Abstract: Global energy consumption has led to concerns about potential supply problems, energy consumption and growing environmental impacts. This paper comprehensively provides a detailed assessment of current studies on the subject of building integrated photovoltaic (BIPV) technology in net-zero energy buildings (NZEBs). The review is validated through various case studies, which highlight the significance of factors such as building surface area to volume ratio (A/V), window-wall ratio (WWR), glass solar heating gain coefficient (SHGC), and others in achieving the NZEBs standards. In addition, this review article draws the following conclusions: (1) NZEBs use renewable energy to achieve energy efficiency and carbon neutrality. (2) NZEBs implementation, however, has some limitations, including the negligence of indoor conditions in the analysis, household thermal comfort, and the absence of an energy supply and demand monitoring system. (3) Most researchers advise supplementing facade and window BIPV as solely roofing BIPV will not be able to meet the building’s electricity usage. (4) Combining BIPV with building integrated solar thermal (BIST), considering esthetics and geometry, enhances outcomes and helps meet NZEB criteria. (5) BIPV designs should follow standards and learn from successful cases. However, to ascertain the long-term reliability and structural integrity of BIPV systems, a comprehensive study of their potential degradation mechanisms over extended periods is imperative. The review paper aims to examine BIPV applications in-depth, underscoring its pivotal role in attaining a net-zero energy benchmark.

Keywords: building-integrated photovoltaic; PV; net zero energy buildings

1. Introduction

Global energy consumption is increasing at an alarming rate, emanating potential supply issues, energy depletion, and environmental repercussions. The energy demand in the building sectors is soaring, particularly in industrialized nations, culminating in several ecological challenges [1,2]. In fact, 36% of the world’s energy consumption is attributed to building activities, which are responsible for 39% of the global carbon dioxide emissions [3]. This emphasizes the critical role of the construction sector in the broader context of global energy and environmental challenges, thereby underlining the urgent need for sustainable solutions and practices in this field. The multilateral institutions have called for collective actions of governments to combat climate change, with the famed Kyoto Protocol [4] and Paris Agreement spotlighting the necessity for rapid actions. Net-zero energy buildings (NZEBs) is widely regarded as an eminent step towards addressing the rising energy demand in the building sector.

NZEBs are structures that generate at least as much energy annually as they use [5]. In 2010, the European Parliament passed a directive mandating all new structures to be ‘virtually zero energy’, beginning from January 2021 [6]. Furthermore, France has urged the transition into energy-efficient buildings by 2020 [7]. Correspondingly, the US Department
of Energy (DOE) aims for ‘Saleable zero-energy houses by 2020 and commercial zero-energy buildings by 2025’ [8]. The report ‘Net Zero by 2050’ [9] advocates that between 2020 and 2050, the size of the construction industry will also expand by 75%, consequently increasing the demand for electrical appliances and air-conditioning equipment in buildings. Thus, substantial energy-efficient retrofits to the building’s air conditioning and electrical systems will be necessary to lower emissions by more than 95% by 2050 [9]. Building integrated photovoltaic (BIPV) is a globally acclaimed technology harnessing solar energy, aiding the transition into NZEBs [10].

The paper aims to critically review the application of BIPV, while demonstrating its significance in achieving the net-zero energy status. Unlike previous review articles about BIPV systems and NZEBs, this paper provides a comprehensive analysis of the integration of BIPV technology in different climatic regions, along with specific guidelines for designing BIPVs in Section 7, which sets this work apart from other reviews. Section 2 elucidates the concept of NZEBs, while Section 3 concentrates on the application of BIPV in depth. The significance of BIPV is detailed in Section 4 by comparing it with the properties of building attached photovoltaic (BAPV), followed by the shading systems in Section 5. The performance of BIPV is well conceived once its application outcomes are analyzed, which is attempted in Section 6. Finally, the guidelines for designing BIPVs are highlighted in Section 7, followed by the conclusion of the study. The paper demonstrates that the use of BIPV technology in buildings is one of the fundamental ways to achieve net zero energy consumption in buildings and the way forward. Additionally, this paper makes unique contributions by proposing novel methods of integrating BIPV with existing structures, offering new insights into energy efficiency, and encouraging the advancement of emission reduction in the building industry in the future.

2. Net-Zero Energy Buildings (NZEBs)

2.1. Definition of NZEBs

NZEBs are low-energy buildings that use renewable energy to offset annual energy usage [5,11]. NZEBs encompass multiple objectives, such as net-zero energy, zero energy costs, and net-zero emissions [12,13]. The NZEB concept’s emphasis has changed due to the widespread concern on the use of fossil fuels and the resulting incentives for renewable. Several nations have committed to achieving carbon neutrality by 2050, striving to keep the temperature rise to less than 1.5 °C (relative to pre-industrial levels), and NZEBs play a crucial role in achieving this goal [11]. To realize NZEBs, various nations and organizations have implemented the necessary policies and programs. The UK is one of the first nations to make the NZEBs widely required, intending to produce zero-carbon houses by 2016 [11,14]. Additionally, all new commercial constructions in the United States must have net-zero energy by 2025 [15], and the American Institute of Architects (AIA) has suggested a practical plan for the built environment to attain net-zero emissions by 2030 [11].

Furthermore, efficient NZEBs employ proven and affordable technology to lower energy consumption and pollutant emissions while maintaining financial viability during the lifespan of the building. Compared to conventional structures, NZEBs significantly improve the built environment by using low-carbon building materials, energy-saving practices, and carbon-neutral renewable energy, making them more affordable and safer for human health [11,16].

2.2. Energy Sources in NZEBs

Generating more electricity from renewable sources or lowering the energy consumption of the building are two prominent methods to attain NZEBs. Regardless of the contextual definitions, NZEBs are composed of (a) connection to energy infrastructure such as the grid, (b) employing conventional methods to decrease the energy requirement, and (c) deploying renewable energy systems to generate electricity [12].

Firstly, the NZEBs are connected to the grid, which is the most popular link in the energy infrastructure, enabling import and export of power. However, due to the timing
mismatch between renewable energy supply and building demand, the demand to generate electricity entirely through renewables is difficult (i.e., on winter nights when heating is needed but solar energy is not available) [12,17]. When renewables are scarce, the grid can fill the supply gap and receive electricity when it generates more than the building needs. The surplus energy can heat the district heating and cooling networks or stored in batteries. However, regional energy networks are only present in a few places and energy storage is still relatively expensive, necessitating further investment for construction [12,18]. Moreover, energy loss is inevitable in the process of conversion. The grid is a desirable energy infrastructure for NZEBs due to its ease of linking, and lack of extra infrastructure Networks of natural gas pipelines play a crucial role in the energy sector [12].

The natural gas pipeline network is another critical energy infrastructure. However, its utilization is exclusive to energy import and must be combined with alternative energy systems to export renewable energy [12]. Though synthetic natural gas (SNG) may be exported to the grid, the procedure requires high technical skills and is expensive. Furthermore, coal-to-gas production is more plausible to be done on a utility-scale than for individual residences [17].

The renewable energy sources that have been well utilized include solar, wind, biomass [12] and geothermal, with solar energy being the prominent one [19]. The off-site energy can be availed from the utility providers as electricity, heat or combined [12,17]. The ease of installation [20,21], affordability, and availability augment the preference for on-site solar photovoltaic (PV) systems [22].

In addition, the adoption of renewable energy technologies, especially PV technologies, should be tailored based on the characteristics of different climatic zones, to concurrently enhance the electro-thermal performance of buildings, thereby facilitating a more efficient transition to low carbon and low energy buildings [23,24]. For example, Agrawal and Tiwari [25] discovered that using solar cells in the BIPV/T system on a laboratory building’s roof provides advantages in meso-cool climates regarding both yearly energy and exergy outputs when compared to conventional BIPV systems. Furthermore, in hot climate regions, photovoltaic windows made from thin-film modules offer a strategy to reduce heat ingress, with empirical data suggesting up to a 31% decrease in annual cooling load, furthering the move towards low-energy and low-carbon architectural designs [26]. For Semi-transparent PV (STPV) demonstrates enhanced energy-saving capabilities in cold temperate areas, such as Beijing and Harbin, while its performance falters in warmer regions such as Guangzhou. In contrast, vacuum photovoltaic technology, besides being suitable for temperate climates, can amplify the air conditioning needs under various climatic scenarios while diminishing the overall energy consumption of buildings [27]. Therefore, before choosing different PV technologies in the building, it is necessary to consider the suitability of the technology and the climate conditions in the building location to more effectively realize the low energy consumption and low carbonization of the building, and then make the building more effectively realize NZEBs.

2.3. Solar Energy Application for NZEBs

Solar energy can be harnessed through PV, solar thermal or a combination of both [12]. Among these, PV systems are frequently used to achieve the NZEBs target [28]. The on-site generation is achieved either by installing BAPV or BIPV [28,29]. BAPV modules are typically superimposed on the surface of an existing finished structure, such as a building roof. However, BIPV replaces the exterior construction elements with materials integrated with solar modules. [29].

NZEBs also rely on solar water heaters, which employ a fluid medium to transfer the heat from the surface of PV, commonly used for generating warm water and regulating indoor temperature [30]. A seasonal thermal energy storage system may be utilized to store extra heat produced in the summer and discharged in the winter [30]. Solar air heaters are another variety that can be employed for room heating, ventilation, and
garment drying [12]. Renewable energy systems based on different energy sources may be integrated to maximize power output under spatial constraints.

Numerous studies have concentrated on the utilization of solar energy systems in NZEBs. In the subtropical regions of Hong Kong, where elevated cooling demands prevent achieving net-zero energy solely with solar PV, Fong and Lee [31] attempted to maximize the utilization of renewable energy by installing solar PV panels on the exterior walls and roofs, along with the flat solar collectors on the roof. An NZEB with a co-generation organic Rankine cycle (ORC) system that circulates water heated by a solar collector and chilled by a solar-powered absorption chiller was examined by Hassoun and Dincer [32]. The ORC uses a low-temperature boiled ammonia solution with a rated turbine capacity of 15 kW connected to a battery pack. The combined heat and power generation (CHP) produces electricity, cool air and hot water while consuming electricity from the pump and solar thermal energy [32].

Good et al. [33] studied Norwegian residential NZEBs, having PV/Thermal, PV/Solar collector, and PV panels. The findings indicate that covered PV/Thermal might provide more energy than solar thermal collectors, making them the optimal choice. Ballarini et al. [34] studied the impacts of building envelope insulation, installation of solar power systems, and efficient artificial lighting systems and observed a 38% reduction in energy demand for NZEBs. To meet the requirements of net-zero energy consumption rural house (NZERH), Jiang et al. [35] designed a combination of foam cement insulation envelope and BAPV system and observed that the solar panels on the rooftop, followed by the south east facade, possessed maximum power efficiency. Furthermore, the solar system generated enough power to cover the building’s heating and energy needs.

The integration of solar energy into building cooling and heating systems primarily adopts two distinct strategies. First, as discussed predominantly in this paper, is the electric-driven approach where energy harnessed from PV panels directly powers the building’s air conditioning system, facilitating both heating and cooling. Conversely, the second strategy involves the conversion of solar radiation to thermal energy, thereby providing heat to the building [36]. However, this approach is predominantly suited for heating requirements of building, primarily sourcing providing hot water. Some technologies have combined solar thermal technology with heat-driven chillers to provide cooling for cooling networks. These can be divided into Absorption and Adsorption categories, but they are not widely used at the current stage [36]. Interestingly, many solar-assisted heating, ventilation, and air conditioning (HVAC), hot water supply and other building electricity systems amalgamate these methods, which named PV/Thermal systems, but even not yet been applied on a large scale [37,38]. In summer, solar-derived hot water serves as a heat source, assisting heat pumps in supplying warmth to interiors. Nevertheless, the majority rely on solar power generation to mitigate the electrical consumption of building air conditioning and other usage.

3. Building Integrated Photovoltaics (BIPV)

BIPVs are incorporated aesthetically into the building design or as functional components of the building construction, making them difficult to distinguish from traditional building materials [10]. BIPV modules have unique advantages over conventional PV modules to suit building and construction specifications better. The BIPV panels encompass PV laminates bonded with PV cells using encapsulants, with protective covers at the front and rear sides of the panels [10]. Ethylene-vinyl acetate (EVA) and polyvinyl butyral (PVB) are the commonly used encapsulating materials [39]. Furthermore, glass laminates are often used to sandwich PV cells, commonly called PV glass laminate (PVGL) [40]. The mechanical characteristics of the laminate are influenced by the properties of the glass sheets and the sealant. To increase the thermal insulation of glass assemblies, PV glass laminates can be used as the top layer of double or multi-layer glazing units [41]. Additionally, low emissivity (Low-E) coating or vacuum seals may be applied to the glass panes to improve the thermal insulation of the PV vacuum insulating glazing unit [42]. Furthermore,
depending on the application, materials such as glass, metals or polymers may be used as the PV back sheet [10]. Notably, the latest combination of photothermal/photovoltaic (PV/T) can be installed on exterior surfaces such as facades, windows, roofs and sunshades to provide electrical and thermal energy [43].

Solar cells may be generally categorized into three generations depending on the adopted technology and material selection. While the single crystal (sc-Si) or multicrystalline (me-Si) silicon-based structures make up the first category [44,45], cadmium telluride (CdTe), cadmium sulfide (CdS), and amorphous silicon make up second-generation solar cells [45]. The recent technological advancements have led to the formation of the third-generation solar cells made of organic photovoltaics (OPVs), perovskite solar cells (PSC), and dye-sensitive solar cells (DSSCs); which do not involve silicon [45,46]. The properties of BIPVs allow the versatility to be installed on discontinuous and continuous roofs, also known as ‘continuous roofs,’ are characterized by their level nature, yet they too can be utilized for solar PV deployment (Figures 1 and 2 show the examples of discontinuous and flat roofs, respectively). However, one challenge in optimizing the energy capture from solar panels is the non-optimal angle of inclination or azimuth of roofs, which reduces energy production. This issue can affect both types of roofs but is particularly significant for continuous or flat roofs where the inclination is non-adjustable or constrained [48]. The first generation solar panels were commonly purposed to be roof-mounted [49], while the emphasis turned to self-bearing and light systems in the second generation. Further advancements have enabled solar cell integration into building perimeters using flexible films, solar floors, and similar technologies.

3.1. Application on Roof

The roofs undoubtedly possess enormous potential for capturing solar energy. Many photovoltaic roof application solutions have been developed over the past few years, from BAPV to waterproof solar tiles [47]. Moreover, photovoltaic modules have replaced and integrated the original building components with the building. While the inclination of discontinuous roofs offers a suitable location for solar PV installation, providing an angle that can capture solar energy, flat roofs, also known as ‘continuous roofs,’ are characterized by their level nature, yet they too can be utilized for solar PV deployment (Figures 1 and 2 show the examples of discontinuous and flat roofs, respectively). However, one challenge in optimizing the energy capture from solar panels is the non-optimal angle of inclination or azimuth of roofs, which reduces energy production. This issue can affect both types of roofs but is particularly significant for continuous or flat roofs where the inclination is non-adjustable or constrained [48].

![Figure 1. Examples of discontinuous roofs BIPV projects [50,51].](image-url)
The most recent trend in energy harnessing is complete roof systems, which cover the entire roof in solar panels (see Figure 4). Additionally, by incorporating solar panels into the entire roof, esthetics of the structure will be enhanced with minimal structural changes and functional disruptions [60]. However, roof solutions necessitate specialized materials and installation systems [61].
3.1.3. Solar Tiles and Slates

Solar tiles or slates are synonymous with traditional roof tiles, with integrated PV cells of different sizes and compositions. Generally, a single solar tile covers an area over 0.5 m$^2$ and may be composed of foils or glazes [53,62]. The similarity of solar tiles to the traditional ones nullifies the aesthetic challenges, blending delightfully with conventional black flat roofs (see Figure 5). As opposed to “large solar tiles”, the smaller ones feature modules that are less than 0.5 m$^2$ with a configuration not influencing the appropriateness for its application [63,64]. Different thin-film solar cell technologies are used in different sorts of semi-rigid systems, such as roof tile PV, roof panel PV, exterior window glass panel PV, and exterior wall PV panel [65]. The roof is often only partially or wholly utilized for solar photovoltaics, with the installation system’s structure being the same as roof tiles [53].

The thermal properties and cooling requirements of PV roof tiles have been studied, with the resistance-capacity (RC) model revealing a relationship between thermal resistance and heat capacity, dependent on environmental conditions [66]. Another study emphasized the importance of an air gap for cooling, finding that larger gaps are required to prevent overheating and enhance efficiency [67]. These characteristics may constrain the application of PV tiles in certain architectural settings, reflecting limitations in their adaptability.

![Figure 4](image1.png)

**Figure 4.** Example of full roof BIPV solution, Novartis Campus’s full roof BIPV [61].

![Figure 5](image2.png)

**Figure 5.** Examples of solar tiles, (a) large solar tiles [68]; (b) small solar tiles [69].

3.1.4. PV Membranes

The flexibility of PV membranes enables the utilization of the solar potential of intricate roof designs. A few members of the technological family of flexible PV devices include thin-film organic photovoltaics (OPV), thin-film silicon, and thin-film copper indium gallium selenide (CIGS) [70–72]. PV flexible laminates can either be attached to the manufacturers’ general construction materials, such as the waterproofing membranes or directly applied
to the existing exterior surfaces (see Figure 6). Additionally, the PV membranes can be mass-produced effortlessly, unfolding the suitability for a rapid transition into NZEBs. The PV membranes possess superior energy efficiency and enormous economic potential, and they are also simple and convenient to install [73].

![Figure 6. Example of PV membranes on the roof [74].](image)

### 3.2. Application on Façade

Integrating solar modules with the building facades can maintain the original function, safety and aesthetic requirements and facilitate electricity generation throughout the year. Moreover, these arrangements can effectively minimize thermal leakage from the interior of the buildings [75]. Depending on the type of application, façade BIPVs are classified into shutter-type photovoltaic power generation systems and window photovoltaic power generation systems [76]. The installation methods of BIPV are designed considering the local climate, building characteristics and user requirements.

#### 3.2.1. Photovoltaic Glass

Laser-scored thin films make glass-based PV panels with filtering effects in crystalline silicon cells with variable pitch [53] (see Figure 7). Extruded aluminum, steel, and timber frames—commonly used in windows or transparent curtain walls—typically make the panels [77]. Due diligence should be maintained to parameters related to the interior temperature, visual comfort and esthetics when employing a high-density glass curtain wall as the building’s exterior [78]. The PV glass panel replaces the building’s light-transmitting functional layer (glass) and integrates the photovoltaic film and conductor wires present. This battery pattern and the combination can replace generic outside shutters, giving a distinctive look to the building’s façade. In order to create architectural light and shadow effects, glass-glass photovoltaic stacks with adjustable light transmittance are commonly used in construction [78].

![Figure 7. Examples of photovoltaic glass: (a) installation of photovoltaic glass on the building’s roof [79]; (b) photovoltaic glass as building curtain wall [79].](image)
3.2.2. Warm Façade

Warm facades are insulation-glazed PV modules aiding in achieving thermal insulation while weather- and sound-proofing the facades (see Figure 8). Furthermore, it is essential to incorporate thermal insulation and visual comfort criteria into designing warm facades [80]. Warm façades are frequently represented by opaque curtain walls or insulating cladding panels without air gaps (such as PV + no air gap insulation) [53].

![Figure 8. Example of warm façade application in Zermatt, Switzerland [81].](image)

3.2.3. Cold Façade

Compared to warm facades, cold façade systems often comprise load-bearing sub-frames, air gaps, and cover panels (see Figure 9). In summer, the air circulates naturally through the holes behind the panel, which can absorb and reduce the working temperature of the PV panel [82]. The structure resembles a ventilated wall with air movement through the gap between the PV panel layer and the façade, cooling the building facade and improving the efficiency of the components [82].

![Figure 9. Example of cold façade, east façade of Palazzo Positivo [83].](image)
3.3. Application as Shading

The PV cells can also be integrated into the shading structures, such as the balconies, to improve energy generation [53]. The systems use appropriate natural light to regulate the interior temperature and lighting, especially in glass curtain wall systems, to maintain indoor temperature and visual comfort [84]. The flexibility of the BIPV to be installed in shading structures such as lamellar, micro lamellar, sails, grids, curtains, blinds, and moveable screens propels the marketability of the system [84,85]. Such approaches simplify the integration of solar cells into shading systems.

4. BIPV vs. BAPV

4.1. Comparison between BIPV and BAPV

PV technology is a clean energy production method that uses solar radiation to generate electricity directly [86]. The photons in the sunlight knock off the electrons in the solar cells, resulting in the flow of electricity. Monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/sulfide are the common materials employed to generate electricity [87,88]. The demand for BIPV is surging globally because of its functional and esthetically pleasing features. In order to shed more light on BIPV, it is essential to compare its features against the traditional ones.

BAPV are the traditional PV modules that are mounted directly over the exterior surfaces of the buildings, such as the roofs [88]. Unlike the conventional PV system, BIPVs are integrated into the external surfaces, replacing the traditional envelope components, and acting as the functional components while not affecting the esthetics of the buildings. Although twin optoelectronic modules may also be installed in older structures, PV systems are progressively being employed as a principal or supplementary energy source in the construction of new buildings [10]. In terms of electricity production, while BIPV may produce lower electricity values than BAPV, its benefits extend beyond mere power generation [30]. For instance, it can enhance wall insulation, leading to savings on heating costs [89]. In addition, compared to the more prevalent attached PV systems, integrated PV can offset the initial cost by lowering the cost of construction materials and labor in the building segments that the BIPV module replaces. However, owing to the complexity of manufacturing, installation, and maintenance challenges, BIPV has a substantially greater overall cost than BAPV, even if counterbalancing the expenditure on roofing, façade, or glazing materials [90]. Contrastingly, BAPV not only makes PV modules overlap with the building envelope, but the models are also uncomplicated in their installation and have the potential for easy expansion [88,90]. Typically, BIPV and BAPV applications employ first-generation cells [91], while the second and third-generation cells are mainly considered for BIPV applications.

The BIPV modules intended to be installed in window segments typically employ first- to third-generation PV cells to control daylight, interior heating, and esthetic application. However, second-generation PV cells are commonly employed in BIPV foils and tiles. The shallow stability of third-generation PV cells is a limitation despite the fact that they are occasionally chosen. The foils are often used as shading for the building against harsh external environments, similar to photovoltaic tiles, with tad attention given to the cell’s power generation [91]. First- or second-generation PV cells are typically utilized in BAPV modules. The lower flexibility of BAPV restricts its use to mainly being installed on roofs [92]. Zhu et al. [93], in their study, indicate that for the same roof area, compared with coal-fired power generation, BIPV and BAPV reduce the emission of pollutants by 129.48 and 102.67 t, respectively, during their lifecycle, with a unit emission reductions of 14.10 and 14.38 kg/W. Several examples of BAPV and BIPV panels are shown in Figure 10a–d. Figure 11 illustrates the various shading types that are generally used in buildings.
Figure 10. (a) BIPV is fitted on the southward facade and roof of the ZICER building at the University of East Anglia, UK, (b) inside perspective of the BIPV facade, (c) BAPV has been installed on the facade that faces southwest, with a 10 cm air clearance between the c-Si PV modules and the wall of the edifice, (d) in Norwich, UK, a residential structure has a BAPV system on its roof (Reproduced with permission from Ref. [94]. Copyright 2022 Elsevier).

Figure 11. Various shading types (Reproduced with permission from Ref. [95]. Copyright 2022 Elsevier).
4.2. Differences in Efficacy and Functionality

The most significant variables impacting PV system efficiency are cell temperature and climatic parameters, including aspects, such as sun radiation, outdoor temperature, dust gales, and the rate of the wind [86]. In general, it is projected that solar PV systems located in areas with unclouded skies and desert-like climates will contribute substantially to PV energy production [86]. However, the performance of PV systems in these areas is frequently impacted by dust accumulation over the PV modules [96]. To enhance the versatility of the BIPV system, several factors, such as the temperature of the PV module, shading, angle, and direction of installation, must be considered. Solar irradiance and PV module temperature are the most crucial of these variables since they directly impact the BIPV system’s power efficiency and the building’s energy efficiency [10,97].

Additionally, the limited convective heat transfer for BIPV will decrease photovoltaic power output and heat the exterior of the buildings, increasing the strain on the air conditioner [86]. In the case of BAPV, there exists a gap between the solar array and the building’s exterior. The gap is essential for the performance of PV modules and structures due to the diffusive heat emission from air or liquid and the impact of temperature on the functioning of the PV system [10]. Though less effective, crystalline silicon and thin films can both operate at higher PV cell temperatures [98]. Phase change material (PCM), forced air flow, or forced water flow are a few techniques employed in BAPV/T systems [98,99], enabling these to run effectively since the water or air will take more thermal energy from it. Architectural esthetics are essential as the BIPV is integrated into the building envelope. Hence, unlike conventional PV and BAPV systems, to mitigate the cell temperature, natural airflow and PCM have been the only options explored and available [30,100,101]. The recent advancements in solar panels paved the way for innovative materials in the market. Transparent and translucent photovoltaic modules that can replace windows to let light through and produce power simultaneously are of interest in current research, and these PV modules can now attain an efficiency of 7% [102].

Building-integrated photovoltaic/thermal (BIPV/T) systems are a subset of BIPV systems that incorporate heat recovery and on-site power generation, primarily by active cooling of the PV surface, considered one of the most promising BIPV systems [86,103,104]. Rounis et al. [30] summarized the PV module electrical efficiency of PV/T and BIPV/T and found that the electrical efficiency of single-pass PV/T was 9–12%, while double-pass PV/T achieved an efficiency of about 10–15%. For BIPV/T, the electrical efficiency is distributed around 6–7% (see Table 1).

Table 1. Comparison between PV and BIPV.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>PV (For Buildings, i.e., BAPV)</th>
<th>BIPV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support</td>
<td>Traditional framework module support</td>
<td>Without the support</td>
<td>[10]</td>
</tr>
<tr>
<td></td>
<td>Can only generate electricity;</td>
<td>Multifunctional solar product that can both generate electricity and be used as a building material</td>
<td>[10,93]</td>
</tr>
<tr>
<td></td>
<td>more resource intensive as construction materials are not replaced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Lower</td>
<td>Higher (High maintenance costs)</td>
<td>[90,93]</td>
</tr>
<tr>
<td></td>
<td>Effortless installation;</td>
<td>The installation and maintenance are difficult</td>
<td>[88,90]</td>
</tr>
<tr>
<td></td>
<td>Mature technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>less affected by temperature</td>
<td>The performance is greatly affected by temperature</td>
<td>[10]</td>
</tr>
<tr>
<td>Temperature influence</td>
<td></td>
<td>Architectural esthetics should be considered in the design process, which can play a role in building appearance beautification</td>
<td>[10,30,105]</td>
</tr>
<tr>
<td>Architectural appearance</td>
<td>Lower priority for esthetic requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced pollutant emissions</td>
<td>Lower</td>
<td>Higher</td>
<td>[93]</td>
</tr>
<tr>
<td>(equivalent roof area)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation area</td>
<td>Roof</td>
<td></td>
<td>[10]</td>
</tr>
<tr>
<td>PV cell</td>
<td>First-generation PV cells</td>
<td></td>
<td>[92]</td>
</tr>
<tr>
<td>PV module electrical efficiency</td>
<td>10–15%</td>
<td>6–7%</td>
<td>[30]</td>
</tr>
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</table>
4.3. Social Impact

Solar power production systems are widely used in different sizes and functions globally [86]. However, the initial capital cost is still out of reach for many, augmented by storage costs and weather dependency [92]. With a relative rise of around 21%, the total installed PV capacity rose from 483.1 GW in 2018 to 580.2 GW in 2019. Among them, Asian countries such as China (175 GW), Japan (55.5 GW), and India (268 GW) have a higher penetration rate of PV, followed by the European countries (Germany (45.9 GW), Italy (20.12 GW) and the UK (13.4 GW)) [86,106].

Countries with high solar irradiance, such as India, hold immense potential to generate PV electricity [92]. Currently, BIPV and BAPV can significantly contribute energy to enhance the interior comfort of buildings in India [107,108]. With 331 million homes and a 77,370 sq km urban settlement area, India has a sizable potential rooftop BAPV capacity of 124 GW and is set to achieve 40 GW rooftop PV generation by 2022. The PV expansion rose significantly over the 2018–2019 fiscal year, adding 1836 MW and increasing the total capacity to 1000 MW [92]. As of September 2019, India had 33.8 GW of installed solar power, of which 12% came from rooftop installations and 88% from PV facilities [109]. Notably, regional infrastructure, such as a 5 MW solar farm, will save carbon dioxide emissions by 5390 t annually for 25 years. However, these facilities demand a considerable area for the establishment, which may invite land acquisition issues. Therefore, BIPV or BAPV are advocated as a practical solutions to address this dilemma [92]. However, the lack of technical and financial expertise, awareness, and resources poses a challenge to the solar PV market [110,111].

Due to the significant growth in demand for solar modules and the exorbitant cost of silicon, researchers have been forced to employ thinner silicon and alternative materials to reduce the costs [92]. However, a significant drop in the cost of solar panels is being observed globally due to technical advancements and environment-friendly policies. The prices are anticipated to fall even further due to the growing demand and scale of the installation. The levelized cost of energy using solar cells will be comparable to conventional energy by 2050. The cost decrease will significantly encourage the use of BIPV technology in society [92,112]. More importantly, the expansion of the PV industry is expected to contribute to more employment, addressing a societal issue.

5. BIPV vs. External and Internal Shading
5.1. Difference in Efficacy and Functionality

The previous sections infer that BIPV is esthetically and functionally convenient for harnessing solar energy. The electrical energy consumed by indoor air conditioning accounts for a considerable amount of the building’s energy consumption. The heat transfer of interior and exterior air is mainly through the heat conduction of the envelope and the convective heat transfer between the indoor and outdoor air and the envelope. In addition to this, another major aspect that affects indoor temperature is solar radiation (when the indoor temperature is high in winter, heat will also be transferred to the outdoors in the form of thermal radiation.) Therefore, maximizing the reduction of these two forms of heat transfer can minimize the energy usage of the HVAC system. The earliest and most uncomplicated method includes using various shading systems, such as window shading, curtains, and glass, with variable light transmittance to reduce the impact of thermal radiation on indoor temperature [95]. Some facilities, such as curtains, can also indirectly reduce heat transfer and convection heat transfer effects, and many researchers have demonstrated that energy consumption of HVAC systems can be reduced by 1–37% after using a pure shading system [113–115].

In the case of BIPV, compared with conventional indoor and outdoor shading, it is crucial to generate electricity without compromising the functionality of the shading equipment [85]. A study showed that shading systems with conjugated energy from photovoltaics could compensate for 62% of the energy demand, which rises to 270% on sunny summer days [85]. Another study advocates that the solar blinds produced using
CIGS thin-film technology offer a yield of about 45 Wp/m², while applications based on silicon may achieve 175 Wp/m² in favorable conditions [116]. However, irrespective of the purpose, the BIPV shading devices significantly reduce the overall energy consumption compared to conventional systems. Table 2 highlights the differences between a BIPV with external and internal shading systems.

Table 2. Comparison of the energy-saving effect between shading and BIPV.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Shading</th>
<th>BIPV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>Only the indoor HVAC energy consumption due to solar radiation can be reduced.</td>
<td>In addition to the function of shading, it can also independently generate electricity to provide considerable power for building appliances.</td>
<td>[85,113–116]</td>
</tr>
<tr>
<td>Cost</td>
<td>Lower</td>
<td>Higher and has high maintenance costs, due to the need to integrate photovoltaic modules More complex, due to the integration of photovoltaic cells, additional installation of electrical circuits, as well as power supply and control equipment, is required.</td>
<td>[93,116]</td>
</tr>
<tr>
<td>Installation</td>
<td>Simple installation process</td>
<td></td>
<td>[95,116,117]</td>
</tr>
<tr>
<td>Reduced energy consumption</td>
<td>Reduce HVAC energy consumption by 1–37%</td>
<td>In addition to reducing HVAC energy consumption, it can provide approximately 62% of the electricity to the building.</td>
<td>[85,113–116]</td>
</tr>
</tbody>
</table>

5.2. Social Impact

As a shading system, PV conserves energy while also harnessing and fostering a sustainable metropolitan environment. A few studies that concentrate on the CAPEX of the systems recommend capping the price of BIPV at 131 EUR/m² [118]. Based on the market price of PV equipment, the price of external shutters PV will take 32 years to pay for itself, and the active shading photovoltaic system will take more time, which has significantly worse cost-effectiveness than conventional rooftop photovoltaic systems [116]. A multi-dimensional evaluation system for 13 types of PV sunshades is created collectively by users, architects, installers, and inspectors [119] (see Figure 12). The study finds that based on photovoltaic power generation, heating and cooling loads, lighting levels, esthetics, exterior landscaping (user comfort), lighting comfort (glare), and performance, the “brise soleil full façade” type is highly favored for the usage [119].

Figure 12. PV sunshade types mentioned in the evaluation system (Reproduced with permission from Ref. [120]. Copyright 2022 Elsevier).

6. Case Studies on BIPV on NZEBs

6.1. Singapore [121]

The case study centers on the analysis of a three-story landed house covering an area of about 306 m², with a floor-to-floor height of 3.5 m. The house features a kitchen, two study
rooms, four bedrooms, four bathrooms, and a living room. The building is configured as an insulated wall, assuming identical thermal conditions without any heat transfer, as two homes jointly share the side wall, similar to a row house. Assuming adequate insulation in the interior ceiling and a brick masonry exterior with a thickness of 100 mm, along with a 20 mm cement plaster layer applied to the sides, the resultant U-value for the building stands at approximately 2.76 W/m$^2$·K.

A zero-energy apartment complex with 25 stories and four units is also the setting for this case. Each unit encompasses an area of 95 m$^2$, similar to the typical Singaporean residential space, with a floor-to-floor height of 3.2 m. Researchers made a difference between the top floor and the floor below because the roof was exposed to the surrounding environment [121]. Push-pull windows on the exterior have an appropriate ventilation ratio of 0.5 and an exhaust coefficient of 0.6 when fully opened. The outside exterior envelope was constructed using 100 mm thick bricks and plastered on both sides with 20 mm thick cement mortar, yielding a U-value of 2.76 W/m$^2$·K.

Assuming that appliances such as television, fans, kitchen appliances, and laundry account for 20% of the entire household energy usage, the minimum annual power consumption of land houses and flats are estimated to be 3167 and 745,265 kWh, respectively [122], with a total demand of 3959 and 931,582 kWh, respectively. The dimensions of the landed house and the landed apartment block’s PV system (assuming an efficiency of 18%) are 16.5 and 3884 m$^2$, respectively, to reach the zero-emission electricity phase. Studies advocate that it is feasible to construct a net zero energy floor house if a minimal floor area of 102 m$^2$ is achieved [121]. However, the apartment complex’s roof is just 412 m$^2$ in size. Hence, the required roof area differs significantly from the usable area on the roof. If rooftop solar systems were the only renewable energy source, about three of the 25 floors could be met. Hence it is of utmost importance to adopt subsequent solutions to achieve net-zero status. The study suggests that mounting solar panels on the exterior walls and windows can power 13 apartments [123].

6.2. Brazil [124]

Brazil case study considers a total of nine public buildings, 89% of them being rectangular. The average width and height of each public building are 30 m, with a proportion of surface area to volume (A/V) of 0.360 and a roof space to total built area ratio of 0.41. Walter Costa et al. [124], in their study, simulated the four-story model with BIPV installed on the rooftop and the north, east, and west-oriented exteriors. The available collective roof area in the study is 830 square meters. The roof receives 50% to 80% of the entire solar irradiance. An opaque, slanted PV module with an ideal slope angle of 24° towards the north is chosen for the simulation, covering the opaque surfaces of all facades. Due to the poor energy generation, the southern elevation of the building was disregarded [125]. Single-crystal cell technology with an efficiency of 18% is adopted for the analysis [126].

According to Walter Costa et al. [124], energy consumption reaches its peak between 80% and 50% of the variable window-wall ratio (WWR), exceeding 110 kWh/m$^2$ annually, while the photovoltaic module only produces 30% to 50% of the energy. Net-zero energy is achieved when WWR reaches 30%, highlighting the significance of WWR in NZEBs implementation [127]. Computer simulations suggest that increasing efficiency in energy usage in a standard four-story construction is feasible and can reduce annual energy usage by 46%. The abundance of solar radiation in the Brazilian capital is also suitable for solar power generation. It is suggested to concurrently utilize both the available roof area and the north, east, and west facades as energy generation zones, aiming to meet the NZEB objectives in office buildings with more than four floors within Brasilia’s climate zone. In addition, the researchers Walter Costa et al. [124] also point out that achieving NZEB is linked with the building’s A/V, WWR, glass solar heating gain coefficient (SHGC), light transmission, and others.
6.3. Alps [128]

Doragno Castle, located in the Alps in the city of Icino, was constructed in 2014 by transforming an old medieval castle into a private historic-home. The combination of building integrated solar thermal (BIST) and BIPV was used to achieve the NZEB goals [128]. The restoration was aimed at re-constructing the dilapidated walls and towers of the castle, and internal insulation was performed while restoring it to its original form. The BIPV system on the roof powers a bidirectional air-water heat pump for heating and cooling the interiors. Additionally, a radiant floor system, which is movable and dry-laid, is employed. The solar system integration during the renovation was carried out without compromising the esthetic and geometric aspects of the building.

6.4. Bern [128]

Between 2011 and 2015, the neo-Baroque style mansion of the Hutterli Rothlisberger underwent a significant renovation. Further to the installation of PV and solar thermal systems, the heat pumps, geothermal detectors, and furnaces were also replaced. Consequently, the overall energy demand fell by 76%, from 46,900 kWh per year to 11,100 kWh/yr. The rooftop consists of a BIPV + PV/T system with an output of 2.7 kWp, providing about 3200 kWh/yr of electricity, and a 13 m² solar thermal slate natural collector was installed, corresponding to a power output of about 5 kWp. Numerous highly effective interventions were performed with minimal esthetic impact, such as external insulation with the IsolOC H2Wall plus 1cm aerogel insulation double-shell blowing system, which was one of its kind in Bern during the period. Solar panels and the BIPV + PV/T + ST (Solar thermal Collectors) system could be seen under the natural slate roof, preserving sections of the original slate roof.

6.5. Japan [129]

The Shinagawa Railway station (35.6 N, 139.7 W) in Tokyo Minato, Japan, has undergone extensive renovations to increase energy efficiency. Shinagawa Station is among the busiest in Japan, carrying around 380,000 passengers annually. The station’s north, west, south, and east walls have an above-ground WWR of 0.4, 0.35, 0.2, and 0.15, respectively, and the floor height is set at 3 m with a total roof area of 20,200 m². If the photovoltaic is installed on the facade, the total amount of sunlight received by the building will exceed 50% of the original maximum (691 kWh·m⁻²). The facade area where PV is installed is 12,425 m², and facade PV is anticipated to produce a capacity of 2.1 GWh. of electricity per year. It is estimated that the windows and facades possess an energy generation potential of 2.1 GWh annually, closer to the annual power output of rooftop solar panels, highlighting the necessity to increase on-site PV generation further using facades. Younghun [129] indicated that in 2018, the photovoltaic roof had achieved economic benefits, and by 2030, it will be significantly improved, with a return on investment period of six years. However, due to the spatial constraints of roofs in large buildings, rooftop PV contributes less (2–9%) to total building demand or CO₂ reduction.

6.6. Greece [130]

With a near-zero positive energy community in Alexandropolis, Greece’s new positive energy community is located at a 4500-hectare site in the Kallithea-N area. The place comprises three independent plots with an overall area of about 42,000 m². The building coverage area accounts for 40% of the total plot area, and the height of the buildings is capped at a maximum of 8 m. Each house covers an area of 60 m² (6 × 10 m), including 120 m² of total heated area. All the houses are oriented south (the main axis is on the east-west axis), maximizing solar energy potential.

The rooftop accommodates the PV panels utilized for on-site power generation and battery storage. Based on preliminary analysis, the neighborhood needs at least 500 kWp of PV capacity to satisfy its power needs. Furthermore, the usable roof area of each building is approximately 37 m². Since the average area of 250-watt crystal panels is 1.65 m² (from
the average of a series of panels in RETScreen database), 5.5 watt-hours per house are considered close to maximum capacity, and 550 kWp is estimated to be the upper limit for the community.

The buildings were refurbished to utilize a low-temperature district heating and central cooling (DHC) network for heat, geothermal heat pumps for heating and cooling, a BIPV system, a wind energy system tailored for buildings, and PV/T hybrid energy technology. However, the research did not consider the internal environment, resident comfort levels concerning temperature, or the effects of the absence of an energy supply and demand monitoring system. Table 3 summarizes the BIPV takeaways from the case studies discussed.

Table 3. Case Studies on BIPV on NZEBs.

<table>
<thead>
<tr>
<th>Location</th>
<th>Climate Type</th>
<th>Brief Introduction of Building</th>
<th>Location of the BIPV in the Building</th>
<th>Renovation Plan—Other Parts of the Building</th>
<th>Energy Performance (After Renovation)</th>
<th>Cost</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapore</td>
<td>Tropical rainy climate</td>
<td>1. Landed house: 3 floors; area of 306 m²; height of 3.5 m. 2. Apartment building; 25 floors</td>
<td>Original installation: Roof</td>
<td>After optimizing and assuming simulations, installation in roof, exterior walls, and windows is proposed</td>
<td>NA</td>
<td>Around 240 kWh/m²·yr</td>
<td>NA</td>
</tr>
<tr>
<td>Brazil</td>
<td>Tropical savanna climate</td>
<td>The study area contains a total of seven public buildings, and 89% of the analyzed buildings were determined to be rectangular. The average building width is 30 m, the average height is 30 m, the surface-to-volume ratio is 0.360, and the roof area/total built area is 0.41.</td>
<td>Roof Facades oriented towards the north, east, and west directions.</td>
<td>NA</td>
<td>35-55 m²·yr</td>
<td>NA</td>
<td>[124]</td>
</tr>
<tr>
<td>Ticino</td>
<td>Mediterranean climate</td>
<td>Monument Doragno Castle: Transformed from an old medieval castle into a private residence</td>
<td>Roof</td>
<td>Solar energy collector (BIST) is also installed on the roof</td>
<td>45.62 (kWh/m²·yr)</td>
<td>NA</td>
<td>[128]</td>
</tr>
<tr>
<td>Berne/BE</td>
<td>Temperate continental climate</td>
<td>A single-family Neo-Baroque House</td>
<td>Roof</td>
<td>Install a PV and a solar thermal system and replace a gas heating system heat pump, geothermal detector, and a furnace.</td>
<td>35.22 (kWh/m²·yr)</td>
<td>1429 CHF/m²</td>
<td>[128]</td>
</tr>
<tr>
<td>Japan-Tokyo</td>
<td>Subtropical oceanic monsoon climate</td>
<td>The floor height of 3 m. Set the above-ground window-to-wall ratio for the west, south, north, and east walls at 0.35, 0.4, 0.2, and 0.15, respectively.</td>
<td>Roof</td>
<td>After optimizing and assuming simulations: roof, façade, and windows</td>
<td>NA</td>
<td>35.33 5kW·yr⁻¹</td>
<td>[129]</td>
</tr>
<tr>
<td>Greece</td>
<td>Site: 4500-hectare parcel in Kallithea-N area Plots: Three independent plots, approximately 42,000 square meters in total Building coverage: Maximum 40% of total plot area</td>
<td>Gas boiler district heating system, low-temperature DHC network provides heat energy, geothermal heat pumps to heat and cool the DHC network. Single-pane windows are substituted with double-glazed windows featuring aluminum frames.</td>
<td>Roof</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>[130]</td>
</tr>
</tbody>
</table>

7. Tools and Guidelines to Design BIPV

The development of more effective NZEBs can benefit from the analysis of the experiences and results from the existing BIPV-equipped buildings [131,132]. The EN 50583 standard [106,133] and the draft international standard IEC 63092 [30,105] are the prime
technical guidelines followed for manufacturing and using BIPV. The UN studio architects also proposed a systematic BIPV design strategy consisting of four levels: material design, module design, facade layer design, and the entire building. Besides the surrounding environment, the adaptation design is also recommended [134]. Such hierarchical steps are often beneficial as a guideline when designing a BIPV. Another article describes various design options for BIPV modules’ electrical systems, module-level esthetics, and constructional integration [118]. The main points outlining the design of a BIPV photovoltaic system are mentioned below (Figure 13).

**Figure 13.** Different architectural scale layers considered in BIPV design [134] (Reproduced with permission from Ref. [118]. Copyright 2022 Elsevier).

### 7.1. Selection of Photovoltaic Modules

Solar cell modules must comply with the relevant regulations of building materials. For example, solar cell modules composed of tempered glass interlayers shall be used in building curtain wall materials, meeting building standards [106,133]. For the design of BIPV, it is necessary to choose the appropriate installation location, size, color and installation method according to the building function, design concept, building conditions and other relevant factors.

### 7.2. BIPV Structure Design

The design inclination angle of BIPV should be comprehensively considered according to the optimal annual inclination angle, seasonal and monthly optimal inclination angle, optimal slope and condition factors to maximize the annual power generation of the building [135]. When the slope is more than 40 degrees, for instance, the direction of the BIPV system in Hong Kong significantly impacts its performance and should be avoided as much as possible [135]. Since the direct sunlight angle is different each season and even at different times of the day, the PV structure design that can actively track and adjust the angle can maximize the power generation efficiency [117].

The influence of temperature on the power generation efficiency of the PV module is also highly significant. Since the surface temperature of the PV panels may rise during operation, the efficiency can be highly impacted [136], making it an essential consideration during the design. The “cold facade” structure, similar to the ventilation wall, can be used to improve the working efficiency of BIPV, or the BIPV/T can be used to reduce the temperature of PV modules by using water circulation and recycling and using the excess heat [82,104].
7.3. Inverter Selection

To ensure the location of maximum power tracking and to successfully overcome adverse situations such as shades, string inverters or micro-inverter topology are employed in BIPV to increase the number of input loops of maximum power point tracking (MPPT) as feasible [137]. Since the configuration of solar arrays influences the power and quantity of grid-connected inverters, the power rating, conversion efficiency, and the maximum number of available MPPT loops must be considered when selecting an inverter [138]. Moreover, placing the string inverter closer to the PV array can aid in minimizing line losses.

7.4. Grid Connection and Access

To determine a safe and reliable scheme, rational economic analysis should be carried out according to the comprehensive evaluation of project construction conditions, capacity scale, and power generation system cost. The BIPV photovoltaic power generation system uses self-generated surplus power to connect to the grid [139]. Combined with the project’s status, a single centralized grid connection mode or a multi-point distributed grid connection mode is adopted, wherein multi-point distributed power loss is more advantageous [140]. The selection of network nodes is closely related to network status, loads, line losses and other factors that highlight the ability of the building distribution network to receive photovoltaic power generation, as well as the rationality and feasibility of the distribution network [141].

8. Discussion

This paper critically evaluates the advancements and practical applications of BIPV over the past few years and demonstrates the importance of BIPV in achieving net zero energy consumption in buildings. The comparison of different energy-saving measures led us to the following conclusions.

- NZEBs are energy-efficient buildings dependent on sufficient renewable energy to meet as much energy the building consumes annually and have a significant impact on achieving carbon neutrality targets. NZEBs also aid in decreasing reliance on fossil energy sources by enhancing energy conservation within the building sector and fostering the generation of renewable energy to meet the operational needs of buildings.

- NZEBs may be reliant on both renewable energy sources and energy infrastructure, such as grid connectivity. Solar energy is deemed to be the most accessible energy source. Currently, on-site solar photovoltaic systems, due to their relatively low cost, dominate other renewable energy systems. BIPVs have numerous applications, such as roofs, facades, and shading systems. Additionally, BIPV can improve the esthetics and integrity of buildings while maximizing the efficiency of photovoltaic power generation due to its extensive installation area. Shading systems are usually required in buildings to minimize the energy usage of the HVAC system due to irradiation, and the combination of photovoltaic technology and shading systems is a perfect solution to increase energy efficiency. However, unlike conventional PV, BIPV photovoltaic modules are closely connected, which may increase surface temperature, thus affecting performance. Additionally, BIPV suffers from complex installation procedures, intensive maintenance, and high capital expenditure. Nevertheless, the utilization rate of BIPV is increasing year by year, saving energy, reducing emissions, and creating new employment opportunities.

- The case studies highlight that the ratio of building A/V, building envelope size, height, WWR, glass SHGC, light transmittance, and others have a significant impact on meeting the standards of NZEBs. A sole focus on roof-integrated PV may not be sufficient to accommodate the energy necessities of the building, thus shifting the attention towards the combination of BIPVs. Additionally, integrating BIPV and BIST can maximize energy utilization, converting the pathway to NZEBs easily. However, there are some shortcomings in the process of realizing NZEBs, such as a few analyses
not considering indoor conditions, residents' thermal comfort, and the shortage of monitoring systems for energy supply and demand.

- When designing BIPVs, it is necessary to comply with relevant standards and pay particular attention to the efficiency of power production, selection of PV modules and inverters, BIPV structure design, and grid-connected design. The design can be rationalized by studying the successful cases built and designed in layers (material design, module design, facade layer design, and the entire building). In the future, the photovoltaic power generation technology led by BIPV should continue to be developed to accelerate further the goal of achieving net zero energy consumption.

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