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Current prospects of building-integrated solar PV systems and the application of bifacial PVs

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Building-integrated solar photovoltaic (BIPV) systems have gained attention in current years as a way to recover the building's thermal comfort and generate sustainable energy in building structures. BIPV systems can provide shade against sunshine while generating ancillary electrical power. Over the last decades, engineers have been trying to improve the efficiency of BIPV systems. BIPV systems with various installation types, including rooftop, balcony, curtain, sunshade, and wall façade types, are being constantly researched and intensively presented for improving power efficiency and reducing air-conditioning use. This work provides an overview of solar BIPV systems and focuses particularly on existing applications of the bifacial type of BIPV systems. The motivation and an overview of BIPV systems are first introduced, followed by the study methodology considered and the contributions. This work discusses PV technologies of bifacial PVs (monocrystalline and polycrystalline bifacial modules), BIPV installation [curtains, rooftop, flat rooftop, transparent faced, balcony windows (transparent), wall opaque facade, flat roof-faced, and skylight sunshade types], simulation and optimization software (simulation software and future trends), zero-energy BIPV technology, and optimization techniques of BIPV systems. Last, suggestion amendments to the current BIPV design that possibly contribute to growing the system's effectiveness, reliability, and cost as future design theories for the whole system are presented.

KEYWORDS

building-integrated PVs, energy yields, energy optimization analysis, PV installation modeling, reliability

1 Introduction

1.1 An overview and motivations

One of the main promising tools for generating electricity is the photovoltaic (PV) system. PV power plants can potentially replace fossil fuel-based electric power plants, which produce huge amounts of greenhouse emissions. However, the PV power plant needs a sizable amount of land area in order to create the same quantity of power due to its efficiency being poorer than a typical power plant. The idea of producing power with less pollution is growing more and more appealing as environmental concerns and interest in environmental issues rise. Solar photovoltaic energy uses free fuel, unlike traditional generation techniques.

Furthermore, as a grid-connected PV application, solar photovoltaic energy systems can be simply installed on the roof of residential buildings and on the wall of business structures to generate power without creating any pollution. Solar photovoltaic energy provides a way to power isolated towns and establishments that are inaccessible to electricity companies, in addition to grid-connected PV systems (Zahedi, 2006).

Solar photovoltaic energy is becoming more popular all around the world. Today, solar PV systems totaling more than 3,500 MW have been built worldwide. The cost of PV systems has steadily declined since 1970 (Peters et al., 2019). The use of small-scale residential PV systems has been encouraged worldwide as a result of this price decline. Recent events have prompted environmental experts to launch substantial research initiatives for using renewable energy sources, such as solar energy. The use of solar photovoltaic energy as a source of power is being taken more seriously, which bodes well for the future of this technology. This contribution's goal is to present the most recent advancements in solar photovoltaic energy systems (Klenk, 2018).

One of the new strategies to sustain renewable energy in the residential sector is by employing solar power-generating devices or systems known as building-integrated photovoltaics (BIPVs) that are smoothly incorporated into the building envelope and are included in building elements, such as windows, roofs, or façades. BIPV systems, which install PV modules that are integrated into the building envelope, have gained popularity in recent years. They reduce the need for building resources since they make it possible to produce renewable energy locally, and they can replace traditional construction components.

BIPV systems have the dual benefits of boosting the potential for renewable energy in the built environment and delivering cost and time savings during construction by displacing conventional building components. BIPVs must deal with the complex challenges of transmission and distribution losses (Reddy, 2020). Therefore, one of the holistic strategies that lessen the need for such enormous land expanses is the incorporation of PV-covered buildings. The Energy Performance of Buildings is the primary legal tool to enhance the energy performance of buildings, along with the Energy Efficiency Directive (Sabry et al., 2017; Tina, 2020). This means that going forward, new structures must achieve the goal of being almost entirely energy-free.

BIPV systems may include shades, rooftops, building awnings, and building facade walls to block sunlight while simultaneously producing auxiliary electrical energy. Recent advancements in PV technology have produced semi-transparent PV modules, such as thin-film solar panels and bifacial silicon solar panels, allowing some amount of light and transparency. This makes the BIPV system applicable to skylight applications, windows, and attractive building facades as it allows a good amount of daylight for a building. Thus, BIPV windows have the advantage of simultaneously producing electricity, reducing the amount of energy needed for building cooling or heating and allowing lighting (Wang et al., 2017).

1.2 Research highlights

This paper's scope is to thoroughly evaluate the integration viability of solar PVs with the building envelope, the annual energy yield, and the electrical energy optimization techniques at the residential building level and techniques to provide accessibility of PV energy injection into the grid. A comparison of this work with other review articles in the literature is shown in Table 1.

The main contributions can be reviewed as follows:

- Presenting a general overview of integrating buildings with solar PVs and focusing particularly on the existing and potential applications of bifacial PV types in BIPV systems.
- Discussing the current prospects of using bifacial modules within the industry of PV technology.
- Providing an overview of the significant findings of the existing bifacial BIPV systems in terms of efficiency calculations, annual energy yields, energy savings, and financial benefits.
- Presenting a clear understanding of the BIPV and bifacial BIPV frameworks that allow to evaluate such systems.
- Providing a comprehensive assessment of the prospects of building-integrated bifacial solar PV systems in terms of installation types for strengthening BIPV systems.
- Discussing the potential use of power optimization techniques for improving bifacial BIPV systems. Furthermore, a comparison between the optimization-based normal PV technology and bifacial PV optimization strategies is also discussed.

2 Classification of BIPV installation

BIPV systems are installed on structures that use the energy they generate, making them neutral systems with the least negative environmental impact. The photovoltaic elements built into a building's envelope (BIPVs) interact with the building in various ways, affecting its laws, standards, safety, performance, maintenance, environmental concerns, durability, design, and constructability (Abdallah et al., 2013; Abdelhafez, 2021). The main components of BIPV systems can be categorized depending on their solar module types, methods of grid connections, intended uses, or applications.

A BIPV system may consist of a grid-connected system, a stand-alone system, or a hybrid system. Energy is produced and delivered where it is needed *via* a BIPV system. It can also supply energy on demand with the help of an energy storage system (ESS). Therefore, this work classifies the BIPV system as a whole categorization structure, including the simulation and optimization, as shown in Figure 1. Most of the studies presented in this diagram will be explained in detail in the following sections of this research.

2.1 PV technologies

Scientists at Bell Laboratories were the first to make use of the phenomenon of photon energy being converted into electricity. They produced a functional silicon solar cell that produced an electric current when exposed to sunshine in 1954. Eventually, solar cells were used to power spaceships, clocks, computers, and other devices. To assist in powering the electric grid, solar systems are now being constructed on a large scale. Solar-powered electricity is now widely available and economically viable. The majorities of

TABLE 1 Comparison of this work with other review articles in the literature.

Review	Bifaciality discussed	Zero-energy BIPV	Covering
Kirimtat (2022)	No	Yes	Control strategies, building types, methods, climates, and energy-saving ratio
Yu et al. (2021)	No	Yes	Façade-based BIPVs, including electricity generation, thermal performance of PV cells, and energy consumption of buildings for space heating and cooling.
Singh et al. (2021)	No	No	Ventilation rate, a tilt angle of PV shading devices, adjacent shading, semi-transparent PV (STPV) glazing design, cell coverage ratio (CCR), transmittance, window-to-wall ratio (WWR), and glazing orientation.
Dai and Bai (2021)	No	No	PV technologies, temperature management, solar irradiation enhancement, and avoidance of excessive mechanical strain.
This work	Yes	Yes	PV technologies of bifacial PVs (monocrystalline and polycrystalline bifacial modules), BIPV installation [curtains, rooftop, flat rooftop, transparent faced, balcony windows (transparent), wall opaque facade, flat roof-faced, and skylight sunshade types], simulation and optimization software (simulation software and future trends), zero-energy BIPVs, and optimization techniques of BIPV systems.

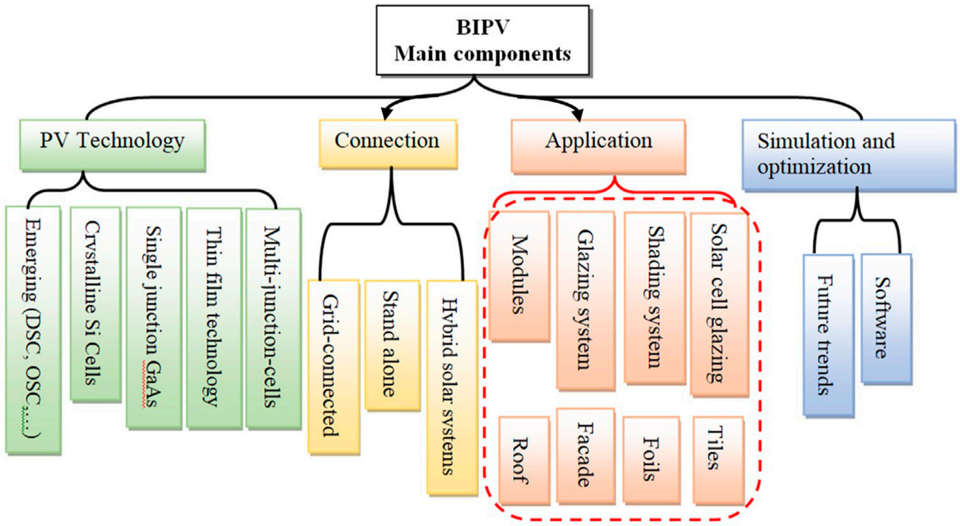

FIGURE 1
Classification of BIPV systems.

solar cells on the market today are silicon-based and offer competitive costs and high efficiency (the rate at which the solar cell converts sunlight into electricity). To produce massive, utility-scale systems, these cells are typically put together into bigger modules that may be mounted on the rooftops of homes or businesses or used with ground-based racks.

The materials of PV module types are classified as follows:

- Si: More than 90% of modern PV systems use modules made of crystalline silicon. The modules' architecture can vary in minor, yet significant, ways. Due to the widespread usage of crystalline silicon modules, other types of modules may exhibit differences in module designs, but to better follow the development of technology, crystalline silicon module types are divided as detailed in the following text.
- Perovskite: these modules are built of materials having the perovskite structure, commonly abbreviated as ABX3, where A denotes an organic or inorganic cation (for example, methylammonium), B denotes a metal cation (generally Pb2+), and X denotes a halide (for example, I- and/or Br-). A hybrid organic–inorganic methylammonium lead halide perovskite is the name given to the structure that is most frequently used. CaTiO3's crystal structure serves as a representation of the overall perovskite structure.
- OPV (organic photovoltaic technology): bulk hetero-junction modules made of organic and/or polymeric small molecules are used in the majority of OPV technologies. The separation of the photo-induced exciton into free electrons and holes that produce photocurrent is made easier by the bulk hetero-junction concept.

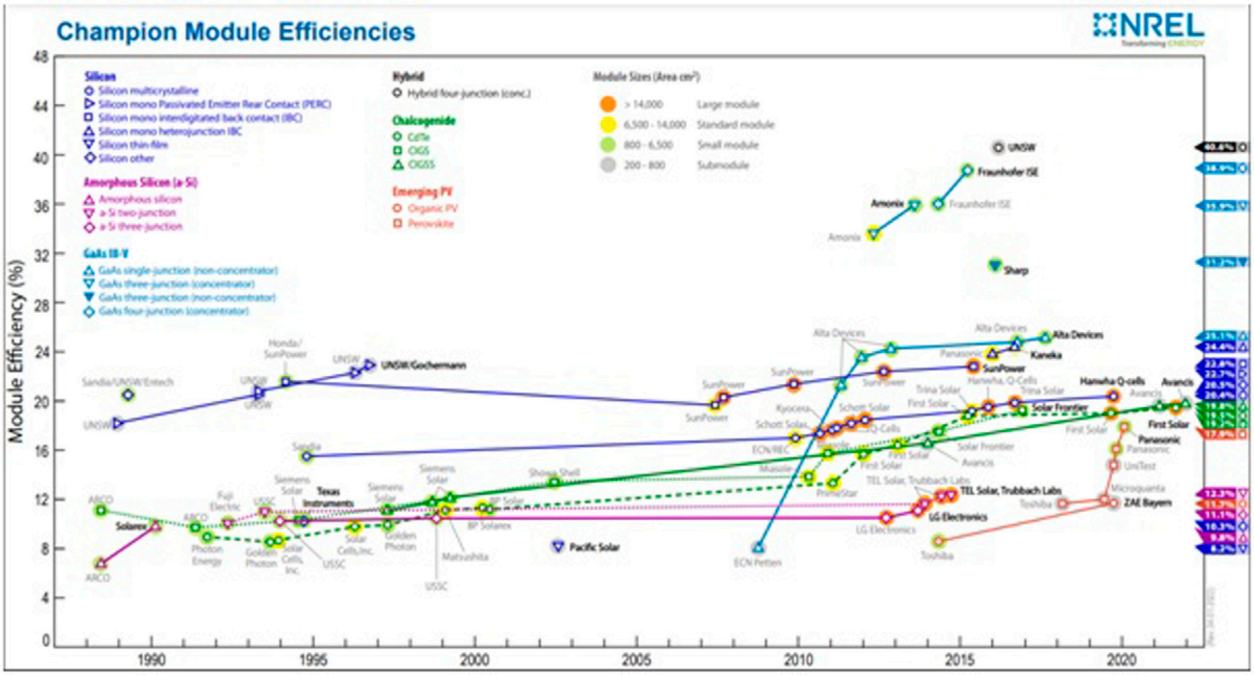

FIGURE 2
Champion efficiency chart of photovoltaic modules (Champion Photovoltaic Module Efficiency Chart | Photovoltaic Research | NREL, 2022).

- III–V: these modules make use of elements from the periodic table's third and fifth columns. Several of these reports are for stacks of multiple layers, often known as multi-junctions, because these materials can be composed of a wide range of band gaps. Because their lattice constants are so comparable, germanium and gallium arsenides are frequently produced together. Modules containing germanium are categorized under this heading for convenience.
- Hybrid: these courses incorporate content from various categories. It consists mostly of a silicon and III–V module combination. In the future, modules manufactured from other material combinations, such as perovskites, may also fall under this category.
- Dye-sensitized: typically, these modules use a porous titanium dioxide matrix coating with a skinny layer of robustly gripping dye. The color absorbs the photocarriers (excitons), and the light is divided at the interface between an electrolyte and titanium oxide, specifically penetrating the titania.
- Chalcogenide: it is a material that has no less than one part of the sixth column of the cyclic table, such as tellurides, selenides, and sulfides. The majority familiar of these are copper indium gallium selenide (CIGS) and CdTe.
- Amorphous silicon: this contains thin-film silicon modules with single, two, and three junctions and is grown on glass or other low-cost sub-materials. Several multi-junction masses include alloys with some partially crystallized and germanium layers to aid get layers with a lesser band gap.

For a variety of photovoltaic systems, from 1988 to the present, the greatest confirmed conversion efficiencies for champion modules are maintained by the National Renewable Energy Laboratory (NREL) in a graph. A figure expressing the champion efficiency of PV modules is shown in Figure 2.

2.1.1 Monocrystalline and bifacial modules

Monocrystalline solar modules, also known as single-crystal modules, are made of silicon that is cut from a single big crystal. This indicates that the interior structure is very well-ordered and that electrons may travel through it with ease. A rod is progressively drawn up out of a pool of molten silicon to form the silicon crystals. A long, cylindrical crystal will form at the end of the rod as it departs under carefully monitored conditions. After that, the column is thinly cut into pieces for the solar modules. Before crystallizing, molten silicon is combined with substances that allow it to display n-type or p-type characteristics (Enaganti et al., 2020; Xu et al., 2021). The void where the edge of the crystal column was in the corners of monocrystalline solar modules can be used to identify them. Due to the crystals' constant orientation, each module will also have a consistent pattern. Although monocrystalline silicon solar modules are the most effective, they are also the priciest due to the technology required to produce their massive, very uniform silicon crystals.

Monocrystalline solar panels are more expensive than polycrystalline solar panels, but this does not necessarily imply that they are not the ideal choice. The silicon structure is the key determinant of the price difference between these two types of solar panels. Manufacturers pour molten silicon into square molds to create polycrystalline panels and then separate the resulting wafers into individual modules. Contrarily, the meticulous control of silicon solidification during the production of monocrystalline

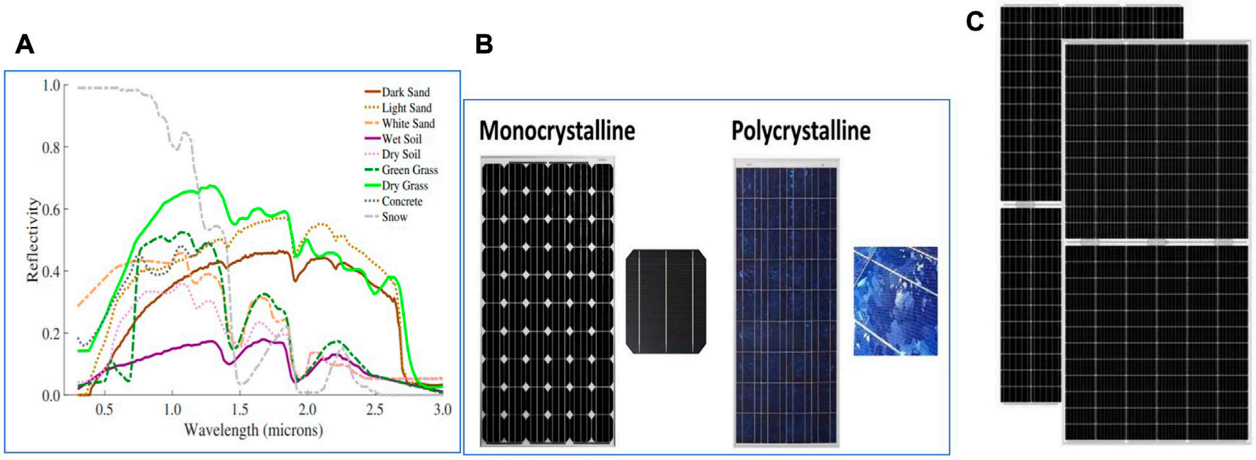

FIGURE 3
(A) Reflectivity R (λ) for nine different earth surfaces based on the "SMARTS" dataset (Gostein et al., 2020), **(B)** monocrystalline and polycrystalline silicon solar modules (China P-type Monocrystalline Bifacial Solar Module LYGF-BP72P factory and suppliers | Linyang, 2023), and **(C)** polycrystalline panel bifacial PV with 144 cells.

panels requires a more complicated procedure, which drives up the cost of single-crystal solar modules. Monocrystalline solar panels are more expensive when comparing the costs of the two types of panels. However, both systems have the same price for inverters, wiring, electrical safety measures, racking, and labor. Additionally, if there is just a little amount of space for a solar panel installation, it is of note that monocrystalline panels may provide a better return on the investment due to their higher efficiency. Finally, it should be noted that the federal solar tax credit is still available for both varieties of solar panels. Monocrystalline silicon bifacial modules are composed of cells that usually refer to as silicon cells. As the name suggests, the entire volume of the cell is made up of a single silicon crystal. It is the cell type whose commercial application is currently more pervasive. Using silicon single crystals, a monocrystalline solar cell is created using the Czochralski process. The monocrystalline structure's efficiency ranges from 15% to 20%. It is built of silicon ingots and has a cylindrical shape. To maximize performance, the cylindrical ingots' four laterals are carved out to accommodate silicon wafers (Fang et al., 2020; Sun et al., 2021). A low-cost industrialized screen printing method that produces bifacial solar cells on CZ monocrystalline substrates was presented by Yang (2011). Additionally, new advancements in this field of study have been made (Janßen, 2009; Yan et al., 2019). The metallization, boron-diffused surface passivation, and BBr3 boron diffusion are the main difficulties with screen-printed CZ bifacial solar cells. A modification of the boron diffusion conditions to reach crucial cell physical properties required for bifacial operation was made by Monokroussos et al. (2020).

The National Renewable Energy Laboratory measured the spectral response of a representative monocrystalline Atonometrics silicon PV reference cell for the study (Gostein et al., 2020). By averaging the calculated spectral reaction curves for the six commercially existing bifacial PV modules reported by Zhang et al. (2020), typical spectral responses from the back and front sides of bifacial PV modules were obtained. To obtain reflectivity R(λ) for each ground material, the study simulated nine distinct ground-surface resources using spectral reflectivity records found in SMARTS modeling software. Figure 3A shows the spectral reflectivities for all equipment.

2.1.2 Polycrystalline and bifacial modules

In conclusion, monocrystalline solar panels often have better efficiencies and include black solar modules built of a single silicon crystal, but the cost of these panels is frequently higher. Multiple silicon crystals that have been fused to form blue solar cells are used in polycrystalline panels. These panels cost less but are frequently less effective. Both mono and poly solar systems will reduce electricity costs. The best financing plan, space considerations, and personal preference are the deciding factors. The purpose of both monocrystalline and polycrystalline solar modules in a solar PV system as a whole is the same, and the knowledge following it is simple: they equally take solar power and convert it to electrical energy. Additionally, they are both formed of silicon, which is a plentiful and incredibly robust element used in solar panels. Numerous companies produce both monocrystalline and polycrystalline solar panels. Both polycrystalline and monocrystalline solar panels can be exceptional options for buildings, but before making the final solar purchasing decision, one should be conscious of numerous significant features. The type of silicon solar module that both of the two technologies use makes the main distinction between them: monocrystalline solar panels use silicon solar modules made from a single silicon crystal, whereas polycrystalline solar panels use silicon solar modules prepared from a lot of silicon fragments that have been melted jointly. Monocrystalline and polycrystalline silicon solar modules are shown in Figure 3B.

The color of the two types of solar panels is what distinguishes them most visibly from one another in terms of appearance: monocrystalline panels are often black, but polycrystalline panels might have a blueish tint to them. The longevity of the solar panels is

TABLE 2 Comparison between monocrystalline and polycrystalline modules on the important key metrics.

Coefficient	Monocrystalline panels	Polycrystalline panels
Temperature coefficient	Lower temperature coefficient/more effective when temperature changes	Higher temperature coefficient/less effective when temperature changes
Lifespan	25+ years	25+ years
Aesthetics	Solar modules have a black hue	Solar modules have a blueish hue
Efficiency	More efficient	Less efficient
Cost	More expensive	Less expensive

mostly unaffected by the sort of silicon module that makes them up. For at least 25 years, monocrystalline and polycrystalline panels will both produce power with efficiency. Similar to efficiency, monocrystalline solar panels often perform better than polycrystalline ones in terms of temperature coefficient. It follows that monocrystalline solar panels work better in high temperatures as a panel's temperature coefficient is simply a measure of how well it performs in warm temperatures (with percentages closer to zero being better) (Sabry et al., 2018). A comparison between monocrystalline and polycrystalline modules on the important key metrics is listed in Table 2.

In the Atacama Desert, a research station for photovoltaics was set up for 8 months under high outdoor irradiation circumstances (Ayala et al., 2018). At a weather station, four IV tracers were attached to monocrystalline, polycrystalline, thin-film, and bifacial modules; two IV tracers were also connected to two PV modules, in order to analyze the soiling phenomenon. Thin-film technology has a performance ratio of 90%, polycrystalline technology of 88%, monocrystalline technology of 78%, and bifacial technology of 96% when just the nominal power of the front face is assumed. After finding a natural cleaning effect caused by high humidity, which frequently happens in the early morning, the soiling ratio was kept at 0.94 and 0.01 for the next 2 months. During the first 2 months, the soiling ratio decreased by less than 2.5%. The PV module reconfigurations using copper indium gallium selenide (CIGS) and polycrystalline PV technology have been examined in the study (Ul-Haq et al., 2020). This report also includes a thorough quantification of the effects of the investigated PV problems on the electricity system. According to the MATLAB/Simulink data, CIGS PV technology outperforms polycrystalline in terms of power output under various fault scenarios. The given results make it clear that optimum PV array reconfiguration can boost energy optimization from PV systems with fewer PV peaks. Consequently, this will result in better PV system performance. A polycrystalline panel bifacial PV with 144 cells is shown in Figure 3C.

The energy yield of such technology can be boosted by up to 30% when combined with the state-of-the-art PANDA n-type crystalline silicon solar cells, which awaken earlier and go to sleep later than traditional p-type solar cells. Electrical structures with series and parallel connections and multiple busbar half cells can lower CTM loss and boost module output power.

2.2 BIPV applications

BIPV systems are composed of PV modules that are used to be integrated with energy-sustainable building skins. This includes rooftops, balconies, curtains, sunshades, and wall types to generate power from direct sunlight, reflected sunlight, and diffusion irradiation. Such systems provide buildings with the ability to perform two tasks. BIPV systems should, first and foremost, meet the standards of traditional building envelope materials, including acceptable structural strength, thermal insulation, weather protection, and noise protection. This is because they serve as the skins for the buildings. Second, BIPV systems produce electricity and serve as a building's power source (Huang and Hewitt, 2020; Kurian and Karthi, 2021).

BIPV modules now on the market are either based on copper indium gallium selenide (CIGS) (Ritzen, 2019), cadmium telluride (CdTe) (Sabry et al., 2018; Sun et al., 2020), thin-film technologies like amorphous silicon (a-Si) (Dai et al., 2021), or crystalline silicon solar modules (c-Si) (Santoyo-Castelazo et al., 2021). With most technologies, semi-transparency can be accomplished, for example, in curtain wall or skylight applications, by either spacing opaque c-Si solar modules or making the thin-film layer transparent. However, when transparency rises, the module's efficiency falls as less sunlight is absorbed by the photovoltaic layer and used to generate power. Ritzen (2019) developed a life-cycle assessment for BIPV configurations on three types of PV technologies, namely, copper indium gallium (di) selenide (CIGS), amorf-Si, and multi-Si, in three types of rooftop BIPV arrangements, that is, ventilated with bamboo construction, ventilated with aluminum construction, and non-ventilated. This evaluation was applied to three scenarios: circulation, recycling, and reusing. The obtained results demonstrated that the assessment of 100% recycling, 1 square meter of amorf-Si non-ventilated configuration shows the lowest ecological impacts.

Sun et al. (2020) discussed the performance of combining thin-film semi-transparent cadmium telluride (CdTe) PV modules with 50% and 10% transparency and PV crystalline silicon type as a south-facing window. The results demonstrated that the window with 10% transparency of CdTeSemi-transparent PV is able to improve the performance of working PV hours in the range between 500 and 2,000 irradiance, which can efficiently decrease the opportunity of glare. Dai et al. (2021) investigated a flexible thin-film amorphous silicon (a-Si) PV module with BIPV development over a sunlight irradiance between 200 and 1,000 W/m^2. The study covered solar PV parameters such as the open-circuit voltage of the adopted a-Si PV module, which was reduced by approximately 0.40% linearly with an increase of 1°C until a temperature of 91.5°C maximum as compared with the PV organic integrated that decreases to 0.12% with 1°C increase until 78°C.

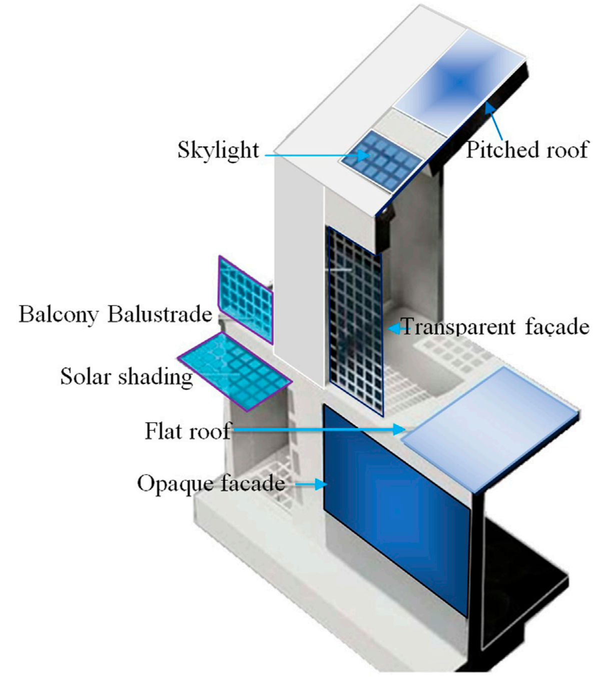

FIGURE 4
Common categories of BIPV installation types.

For the application of multi-crystalline silicon module integration in buildings, Santoyo-Castelazo et al. (2021) installed a solar PV system with a capacity of 12 modules (3 kWp) with 20° southward tilt and an inverter of 2.5 kW. This system produces 1,282 kWh/kWp on average annually at a performance factor of 0.75. Three traditional photovoltaic generation systems based on various technologies were contrasted with the multi-crystalline silicon photovoltaic system evaluated in this study (the copper–indium–selenium solar modules, the amorphous silicon, and the single-crystalline silicon). The results demonstrated that the life-cycle evaluation of multi-crystalline silicon modules, as compared to other systems, contributes more pollutants throughout their lifetimes and nearly always has lower environmental burdens across the majority of impact categories (six out of eleven).

The BIPV peel serves both as an architectural language element for a building and its waterproof barrier. The exploration of high-performance façade products and technologies, such as PV materials, by developers and architects is prompted by stricter building requirements and regulations regarding green sustainability and architecture. BIPVs are a component of construction systems, as opposed to typical PV applications, when taking into account the context of installation, production sequence, jointing, construction, and materials (Adamovic et al., 2017). PV modules have significantly improved in terms of performance, form, and color to fit diverse building PV peel alternatives because architects need a significant amount of design freedom concerning technology solutions for the customization of building skin (Hemmerle, 2017).

In addition to the BIPV module serving as building skin, it also can provide a component of the construction system and can take the place of traditional building elements. With the aid of conventional construction materials, BIPV systems eliminate the need for heat transfer through the building envelope (Oliveira et al., 2021). BIPV systems are often divided into three categories: roofs (modules on a lightweight substrate or transparent laminates for flat roofs, modules with integrated solar modules as roof covering elements, solar laminates, photovoltaic roof shingles, photovoltaic roof tiles, etc.) (D'Orazio et al., 2013), façades (BIPV cladding walls and curtain walls), and accessories (BIPV shading devices and balconies). Common categories of BIPV systems are shown in Figure 4, while the references according to the classification of BIPV installation type are listed in the following subsections.

2.2.1 Curtain installation

Martín-Chivelet et al. (2022) used BIPV curtain walls and rain screens to evaluate two steady-state PV module temperature models. To cover the mounting configurations under examination, the experimental setups positioned the BIPV modules perpendicularly and with various rear border circumstances. Four separate metrics, coefficient of determination, mean bias error, root mean square error, and mean absolute error, were used to compare actual and simulated temperatures over an entire year as the experimental base for evaluating each model. The evaluation revealed that the Ross model is most suited for forecasting the annual PV energy in applications such as rain screens and curtain walls. In the same context, BIPV curtain walls were analyzed, tested, and designed, their application potential was determined, and improvements and suggestions were proposed by Li et al. (2021). It can significantly increase PV module efficiency and offer a more consistent interior lighting environment. According to the real-time findings, the BIPV curtain system's transmittance reaches 9.1% in clear weather. Winter had the highest generating efficiency of the BIPV curtain system (26.5%), followed by autumn and summer separately. Additionally, the BIPV curtain system may meet the needs of building insulation and produce a more consistent indoor lighting environment.

Techniques for thermal improvement, such as a newly developed flow deflector, semi-transparent PV technology rather than opaque PV technology, and multiple inlets, were assessed by Rounis et al. (2021). According to their test results, thermal efficiency could reach 33%. Behind the PV panel, a multiple-inlet layout helped by a flow deflector was found to improve thermal performance by up to 16% and decrease peak PV temperatures by 3.5°C, with only a slight improvement in electrical efficiency. A more extended approach is required for the modeling of convective events in BIPV systems because the recorded Nusselt numbers were found to have poor or marginal agreement with the formulations reported in the pertinent literature. Lai and Hokoi (2017) developed ventilated BIPV curtain walls that can autonomously adjust an environment using buoyant force by integrating a PV system, a double-skin construction, and a thermal flow mechanism. Computational fluid dynamics and full-scale experimental simulations were conducted to investigate the thermal performance of the ventilated BIPV curtain walls and the flow pattern characteristics for the channel airflow under various heating conditions, wall thicknesses, and types of openings. While keeping appropriate wall thermal performance, the created ventilated BIPV curtain walls successfully reduced their solar heat

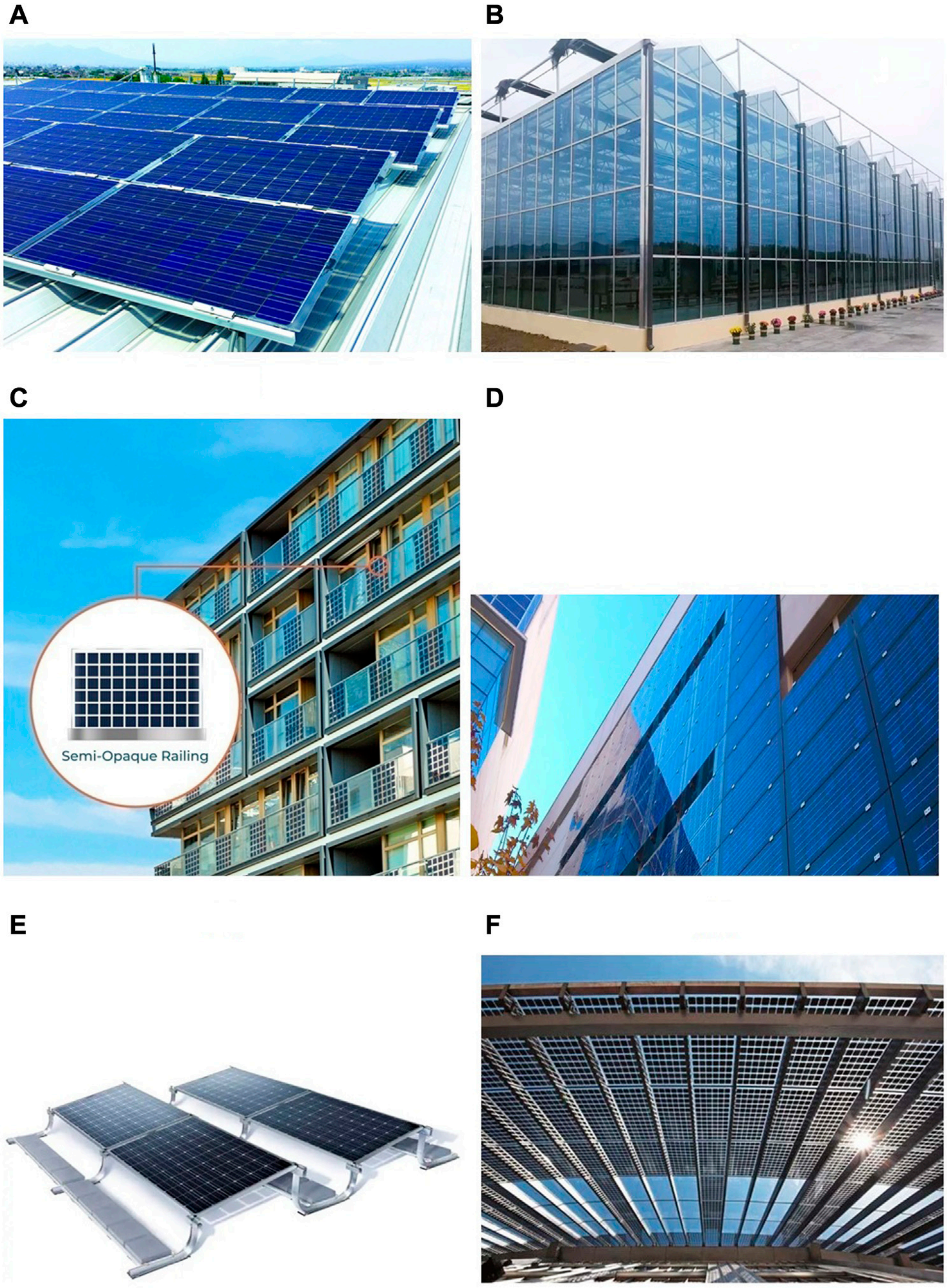

FIGURE 5
(A) An example of a bifacial PV rooftop installation (opaque) headquartered in California (Sunpreme's 'Maxima' bifacial modules offer 380W and impedance matching performance – PV Tech, 2022). **(B)** An example of a transparent bifacial PV installation (Yin et al., 2022). **(C)** An example of a window with transparent bifacial PV technology used in a hotel in Greece (EU SmartFlex project finishes reference solar façade | glassonweb.com, 2022). **(D)** An example of a wall opaque facade bifacial PV installation (Electricity from the house wall – the great potential of building facades to capture solar energy – Leibniz Institute of Ecological Urban and Regional Development, 2023). **(E)** An example of a flat roof-faced bifacial PV system. **(F)** An example of skylight sunshade type bifacial PV installation.

gain. Huang et al. (2018) provided a thorough analysis of a unique vacuum photovoltaic insulated glass unit's thermal and electrical performance. The comparative investigation demonstrates the superior thermal insulation capabilities of vacuum photovoltaic, which can reduce heat gain and loss in Harbin (HB) and Hong Kong (HK) by up to 81.63% and 75.03%, respectively. In various climatic situations, net energy savings of between 37.79% and 39.82% can be attained by installing vacuum photovoltaic systems in all of the prototype building's available facades.

2.2.2 Rooftop installation (opaque)

Installing bifacial solar panels on the flat rooftops of commercial buildings is a good approach to increase production. The bifacial gain is largely determined by the flat roof's albedo. It is challenging to predict the power output of bifacial PV systems over time since it varies as a result of soiling and moss growth. Several previous studies discussed the rooftop installation systems, such as the study by Muehleisen et al. (2021), which rated and evaluated bifacial PV rooftop systems using 20 panels located on a rooftop with white-painted color, power optimizers, and an east-west orientation. It was reported that when compared to panels with 70% bifaciality, which is the ratio of the nominal efficiency at the front side to that at the rear side, the utilization of panels with 92% bifaciality produced a yield that was up to 3% greater. Figure 5A shows an example of rooftop installation (opaque).

The appropriate module area, module efficiency, and area ratio assumptions have a significant impact on the industrial PV possible calculation. Kutlu (2022) proposed an open-source model to estimate the potential energy yield of five different modules of rooftop PVs with different efficiencies, which was verified for all roof types of PVs. According to the findings, the greatest outcome is obtained by thin-film (M5) and mono-Si halfcut (M2) modules in the residential sector and mono-Si and M2 bifacial modules (M3) in commercial and public buildings. One-month simulation and operation studies were presented by Joge (2003) but without quantitative results, while calculations of a rooftop bifacial PV energy potential over 1 month were also considered in Dubai, UAE (Ahmad et al., 2021), to reduce consumption and enhance energy production. Different configurations for the rooftop and façade BIPVs were used for solar PV simulations. Energy production has increased by 9.93% for bifaciality and 19.88% for rooftop tracks. The simulation output of the energy system from a bifacial solar PV system in November was 1965.4 kWh and was 25625.9 kWh annually in Dubai, UAE.

2.2.3 Bifacial flat rooftop

Installing bifacial solar panels on the flat rooftops of commercial buildings is a good approach to increase production. The bifacial gain is largely determined by the flat roof's albedo. It is challenging to predict the power output of bifacial PV systems over time since it varies as a result of soiling and moss growth (Muehleisen et al., 2021).

Using bifacial solar cells, bifacial PV panels have been created and are now prepared for mass manufacturing (Joge, 2003). On a building rooftop, a fence-integrated system was built as one of the applications to test the bifacial PV panel's field performance. The following has been confirmed based on the results of the simulation studies and 1-month operation. 1) The system is capable of producing electrical power comparable to that produced by a typical monofacial array set to the south with an ideal tilt. 2) On a good day, output power rises quickly with sunrise and remains practically flatly high until dusk, resulting in perfect daily and yearly power distributions.

2.2.4 Transparent faced

The building envelope, especially the facades, is a crucial component since it affects the internal thermal loads while also providing sizable space for energy generation. However, many design elements affect how well bifacial solar modules work. Therefore, a bifacial PV module performance analysis should be performed to apply bifacial solar modules to buildings. This analysis should take into account different design factors and reflect a variety of installation conditions. A transparent bifacial PV system was addressed by Muehleisen et al. (2021) by comparing it with a corresponding one with a black back sheet, where the results obtained a gain of 17% concerning that of 15%. Song et al. (2022) reviewed transparent bifacial solar modules in design domains, where bifacial advantages and theories are summarized. The study discussed the environmental and economic costs, device durability, and power output. A transparent bifacial glass-to-glass semi-transparent PV device with esthetically pleasing colors and emotionally inoffensive characteristics was developed by Myong and Jeon (2016), combining the color of the back glass by transparent back contact and testing at an ideal tilt angle of 30°. The semi-transparent PV module's performance ratio was about 124.5% practically, which surpasses its simulated prediction by a drastically high value. Bifacial PV generation can make up for the loss of reduced direct plane-of-array irradiation at a greater tilt angle because the reflected albedo tends to rise toward higher tilt degrees. By harvesting reflected and lit light, the transparent bifacial PV system is appropriate for vertically mounted BIPV modules for usage in traffic noise barriers, roofs, façades, and curtain walls (Myong and Jeon, 2016). The findings of Kang et al. (2016) indicated that the transparent space ratio design aspects and reflectivity have the biggest effects on performance levels. Performance was less affected by the distance between the module and the wall. Depending on the design components, the bifacial BIPV module provided output up to 30% higher than the output of monofacial PV modules. Transparent space ratios of at least 30% should be present in bifacial BIPV modules themselves. Bifacial BIPV modules with transparent space ratios of 40% and higher should be used when a dark color with a reflectivity of 50% or less is used on the exterior wall. An example of a transparent bifacial PV module is shown in Figure 5B.

In order to capture more solar energy and guarantee higher efficiency than traditional PSCs, bifacial transparent perovskite solar modules (BTPSCs) were developed (Gao et al., 2017). A significant factor in attaining photo-to-electricity exchange efficiency was the transmittance and resistance of Au electrodes (PCE). The maximum PCE of 14.74% was achieved by engineering the constructed BTPSCs' capacity to gather light. Furthermore, it was shown that the main variables impacting PCE were the illumination angle and the intensity of the reflecting light. These BTPSCs could be used for PV building integration, such as Venetian blinds or semi-transparent PV windows.

2.2.5 Balcony windows (transparent)

PV modules were formerly solely thought to be installed on building rooftops. However, there are numerous types of PV modules available now that can be mounted on various building surfaces, including balconies, windows, and curtain walls. Given that the layout design (the orientation of the modules, location, type, and size) has a significant impact on the productivity of the PV system, it is essential to carry out a thorough simulation of radiation potential on various building surfaces to determine the most effective PV layout. A case study for a tall skyscraper in Montreal, Canada, was discussed by Salimzadeh et al. (2020), in which various scenarios were thoroughly compared and designed from a cost and energy standpoint. The study presented a model for the initial investment against the annual average ROI (region of interest) for unlike payback time. This model can help the investor to recognize the correct investment approach according to budgetary restrictions. For example, if the reachable financial plan for PV component setting up at year zero was a 100K$, the investor may be expecting payback periods of 3, 5, 10, 15, 20, and 25 years for an ROI of 18%, 30%, 36%, 37%, 36%, and 34%, respectively. An example of a window with transparent bifacial PVs is shown in Figure 5C.

2.2.6 Wall opaque facade

A partially ventilated and transparent PV facade incorporated into an energy-efficient building's envelope is continually growing. Such a setup takes advantage of the heat transfer between the building's main wall, the PV façade, and cavity air for heat recovery in the winter (mechanical ventilation) and PV cooling in the summer (using natural convection). When compared to a normal wall, the opaque ventilated photovoltaic/thermal (PV/T) façade can cut the heat flow through the external envelope by 40% (Liang et al., 2020). The particular PV/T facade can be a hybrid module made of a single-sided inflatable plate collector, solar modules, glass lamination, and ethylene–vinyl acetate. According to Liang et al. (2020), the results of the average PV conversion efficiency may reach around 9%, and the developed system's performance coefficient can reach 3.1%. An example of a wall opaque facade bifacial PV module is shown in Figure 5D.

Saadon et al. (2016) discussed the simulation of a PV facade incorporated into an energy-efficient building envelope that is partially ventilated and transparent. It is reported that the impact of the façade on the heat needs is minimal because these requirements are low for every location analyzed in Toulouse, France. It was discovered that the ventilation requirements are somewhat higher for all of the locations measured.

The case of Universitas Ciputra, which is a building designed with green features, was discussed by Susan and Wardhani (2020). The purpose of this study was to track efforts made to maximize the production of electrical energy from renewable energy sources and the amount of optimal electrical energy produced in comparison to mobile green building requirements. Using the best tilt and orientation angle, the PV panels were integrated into the building façade components (shading device, transparent wall, opaque wall, and roof). The outcome demonstrated that 6%–22% of the required maximum power demand might be replaced by the use of the BIPV concept. The predicted BIPV efficiency of electricity production was found between 8% and 9.5%, with no effect of outdoor air temperature and ventilation airflow rate on PV module cooling. A total of 7.5%–4.5% of daily solar radiation can be used as heat gains through opaque envelope walls, and between 75% and 35% of daily solar radiation can be used to pre-heat the air for space ventilation (Domjan et al., 2020).

2.2.7 Flat roof-faced

Sustainable buildings with bifacial PV modules installed on flat rooftops are an effective method to enhance the bifacial gain, and consequently, the energy yields determined by the albedo of the flat roof. It is challenging to predict the power output of bifacial PV systems over time since it varies as a result of moss and soiling growth. An example of a flat roof-faced bifacial PV module is shown in Figure 5E.

A fence-integrated building was installed on a rooftop as one of the applications (Joge, 2003), and a small plant with 20 panels, including dummies, was set up to study the impact of bifacial PV rooftop systems. A commercial bifacial PV module supporting construction was installed on a white-painted flat roof to ensure an ideal output (Muehleisen et al., 2021). It is reported that initially, the east- and west-oriented panels of the bifacial module with a transparent back sheet outperformed those of the module with a black back sheet by 17% and 15%, respectively. Due to albedo loss from moss growth and pollution, after 1 year of operation, the east- and west-oriented panels still provided a measured benefit of 7% and 5%, respectively. When compared to panels with 70% bifaciality, the utilization of panels with 92% bifaciality produced a yield that was up to 3% greater.

2.2.8 Skylight sunshade type

PV panels can be connected with structures in a variety of ways, including skylights and sunshades, which not only aids in the production of energy but also creates thermal heat and daylight. It also improves the building's esthetic appeal. The building industry consumes more than one-third of the world's energy. One study investigated skylights and sunshade installation types in Varanasi, India (Gupta and Tiwari, 2017). It is reported that the life-cycle conversion efficiency, energy production factor, and energy payback time for average daily solar radiation = 450 W/m^2 and ΔT = 8°C was obtained as 0.47 years (for 300 years), 19.58 years (for 300 years), and 15.32 years, respectively. An example of a skylight sunshade bifacial PV module is shown in Figure 5F.

2.3 Simulation and optimization software

2.3.1 Simulation software

Simulation and optimization techniques are of great significance for the BIPV system analysis. In academic studies, simulation work has increased due to recent technological advancements. These advancements make the analysis and design of BIPV systems simpler and more affordable. Table 3 lists the software programs that are used for design and analysis.

Generally speaking, modeling was performed to assess BIPV performance through thorough fluid and temperature analysis. Software that resolves difficult mathematical equations was also used to conduct theoretical calculations. Saretta et al. (2020) proposed a computational technique to match the architectural characteristics of façades with the current PV radiation analysis using building typological indicators. In the same context, Tablada et al. (2018) presented a concept of a productive façade method to integrate PV modules as shading elements and for farming planters. The maximum façade systems were set based on the conditions, the availability of resources, and the context of the Singapore Tropical Technologies Laboratory, where they were installed. Salimzadeh and Hammad (2017) discussed PV panels' location optimization on balcony windows by optimizing the layout, number, and size of PV modules to achieve maximum energy generation and maximize the panel capacity.

2.3.2 Future trends

The existing studies demonstrated that BIPV systems are a promising field to sustain energy generation toward nearly net-zero-energy building, especially when the BIPV system is a bifacial

TABLE 3 Software and simulation programs that are used for optimization, design, and analysis of BIPV systems.

References	Software	Main aim
Chen and Yin (2016); Tarigan (2018)	RETScreen	Annual electricity generation
Chen and Yin (2016)	eQuest	Calculating the yearly electricity usage
Kamel and Fung (2014); Shimoda et al. (2021)	Bottom-up simulation	Equation and algorithm solutions
Yoo and Manz (2011)	VR4PV	Shadow factor
Li et al. (2015)	Green Building XML	BIPV analysis and simulation
Bakos et al. (2003); Huang et al. (2004)	*PROTEUS*	Equation and algorithm solutions
Bakos et al. (2003); Peng et al. (2011); Wittkopf et al. (2012); Yu et al. (2015)	MATLAB	Equation and algorithm solutions
Vuong et al. (2015)	CIELAB	Systematic analysis of colors
Wang et al. (2015)	MOSEK	Equation and algorithm solutions
Defaix (2012)	THERM	Energy simulations
Bambrook and Sproul (2012); Radmehr et al. (2014)	PVsyst	PV modeling and data analysis
Yang and Athienitis (2014); Agrawal and Tiwari (2011)	ESP-r	Calculating the power output from the photovoltaic system
Lu and Law (2013)	FLUENT	CFD analysis and simulation
Vuong et al. (2015)	PHEONİCS	BIPV analysis and simulation
Religiana and Wiyantara (2014); Jayathissa (2016); Lydon et al. (2017)	Energy Plus	BIPV analysis and simulation
Vuong et al. (2015); Arnaout et al. (2020); Zomer et al. (2020); Ajithgopi et al. (2021); Chandrika (2021)	PVsyst	BIPV analysis and simulation
Hwang et al. (2012); Pérez-Alonso et al. (2012)	TRNSYS	Building thermal analysis and simulation

PV type. However, gathering non-uniformly dispersed back incident illumination is a very challenging issue in BIPV systems, and the majority of studies are unable to handle huge sets of plan variables and automatically provide a collection of different best designs. On the cellular, modular, and systems levels, there are still a lot of bifacial PV-related development and optimization opportunities. A document released by NREL (Sahu et al., 2021) provides a summary of the technical themes from the virtual Bifacial PV Workshop 2020. Bifacial PV with power optimization could be one of the solutions for improving the robustness of BIPV systems. Therefore, this work compares the optimization-based normal PV and bifacial PV optimization strategies.

3 Survey on related reviews

According to the collected publications in the field of BIPVs, several review studies discussed such systems in terms of design topologies, applications, installation types, energy yields, optimization techniques, luxury, and thermal comfort. Table 4 lists several valuable literature studies classified according to the area of electrical energy yield and thermal performance with their associated applications.

The table demonstrates a number of points that can be highlighted. For electrical energy yield and thermal performance areas, the studies by Biyik et al. (2017), Pandey (2016), and Yu et al. (2021) benefit researchers and practitioners working on or interested in BIPV system design, analysis, modeling, performance evaluation, financial development and incentives, and new techniques and trends. Electrical energy yield has interesting areas, such as the papers by Zahedi (2006), Martín-Chivelet et al. (2018), Akbari et al. (2019), Irshad et al. (2019), Idzkowski et al. (2020), Dai and Bai (2021), Singh et al. (2021), Uzum (2021), and Lamnatou et al. (2022), which addressed the function of energy storage for PV in the situation of prospect energy storage progresses, provided an assessment between the advantages and disadvantages of the key methods, and examined the resolution techniques which used machine learning, deep learning, and artificial intelligence-based optimization. According to these studies, an increase of 22% in potential energy saving and a reduction of 5°C–10°C interior temperature from the ambient surroundings can be achieved. A categorization of façade building-integrated photovoltaic thermal systems is shown in Figure 6.

Due to environmental concerns, the need for energy independence, and the high cost of fossil fuels, renewable and sustainable energy-producing technologies have taken the lead. Researchers and practitioners working in or interested in financial development, performance evaluation, modeling, analysis, design, incentives, innovative approaches, and trends of BIPV systems are anticipated to benefit from such thorough review studies. Intelligent demand-side management must be used in conjunction with effective and affordable energy storage solutions for photovoltaic systems to be completely integrated into networks.

TABLE 4 Literature studies classified according to the region of interest with their focus and significant findings.

Region of interest	References	Focus on
Electrical energy yield and thermal performance	Biyik et al. (2017)	BIPV and BIPV thermal applications.
	Yu et al. (2021)	The designs of BIPVs and their influence on electricity generation, thermal performance, and energy consumption for space heating and cooling.
	Pandey (2016)	BIPV, concentrated photovoltaics (CPVs), and photovoltaic thermal (PV/T) performance.
Electrical energy yield	Martín-Chivelet et al. (2018)	Building case study into a new ventilated façade for large-scale actions.
	Akbari et al. (2019)	Types of energy storage systems that can be integrated with BIPV and thermal energy storage systems.
	Uzum (2021)	Rooftop BIPV technology on the distribution network in terms of voltage quality, power quality, system protection, and system stability.
	Singh (2021)	Building envelope roof and facades, such as PV-roof, PV-skin facade, PV-Trombe wall, PV claddings, and louvers.
	Lamnatou et al. (2022)	Smart grids/smart technologies concerning IPV systems, storage, buildings, and the environment.
	Irshad et al. (2019)	Wall-installed BIPV system and its benefits in terms of building energy consumption.
	Zahedi (2006)	Recent developments of research projects for harnessing renewable energy sources.
	Dai and Bai (2021)	The selection of proper PV technologies, temperature management, solar irradiation enhancement, and avoidance of excessive mechanical strain.
	Idzkowski et al. (2020)	Mathematical models and actual measurement data.
Energy optimization	Ramos et al. (2021)	Energy communities to support the innovative BIPV models.
	Mellit (2020)	Recent applications of AI techniques, particularly in machine learning (ML) and deep learning (DL).
	Hashempour et al. (2020)	Decision-making model, measures and variables, objectives and criteria, software tools, optimization methods, case studies: geographical locations, and case studies: building types.
Electrical energy and solar irradiance	Liu et al. (2021)	Application advantages of BIPV systems in terms of the energy supply and aesthetic value of buildings.
Thermal energy	Zhou (2021)	Technical feasibility of BIPVs.
Economic viability	Barzegkar-Ntovom et al. (2020)	The economic viability of hybrid PV-and-storage systems at the residential building level under a future pure self-consumption policy.

Increasing onsite use of power generated by PV technology will become crucial to maintaining the integrity of the energy grid as the worldwide market for solar photovoltaics expands beyond 76 GW. The analysis of all the different electrical and thermal energy storage systems that can be coupled with PV was discussed by Akbari et al. (2019). Along with the function of energy storage for PV in the context of upcoming improvements in energy storage, the integration of PV energy storage in smart buildings was considered (Pandey, 2016). BIPVs has excellent integration possibilities for supplying electrical and thermal loads in buildings. Biyik et al. (2017) thoroughly examined the performance, efficiency, nominal power, energy generation amount, and type of assessment methods of BIPV and thermal BIPV applications. The two primary research areas in BIPVs are found to be 1) system efficiency improvements through ventilation, resulting in a better yield with a lower panel temperature, and 2) cutting-edge thin-film technologies that are excellent for integration into buildings.

Solar collectors and solar PVs are combined for combination with building façades to produce electricity and create heat power. As a result, the cooling/heating load on buildings can be decreased, while solar energy efficiency can be greatly boosted. Thus, such an application offers a viable way to create low- or even zero-energy buildings by drastically reducing building energy consumption (Yu et al., 2021). Chan (2019) presented a survey to select and identify 25 accessible commercial constructions with various degrees of adjacent shading [in terms of orientations and ranging (0.16–0.95) sky view factors]. The total installed PV capacity in some countries like India reached 33.7 GW by the end of December 2020, as reported by Reddy (2020), who stated that in terms of reducing the HVAC load on the building, BIPV systems are the greatest option for the Indian context. A framework overview of the BIPV system, including models used, outputs, and data inputs, is shown in Figure 7.

In the energy optimization area, the studies by Mellit (2020), Hashempour et al. (2020), and Ramos et al. (2021) present concepts sustained by formulation for the optimization difficulty to be explained by the society administrator, features of comfort environment, and some types of weather conditions, except thermal comfort. Liu et al. (2021) reviewed the field of electrical energy and solar irradiance to present precious information for the expansion of BIPV schemes in sections with high solar irradiance. In another context, Zhou (2021) addressed only the thermal energy issues. It is reported that BIPV can improve solar comprehensive

FIGURE 6
Categorization of façade building-integrated photovoltaic thermal systems.

utilization efficiency and present original ideas for potential studies on energy harvest payment. Finally, the study by Barzegkar-Ntovom et al. (2020) evaluates the economic viability of hybrid PV-and-storage systems for BIPV systems.

These studies discussed BIPV systems thoroughly in terms of design topologies, applications, installation types, energy yields, optimization techniques, luxury, and thermal comfort. However, all the studies review the integration of PVs with low- and large-scale buildings but not bifacial PVs.

4 Bifacial PV-based integrated buildings

If the electricity generated by the bifaciality is captured, bifacial PV modules could be a compelling substitute for monofacial PV modules even in the context of building combinations. Bifacial PV modules are able to produce more energy than conventional PV modules (Appelbaum, 2019). The influence of a bifacial PV module on the indoor environment is more complicated as a result of the thermoelectric effect, which is produced due to the module's losses at the back. Through experiments and simulations of the PV building (Zhao et al., 2022), investigated in the internal environment of bifacial PV modules as the building envelope, it was discovered that the optimization design greatly improved the indoor environment and extended the annual thermal comfort by about 8%.

In simulations of buildings with integrated active facades, a numerical model that permits assessing the thermal and electrical energy equilibrium of BIPV façades was presented by Tina et al. (2021). The glass–glass bifacial photovoltaic façade generates an energy yield of roughly 5% greater than the monofacial BIPV façade, according to the calculations made using the meteorological data from Catania, Italy. Kim et al. (2021) discussed bifacial BIPVs for zero-energy buildings for achieving high power output through gathering light from both sides, but harvesting non-uniformly distributed back incident light is a very challenging issue in bifacial BIPVs.

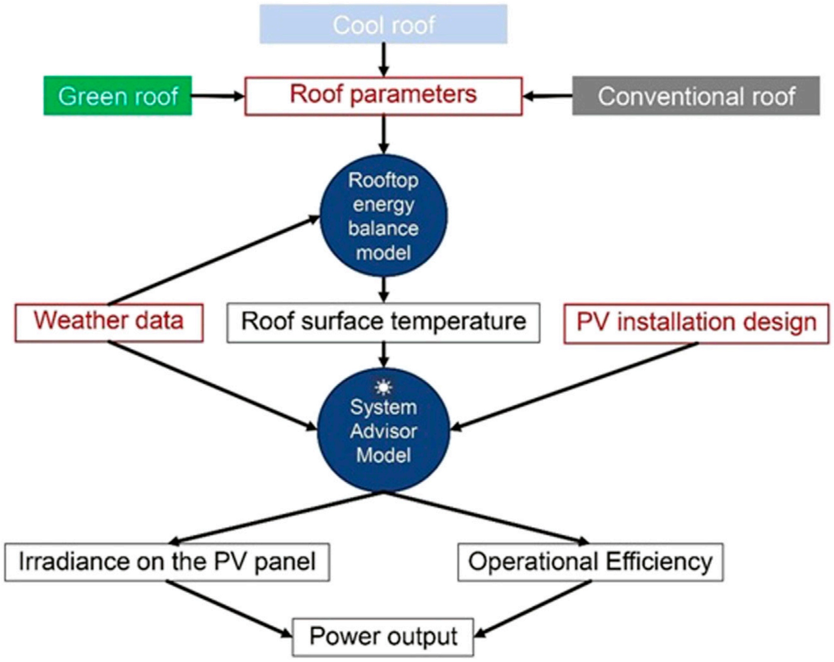

FIGURE 7
Framework overview of the BIPV system, including models used (in blue), modeling outputs (in white), and data inputs (in red) (Cavadini and Cook, 2021).

For BIPV window applications, passive solar concentrators made of the film were used (Cook and Al-Hallaj, 2019). In order to make window glass act as a waveguide and direct light onto the back of bifacial BIPV modules, micro-facets were used to generate complete internal reflection. Two readily available films were used in experimental validation. Both films made the module used as a passive solar concentrator by allowing solar energy to reach the rear side of the module over the range of incident angles that were considered. There was a maximum of 35.1% increase in power. The findings show that film-based optical components could be used in BIPV applications as passive solar concentrators. According to Appelbaum (2019), the vertical mounting's performance for the equatorial regions of the bifacial PV panel is marginally inferior to that of the latitude-mounted mounting. One model for bifacial BIPV application that achieved an accuracy of 99% is described by Alam et al. (2021) using the finite element mesh generation method to form quasi-uniform grids.

The annual incident energy (global energy, diffuse, and beam) on overhangs made up of conventional and bifacial PV modules is computed by Appelbaum et al. (2019) together with the fluctuation in shadows produced by overhangs on doors, windows, and carports. The portion of the bifacial PV module's backside receives reflected energy (5% or more) from the ground and walls. With mean photovoltaic module temperatures reaching 68.3°C in the warm season, a considerable thermal gradient is seen throughout the façade, as expected, and is mostly caused by site albedo. The creative facade generated 63.8 kWh/m^2 of cumulative electrical energy annually, with a performance ratio of 0.7 and an annualized average efficiency of 6.28%. In comparison to the benchmark, a significant decrease in the building's overall energy use of up to 92% is seen throughout the winter (Assoa et al., 2021). The tilt angle induces variations in the power equilibrium of two unlike types of PV modules, bifacial and monofacial, which were discussed by Bilčík et al. (2020). To test the effectiveness of an integrated bifacial solar PV system and cool roof technology to enhance solar energy production and decrease building energy consumption, Ahmad et al. (2021) presented the design and performance analysis of a bifacial solar PV system for an energy-efficient home with and without a tracking system. By combining several technologies, energy production increased by 19.88% for rooftop tracking, 9.93% for bifaciality, and 10.14% for façade monitoring. The tracking system self-consumes at a rate of 4.66%. Comparing the results to those of a traditional monofacial fixed installation, a total improvement of 35.29% was noted. The output of the energy system from the simulation was 25,625.9 kWh annually. The output of a bifacial solar PV system in November was 1,965.4 kWh. Table 5 presents a brief comparison of the previously conducted studies for bifacial PV-integrated buildings.

5 Monofacial solar PV-integrated buildings

In order to capture solar power through PVs and heat consumption, a building-integrated multifunctional roofing system has been expanded. This system minimizes PV efficiency and eliminates the labor and material redundancy of a standard PV system. Elnosh et al. (2018) examined PV modules that faced south over 2 years in Dubai, United Arab Emirates, at three different tilt degrees (5, 25, and 90). It has been discovered that while the tilt angle

TABLE 5 Comparison table of the previously conducted studies for bifacial PV-integrated buildings.

References	Main target	Exp/ Sim	Configuration	Significant results
Zhao et al. (2022)	Thermal analysis	Exp/Sim	The coverage is changed with a heat insulation reflective layer behind PV modules.	Annual thermal comfort increased by 8%.
Kim et al. (2021)		Exp	A large difference in the reflectance inside the rear reflector installed close to module.	Compared with a uniform rear white reflector (163.5 W/m^2), 12% less power (146.2 W/m^2).
Appelbaum et al. (2019)	Reflective energy	Sim	Horizontal pole shadows cast by horizontal plates, inclined poles, and shaded area.	The contribution with reflective energy was 5%.
Myong and Jeon (2016)		Sim	TBC a-Si:H and OBC a-Si:H semi-transparent PV modules are tested over 1 year.	The performance ratio was about 124.5%.
Najafi et al. (2022)		Sim	A bifacial equivalent power output.	Provides more stable power of 21.3 W/m^2 on the front side and 33.5% with reflected albedo.
Alam et al. (2021)	Electrical energy yield	Sim	The view factor computation model.	It varies from 180 s to 257 min for the iteration size of 7.67 billion to 765 billion.
Tina (2020)		Exp	Multilayer one-dimension dynamic thermal model of monofacial glass-back sheet and bifacial PV module.	Glass–glass PV can produce 5% energy more than the monofacial PV module.
Tina et al. (2021)		Sim	Simulations under transitory conditions considering four configurations of BIPV facades.	Glass–glass bifacial PV façade provides an energy yield of 5% more than the monofacial BIPV façade.
Bilčík et al. (2020)		Sim	Using solar inverters (FRONIUS IG) and the pyranometer CMP 11.	The energy production depends on roof surface reflection coefficients.
Cook and Al-Hallaj (2019)		Exp/Sim	Using two commercially available films.	Film-based optical elements have the potential as passive solar concentrators for BIPV applications.
Ahmad et al. (2021)		Sim	Using different configurations for the rooftop.	Annual energy of 25,625.9 kWh.
Elnosh et al. (2018)		Exp	A combination of module efficiency and performance losses.	Can assist to select the most suitable technology, type, and tilt angle of BIPVs.
Appelbaum (2019)		Exp	Acquiring data for a bifacial panel setup.	Vertical mounting's performance is slightly below the latitude-mounted bifacial PV module.
Shoukry et al. (2018)		Sim	An optical model for the rear side irradiance of bifacial PV modules.	Additional yield compared to a standard PV module for various installation parameters.
Schneider et al. (2018)		Exp	PV applications in vertical installations (fences and balconies).	Higher energy yield with minimal technical change or investment.
Klenk (2018)		Sim	An improved energy yield on stand-alone modules in various orientations.	Expected additional energy yield.
Russo (2012)	Optimize energy	Exp/Sim	A baffled multi-detector sensor with a discrete azimuthally and declination angle combinations.	Optimizing energy harvesting of systems.

has no bearing on temperature loss, it has a considerable impact on soiling losses, with lesser tilt angles leading to more soiling losses. The research findings can be used to choose the best PV module technology, type, and tilt angle for installations of building-applied photovoltaic (BAPV), which is powered partly or totally by solar PVs, and building-integrated photovoltaic systems in various geographical locations. A modified building system in which normal PV modules are incorporated with a ventilated façade was also discussed by Martín-Chivelet et al. (2018). The study reported that for a typical meteorological year, the grid-connected PV system is predicted to produce 20 MWh of electricity annually. This amount equaled 4.6% of the building's 432 MWh/year total annual electric power consumption before the rehabilitation project. There was a 19-MWh/year production monitored over a full year, from October 2016 to September 2017. When the energy retrofit is finished, including the replacement of the windows and lighting, a 30% reduction in energy usage is anticipated. PV energy will then account for 6.6% of the total consumption.

The two primary techniques for increasing the energy sustainability of buildings at a neighborhood size are the incorporation of renewable energy sources and architectural rehabilitation, although optimizing these processes concurrently is challenging. The findings of Guen (2018) demonstrate that upgrading all buildings decreases the need for space heating by 70%–85% and lessens energy demand swings, enabling the integration of additional renewable energy. According to the calculations, BIPVs can meet the village's whole yearly energy consumption. The energy system assessment reveals that, even with the integration of non-dispatchable renewable energy technologies, it is challenging to go beyond the 60% mark. As a result, there are now opportunities for the installation of PV

TABLE 6 Comparison table of the previously conducted studies for monofacial PV-integrated buildings.

References	Main target	Exp/ Sim	Method	Significant results
Yin et al. (2013)	Electrical energy yield	Sim	Silicon PV modules are embedded between a transparent protective layer and a graded material layer.	Achieving a high degree of energy efficiency.
Guen (2018)		Sim	Swiss energy maps to identify the most promising renewable energy sources with three scenarios.	Reducing the space heating demand by 70%–85% and reducing the fluctuations in energy demand.
Skandalos and Karamanis (2021)		Sim	Four bifacial PVs effect on the built environment for three different climatic zones.	BIPVs could substantially contribute to the transition to zero-energy buildings.
Boccalatte et al. (2020)		Sim	Considering a multi-thermal zone reference building located inside a district of similar characteristics.	60% rooftops energy of 60% the total area of the façades, with an 11% decrease in energy.
Makinde et al. (2021)		Sim	Grid-connected and off-grid photovoltaic (PV) systems.	71.2% for grid-connected and 75% for off-grid.
Zogou and Stapountzis (2011)		Sim	PV modules into the building wall using a double façade.	Contributing to the building's energy performance improvements.
Fathabadi (2015)		Sim	Studying energy efficiency of the PV converter battery.	Verifying an increase of 9.3% in the energy efficiency.
Jung et al. (2021)		Sim	Artificial neural network (ANN)-based control logic.	Can produce 3.0%–3.1% more electric power.
Wang et al. (2017)		Sim/ Exp	PV-DSF and the PV-IGU simulation and experimental setup in five different climates of China.	Up to 28.4% average energy saving compared to glass window.
Kumar et al. (2019)		Sim	A roof building and its performance in BAPV and BIPV configurations with crystalline (c-Si), CIS, and CdTe.	CdTe is observed to perform better than CIS and c-Si.
Sivaram et al. (2020)		Sim	Energy, environment, and economic analyses are carried out for the BIPSET.	The unit cost of electricity was 18% less when 30% government subsidiary is used.
Martín-Chivelet et al. (2022)		Exp/ Sim	The experimental setups arrange the BIPV modules vertically and with different backside boundary conditions.	The estimation of PV energy can assess the suitability of each temperature model.
Susan (2021)		Exp	The boundaries added with the limitation of structure and limitation of potential-available integrated area.	The model generated more than 777,741 kWh/year of electrical energy.
Dalal et al. (2021)		Sim	Techno-economic analysis of a grid-integrated 3-kWp rooftop solar PV plant using RETScreen software.	Estimated payback was up to 3–7 years.
Alkhateeb and Abu-Hijleh (2019)		Sim	The impact of some strategies on reducing electricity consumption to highlight the optimal scenario before.	The passive strategies reduced electricity demand by 14.7%, while active measures reduced by 63.2%.
Khan (2018)		Exp	A bi-reflector solar PV system (BRPVS) with a thin-film Al-foil reflector and an LLC converter for a BIPV system.	28.47% enhancement in output power.
Shanmugavalli and Vedamuthu (2021)			Mapped on the roofs and façades through color solar insolation mapping.	Rooftops and BIPV enable buildings to move toward self-reliance of their energy needs.
Akbari Paydar (2020)		Sim	BIPV system installed over the window without distance.	The annual electricity was 2% higher than the fixed mode.
Shankar et al. (2021)		Sim	A semi-transparent BIPV module at the building to allow reducing daylight harvesting.	A competent levelized cost of energy (LCOE) compared with existing utility grid.
Abdelhafez (2021)		Sim	Using PV*SOL simulation software, the performance ratio, the system efficiency, and the annual energy output in several tilt angles were determined.	Better climate and energy efficiency as well.
Dobrzycki et al. (2020)	Thermal analysis and energy	Sim	Determining the heat transfer coefficients across the partition to estimate the potential thermal energy savings.	Improvement in thermal building wall, gas consumption, and generation of electricity.
Rabani, Bayera Madessa and Nord (2021)		Sim	Coupling of indoor climate and energy simulation software (IDA-ICE) with a generic optimization tool and graphical script interface.	Decreasing building energy by up to 77%.
Giouri et al. (2020)	Energy optimization	Sim	Energy simulations with Design Builder and EnergyPlus are used as a benchmark for the optimization.	Annual energy reduction of 33%.
Guzman et al. (2021)		Sim	An aggregation strategy that maximizes a green energy index (GEI) for the smart charging coordination of EVs.	Optimizes usage of the energy to charge EVs.

(Continued on following page)

TABLE 6 (*Continued*) **Comparison table of the previously conducted studies for monofacial PV-integrated buildings.**

References	Main target	Exp/ Sim	Method	Significant results
Gremmelspacher et al. (2021)		Exp	Covering the primary energy use of the building on a net annual basis.	Reaching Net-ZEB was possible.
Mesloub et al. (2020)	Optimum BIPV window design	Exp/ Sim	Double-glazing PV modules (A) with medium WWR and 20% VLT in the southern facade and 30% VLT toward the east–west axis.	Improvement in overall energy savings.

modules in double façades. It is preferable to space PV modules away from south-facing building walls to allow heat rejection, prevent overheating, and maintain efficiency (Zogou and Stapountzis, 2011). In the same context, according to a study on Australia's city of Melbourne, the majority of the city's solar energy potential is provided by PV rooftops. It is demonstrated, however, that the PV prospective of windows becomes more pronounced for specific buildings with high compactness of glazed and high-rise buildings (Panagiotidou et al., 2021). The technological workflow described here allows various cities to simplify decision-making regarding the achievement of PV in urban settings (Panagiotidou et al., 2021).

The performance ratio (PR), which is the ratio of measured output to expected output for a specific reporting period, of a BIPV grid-connected system at the research site was found to be 71.21%, whereas the PR for standing PV systems was determined to be 75.1%. This is true for the grid-connected PV system (Makinde et al., 2021). The study estimates that the roofs and facades of campus buildings can generate 8.1 GWh of PV energy per year, which can gather 10% of the current energy demand, with the campus as a whole requiring 82.6 GWh of electricity annually (Zhou, 2022). Table 6 presents a brief comparison of the previously conducted studies for monofacial PV-integrated buildings.

As epitomized in Table 6, the mismatching sags of the DC grid voltage and the control issues with energy transfer for the PV microgrid are rarely recognized. Instead of rating systems based on how efficiently they convert or transport energy over the course of a day, all published research competes on the fast-tracking of MPPs. The challenge is in getting the MPP values while using a high sample frequency. This problem is critical for MPPT in grid-connected PV systems without batteries, which, in turn, calls for a fast processor and memory. Power modules may be put under more stress and have a shorter operating lifespan due to these high switching frequencies (Jia et al., 2018). Thus, switching at a somewhat lower frequency and maintaining a stable DC voltage are essential for a microgrid system to produce quality power and function reliably.

6 Zero-energy buildings integrated with PVs

The idea of "zero-energy buildings" focuses on first enhancing the building envelope's energy efficiency and then incorporating renewable energy sources to meet the balance of the energy demand. In this situation, PV systems offer a dependable option for electricity delivery in both new and existing structures. The nearly zero-energy buildings (nZEBs) concept, proposed by Tina (2020), emphasizes improving the energy performance of the building envelope and integrating RESs to satisfy the energy demand. When bifacial PV modules are included in a building's façade, they work as both an active system that produces green energy and a passive system that lessens the need for cooling the building. It has been shown that bifacial glass–glass PV modules can produce an energy yield that is approximately 5% higher than that of monofacial PV modules (Tina, 2020). Semi-transparent photovoltaics (STPVs) or PV shading devices (PVSDs) are two examples of BIPVs that concentrate on windows and are suggested as effective methods for generating electricity and enhancing building energy performance (Skandalos and Karamanis, 2021). However, because it takes more than a thousand years to develop transparent window glass with good visibility, the replacement of the glass with modern PV concepts requires careful consideration of energy and environmental impacts. There are few comparative studies of the suggested PV integration options and the best integration solutions for various climatic regions despite the abundance of published studies about the performance of each technology.

BIPVs represent an effective technology to reach zero-energy buildings (ZEBs) by means of solar power utilization. A BIPV system can seamlessly integrate PV modules into external building surfaces, such as walls, roofs, shading devices, and decorative components. BIPV surfaces can be used on roofs and façades, and their effectiveness and productivity are influenced by factors such as direction, shade, and surface reflections (Boccalatte et al., 2020). It is found that the annual NZED criteria are met in this instance by collecting solar energy on 60% of rooftops and 60% of the total area of façades, with an 11% loss in energy production per PV unit area due to "darkening" effects caused by PV surrounding buildings.

To achieve the maximum potential financial results for the electricity operating cost for the castle when weighed with the rate to feed power to the utility (Gremmelspacher et al., 2021), a second PV system's azimuth and tilt were optimized for maximum electricity production. Nine financial scenarios were used in this study to examine the viability of both PV systems using life-cycle cost calculations, using the net present value technique. A comparison of the primary energy generated and used by the historic structure was provided for two scenarios, and it demonstrated that the case study object might reach net-ZEB.

For an office building, a smart lighting system incorporating daylight harvesting by BIPVs was suggested by Shankar et al. (2021) to reduce energy use and improve tenants' visual preferences. For the proposed system at ZEB, the benefits of a low-voltage DC supply system were emphasized. Additionally, the potential for energy savings across the proposed artificial lighting system with BIPVs as the building's envelope was explored for occupants' visual

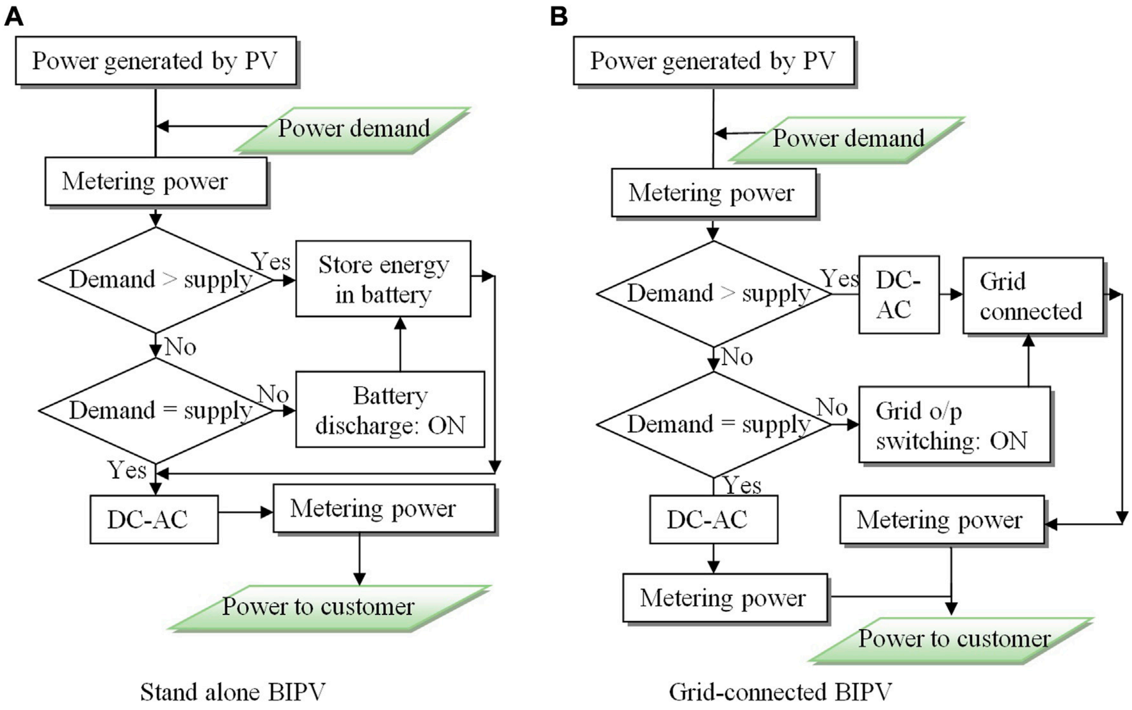

FIGURE 8
Compassion diagram showing the methodology for stand-alone and grid-connected BIPV modules: **(A)** Stand-alone BIPV, **(B)** Grid-connected BIPV.

preferences under various sky conditions. The paper's results indicated that the energy produced by the BIPV module can fully power the suggested lighting system. Additionally, a considerable amount of extra energy was noticed. Comparing the outcome to the utility grid that is now in place, the levelized cost of electrical energy (LCOE), which is a determination of the average net current price of electricity production of a generator concerning its lifespan, is found to be competent.

7 Optimization of BIPV systems

Building-integrated photovoltaic envelope design calls for the consideration of a sizable number of PV- and envelope-related characteristics and competing performance standards. As a result, BIPV design optimization is essential and is now a challenging task discussed by a few studies. Russo (2012) stated that with improved prediction skills, it will be possible to design more efficient building-integrated PV applications and maximize energy harvesting from systems with unusual mounting situations (Susan, 2021).

Samarasinghalage et al. (2022) introduced a framework that includes several envelope design parameters in addition to PV-related features, such as PV product type, PV positioning, window-to-wall ratio (WWR), and tilt angle. The study produced a list of the top BIPV design possibilities based on a variety of goals, structural characteristics, and PV products. The best BIPV product and building surface attributes for a certain performance criterion are examples of alternative designs. The findings of Samarasinghalage et al. (2022) demonstrated that MOO is functional for early BIPV design choices based on technical energy and cost factors. Jung et al. (2021) assessed the PV power generation and reduced the heat effects of windows using a mobile shade device and using artificial intelligence approaches to analyze the effects on window heat transfer. The paper found that the window heat transfer in ANN control was 86.3% lower during a cooling period and 9.7% lower during a heating period. Furthermore, during the cooling period, the PV system generated 3.0%–3.1% more electric power when it was controlled properly. A compassion diagram showing the methodology for stand-alone and grid-connected BIPV modules is shown in Figure 8.

Fathabadi (2015) suggested a plan using a PV converter battery to improve BIPV energy effectiveness. Results from both simulated and actual experiments showed an increase of roughly 10% and 9.3% in energy efficiency, respectively, while the study by Chen et al. (2019) presented a comparative analysis with the holistic design optimization method. The variance-based and screening-based sensitivity analyses are combined with the non-dominated sorting genetic algorithm-II (NSGA-II) and hybrid generalized pattern search particle swarm optimization in the holistic design optimization technique (HGPSPSO). This study conducted the experiments under Hong Kong's hot summer and warm winter conditions and reported that the net construction demand can be decreased by up to 71.36% with the ideal design configuration. Omar et al. (2022) proposed a conversion approach from a traditional educational facility to a net-zero-energy building (NZEB). In order to put such a system of retrofitting strategies into practice, a school building in Egypt is chosen as a case study. It is found that optimized sizes are

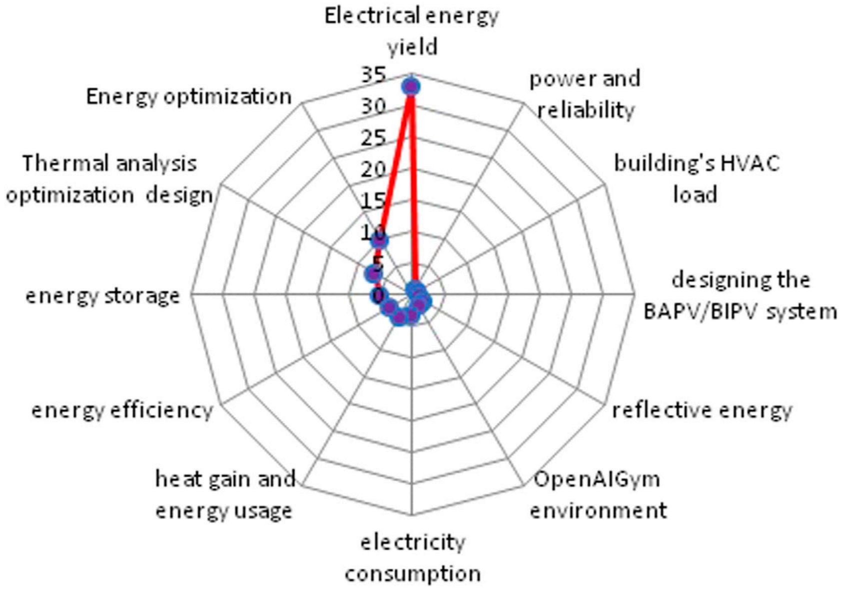

FIGURE 9
Graphical representation of the number of publications on the main investigated area of the energy optimization techniques for BIPV systems.

140 kW and 120 kW, with capital costs of $30,399 and $98,000 for the inverter and PV kit, respectively. These components are integrated into the building after increasing its energy efficiency. Additionally, it will take 24 years for the PV/grid system for the new load to make back all of its expenses (after using the retrofitting technique).

The findings of these studies can be used in the early planning stages of low-energy building guidelines and integrated PV applications. However, the majority of studies are unable to handle huge sets of design variables and to automatically provide a collection of alternative optimal designs. The design of a BIPV envelope now heavily relies on an optimization methodology. A graphical representation of the number of publications on the main investigated area of the energy optimization techniques for BIPV systems is shown in Figure 9.

This figure shows that the largest interest was in computing the electrical energy yield of BIPV systems and that the annual energy yield is the key factor to evaluate the system performance. The survey results are expected as high energy demand has been seen in most cities in recent years as a result of industrialization and rapid population increase. One of the top concerns of scientists and policymakers around the world is providing enough electrical energy while lowering greenhouse gas emissions. The energy authorities in most countries are becoming more conscious of the need to reduce the negative environmental effects of non-renewable energy by investigating alternative sustainable energy sources and enhancing the energy efficiency of buildings. BIPV technology has gained recent attention as a possible method for providing buildings with instantaneous sustainable energy. Solar energy should be widely used in residential structures within the urban context to make a significant contribution to zero-energy buildings.

8 Conclusion

The presented paper thoroughly discussed and evaluated the integration viability of solar PVs with the building envelope, the annual energy yield, and the electrical energy optimization techniques at the residential building level. A general overview of the principles for BIPV and bifacial PV systems and their characteristics have been provided, and knowledge of some weather parameters and their devastating consequences. A discussion about the differences in the calculation of the efficiency of BIPV and bifacial BIPV systems has also been addressed. Providing a clear understanding for the examination of such systems and presenting a comprehensive assessment of current research on proactive BIPV and bifacial PV enhancement measures. The use of bifacial PV-integrated systems and installation types for strengthening BIPV systems is one of these solutions, which has been fully discussed in this study.

The use of BIPVs, especially with bifacial PV modules, is currently still limited in real conditions despite the recent increase in attention given to BIPV systems. Sustainable buildings with bifacial PV modules installed on building envelop spaces are an effective way to enhance the bifacial gain and, consequently, the energy yields determined by the albedo of these building spaces. Given that the layout design (the orientation of the modules, location, type, and size) has a significant impact on the productivity of the PV system, this study found that it is essential to carry out thorough research on radiation potential on various building surfaces to determine the most effective PV layout. The existing studies demonstrated that the BIPV systems are a promising field to sustain energy generation toward nearly net-zero-energy buildings, especially when the BIPV module is a bifacial PV type. However, cropping non-uniformly spread back incident daylight is an extremely challenging problem in BIPV systems, and the majority of studies are unable to handle huge datasets of plan variables and automatically provide a collection of substitute best possible configurations.

It is preferable to space PV modules away from south-facing building walls to allow heat rejection, prevent overheating, and maintain efficiency in all locations that have been covered in this paper. Another difficulty is making use of the heat that the PV modules reject, especially in countries with hot climates. The graphical representation for the number of publications on the main investigated area of the energy optimization techniques showed that the largest interest was in computing the electrical energy yield for BIPV systems. The design of a BIPV envelope now heavily relies on an optimization methodology. The existing publications discussed the optimization issue only in terms of software retrofitting. Therefore, future directions need to focus on developing new hardware configurations to optimize the PV power generation for each installation type individually since every installation type has its weather environment.

Author contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by ZA, MD, and AS. The first draft of the manuscript was written by ZA, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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