summarized in Table 2, 14 of the 33 models reviewed use this correlation or a modified version. Some modifications of the correlation have been suggested in the literature, including parameters such as low radiation, incidence angle, and no ideal inverter, among others. A second solution used was one-diode equivalent circuits models; see Figure 6. These were implemented assuming that the module operated under the maximum operation point [73,82,84]. However, this approach also allowed for modeling the interaction with the inverter, hence allowing for system design and operation optimization. Finally, the third approach identified was the Sandia National Laboratory model [38,110,123], exclusively used by EnergyPlus users. However, this model relies on experimental data that are not readily available, making
specific use for ST- and T-BIPV difficult. Research studies using the Sandia model have used the available generic thin-film a-Si.

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

(1)

where \( \eta_c \) is the effective efficiency, \( \eta_{ref} \) is the nominal efficiency at reference conditions, \( \beta_{ref} \) is the temperature coefficient, \( T_c \) is the cell temperature, and \( T_{ref} \) is the temperature at reference conditions (usually 25 °C).

![One-diode equivalent circuit for PV performance modeling.](image)

**Figure 6.** One-diode equivalent circuit for PV performance modeling.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Tool</th>
<th>Cell Type</th>
<th>Integration Type</th>
<th>Optical Model</th>
<th>Thermal Model</th>
<th>Electric Model</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain (Madrid)</td>
<td>2001</td>
<td>TRNSYS</td>
<td>c-Si</td>
<td>Single-pane cell cladding</td>
<td>TRNSYS</td>
<td>PV effect not included in the energy balance.</td>
<td>Temperature-dependent, but not specified</td>
<td>[115]</td>
</tr>
<tr>
<td>Spain (Mataró)</td>
<td>2004</td>
<td>Custom</td>
<td>m-Si</td>
<td>Double-skin ventilated façade with outside skin cell cladding</td>
<td>Not specified</td>
<td>1D (longwave radiation considered for PV thermal model)</td>
<td>Not specified</td>
<td>[62]</td>
</tr>
<tr>
<td>Japan (Osaka)</td>
<td>2005</td>
<td>Custom</td>
<td>p-Si</td>
<td>Single-pane cell cladding (p-Si) or homogeneous PV glazing (a-Si)</td>
<td>Constant optical properties.</td>
<td>Custom 1D model. 1 node per layer plus surface nodes. Thermal mass considered. PV production introduced in energy balance.</td>
<td>Modified Evans and Florschuetz [97]</td>
<td>[72]</td>
</tr>
<tr>
<td>China (Hong Kong)</td>
<td>2007</td>
<td>FORTRAN</td>
<td>a-Si</td>
<td>Double-glazed window with PV cell cladding</td>
<td>Ray tracing. Daylighting with EnergyPlus.</td>
<td>2D model with one node per layer in depth direction.</td>
<td>Evans and Florschuetz [97]</td>
<td>[99]</td>
</tr>
</tbody>
</table>

Table 2. Summary of simulation research articles for T- and ST-BIPV reviewed.
Table 2. Cont.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Tool</th>
<th>Cell Type</th>
<th>Integration Type</th>
<th>Optical Model</th>
<th>Thermal Model</th>
<th>Electric Model</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan (Kagoshima, Osaka, Matsumoto, Aomori, Sapporo)</td>
<td>2008</td>
<td>Custom + EnergyPlus</td>
<td>Double-glazed window with cell cladding</td>
<td>EnergyPlus</td>
<td>1D model considering one node per material in the laminate, plus nodes in the inner and outer surfaces coupled to EnergyPlus.</td>
<td>Evans and Florschuetz [97]</td>
<td>[58]</td>
<td></td>
</tr>
<tr>
<td>China (Hong Kong)</td>
<td>2008</td>
<td>Custom m-Si</td>
<td>Single-pane cell cladding</td>
<td>Fresnel relations</td>
<td>1D model, several nodes.</td>
<td>Not specified</td>
<td>[60]</td>
<td></td>
</tr>
<tr>
<td>United Arab Emirates (Dubai)</td>
<td>2008</td>
<td>TRNSYS</td>
<td>Homogeneous PV glazing</td>
<td>TRNSYS</td>
<td>TRNSYS</td>
<td>Not specified</td>
<td>[68]</td>
<td></td>
</tr>
<tr>
<td>Canada (Yellowknife, Montreal, Iqaluit)</td>
<td>2008</td>
<td>Custom c-Si</td>
<td>Double- and triple-pane window with cell cladding</td>
<td>Not specified</td>
<td>Custom 1D model with one node per glass. PV output included in the PV laminate energy balance.</td>
<td>Evans and Florschuetz [97] modified to include low radiation effect.</td>
<td>[98]</td>
<td></td>
</tr>
<tr>
<td>Spain (Lleida)</td>
<td>2008</td>
<td>TRNSYS</td>
<td>Cell cladding</td>
<td>TRNSYS for transparent part. IAM for beam radiation with Fresnel equations for opaque cells.</td>
<td>TRNSYS</td>
<td>1D finite elements. Includes thermal mass. Does not include PV production.</td>
<td>Temperature- and radiation-dependent. Uses transmittance-absorptance factor modified by IAM.</td>
<td>[120]</td>
</tr>
<tr>
<td>China (Hong Kong)</td>
<td>2009</td>
<td>ESP-r</td>
<td>Double-skin ventilated façade with homogeneous PV glazing</td>
<td>Simplified diffuse irradiance model for tilted surface from [124]</td>
<td>ESP-r</td>
<td>ESP-r expression developed in the frame of JOULE PV-HYBRID-PAS project [125].</td>
<td>[89]</td>
<td></td>
</tr>
<tr>
<td>Canada (Montreal)</td>
<td>2009</td>
<td>Custom c-Si</td>
<td>Cell cladding</td>
<td>Radiosity theory after infinite interreflections from [103]</td>
<td>None. Nominal operating cell temperature.</td>
<td>Evans and Florschuetz [97]</td>
<td>[101]</td>
<td></td>
</tr>
<tr>
<td>Korea (Yongin)</td>
<td>2011</td>
<td>ESP-r</td>
<td>a-Si PV glazing</td>
<td>ESP-r</td>
<td>ESP-r</td>
<td>Not specified</td>
<td>[88]</td>
<td></td>
</tr>
<tr>
<td>Standard operation conditions</td>
<td>2011</td>
<td>Custom m-Si</td>
<td>Single-pane cell cladding</td>
<td>Constant</td>
<td>Power balance of window. Includes electrical output and thermal mass.</td>
<td>Evans and Florschuetz [97]</td>
<td>[96]</td>
<td></td>
</tr>
<tr>
<td>Spain (Almería)</td>
<td>2012</td>
<td>Custom a-Si</td>
<td>Cell cladding</td>
<td>-</td>
<td>-</td>
<td>Experimental data used to train artificial neural network for predicting PV output.</td>
<td>[67]</td>
<td></td>
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## Table 2. Cont.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Tool</th>
<th>Cell Type</th>
<th>Integration Type</th>
<th>Optical Model</th>
<th>Thermal Model</th>
<th>Electric Model</th>
<th>Ref.</th>
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<tr>
<td>Hong Kong</td>
<td>2013</td>
<td>Custom</td>
<td>-</td>
<td>Double-skin façade homogeneous PV glazing</td>
<td>Not specified</td>
<td>2D, applied to cavity air flow.</td>
<td>Not used</td>
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<td>Poland (Lodz)</td>
<td>2015</td>
<td>ESP-r</td>
<td>a-Si:H</td>
<td>Triple-glazed homogeneous PV glazing</td>
<td>ESP-r multi-layered. Energy balance of special node representing PV cell, where electricity production is subtracted from absorbed solar radiation.</td>
<td>ESP-r multi-layered. Empirical one-diode model assuming maximum power point operation. Consider temperature dependent short circuit current and open voltage, but constant shape factor.</td>
<td>[82]</td>
<td></td>
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<tr>
<td>Location</td>
<td>Year</td>
<td>Tool</td>
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<td>Integration Type</td>
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<td>Electric Model</td>
<td>Ref.</td>
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</tr>
<tr>
<td>China (Hong Kong)</td>
<td>2016</td>
<td>EnergyPlus</td>
<td>a-Si</td>
<td>Double-skin façade homogeneous PV glazing</td>
<td>EnergyPlus multi-layer model. PV integrated in outside surface face of window.</td>
<td>Sandia Power Module for thin-film model [128]</td>
<td>[123]</td>
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<td>China (Hong Kong)</td>
<td>2016</td>
<td>EnergyPlus</td>
<td>a-Si</td>
<td>Double-glazed homogeneous PV glazing</td>
<td>EnergyPlus</td>
<td>Sandia Power Module [128] [110]</td>
<td>[110]</td>
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<td>China (Hong Kong)</td>
<td>2016</td>
<td>EnergyPlus</td>
<td>a-Si</td>
<td>Single-pane homogeneous PV glazing</td>
<td>EnergyPlus</td>
<td>EnergyPlus. PV electrical generation included in energy balance.</td>
<td>Parameters validated in [129].</td>
<td>[38]</td>
</tr>
<tr>
<td>Australia (Sydney)</td>
<td>2017</td>
<td>TRNSYS</td>
<td>a-Si</td>
<td>Double-skinfacade with homogeneous PV glazing.</td>
<td>TRNSYS</td>
<td>TRNSYS + TRNflow for ventilated façade. PV electrical generation not included.</td>
<td>Evans and Florschuetz [97]</td>
<td>[117]</td>
</tr>
<tr>
<td>Australia (Sydney)</td>
<td>2018</td>
<td>TRNSYS</td>
<td>a-Si</td>
<td>Double-skinfacade with homogeneous PV glazing.</td>
<td>TRNSYS</td>
<td>TRNSYS + TRNflow for ventilated façade. PV electrical generation not included.</td>
<td>Evans and Florschuetz [97]</td>
<td>[118]</td>
</tr>
<tr>
<td>India (New Delhi)</td>
<td>2019</td>
<td>MATLAB</td>
<td>-</td>
<td>Cell cladding</td>
<td>Constant optical properties.</td>
<td>MATLAB 1D model for the whole device.</td>
<td>Evans and Florschuetz [97]</td>
<td>[22]</td>
</tr>
<tr>
<td>Spain (Madrid)</td>
<td>2019</td>
<td>MATLAB</td>
<td>-</td>
<td>Single-pane cell cladding</td>
<td>Constant optical properties.</td>
<td>MATLAB 1D model with a node per material in the laminate.</td>
<td>Evans and Florschuetz [97]</td>
<td>[21]</td>
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<tr>
<td>China (Shenzhen)</td>
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<td>FLUENT</td>
<td>a-Si</td>
<td>Single-pane homogeneous PV glazing</td>
<td>Constant optical properties.</td>
<td>2D (height/depth) window model. Room air distribution model with FLUENT.</td>
<td>Evans and Florschuetz [97]</td>
<td>[83]</td>
</tr>
<tr>
<td>Canada (Ontario)</td>
<td>2019</td>
<td>TRNSYS</td>
<td>c-Si</td>
<td>Single-pane cell cladding</td>
<td>TRNSYS simple window. Cladding modeled with effective approach, area weighting the opaque and transparent sections.</td>
<td>TRNSYS simple window. PV effect modeled as negative heat gain on the outdoor surface.</td>
<td>Evans and Florschuetz [97]</td>
<td>[24]</td>
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<table>
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<th>Electric Model</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>2019</td>
<td>TRNSYS</td>
<td>a-Si, Perovskite</td>
<td>TRNSYS</td>
<td>TRNSYS +</td>
<td>TRNflow for ventilated façade.</td>
<td>None</td>
<td>[119]</td>
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<td>(Sydney, Darwin, Canberra)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>2020</td>
<td>MATLAB</td>
<td>c-Si</td>
<td>Single-pane cell cladding</td>
<td>Constant</td>
<td>MATLAB 1D single node model for the whole device.</td>
<td>Evans and Florschuetz [97]</td>
<td>[57]</td>
</tr>
<tr>
<td>(Varandi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>optical</td>
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</table>

4. Discussion

Typical glazing systems in buildings are said to present an average visible transmittance (AVT) in the range of 70–80%. However, these values may need to be much lower in low latitude locations and hot climates. Similarly, in high latitudes and cold climates, AVTs above 80% could be desired, aiming in all cases to optimize the solar heat gain coefficient (SHGC) and daylight of the building. In addition to the AVT, the quality of a lighting system (evaluated by means of the color rendering index, CRI) is another key parameter in building fenestration systems. This parameter, which is of vital importance for the final user acceptance, is widely disregarded in the research studies found. Therefore, T- and ST-BIPV systems must seek to meet the optimum AVT and CRI values for each particular building application.

Research conducted on the T- and ST-BIPV systems, shows two main types of building applications—cell cladding and homogeneous PV glazing (with non-homogeneous and homogeneous transparency, respectively). On the one hand, non-homogeneous ST-BIPVs allow for integrating the Si-based PV technologies, which are opaque and represent the vast majority (<95%) of the global PV market, into the building fenestrations. On the other hand, homogeneous PV glazing systems are the ones exhibiting—or have the potential to exhibit—properties and aesthetics very close to those of standard building fenestration systems.

Among state-of-the-art PV cell technologies, mainly those already established in the market and of relatively low cost (<0.6 EUR/W) were found to have been studied in detail for T- and ST-BIPV applications. Medium-low-cost PV cell technologies already established in the market, opaque Si-based PV (c-Si, m-Si, and HIT), and semi-transparent thin-film PV (a-Si, CdTe, and CI(G)S) cells are not the only ones presenting great potential for glazing applications in buildings. There are a number of emerging (transparent) PV technologies (DSSC, perovskites, perovskite/Si- and perovskite/CIGS-tandem, organic or inorganic cells) presenting interesting AVT percentages (in the range of 20 to 80%) and with the potential of being manufactured at a very low cost. Thus, they present the potential to meet the desired AVT and CRI values in buildings integrated with homogeneous PV glazing systems. From the literature review conducted, focusing on the T- and ST-BIPV system modeling, it stands out that only a single study considered the integration of these emerging transparent PV cell technologies, including perovskite, in building envelopes (see Figure 7). Thus, further research on T- and ST-BIPV modeling integrating these new PV cell technologies is needed to narrow down their real potential for building glazing applications.
Within the modeling literature, two main lines of research could be observed regarding T- and ST-BIPV. On one side, custom detailed models were used to assess the thermal behavior and PV efficiency of the cells. Usually, these were implemented in 1D models for the heat transfer through PV windows. More detail was added in the research, including the evaluation of ventilation effects and convection heat transfer coefficients, which implemented 2D models to account for the temperature gradient in the vertical axis. This type of research was usually related to experimental validation. However, it was observed that the optical calculations were not always described in the papers. On the other side, the evaluation of T- and ST-BIPV was also implemented with common building modeling tools. Here, the focus was to evaluate the overall impact of these systems on the building performance, and thus, considered the impact on lighting, heating, and cooling. Nevertheless, some shortcomings were also found in this type of research. The building modeling tools offer different window models, but few articles detail which are implemented in the presented research. Moreover, the tools used do not have specific models for T- and ST-BIPV, yet researchers have proposed solutions for modeling these technologies using the currently available inputs and outputs to the window models. However, it was found that some articles did not specify if the PV output was included in the window energy balance or if the cell temperature calculation was linked to the window. Furthermore, most modeling articles reported very different data on the systems’ optical and efficiency performance. Therefore, a need was identified to review how T- and ST-BIPV optical and thermal models are developed and reported. Specific points to solve include the need to consider the thermal mass of the window, including the PV output in the window energy balance, and the calculation of the cell temperatures in laminates included in complex fenestration systems (i.e., double- and triple-glazing). In addition, validation studies were performed mainly on custom models, but a lack of validation of the models implemented in building simulation tools was identified. Only two EnergyPlus studies [28,110] and one using ESP-r [89] included comparisons with experimental data.

As an interesting finding, all of the research highlighted the capability of T- and ST-BIPV for reducing the building energy use in different types of buildings and climates. The research studies considered highlighted the relevance of the location and orientation, as well as the envelope design (i.e., window-to-wall ratio), daylighting control strategies (shading and automatic light control), and ventilation strategies that need to be considered in the selection of the optimal T- and ST-BIPV, for which most researchers focused on the balance between transparency and efficiency. This optimization needed to be performed considering the impact on heating, cooling, lighting loads, and PV output; hence, different authors proposed a similar metric for summarizing the overall impact: net electricity benefit (NEB) [65], energy balance index (EBI) [79], and overall annual energy performance [110]. Despite this, in the literature review conducted, few studies have considered the cost
or economics of these BIPV applications. While the energy savings and the operational costs are often considered, an effort of this research may be the need to evaluate the profitability of these systems for different building types, locations, and climates. Moreover, not only from the economical view but also from the sustainability point of view, the life cycle cost analysis (LCA) should be considered. In this regard, there is an economic need to consider the impact of the variable pricing of electricity and the feed-in tariffs for exported electricity [13]. Furthermore, the scenario of a high penetration of PV in the energy market needs to be taken into account, as electricity prices may drop, such as the “super-valley” tariff implemented by the California Independent System Operator in 2013 [130]. Moreover, none of the studies evaluated the comfort and indoor air quality (IAQ). A common conclusion was that ST- and T-BIPV impact the building thermal behavior, yet the thermal comfort has not been addressed in any of the reviewed studies. The different temperatures of BIPV windows may affect the radiant temperatures of rooms, cause radiant asymmetry, and, as result, thermal discomfort. Moreover, while the daylighting was often taken into account, the visual comfort and occupants’ perceptions were not evaluated. Finally, some research highlighted that T- and ST-BIPV affect the U-value and SHGC of the windows [21,73], mainly by reducing the SHGC, compared to its optical properties alone. Hence, the standardization of these systems needs to be reviewed. This was already considered in the PVSTES project [131], in which a method for calculating the solar factor was proposed [132]. It is also a part of the BIPVBoost [133] project goals, and it is included in IEA Task 15 [134].

Finally, the locations of the studies found on T- and ST-BIPV, see Figure 8, show that China is leading the simulation research on the topic. The next most represented country is Spain, followed by Canada, Australia, and Japan. This trend is representative of the countries with good BIPV potential, favorable legislation, and/or good economic and research capabilities. Moreover, up to 14 of the 33 studies reviewed included at least one reference city in a low-latitude location, with Hong Kong alone appearing up to six times. However, none of the studies have addressed the shift of solar spectra to shorter wavelengths in lower latitudes [135]. This affects the PV performance, with the larger band gap cells (a-Si and CdTe) being more sensitive.

![Figure 8. Countries included in T- and ST- BIPV simulation studies.](image-url)
5. Conclusions

A review was conducted on the simulation research of transparent and semi-transparent building-integrated photovoltaics (T- and ST-BIPV) for fenestration applications. Although the topic has attracted a lot of research over the last two decades, it was found that there is not a common nomenclature for the different systems implemented, as semi-transparent systems were used for both cell-cladding (with spaced opaque cells) and thin-films with low visible transmittance.

Transparent and semi-transparent BIPV systems have evolved in line with PV cell technology development, from opaque PV cells embedded in fenestration systems—cell cladding—to homogeneous PV glazing systems with homogeneous transparency. The latter, when integrating emerging transparent PV technologies, presents the potential to exhibit properties and finishes very close to those of standard buildings’ fenestration systems. However, regarding T- and ST-BIPV modeling, only a single study considered the performance of one of these emerging PV cell systems integrated into a building’s envelope. The modeling research has mostly considered conventional PV (Si-based PV and thin-film) technologies.

The main modeling challenges identified are the optical model, the inclusion of the PV output in the window energy balance, and the calculation of the cell temperature for the correct assessment of the cell efficiency. The review highlights that different modeling approaches have been developed from custom models with simplified or physical models to the use of building modeling tools. The results of the review point to some gaps in the modeling and simulation studies of ST- and T-BIPV:

- Uniform reporting of ST- and T-BIPV properties;
- Inclusion and validation of default T- and ST-BIPV models in the building simulation tools;
- Economic evaluation accounting for variable electricity prices and feed-in tariffs in scenarios of a high penetration of renewable energies;
- Evaluation of emerging PV technologies’ impact on the building environment;
- Evaluation of the low-latitude impact on PV performance;
- Evaluation of the impact on thermal and visual comfort.

Nevertheless, all the research agrees on the great potential for the reduction of buildings’ energy demand with T- and ST-BIPV. Beyond solving the modeling and data report discrepancies and addressing the aforementioned challenges, the next research steps must include the emerging transparent PV technologies as well as the full assessment of the life cycle from both the economic and environmental points of view.


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

AVT Average visible light transmittance
BIPV Building-integrated photovoltaics
BSDF Bidirectional scattering distribution function
a-Si Amorphous silicon
a-Si:H Hydrogenated amorphous silicon
CdTe Cadmium telluride
Cl(G)S Copper indium (gallium) selenide
CRI Color rendering index
c-Si Crystalline silicon
DSF Double-skin façade
DSSC Dye-sensitized solar cells
EBI Energy balance index
Fc Solar reduction ratio
\( g_{\text{trans}} \) Solar gain
\( g_{\text{vent}} \) Ventilation solar gain
GaAs Gallium arsenide
GHG Greenhouse gases
HIT Silicon heterojunction solar cell
HOE Holographic optical elements
IAQ Indoor air quality
LCA Life cycle cost analysis
LCC Life cycle cost
m-Si Multi-crystalline silicon
NEB Net electricity benefit
NOCT Nominal operating cell temperature
NZEB Net-zero energy building
PV Photovoltaic
PVT Photovoltaic–thermal
QD Quantum dot
SHGC Solar heat gain coefficient
STPV Semi-transparent photovoltaic
ST-BIPV Semi-transparent building-integrated photovoltaics
T-BIPV Transparent building-integrated photovoltaics
TCO Transparent conducting oxide
TiO\(_2\) Titanium dioxide
TSC Transparent solar cells
\( U_{\text{rms}} \) Thermal transmittance
\( U_{\text{vent}} \) Ventilation thermal transmittance
ZnO Zinc oxide

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