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Review

State-of-the-Art Technologies for Building-Integrated Photovoltaic Systems

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Abstract: Advances in building-integrated photovoltaic (BIPV) systems for residential and commercial purposes are set to minimize overall energy requirements and associated greenhouse gas emissions. The BIPV design considerations entail energy infrastructure, pertinent renewable energy sources, and energy efficiency provisions. In this work, the performance of roof/façade-based BIPV systems and the affecting parameters on cooling/heating loads of buildings are reviewed. Moreover, this work provides an overview of different categories of BIPV, presenting the recent developments and sufficient references, and supporting more successful implementations of BIPV for various globe zones. A number of available technologies decide the best selections, and make easy configuration of the BIPV, avoiding any difficulties, and allowing flexibility of design in order to adapt to local environmental conditions, and are adequate to important considerations, such as building codes, building structures and loads, architectural components, replacement and maintenance, energy resources, and all associated expenditure. The passive and active effects of both air-based and water-based BIPV systems have great effects on the cooling and heating loads and thermal comfort and, hence, on the electricity consumption.

Keywords: BIPVT; performance; renewable energy; PV modules; building; economic aspects

1. Introduction

Terrestrial solar energy amounts to around 1.8 × 1011 MW every year, which is around 10,000 times the rate of the global energy demand [1]. In developed countries, buildings consume about 30–40% of yearly electrical energy produced, and in developing countries, it expends from approximately 15% to 25% [2]. Increasing consumption of electrical energy from primary energy resources increases CO_2 emissions, which has a great impact on the environment [3–5]. Intuitively, mitigating energy demands in buildings will substantially curtail the required supply of energy and, hence, minimize greenhouse gas (GHG) emissions [6–8]. Therefore, there is a genuine interest in net-zero energy buildings (NZEBs) from engineers and scientists, focusing on the tangible measure of energy conservation and enhanced performance efficiencies [9,10]. Net zero-energy installation is central to the Concerted Action Energy Performance of Buildings Directive (EPBD), prompting the development of a protocol to collect fundamental data through surveys and interviews, to highlight challenges and benefits of NZE buildings [11].

As an abstract definition, NZEB are the buildings that mutually consume as much annual electrical/thermal energy as they produce [12,13]. Incorporating solar energy by employing solar PV panels in residential and commercial buildings may become mainstream in the "practice" solution toward reducing CO_2 emissions and to create net-zero buildings [14]. Note that industrial installation may not be a direct benefactor of such an approach, as the incorporation of solar photovoltaics may not be a priority in the near future. However, generally, increasing the capacity of building installation of photovoltaic (PV) could support the transforming of the power system away from the dependence on the traditional fossil fuels to potentially become one of the principals of energy transition around the world by 2030. Since the 1990s, there have been prompt developments around the world in BIPV solar technology. The BIPV systems mostly generate electrical energy, potentially resulting in reduced effective system costs when compared to stand-alone PV systems [15].

Most renewable energy resources, for example solar [16], wind [17], hydro [18], geothermal [19], tidal [20], and biomass [21], could be directly or indirectly converted into electrical energy, relayed either to on-grid units or isolated or off-grid loads [22,23]. Such renewable energy sources have low or no environmental impacts [24,25]. Technologies based on solar energy are thermal (heating/cooling), photovoltaic (PV), or thermoelectric. Integrating some (or all) of these into architectural endeavors can contribute significantly towards resolving the most increasing energy world demands.

Generating electricity from solar energy depends on the required area, price, locations, national energy policy, size of the power supply system, etc. Photovoltaic (PV) solar systems are the most obvious options for remote areas to satisfy low/medium energy demand levels [26]. PV systems produce electric power without mechanical motions have the least harmful impacts on the environment. More so, the rapid decrease in PV power plant costs and the significant increase in their maturity and efficiency ushered a prominent role in reliably generating electricity around the world [27].

A significant amount of experimental and simulation literature on BIPV technology has been available for the past three decades, as progressive urbanization became the trend in modern societies. After the turn of the current century, more countries around the world took interest, as fossil fuel depletion and consumption necessitated the search for holistic solutions [28,29]. Nevertheless, real project applications and successful case studies are still limited at this stage.

The main objective of the present review is to introduce the basic philosophy of BIPV systems as they are devised to enhance the electrical and thermal power integration with the demand side. This goal intrinsically considers the design and operational aspects employed to achieve the optimum balance between supply/demand cycles. The understanding of highly technical aspects of BIPV systems is essential for the success of this approach. Thus, a thorough grasp of the electrical characteristics of PV panels utilized in the BIPV system and the working fluids employed for removing the heat from the PV panels are of paramount importance. Moreover, protocols for solar energy mitigation using air flow for heating/cooling or ventilation [30,31], and water circulation [32] are presented. The capacities of different working fluids employed in BIPV systems to gathering solar energy were evaluated, considering both the heat collected for utilization as well as the electricity generated. The effects of the economic parameters on the electrical and thermal performance of BIPV systems were reviewed in order to investigate the developments in the planning and installation of the BIPV systems [33,34]. In addition, PV modules of all types operate best at certain tilt angles with respect to facades or roofs, which prompted the examination of innovative solutions to optimize incident solar irradiation by the PV cells, to produce said thermal and electrical energy [35–37].

2. Performance Assessment Tools of Photovoltaic (PV) Modules

The efficiency of converting the solar energy into electrical energy depends essentially on the PV panels that produce electrical power [38]. Currently, the power energy efficiency of the PV panels for the commercial engineering applications is within the range of 12–23% (for multi- or mono-crystalline modules, respectively) measured at the Standard Test Conditions (STC) of 1.0 kW/m^2, ambient temperature of 25 °C, and wind speed of 1.5 m/s [39].

Modern solar modules can have either single or multiple (tandem) active layers to enhance the absorption of the whole solar spectrum in the visible region [40]. PV panels are classified according to the solar cell technologies and the employed material to three main generations: the first, second, and third-generation [41]. The first generation has crystalline silicon (c-Si) base structure [42], which may be single crystal (sc-Si) [43,44] or multi-crystalline (me-Si) [45,46]. While, the second generation of solar cell has a thin film including cadmium sulfide (CdS) [47,48], cadmium telluride (CdTe) [49,50], amorphous silicon [51,52], etc. The last type does not include silicon like dye-sensitized solar cells (DSSCs) [53,54], perovskite solar cells (PSC) [55,56], and organic photovoltaics (OPV) [57,58].

PV panels have limited overall efficiency and are very sensitive to weather conditions, such as dust, humidity, overcast conditions, and panel temperature increases. There are also the passive components necessary for energy transmissions, such as regulators, battery, cabling, and inversion of the supply to alternating current (AC) [59,60]. Some investigations were conducted to examine the influence of the inclination angle of PV panels and its orientation on the gained amount of solar irradiation and, hence, the output electrical power [61]. Where a cloud covered a portion of solar photovoltaics will reduce the total energy output [62,63]. Predicted methods are required to evaluate these effects and their costs on other systems to connect the solar PV panels to the buildings [64]. Furthermore, the electrical power supplied by the PV panels depends on its temperature and PV voltage; it is indispensable to illustrate the maximum power of the PV panel [65,66]. Under constant solar intensity (G) of 1000 W/m^2, the current/voltage and power/voltage characteristics for different temperatures of the 10 W polycrystalline silicon photovoltaic module are illustrated in Figure 1.

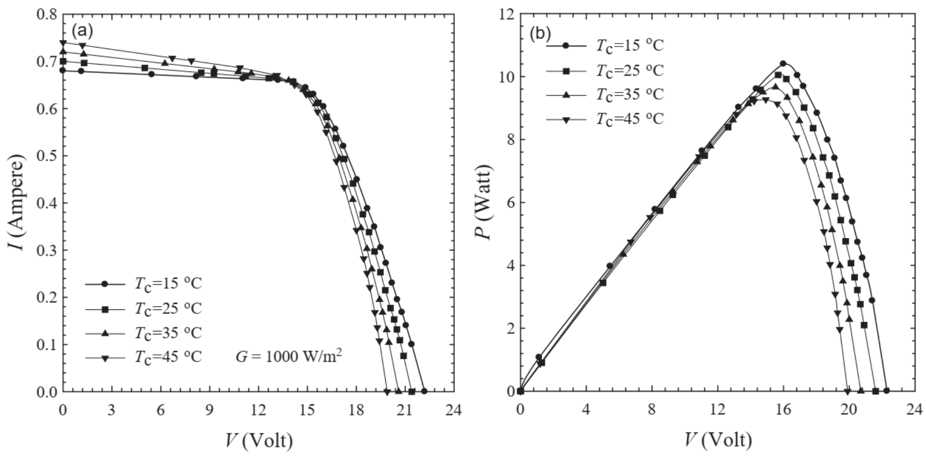


Figure 1. (**a**) I-V (**b**) P-V Characteristic curves of the PV cell at different temperatures. Reprinted with permission from ref. [66]. Copyright 2014 Taylor & Francis.

The appeal of PV modules for electrical power generation stems mainly from cost and on the efficiency of energy conversion, viability, availability, and affordability. Various methods and techniques have been developed and suggested to maximize the electrical power output of PV modules using concentrated photovoltaic [67,68], hybrid solar photovoltaic/thermal (PV/T) [69,70], nanofluids [71–75], evaporative cooling [76–79], phase change material (PCM) [80,81], thermoelectric [82,83], etc. A combination of photovoltaic/thermal (PV/T) can be augmented into façades, windows, rooftops, and shading devices to provide both electrical and thermal energy [84]. The integration of BIPV thermal systems with the façade is not straightforward; however, it positively affects the energy performance for both building and PV modules [85]. The performance of BIPV is usually closely associated with the purpose of the application, so the façade-based BIPV systems are classified into four classes—air-based, water heating, space heating, and ventilation systems.

The rising surface temperature of PV modules not only decreases the generated electrical energy, but also decreases the life of PV modules by creating hot spots and increased shunt resistance. Combining PV modules with thermal collectors can also help control the overheating of PV as well as ventilation air pre-heating [86,87], underfloor heating system [88], domestic hot water [38], passive and active cooling [89], and heat storage [90,91].

Additionally, to enhance PV modules efficiency, they can depart from fixed array installation into either one-axis or two-axis tracking systems. PV modules with fixed-tilt (tilt angle chosen depending on geographic location) are less cost to install, operate, and maintain. Thus, arrays with two-axis tracking systems are more expensive due to adding the tracking mechanisms for the sun radiation [92]. The most common economic assessment criteria of levelized cost of electricity (LCOE) was calculated for several locations and different configurations of PV panels, i.e., fixed axis systems, one-axis tracking systems, and two-axis tracking systems [93]. The results revealed that the differences in LCOE for fixed, one-axis, and two-axis tracking systems were up to 213%, 240%, and 262%, respectively. On the other hand, the operating and maintenance costs for the fixed axis systems, one-axis tracking system, and two-axis tracking system were 25, 30, and 35 USD/kWp/year, respectively [94]. However, PV modules with one and two-axis tracking systems intercept a greater amount of solar radiation, but this increase has to be justified in magnitude and in terms of the parasitic energy required to operate the tracking system [95]. Since installation cost of electricity from the PV modules with a one-axis tracking system was found out to be the smallest among the three types of projects [96], one-axis tracking modules will be singled out for economic and environmental focus. Considerable efforts have been reported consistently to track solar radiation and consequently to improve the efficiency to make solar PV modules more attractive for energy conversion [97,98].

Several methods are available to assess output power of solar PV installations. Maximum power point tracker (MPPT) of a PV system that was adapted for a fixed voltage was presented by Salameh et al. [99]. The results reveal that the proposed controller was valid for various loads such as batteries or water pumps. The various applications of PV modules throughout the benchmark analysis are presented in Figure 2. For example, Wolf [100] introduced the fundamental concepts of the photovoltaic/thermal (PV/T) system over a one year for a single-family residence.

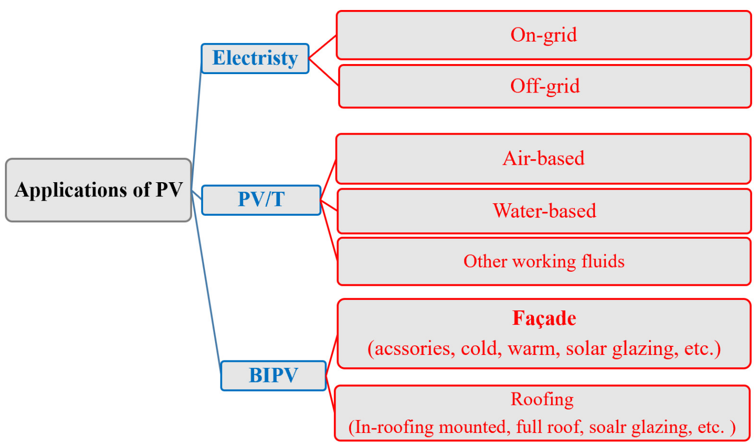


Figure 2. Application of PV modules throughout the benchmark analysis.

3. Building-Integrated Photovoltaic (BIPV) Systems

3.1. Overview of BIPV Systems

The BIPV is an energy producing system that combines the solar PV panels as part of Façades, windows, or roof devices with buildings. When an active heat recovery is cooperated with the BIPV systems, either in closed loop or in an open loop with forced circulation of working fluids, they are well-known as the building-integrated photovoltaic-thermal (BIPVT) systems [101]. In cold weather, air-based BIPV thermal systems have the benefit of supplying space heating during the year due to low ambient air temperatures [91,102]. Designing and achieving the operation at zero energy buildings (ZEBs) can be done by incorporating BIPVT systems [103]. However, it should maintain technical and economic requirements, aesthetical aspects prior to integrating into the building envelopes to fulfill the necessary factional requirements [104–106]. The initial maintenance and replacement costs, cost-efficiency, codes and standards, PV types, building load and location, psychological and social factors, are the main parameters that influence the BIPV systems [107–109]. Additionally, the progress of BIPV systems is restricted by the operational expertise, data collection, and planning analysis, commissioning, national manufacturing, the potential of the national market, standardized technology, etc. [110,111]. The positive energy district (PED) is currently supposed to be an integral portion of the district or urban energy system by positive influence [112]. The clear categories for different types of positive energy districts (PEDs) in the renewable energy market, for example in the EU, are presented by Lindholm et al. [13]. They offered a detailed analysis of fundamental factors in PED planning process. The challenges of the PEDs are still open for discussion in order to eventually drive the development of PEDs major advances forward, as described by Hedman et al. [113].

Recently, semi-transparent thin-film solar photovoltaic modules (STPV) for BIPV in windows and facades have generated many studies due to their superior performance levels [114–117]. A number of experimental and simulation studies considering the energy efficiency of semi-transparent thin-film PV (STPV). For the application of air conditioning systems, the STPV windows/facades produce both electrical energy and simultaneously minimize the cooling load of air-conditioning system by mitigating solar heat gain [118–120]. Furthermore, the BIPV based on STPV windows with convenient transmittance levels enables full utilization of daylighting [121–123]. Figure 3 summarizes publications available on the topic of BIPV systems within the past three decades (Web of Science database, 2021). It should be noted that these publications do not present all available research papers, but they show the strong trend of increased investigations of BIPV systems.

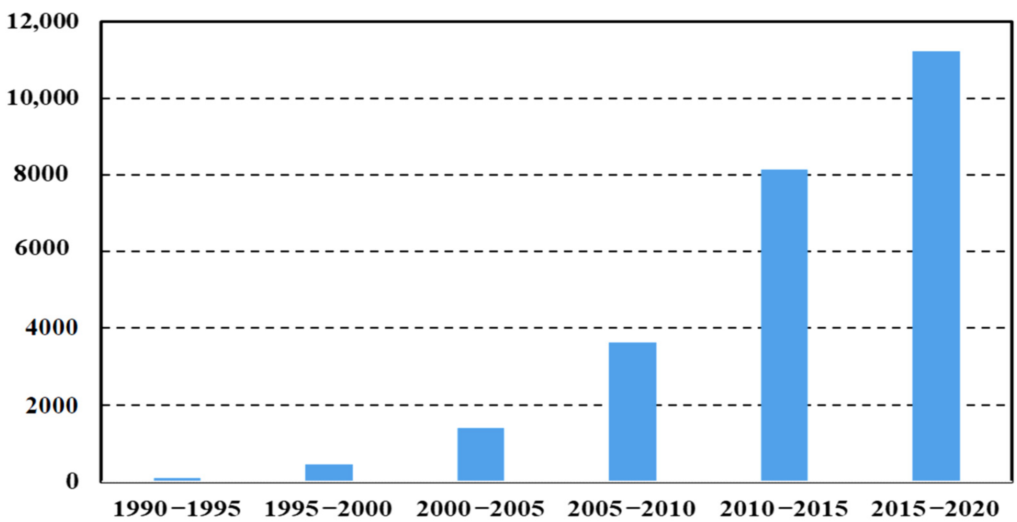


Figure 3. Number of publications on BIPV systems in the past 30 years.

Currently, there are different products of BIPV systems, depending on the application area, as presented in Table 1. In-roof mounting BIPV systems comprise different mounting systems integrated with the frameless (or not) PV module to the roof of the building [124,125]. These systems achieve desired functions usually devoted to the building materials. However, with the utilization of regular PV modules, the aesthetical consideration is not important, and the integration is partial. On the contrary, the full roof solutions are more integrated, and the aesthetically has an essential function. These proposed solutions of the BIPV element accomplish the functions of the traditional roofing and sometimes it is designed as thermal insulation with different color choices. Therefore, this integration can be considered as an optimal function.

Table 1. Products of the BIPV systems depending on the application area.

Product Type	Application Area	
	Façade	Roof
In-roof mounted		*
Full roof solution		*
Shingles and tiles		*
Glazed roofing		*
Standing-seam metal		*
Flexible lightweight PV modules	*	*
Non-ventilated solar façade elements	*	
Rainscreen façade components	*	
Accessories	*	

* = In Operation.

In addition, metal roofing refers to lightweight metal roofing, with a supplementary layer of PV thin film, typically composed of copper indium gallium selenide (CIGS) photovoltaic cells [126,127]. The flexible lightweight modules that are lightweight BIPV systems, such as rolls and membranes, can be positioned on various surfaces by simple sticking onto the surface without any mounting elements [128]. Therefore, these types of BIPV systems are convenient for both façades and roof applications. Moreover, it can be combined with traditional building components in the manufacturing stage, to fulfill further functions. The non-ventilated or warm façade elements are elements of the BIPV systems constitutive of curtain walls in buildings. The rainscreen or cold façade are constitutive elements in the BIPV systems installed as a façade cladding [129]. Mostly, these types are a ventilation space between the elements of the BIPV systems and the second layer of the building façade. Finally, accessory types encompass a shading device, such as balustrade, balcony components, or louvers [130].

The experimental analysis to study the characteristics of real conditions in the mild Mediterranean climate of a BIPVT installed in a façade was done by Bot et al. [131]. The weather parameters ambient temperatures during one year, global radiation, diffuse radiation, indoor room temperatures, and normal direct radiation components were registered. Results also indicated that the electrical efficiency was around 15.1% and the system presented clear advantages to buildings, essentially due to the electrical power generated by PV modules, also to participate to heat the adjacent zone to the building. A dynamic simulation model based on TRNSYS to assess different options of energy efficiency, primary saving of energy, payback period, and CO_2 emissions including different buildings in various districts i.e., Naples in Italy and Fayoum in Egypt, was developed [132]. The model included the energy balance for transient operation, while incorporating the geometrical building envelope. The suggested options of energy efficiency included a building heating system using a hot water supply, air-to-air heat pump elements for cooling/heating of the enclosure by integrating the solar thermal systems and photovoltaic modules. The simulation results provide important guidelines for accurately selecting the optimal hybrid system designs and configurations of the BIPV system, as well as proposing guidelines for legislators to assess de-carbonization goals under different scenarios. It is interesting to note that the model is sensitive to change in ambient conditions and geometric location. For example, the payback period of the proposed energy system in Naples (Italy) was five years, however, in Fayoum (Egypt), it was 23 years.

3.2. BIPV–Based Air Cycle

The building-integrated photovoltaic/thermal (BIPV/T) system absorbs solar irradiation incident upon a building envelope and is responsible for converting a fraction of the solar energy into electrical and thermal energy [133,134]. The crystalline PV module converts typically almost 15–20% of solar radiation energy into electrical energy, and the rest is either reflected by 5–10% or converted into thermal energy (heat), which increases the surface temperature of the PV modules. For large-scale applications, peak temperature of a PV module can easily reach 60 °C (higher on hot summer days) [135]. Air-cooling is a heat mitigation technique that has been comprehensively investigated as a cost-effective method. Incorporating a gap of air between the PV panels and the building fabric i.e., façade or tilted roof is employed for forced air circulation to considerably cool the PV panels, and the produced pre-heated air is a practical supply of thermal requirements for buildings [118,136].

The PV modules are commonly installed in the BIPV systems on a rooftop or façade, and the most practical technique to adjust the temperature of modules is employing the forced convection using a fan. However, it causes additional capital investment and consuming more electrical energy [137]. While, the electrical energy consumption is reduced by nearly 20% in the installed HVAC systems with solar ventilated façade [138]. Moreover, it is usually preferred to install air-based BIPV/T systems in an open-loop arrangement to utilize the heated air for space heating. In the air-based BIPV system, the airflow supplied for space heating is guided by a fan to avoid air trapping into the air gap cavity leading to increasing the heat transfer rate to the building spaces. The influence of fans on the system operation concludes that the BIPV system efficiency can be improved by almost 9% [139]. The air gap BIPV/T with indoor air flow, results to be the more effective in decreasing the building heating load by 27% lower, and it is capable to avoid the decreasing of PV efficiency compared to the BIPV systems with no ventilation or air gap BIPV/T system [140]. Air gap in the BIPV systems allows natural circulation of air (no additional fan required) and the flow of air is achieved by the density difference that generates buoyancy forces, namely the stack effect that occurred in the BIPV/T air gap [141]. Theoretical and experimental studies incorporating buoyancy-driven air currents behind the PV modules was investigated by various researchers [142], using various air flow configurations [143], via the integration of semi-transparent PV panels by a double-pass façade [144], by employing the exergy analysis [145], by connecting in series PV/T air collectors [146], and by employing ventilator of wind-driven [147].

An air-to-water heat pump heating ventilation air conditioning (HVAC) system with a rooftop PV was simulated using TRNSYS software by Stamatellos et al. [148]. The results were utilized to evaluate the building energy performance, inverter-driven heat pump, the efficiency of the rooftop PV panels. Moreover, objective functions were introduced for optimizing the constructed area of the PV panels and their tilt angle, based on the price of the alternative electricity considering the net metering policies. The annual results of the system's performance with 20 lifetimes and the optimum value of the tilt angle of PV modules of 30 degrees are presented in Figure 4. In addition, the results revealed that the net metering tariffs to support were employed more effectively for the new designs for further expansion of BIPV systems in existing and modern buildings.

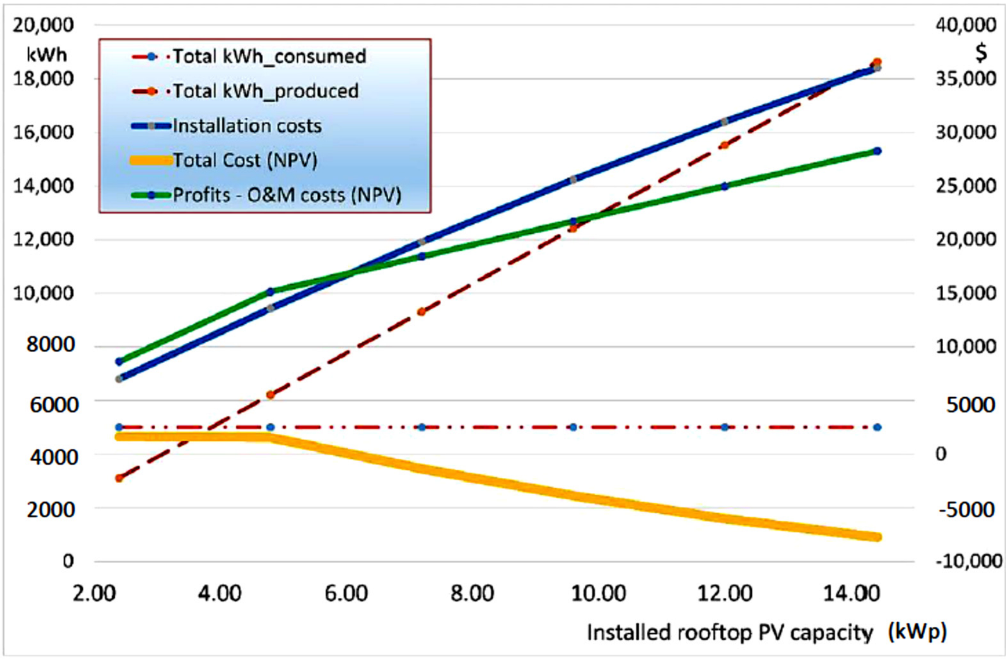


Figure 4. Different system costs with variable capacity of PV panels; reproduced from [148].

Baljit et al. [149] present a comprehensive review of BIPV for thermal systems and their applications covering years 2006 to 2016. Roof and wall integrated BIPVT systems are water-based or air-based, which loop back into the building. Agathokleous et al. [150] presented double skin façades (DSF) and BIPV with a focus on airflow and other heat transfer characteristics. According to the use of thermal energy from the PV modules, the BIPV thermal systems are classified into three categories: cooling of PV, water heating, and air heating [151]. Debbarma et al. [101] reviewed BIPVT and BIPV technologies taken with a focus on aesthetics, cost, functions, and eventual applications. Modeling thermal performance and the energy and exergy analysis of BIPVT were reviewed by the same group in the work of Debbarma et al. [152]. Moreover, the application of the Trombe wall in different buildings was studied by Hu et al. [153]. Further, Saretta et al. [154] and Riaz et al. [155] reported on BIPV façades prior to 2019 for the energy renovation of heritage buildings.

Shahsavar et al. investigated the energy-saving of a building due to using the BIPV; using the cooling potential of ventilation of air exhaust from building PV cooling and heating ventilation air, by the eventual heat rejection from PV modules, was investigated numerically [156]. The results showed that exhaust air and ventilation air in heating ventilating A/C systems could be employed efficiently as part of the ventilated heating load. An experimental investigation of the thermal characteristics of a two-inlet air-based open loop BIPV system under full-scale solar simulator was introduced [157], as presented in Figure 5. Opaque and semi-transparent silicon mono-crystalline PV modules were used for the study. The results revealed that a two-inlet system with frameless PV panels enhance thermal efficiency by 5% compared with the traditional single-inlet configuration. The BIPV/T system with semi-transparent modules maintained 7.6% more thermal efficiency compared with that of opaque ones.

The thermography of PV surface temperature with airflow carrying different moisture content was performed to help understand transport mechanisms underneath and above the PV modules, by Mirzaei et al. [158]. To achieve this goal, a setup consisting of a BIPV model with cavity airflow ventilation in addition to a solar simulator inserted in a wind tunnel was developed as shown in Figure 6. Moreover, particle image velocimetry (PIV) and infrared thermography were utilized to observe the surface operating temperature of PV modules and airflow underneath and above the panel. The results revealed that the proposed arrangement would reduce the risk of BIPV systems due to the airflow and moisture entrance by lowering the areas of high pressure adjacent to the PV panels.

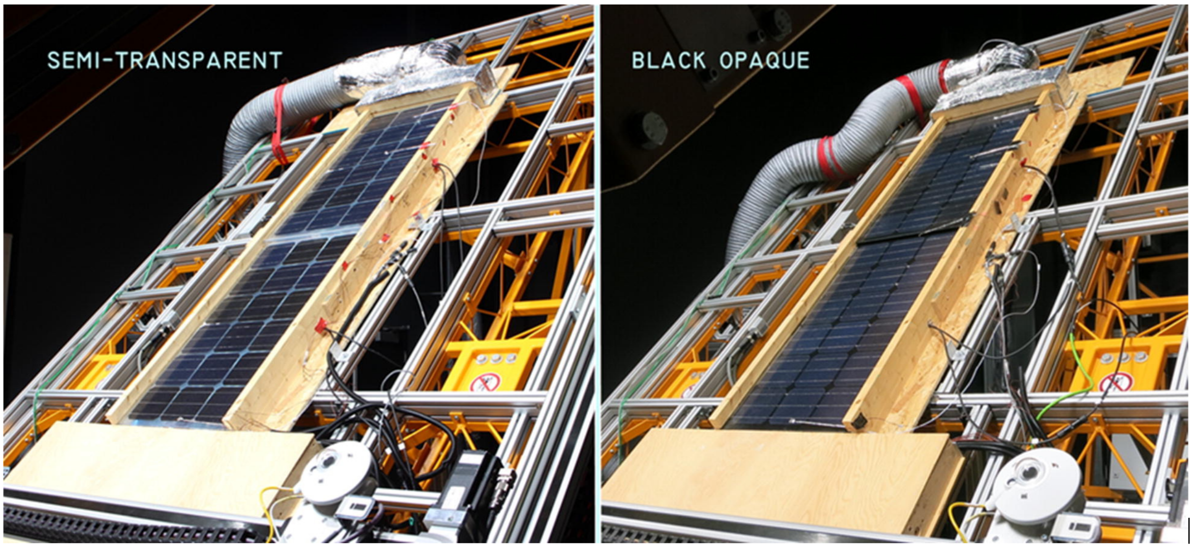


Figure 5. Real photos of BIPV system using semi-transparent and black opaque PV panels. Reproduced with permission from ref. [157]. Copyright 2014 Elsevier.

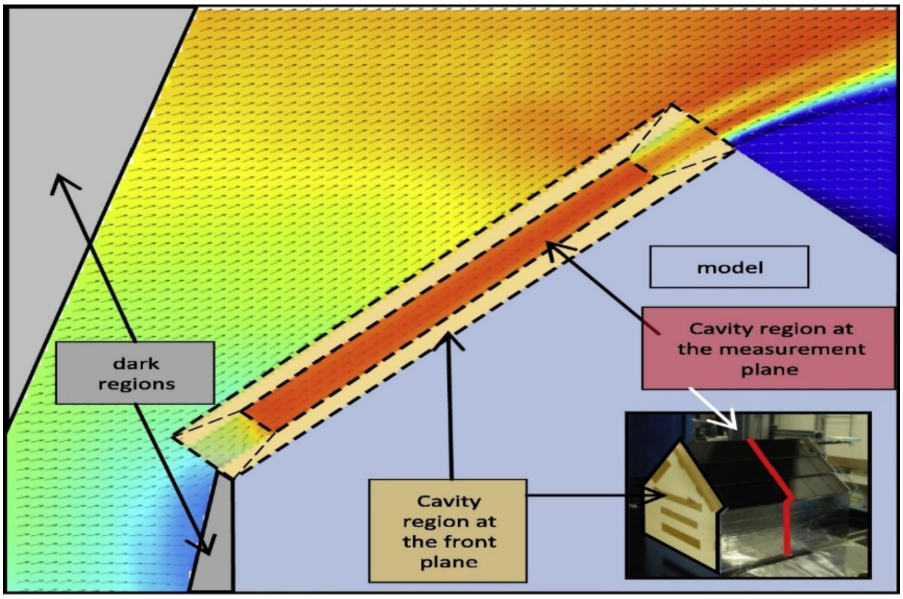


Figure 6. The proposed BIPV system with cavity ventilation air. Reproduced with permission from ref. [158]. Copyright 2014 Elsevier.

Noor Muhammad et al. investigated the performance of a hybrid system of solar PV/T systems and heat pump depending on the re-uses of the thermal energy generated from solar PV modules, cooled by heat pumps, and then pumped into the ward for cooling purposes, as shown in Figure 7 [159]. The proposed hybrid system was preferred to cool the natural ventilation space in buildings, particularly involving the health facilities in hospitals for the tropical weather conditions. Peng et al. numerically evaluated the potential of energy saving and the annual energy performance of a ventilated photovoltaic with a double-skin facade (PV-DSF), as illustrated in Figure 8, for the summer season in the Mediterranean climate region [116]. Moreover, a sensitivity analysis based on the numerical model to investigate the width of the air gap and the ventilation modes was achieved to optimize the unit's design and assess the operational strategy of PV-DSF. It was found that the proposed PV-DSF was able to generate yearly electricity of about 65 kWh per unit area. In addition, the annual energy output could be doubled due to utilizing the cadmium telluride (CdTe) semi-transparent PV panels. The efficiency enhancement of semi-transparent PV panels would further improve the energy-saving potential of a PV-DSF and hence make this sustainable technology more appropriate. In addition, the PV-DSF with glazing systems increased net electricity by about 50%. Krauter et al. [160] proposed different designs of BIPV system to the configuration of PV and façades i.e., PV panel with ventilation and PV without ventilation as illustrated in Figure 9. The results show that module temperature was reduced by 18 K, while electrical efficiency was improved by 8% at a wind velocity of 2 m/s.

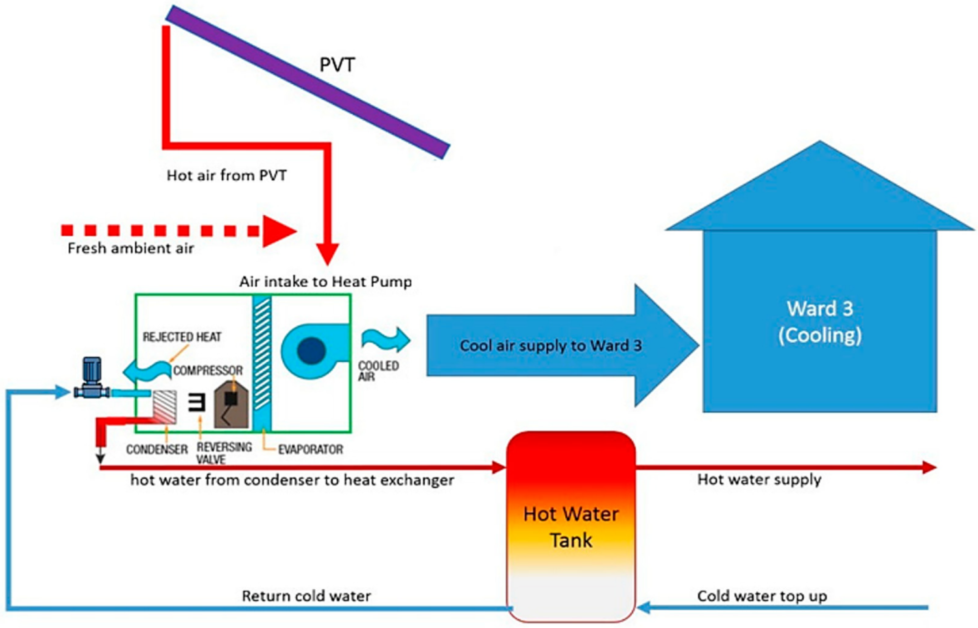


Figure 7. Hybrid system of PV/T and heat pump for naturally ventilation in building; reproduced from [159].

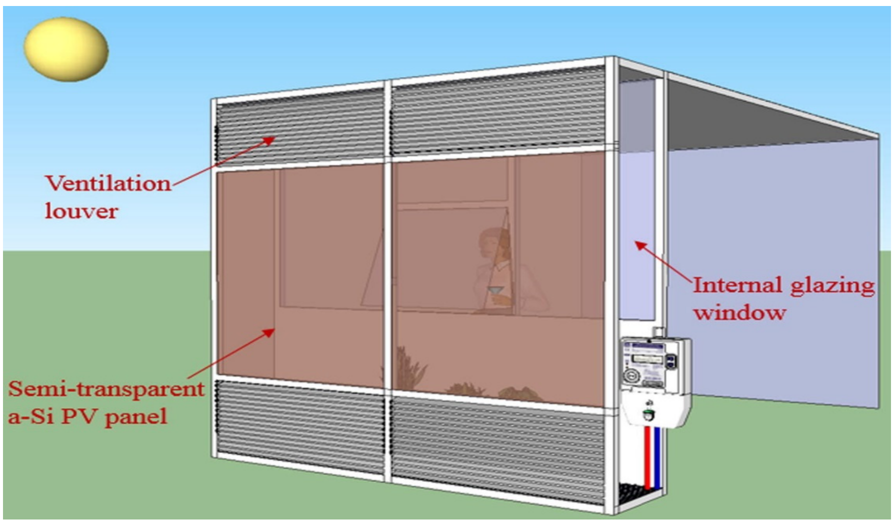


Figure 8. Schematic of the suggested photovoltaic with double-skin facade (PV-DSF). Reproduced with permission from ref. [116]. Copyright 2016 Elsevier.

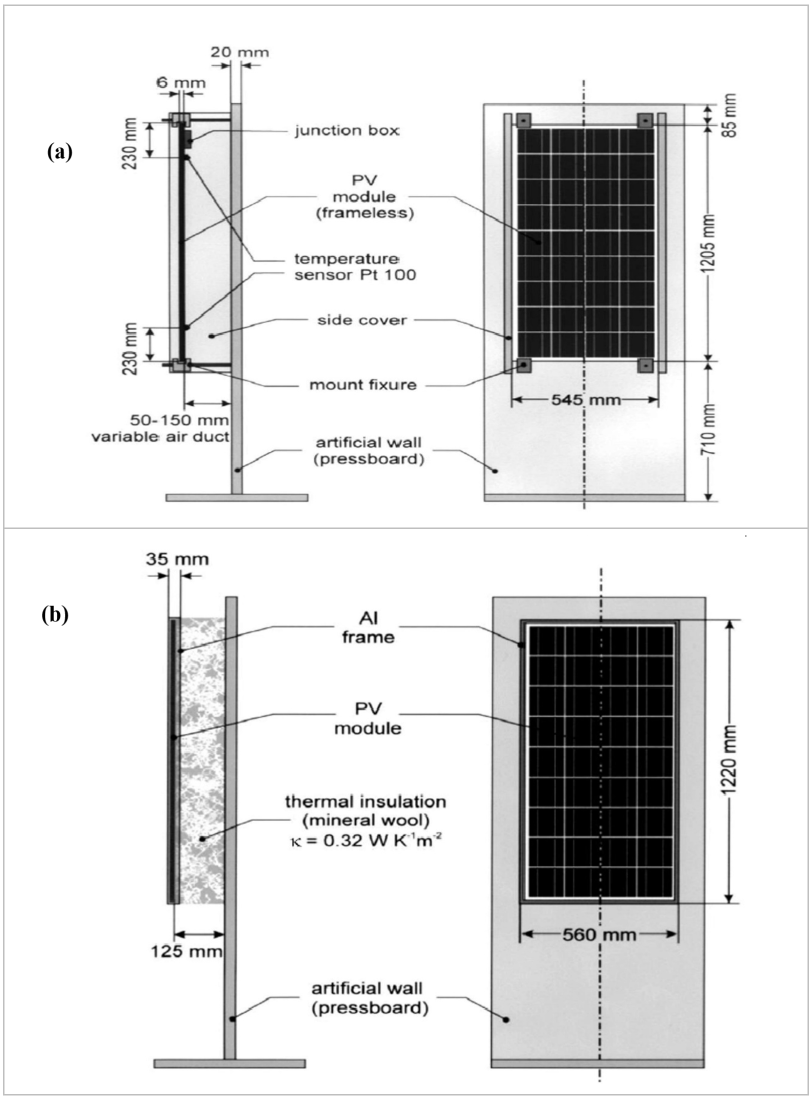


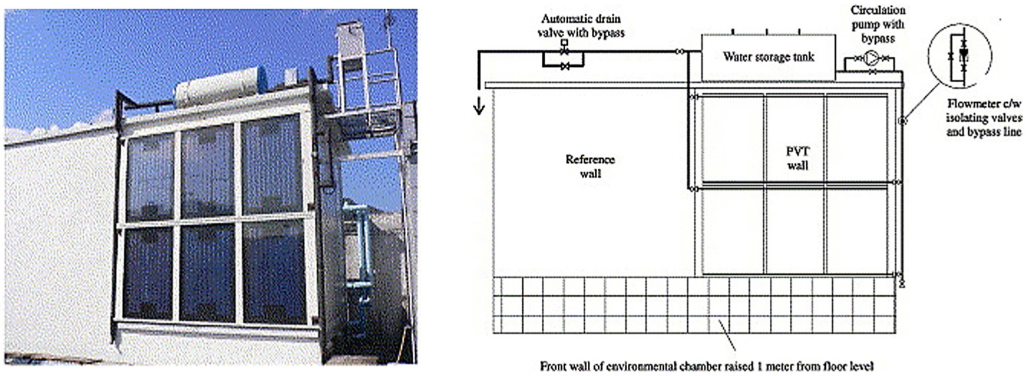
Figure 9. The proposed PV module (**a**) with ventilation (**b**) without ventilation. Reproduced with permission from ref. [160]. Copyright 1999 Elsevier.

3.3. BIPV-Based Water Cycle

Utilizing water as a working fluid for carrying the generated heat from the photovoltaic modules in BIPV systems is, intuitively, more efficient than air due to its superior thermophysical properties [156]. A water-based PV cooling system is employed to operate at higher heat removal rates than air-cooled systems of PV panels and for critical applications. When the temperature of the circulating water is below the temperature of the PV cell, the energy conversion efficiency of PV is seen as significant [161,162]. Moreover, the flowing circulating water could absorb undesirable heat from modules as the temperature of the water rises gradually. This water could then be employed as a heat resource for thermal applications associated with buildings and solar-assisted heating/cooling energy technologies [163,164].

Using hybrid solar energy systems in different building configurations has the promising benefit of increasing the energy-generated output per unit area of the installed collector [16]. Apart from useful solar energy conversion of the BIPV systems, the reduced radiation transmittance into the building will lower space cooling/heating energy requirements, as well as save the building materials through the suitable design and appropriate construction integration [104,165].

Centralized PV modules and hot water collectors can be wall-mounted in vertical facades to serve as water pre-heating systems (see Figure 10), as investigated experimentally under different operating modes [166]. Results reveal that a naturally circulating water system is better for forced circulation in a hybrid solar collector pre-heating system than any other working fluid. The reported thermal efficiency was 38.9% at zero reduced temperature, the corresponding electrical efficiency was 8.56% during summer season, and it increased with avoiding the shading effects. A preferred thermal insulation performance was established on the façade of BIPV in both winter and summer.



(**a**) (**b**)

Figure 10. Experimental set-up of BIPVT (**a**) real photo (**b**) schematic diagram. Reproduced with permission from ref. [166]. Copyright 2007 Elsevier.

An experimental implementation to study the performance of the PV/T solar heat pump A/C system was reported [167]. The effect of the evaporator and condenser pressure variations on the coefficient of performance (COP) of the heat pump A/C system, water temperature, overall system heat capacity, PV module surface temperature, and its efficiency were reported. The results indicated that the efficiency of the PV/T solar heat pump A/C system reached 10.4% with an improvement of 23.8% over the base system. Moreover, the COP of the heat pump A/C system was attained at 2.88 and the water temperature in the water heater increased to 42 °C.

The economic, energy, and exergy analysis of integrated polyethylene heat exchangers underneath PV panels was investigated experimentally and numerically [168]. A thermal model was adapted to study the thermal performance of the roof proposed unit as illustrated in Figure 11 and the numerical model was conducted utilizing the Engineering equation solver (EES) considering climate and the design parameters of the BIPV/T roof collector. The experimental results showed that the water temperature difference reached up to 16 °C, and the overall thermal efficiency of the system was maintained, up to 20.25%. The system achieved an annual energy savings of 10.3 MWh/year with the cost of power generation of 0.0778 EUR/kWh.

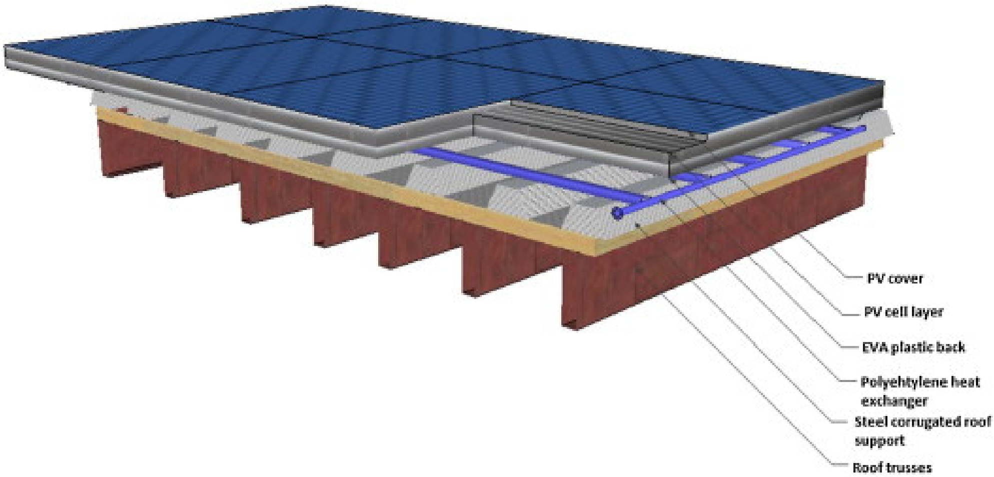


Figure 11. The integration of polyethylene heat exchanger underneath PV panels. Reproduced with permission from ref. [168]. Copyright 2014 Elsevier.

4. Passive and Active Effects of BIPV Systems

The overall attainable energy savings of air-based and water-based BIPV systems depend essentially on several factors, such as the optimal selection of operating parameters and accurate design parameters of the equipment, the insulation type, and the building construction materials. The schedules of cooling and heating, the control system, and the predominant climatic conditions considerably affect the energy efficiency [169]. According to the electricity consumption, it is important to minimize the peak demand, to avoid the equipment oversizing of power plant. The proper system sizing should rely upon a detailed system simulation including the building envelope and the detailed selection and control of HVAC equipment. The matching between the production and consumption of electricity can be advantageous to the stability of the national grid and the electricity cost.

4.1. Passive Effects

The integration of solar PV modules with the building envelope makes significant changes that are related to the thermophysical characteristics with resultant changes of the building cooling and heating demands and, hence, indoor thermal comfort. These phenomena are well known as the passive effects include the building wall temperature, cooling and heating loads and demands, and the building's indoor thermal comfort [140]. The wall temperatures of integrating solar PV modules are subjected to non-negligible changes with respect to those of standard walls without collectors [170]. The expected changes maintained for wall building and indoor air temperatures influence the indoor thermal comfort of the building. The free-floating temperature regime during switching off the HVAC system shows the passive effects of BIPV systems onto the conception of the thermal comfort. The predicted mean vote (PMV) is a function mainly of relative air velocity, mean radiant temperature, and indoor air temperature. The PMV that relates the thermal comfort to a large population is affected significantly by the indoor air and the wall temperatures [171].

4.2. Active Effects

Here, the reported results regarding the active effects of the BIPV system are divided into subsections, namely the electricity production of PV; preparation of domestic hot water (DHW) for water-based BIPV systems; and production of hot-air for only air-based BIPV systems. The correct choosing of cooling systems for the PV panels reduces the operating temperatures of PV cells and consequently enhances both the useful life and the PV electric efficiency [172]. The operating temperature of the working fluid passing inside the air cycle-based BIPV system is lower than that maintained by the water cycle-based BIPV system. In turn, the lower surface temperature of PV panels and, thus, enhanced yielding electricity, is achieved by adopting the air-cooled BIPV/T over the water-cooled one [173]. The hot water supplied by water cycle-based BIPV system is exploited for preparing domestic hot water (DHW) [171,174]. The hot air generated from air cycle-based BIPV system is employed for space heating applications and as pre-heated air for a drier machine, etc. [175,176]. A considerable reduction in space heating is maintained for the air-based BIPV systems as a result of free space heating, leading to saving the yearly heating energy of the HVAC system [177].

5. Economic Considerations of BIPV

The building sector accounts for around 40% of energy consumption globally. Thus, a paradigm shift towards BIPV systems can enhance interest in replacing traditional construction materials for the envelope with a new building, with provisions for incorporating PV modules. This opens the door for the introduction of innovative construction material with high thermal insulation and an electrical energy producer. The BIPV systems encompass both energy-related aspects considering electricity production and building-related aspects linked to the functions of the construction material. The most important challenge of widespread BIPV systems are the economic national policy based on the public acceptance, feed-in-tariff implementation, the national economic support, as well as the technical aspects, such as the losses of energy conversion and the considerations of different architectural elements [178]. Therefore, the economics of the BIPV can be segmented into categories based on the aforementioned criteria.

The economy of the BIPV systems depends on the category of buildings on which BIPV products are employed such as residential or non-residential buildings considering the architectural characteristics, occupancy profile, techno-economic feasibility, national economic support, annual costs of maintenance and replacement, available codes of the BIPV systems, building loads and structure, etc. Thus, the fundamental drawback associated with BIPV systems is the high cost/kilowatt per hour of electrical energy generated [158]. Thus, an expensive technology BIPV system at the current time; only 0.05% of primary consumed energy is currently generated by this promising technology [179]. For example, Yang [180] classified barriers for BIPV proliferation in terms of application, lifecycle, design, construction, and installation to commission and maintenance.

A number of BIPV systems have been simulated to study the energy requirements for residential/non-residential buildings. Appropriate designing of the BIPV systems with improper installation well contributes to achieving an acceptable growth in the energy expenditure to ensure thermal comfort in buildings. The performance of a three-zone residential building with an air/water heat pump heating, ventilation and air conditioning (HVAC) system combined with a rooftop PV installation, was simulated using the TRNSYS environment [148]. The results were employed to evaluate the high performance of the energy building using an inverter-driven heat pump by scroll compressor as well as the high efficiency of PV panels. Furthermore, objective functions were presented to optimize the area of installed PV panels and their tilt angles, considering the pricing of alternative electricity and subsidies. In addition, this type of financing was effective for growing the rooftop PV installations on existing and new houses under zero interest rates would be downpayment of the government bank loan.

The ventilated façade system with phase change material (PCM) introduces superior thermal comfort conditions compare with the traditional building as well as it also reduces the utilization of electrical power, commonly for HVAC systems [181]. The thermal performance of ventilated double skin Façade integrated with phase change material for building heating in winter months was assessed by Gracia et al. [182]. Three methods were investigated; free-floating or natural ventilation mode, controlled temperature mode desired electricity to drive the heat pump, and demand profile operated on both natural ventilation and mechanical mode. The result indicated that the proposed system provided indoor temperature on mild and severe winter season and free-floating mode achieved the best thermal comfort than other modes. Investigating the interactions effects between the building envelope and the HVAC systems is fundamental to maintain the NZEBs [183].

The prerequisite information of technology, performance, and the parameters to operate and design the integrated HVAC and domestic hot water (DHW) production systems for buildings were presented by [184]. Where the review concerned with the integrated energy systems introducing the required space heating and DHW production; cooling and heating for HVAC and DHW production; electricity and DHW production; mechanical ventilation and DHW production.

Furthermore, it was found that the economic evaluation of the BIPV systems is usually required for renovations and retrofits to evaluate the system payback time. For the new, under-construction buildings, the economic assessment is uncomplicated because it is not influenced by the materials cost that will be substituted by the components of the BIPV. Nevertheless, in new or old buildings, the total cost, payback time, and feed-in-tariff are necessary to be considered for optimizing the system economic for different applications of BIPV systems. Concerning the purpose served by the BIPV systems for achieving the national sustainable development goals (SDGs), the analysis of the life cycle is also critical [185].

The market segmentation encompassing technical and economic aspects of the BIPVT systems is presented in Figure 12. Where the cladding typology is the combination of the thermal property such as the insulation property or not and the visual property such as the transparent or opaque of a BIPV technology. The market segmentation introduces multiple possibilities when it comes to the BIPV systems, and it gives the reality that it is a promised market, considering different technical and economic aspects of the BIPV systems, allowing a clear package of mutually building and cladding typologies. This enables the development in planning and installation of the BIPV systems.

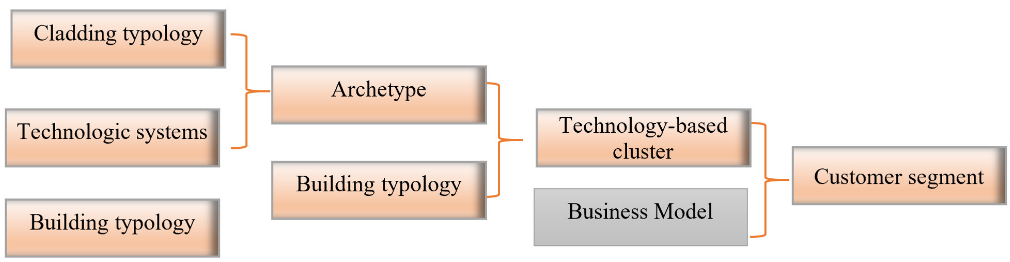


Figure 12. Market segmentation, including the economic and technical aspects.

6. Discussions

Heat generation issues associated with the design and implementation of BIPV systems are fundamental problems that require systematic mitigation and development. Overheating of PV modules and transferring this heat into the building can inadvertently increase the cooling load and increase the power consumption for A/C equipment. The target of reducing average energy consumption in buildings to levels that can be handled by passive technologies will still have to contend with a total primary energy demand at 60 kWh/m^2 [9]. There are significant climatic conditions, such as high sunshine and mild climate; the available urban areas, economic government policy, humidity, and temperature, etc., affecting the perforce and installation of BIPV systems. Building materials and house constructions are different from one country to another, but the photovoltaic technology is almost similar and international.

The majority of the BIPV systems depend on the fixed-tilt PV modules system, which have low efficiency of energy conversion, so more effort is required for examining the one and two-axis tracking system as possible as the possibility of the building design and architectural considerations. The architectural envelopes of buildings integrated with PV module systems offset the installation cost that is equivalent to conventional components [165].

Moreover, deploying tracking systems for the PV modules will definitely complicate the architectural elements of integrating BIPV systems. These trackers should be lightweight with an acceptable level of electrical efficiency for the building advancement [186]. Predicting the annual energy performance of the BIPV system requires sophisticated telemetry equipment and analysis software to provide necessary performance and meteorological data for validating the computer simulation models, which could then be employed. On the other hand, sensitivity analyses based on the simulation models are required to evaluate the overall annual energy and thermal performances of BIPV systems for cooling/heating in summer/winter for different climate zones, considering different guiding factors, such as geographical, climatological, space utilization, various costs, system design, operating parameters, etc.

Architects and designers may overlook maintenance provisions/costs and the possibility of replacing a single or more PV module/s during the BIPV system design phase. There is no available accessibility to the external fixing of defected PV modules and there is a serious obstacle. Replacements of PV modules are complex and tedious because of the huge amount of wiring that interconnects the modules to each other.

The building electrification with installing the rooftop/façade PV panels on existing or new buildings based on mortgage extensions or private investment is a valid solution that can strongly support the energy sector. Thus, the existing legislation needs to be improved national economic support such as feed-in tariffs. Similarly, the measurement standards of the payback period should be established for BIPV system to evaluate the profitability of the proposed hybrid system more accurately. Moreover, more methodologies are required to estimate the economic viability for financing investment scenarios, where such projects are covered by loans from banks. Moreover, BIPV systems have a significant potential to utilize the low natural convective heat transfer at the rear side of the BIPV to act as a thermal insulating layer rather than employing additional costly insulation material [125].

The proposed BIPV systems for the renewable district based on a domestic hot water network supplied by PV modules represents a more convenient and promising energy measure to decarbonize residential territories. The air-to-air heat pumps integrated with PV panels can considerably minimize the primary heating/cooling energy consumptions for buildings. Therefore, the BIPV system is a promising technology that may be quickly and easily adopted by districts, where the performances of heat pumps are essentially high. However, further work may require an electric energy storage system to better address the mismatch of power production and consumption.

Regarding the commissioning purposes, there is no monitoring system for the system performance after the installation of the BIPV system that ensures that the functions of the BIPV system are attainable for the long-term. Periodic comprehensive monitoring procedures are prerequisites in order to inspect any malfunctions and to decide the system changes to ensure maximum performance for a long time.

The integration of PV modules with building envelopes introduces remarkable changes that consider the thermophysical characteristics, with changes of cooling and heating of building demands and, hence, indoor thermal comfort. The passive and active effects of air-based and water-based BIPV systems include the indoor and wall surface temperature, cooling and heating load and, hence, thermal comfort. These effects place an essential load on the electrical energy consumption of buildings and, consequently, have great influence on designing the national grid of electricity.

The HVAC integrated BIPV system provides energy required for the cooling and heating of buildings, domestic hot water, air handling for ventilation, etc., in one package, set-up with air or water airsides, and is a sophisticated technology for a new ZEB construction. The overall energy characteristics and the economic feasibility of these systems should be studied to evaluate the system benefits and drawbacks. The optimization of potential benefits requires a whole-building approach and design concept stage, and the technical, environmental, financial, and energy characteristics that influence one another are holistically coincided to achieve optimal conditions. Moreover, the electricity consumption of the HVAC system versus that of traditional buildings is influenced by passive effects.

7. Conclusions and Outlooks

The essential factors that greatly impact the development of the BIPV market are the price of the related components of the PV and the performance. This is accompanied by growing interest in recent technologies based on sustainable energy and the increasing possibilities of the aesthetics of the BIPV systems. Moreover, design aspects, such as standardization and coding of the BIPV systems, enable the installation processes, and reduce the possible risks. In addition, it is crucial to have sufficient awareness and knowledge regarding the BIPV system in the construction sector. Increasing the possibilities of electrical energy by distributed PV systems is a fundamental motivating parameter.

The most interesting result of the BIPV system was predicting the impact of the variable pricing of electricity by net metering. Such national policies could increase the significant growth in renewable electricity, particularly in the countries that are currently phasing out traditional power plants based on depleted fossil fuels. Thus, reasonable designs for BIPV systems, based on net metering tariffs, are recommended, to support further expansion of these systems in new (and existing) buildings. Furthermore, more studies on roof/façade PV installation should be investigated with different economic methodologies, showing a combination between PV systems and other components of buildings, including battery storage, which may impact the economic profile of the overall energy system of the building.

Exhaust-ventilated air from the building was used as a cooling fluid to reduce the operating temperatures of the PV panel and, hence, it increased the electricity production of the BIPV systems with optimum values, depending on the surface area and the mass flow rate of air. Without shadings on BIPV systems in the early morning and in the late afternoon during the sunny hours per day, particularly during the winter solstice, better electrical performances could have been achieved. Additionally, any modifications that could be achieved to improve the absorption of long-wave radiation into the BIPV system, where increasing the transmittance/absorptance products results in a considerable increase in thermal efficiency of all the design and operating parameters, without significantly reducing the electrical efficiency of the integrated system.

Utilizing environmentally friendly–sustainable technology of the BIPV systems is in line with the sustainable developments goals of governments, to reduce carbon emissions and minimize greenhouse gas emissions (GHGs). In addition, renewable energy measures the building-integrated photovoltaic panels for various applications, such as solar collectors and air-to-air heat pumps, maintaining promising primary energy savings, depending on the solar radiation, national cost of electricity, etc. The overall energy savings for both air-based and water-based BIPV systems depends fundamentally on a number of parameters, such as the optimal operating parameters and correct design parameters of the equipment, insulation type, and building construction materials.

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