Hindawi
International Journal of Photoenergy
Volume 2019, Article ID 5214150, 17 pages
https://doi.org/10.1155/2019/5214150

*Review Article*

# Semitransparent Building-Integrated Photovoltaic: Review on Energy Performance, Challenges, and Future Potential

**Benedicto Joseph**[1,2] **Tatiana Pogrebnaya,**[1] **and Baraka Kichonge**[3]

[1]*Department of Materials and Energy Science and Engineering (MESE), Nelson Mandela African Institution of Science and Technology (NM-AIST), P.O. Box 447, Arusha, Tanzania*
[2]*Department of Electrical and Electronics Engineering, St. Joseph University in Tanzania (SJUIT), P.O. Box 11007, Dar es Salaam, Tanzania*
[3]*Department of Mechanical Engineering, Arusha Technical College (ATC), P.O. Box 296, Arusha, Tanzania*

Correspondence should be addressed to Benedicto Joseph; josephb@nm-aist.ac.tz

Received 4 June 2019; Accepted 3 September 2019; Published 20 October 2019

Academic Editor: Wing-Kei Ho

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Buildings consume large amounts of energy, and their transformation from energy users to producers has attracted increasing interest in the quest to help optimize the energy share, increasing energy efficiency and environmental protection. The use of energy-efficient materials is among the proposed approaches to increase the building's energy balance, thus increasing the performance of building facades. Semitransparent building-integrated photovoltaic (BIPV), being one of the technologies with the potential to increase a building's energy efficiency, is considered as a feasible method for renewable power generation to help buildings meet their own load, thus serving dual purposes. Semitransparent BIPV integration into buildings not only displaces conventional building facade materials but also simultaneously generates energy while retaining traditional functional roles. The awareness in improving building energy efficiency has increased as well as the awareness in promoting the use of clean or renewable energy technologies. In this study, semitransparent BIPV technology is reviewed in terms of energy generation, challenges, and ways to address limitations which can be used as a reference for the BIPV stakeholders.

## 1. Introduction

Energy plays an important role in economic as well as human development. Access to clean, cheap, and reliable technologies is considered as a means to achieve sustainable development goals [1, 2]. An energy deprivation in terms of quantity along with quality causes poor development, thereby resulting in poverty and increased human sufferings [3–5]. About 1.5 billion people in the world, mostly from rural areas in Africa and Asia, are approximated to live without access to electricity [6]. This situation also affects Tanzania, as only 23% of people have access to energy as reported in NBS [7]. On the other hand, the historical world dependence on fossil fuels at approximately 80% has contributed significantly to climate change, and thus increasing the suffering of poor communities [8–11]. Climate change, being an impending crisis, is expected to intensify the challenges facing the poor. Moreover, the cost of producing electricity using fossil-based sources is expected to progressively increase owing to rapid population and economic growth, thus leading to the depletion of existing proven fossil fuel reserves [12]. The global energy consumption increases at about 8-10% annually, and expectations will reach 40% in the year 2040 as depicted in Figure 1. The fast economic development in developing countries is expected to increase global energy demand by the year 2040; hence, renewable energy is projected to be the fastest growing energy source providing 14% of the primary energy in the year 2040 [13].

Generally, industry, transportation, buildings, and building constructions are the primary energy-consuming sectors. The building and building construction sectors, when combined, are accountable for approximately 36% of the worldwide final energy consumption, and thus contributing closely to 40% of the total carbon dioxide-related emissions [14]. Energy demand from buildings and building constructions is projected to continue to rise, attributed to improved

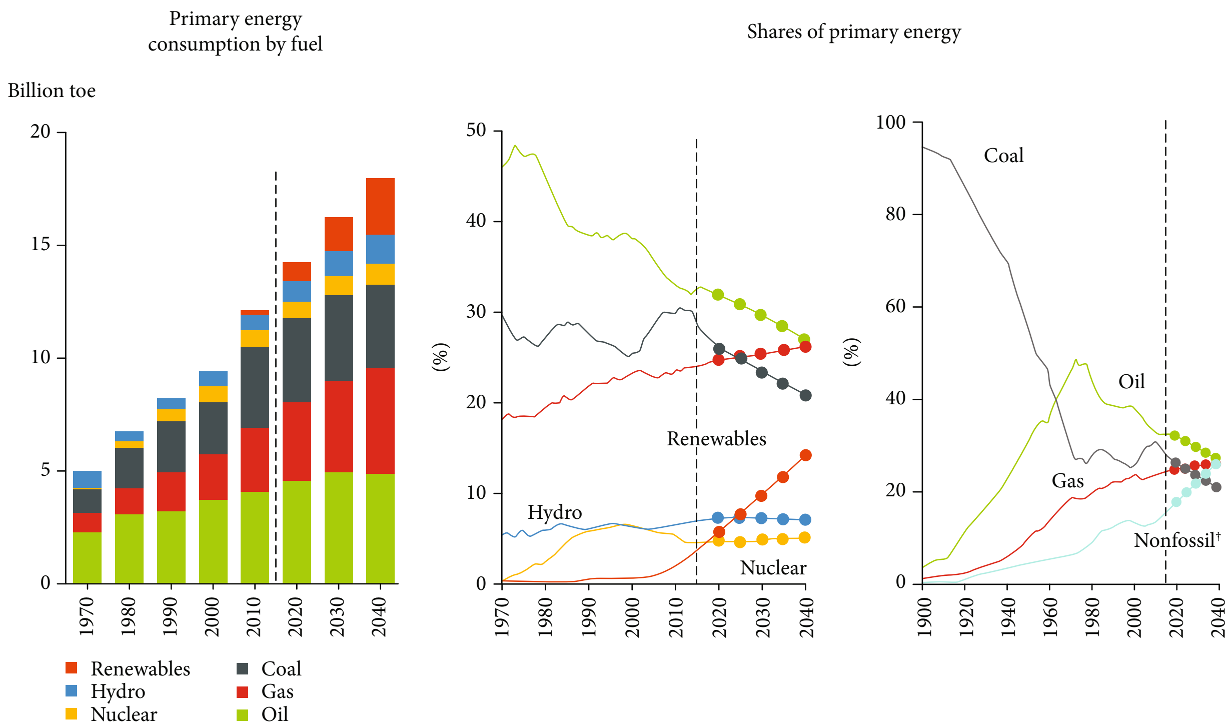



Figure 1: World energy consumption for 1970-2040 [13].

global economy and, therefore, access to energy in developing countries and increased ownership and use of energy-consuming appliances, coupled with the rapid growth in the global building floor area, at nearly 3% per year [14–16].

As a result of the projected rapid population increase and economic growth in energy consumption, alternative sources of energy are required to be gradually included in the future global mix [17, 18]. Varieties of solar technologies are widely recognized as clean with minimal greenhouse gas emissions; thus, they contribute to the efforts towards climate change mitigation through a direct reduction in $CO_2$ emissions [19–21]. Solar energy is radiant energy which is harnessed using a range of advanced technologies such as building-integrated photovoltaic (BIPV), solar heating, solar architecture, solar thermal energy, and artificial photosynthesis according to Shukla et al. [22]. BIPV are basically photovoltaic systems forming the integral parts of the building envelope. Photovoltaics is currently the fastest growing and elegant technologies available for harnessing energy in buildings [23–25]. The BIPV technology is increasingly becoming one of the efficient approaches in harvesting renewable energy for buildings in the quest to minimize the energy crisis through overdependence on fossil fuels and other unclean energies [12, 26, 27]. Conversion of solar radiation into electricity is achieved through PV materials such as monocrystalline silicon, polycrystalline silicon, and amorphous silicon [6, 28].

With 30% to 40% of the world's total end-use energy consumption delivered for commercial and residential building applications, energy-efficient buildings become very attractive at reducing lighting, cooling, and heating-related energy consumption [16, 29]. The use of BIPV to replace the conventional materials in the building offers a combination of properties which not only preserve energy but also generate electricity through the efficient conversion of solar radiation [26, 30, 31]. BIPV technology addresses the goals that intend to achieve "building net-zero energy" consumption through transformations of buildings from energy consumers to sustainable energy producers [32–34]. A sustainable building is capable of minimizing energy consumption, while at the same time supplying its own energy demand through self-generation.

Applications of BIPV technology enable the photovoltaic modules to serve several purposes such as roofs, facades, thermal insulators, noise protectors, and weather protectors [24, 25, 30, 34, 35]. The BIPV technology development and the corresponding utilization in building construction provide aesthetic, economic, and technical solutions in solving environmental challenges and allow daylight harvesting for the provision of the natural light during the day [35, 36]. BIPV is rapidly emerging as an attractive option for research and application as a result of technology developments, a continual decrease in PV material cost, and the rise in renewable energy technology promotions among important players [36]. Among the BIPV technologies, the semitransparent integrated PV is the most used technology in facades, windows, and greenhouses because it generates a good environment by allowing natural light to enter into the building while producing electricity; thus, it is the most promising future energy system in the urban environment.

Through this review, several benefits of BIPV technology are identified and the prospect of its development is clearly established. Its results are expected to provide expressive reference and supports for future BIPV technology research and development. Therefore, in this study, we present a broad review of the current status in the semitransparent BIPV area and organized it as follows: Section 2 provides an overview of the PV systems and PV cells with their categorization and installation types, while technical details of different BIPV products and parameters affecting the BIPV are presented in Section 3. Semitransparent BIPV systems described in this study are then reviewed regarding electrical, thermal, and optical performances and tabulated, while their details and the market names of the products based on them are considered in Section 4. The challenges and future technology prospects and opportunities are presented in Section 5.

## 2. Overview of the PV Systems

This section will cover PV structures, installation types, and PV cell categorization of the first, second, and third generations of PV from different studies. Different materials were studied, including dye-sensitized solar cells (DSSCs), thin-film solar cells (CdTe, CIS), and amorphous and nanomaterials such as quantum cells [37, 38]. Efforts were made using different technologies in order to reduce the manufacturing cost of PV per Wp and at the same time increase its efficiency [39, 40].

*2.1. PV Installation Types.* PV may be installed using three different techniques: building added/applied PV (BAPV), building-integrated PV (BIPV or BIPVT), and open rack-mounted PV (ORMPV). BAPV are added to the building and do not add anything to the system besides producing electricity. ORMPV are PV systems that can be mounted on rooftops, normally with a few inches gap and parallel to the surface of the roof. And, besides, they can be ground mounted and produce energy, as well as used as a canopy for shading purposes. In ORMPV systems, the main factor is to increase energy generation; hence, PV panels are positioned to face the optimal azimuth and tilt angles. These systems are only intended to generate electricity.

BIPV are PV installed in either roofs or other parts of the building such as facades, windows, or balconies. They are used where solar PV modules are joined into the building structure [34, 41]. BIPVT is a building-integrated photovoltaic-thermal system, which is used for the simultaneous conversion of the energy of radiant solar energy into electricity and thermal energy [42, 43]. The system contains a PV panel for the conversion of solar energy into electricity due to the photovoltaic effect and into thermal energy through the absorption process [44]. The BIPV system applied as thermal insulation to the building envelope in hot and humid climates showed the significance of insulation on the energy use in residential and commercial buildings [31]. Figures 2–4 show different PV installations to the building on a roof and walls with BAPV, BIPV, and ORMPV.

*2.2. Comparison of BIPV and BAPV.* In this subsection, the comparison of BIPV and BAPV is discussed in detail in terms of market penetration, classification, function/power generation, and heat and light harvesting. The PV system is used mainly on buildings due to its resourcefulness and nonstop growth. However, a PV installation only prioritizes energy generation while ignoring aesthetic considerations; this creates a negative visual impact of $CO_2$ emission and toxic chemicals [47, 48]. Various studies have studied BIPV and BAPV, where the main difference is that BIPV has three functions which are replacing the conventional elements of construction, generating electrical energy, and light harvesting to be used during the day [49]. The current BAPV systems in buildings generally focus only on maximizing energy generation with nothing added, while the energy generated is regarded as a design parameter [28, 50].

According to Zomer et al. [50] and Debbarma et al. [23], PV systems in buildings can be categorized into BAPV and BIPV. In BAPV, PV components are installed in the overlap of the panel parallel to the skin of the building. In these systems, the energy performance is evaluated by the nonoptimal orientation of the building envelope surfaces where PV is placed and it does not replace a building material. In BIPV, it consists of PV elements with two functions: (a) replacing the conventional elements of construction and (b) generating electrical energy. They are architecturally incorporated into the building design and serve as building covering material and power generator at the same time.

According to Kumar et al. [48] and Biyik et al. [15], BAPV and BIPV are estimated in terms of volume and cost. The market volume for BIPV is very limited in comparison with BAPV because in a residential housing unit only a small percentage of the area of the building undergoes a complete renovation of the roof; only renovation essential for the limited replacement with PV panels appears to be more economical and attractive. So BAPV are mostly used on any roof on which the sun shines. For example, about 5.3 MW of photovoltaic solar energy has already been installed in Tanzania from the report of NBS [7]. But installations have not been done at the building level because of lack of awareness and its cost. Figure 5 shows the market share for the four European PV markets of BIPV, ORMPV, and BAPV.

In Figure 5, the market growth is shown for BIPV, BAPV, and ORMPV for the four European countries of Germany, Spain, Italy, and France. In Germany, about 82% were installed as BAPV, 17% were installed as ground-mounted PV, and only 1% was integrated into the building. In Spain, ground-mounted installations have been very popular accounting for 75%, followed by BAPV accounting for 23%, and finally BIPV accounting for only 2%. In Italy, BAPV and ORMPV each have a market share of 35%, followed by BIPV with 30%, which means the level of awareness on both systems is greater. In France, the market share of BIPV is a greater at 59%, followed by ORMPV at 30%, and BAPV at 11%. We might suggest that the higher growth of BIPV installation in France is due to self-sufficiency, energy efficiency, and thermal insulation as well as level of awareness among stakeholders.

*2.3. PV Cell Categories.* In this subsection, different PV cell categories will be discussed such as silicon-based cells, nonsilicon-based cells, and nanomaterial cells as new concept devices and future technology. Also, different solar cell modules made from crystallines such as monocrystalline, polycrystalline, and ribbon will further be reviewed. Figure 6

Figure 2: BAPV installation: the modules are installed on the top of the existing roof.

(a) (b)

Figure 3: BIPV installation: (a) framed in-roof system—less homogenous appeal is due to the contrast of the aluminum frame and PV panels; (b) MegaSlates' full-roof BIPV installation on a house [45].

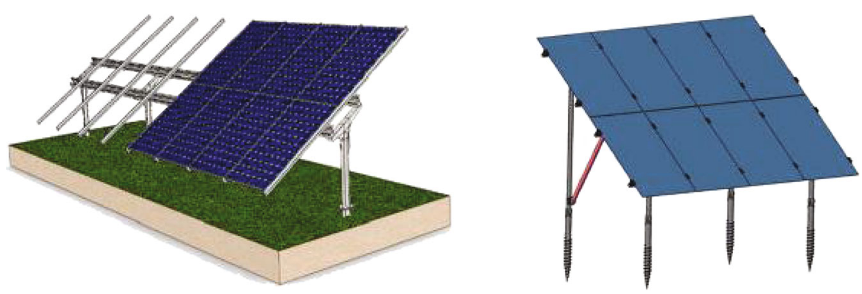


Figure 4: ORMPV installation: photovoltaic system in an open rack installation configuration [46].

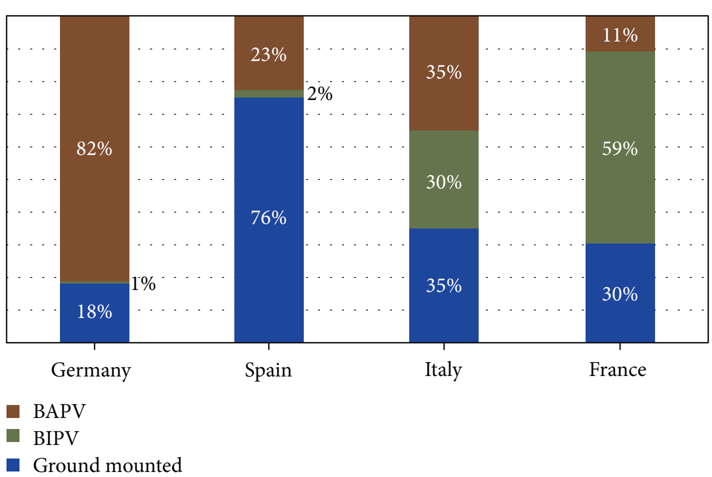



Figure 5: Market share for the four European PV markets [12, 47].

shows the PV solar cell categorization regarding technology to summarize this section.

In a study carried out by Yoo and Manz [51], Tripathy et al. [12], and Green et al. [52], the technologies discussed were crystalline silicon wafer-based cells (c-Si) and thin films such as amorphous (a-Si), organic PV (OPV), DSSCs, and CIGS. The most efficient solar panels on the market today have efficiency ratings as high as 26%, which are monocrystalline and polycrystalline, whereas the majority of the panels range from 11% to 17% efficiency. PV module efficiency

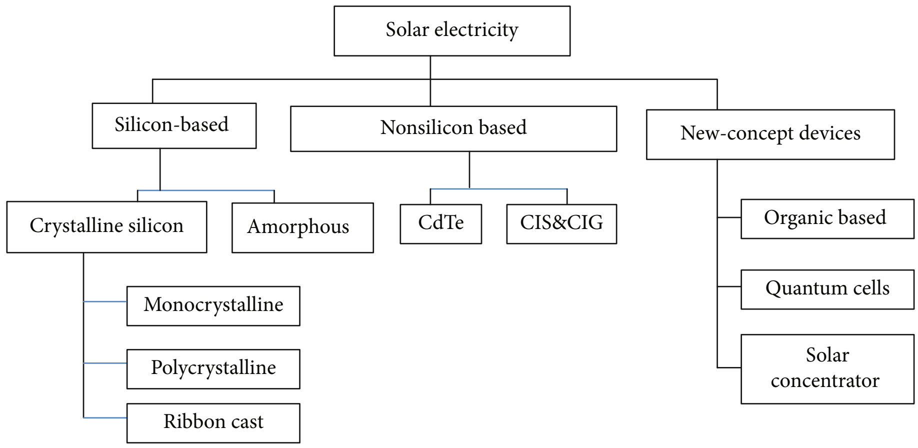



Figure 6: PV cell technology categorization [12, 23].

means a solar panel's ability to convert sunlight into electricity. Given the same amount of sunlight shining for the same duration of time on two solar panels with different efficiency ratings, the more efficient panel will produce more electricity than the less efficient panel. Table 1 shows different PV modules with their efficiency at the Standard Test Condition (STC).

In the article by Lee and Ebong [56], different PV cells were discussed such as crystalline silicon PV, thin-film PV cells, and 3rd generation technologies (OPV and DSSCs). The report showed the advantages of the crystalline silicon PV as silicon is simple to fabricate and available in the market, as well as cheap. The report demonstrates good opportunities for the organic PV and DSSCs as they are opaque films that are integral to the semitransparent and transparent parts of the tinted glasses. These are used for the architectural decoration of doors and windows for the penetration of daylight in offices and residential buildings as it was also further discussed by Kishore [20].

The author Debbarma et al. [23] studied monocrystalline Si PV cells which refer to modules made by integrating cells of large crystals of pure silicon ingots, which are cylindrical in shape. They are formed by melting pure silicon with few percentages of impurities in a crucible at 1425°C. During the melting process, silicon is doped by a group V (for the n-type semiconductor) or a group III dopant (for the p-type semiconductor); for PV cells, boron is the most preferred dopant [27]. Most of the studies show monocrystalline solar cells have an efficiency range of 11-16% [24, 25]. They are chemically stable and can last for a very long time if properly protected. In sub-Saharan Africa, these solar panels are not mostly used and installed because they are expensive and are affected by temperature. Figure 7 shows monocrystalline and multicrystalline Si solar cells which have different colors.

According to Ibn-Mohammed et al. [57], multijunction solar cells are reported as the solar cells with the highest efficiency of about 18-20% which use multiple materials with band gaps that span the solar spectrum. They consist of some single-junction solar cells stacked upon each other, so that each layer going from the bottom to the top has a smaller band gap than the previous; therefore, it absorbs and converts the photons that have energies greater than the band gap of the lower layer and less than the band gap of the higher layer according to Nasr [58] and Green et al. [59].

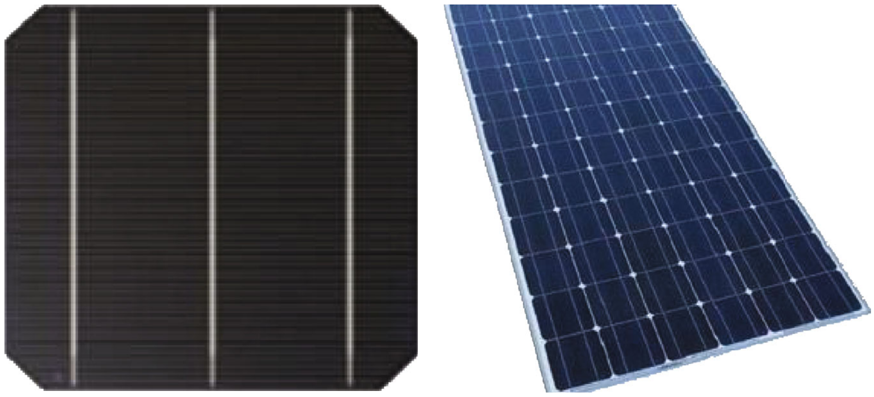
Table 1: Efficiency values of different PV modules.

| Type of PV module | Module efficiency at STC (%) |
|---|---|
| Monocrystalline silicon (mo-c-Si) | 15-26 |
| Polycrystalline silicon (po-c-Si) | 11-22.3 |
| Copper indium gallium selenide (CIGS) | 10-19.2 |
| Cadmium telluride (CdTe) | 9-22.1 |
| Amorphous silicon (a-Si) | 5-11.9 |
| Heterojunction (HIT) | 18-20 |
| Dye-sensitized solar cell (DSSC) | 2.9-11.9 |
| Organic photovoltaic (OPV) | 4-11.2 |
| Micromorph silicon (a-Si/$\mu$c-Si) | 8-10 |

Sources: Yamawaki et al. [53]; Maturi et al. [54]; Debbarma et al. [42]; Green et al. [55].

The author Kato [61] discussed the polycrystalline cells which are made by integrating cells from many silicon wafers. They are very similar to monocrystalline modules except for the fabrication process. In 2015, Trina Solar announced that it had produced a multicrystalline cell with an efficiency of 21%, but different studies show its efficiency between 9 and 13%, very close to monocrystalline [62]. The polycrystalline cells are fabricated from pure molten Si in a square-like tank; in order to determine the grain size and the distribution of impurities, cooling down is an essential step. Compared to monocrystalline Si, the structure is less ideal, resulting in a loss of efficiency of about 1% [63]. Polycrystalline cells are blue in color because of the missing absorption of higher energy photons. They are mostly used in sub-Saharan countries because they are not expensive and have a long life with no degradation over time but easily affected by temperature [24, 25]. Figure 8 shows the polycrystalline panels which appear to be blue in color.

From Oulmi et al. [64], noncrystalline PV cells were reported. These are in the second-generation and noncrystalline



(a) (b)

Figure 7: Monocrystalline (a) and multicrystalline (b) solar cells [45, 60].

Figure 8: Polycrystalline solar panels [60].

form of silicon which is new technology compared to mono- and polycrystalline cells and would not be considered a mature technology as vast improvements in this technology are expected in the coming years. They are fabricated using the vapor-deposition process which deposits a photovoltaic substance onto a solid surface like glass or metal to create a thin layer of silicon material of about 1 $\mu$m thickness. A thin-film panel can be identified as having a solid black appearance. This paper concludes that a noncrystalline PV solar cell has an advantage and has the possibility of depositing amorphous silicon at very low temperature; they also have a lower cost with a high absorption coefficient. Figure 9 shows the thin-film solar cell and its structure.

## 3. Technical Details of BIPV

In this section, the technical details of BIPV are discussed based on different studies. This will include categorization of BIPV and basic parameters of the BIPV monitored by researchers. Finally, the factors affecting the performance of the semitransparent BIPV are detailed from different studies.

*3.1. Categorization of BIPV.* In this subsection, the categorization of the BIPV systems is considered based on the PV technology, application type, or the market names. Figure 10 summarizes the categorization of these BIPV.

As described in Zogou and Stapountzis [67] and Biyik et al. [15], BIPV are categorized based on silicon-based PV and non-silicon-based PV. The silicon-based PV are monocrystalline, polycrystalline, amorphous, and ribbon cast polycrystalline while the non-silicon-based PV cells are composed of cadmium telluride (CdTe), copper indium selenide (CIS), and copper indium gallium selenide (CIGS).

On the other hand, and as described in Gagea et al. [68], BIPV are categorized based on their application as a roof system and on their application in facades and they can be semitransparent, transparent, or opaque. Roofing PV is an integrated part of the building that replaces conventional materials [69, 70]. Transparent BIPV can also be a part of energy-efficient glazing, where they are used instead of usual glass and also in storage houses for the provision of natural lighting during the day, while opaque is used as a roof for energy generation. Facades are part of the fabric or function as additional walls, and installation is affected by the geographical position of the site, which requires considering such factors as weather parameters (solar irradiation and temperature) and tilt angle. Facades can be installed in windows or walls and greenhouses. Figures 11 and 12 show BIPV applications as roof and facade systems.

According to Maturi and Adami [73] and Jelle et al. [74], BIPV are categorized based on their market names as foil products, tile products, solar glazing products, and module products. In module products, they are used with several types of roofing material and are similar to the conventional PV materials. The solar glazing products are normally integrated into the facade, roof, or window products and provide various aesthetic solutions. The foil products are lightweight and flexible, and they are simple to install. The tile products can cover the entire roof or just parts of the roof. They are generally arranged in modules with the appearance and properties of standard roof tiles and substitute a certain number of tiles [75]. Table 2 shows the products according to markets names.

*3.2. Basic Parameters and Factors Affecting the Performance of Semitransparent BIPV.* According to Kha [72] and Shukla et al. [22], many researchers have been focused on different parameters and factors affecting the performance of BIPV. The parameters are electrical, optical, and thermal. Table 3 summarizes the basic parameters of the semitransparent BIPV.

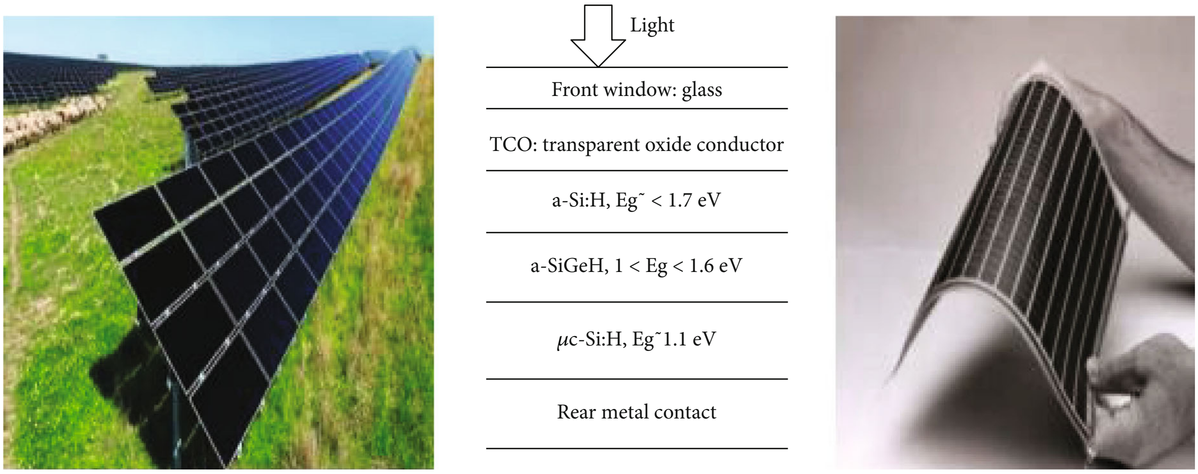



Figure 9: Thin film solar cell [65].

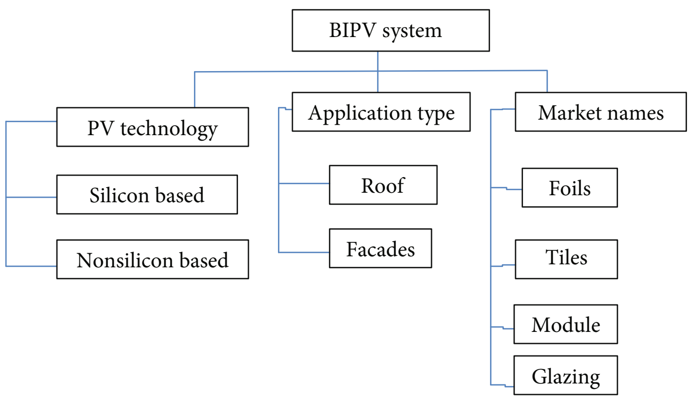



Figure 10: Categorization of BIPV [15, 66].

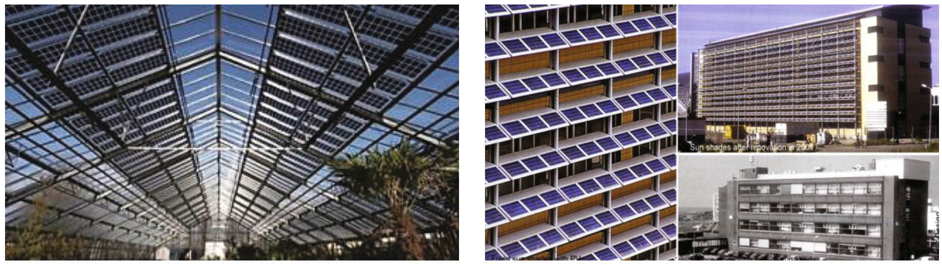
(a) (b)

Figure 11: (a) Facade with black micromorph and semitransparent thin-film modules in Germany and (b) rooftop application of opaque photovoltaic modules in the Netherlands. Sources: Bambara [71]; Kha [72].

The electrical parameters include current and voltage flowing and are automatically recorded by a data logger for the monitoring of the system. These values help in plotting current-voltage ($I-V$) and power-voltage ($P-V$) curves as shown in Figure 13. The $I-V$ and $P-V$ curves provide important performance information about PV modules such as open circuit voltage $V_{OC}$, short circuit current $I_{SC}$, maximum rated power $P_{max}$, current at the maximum power $I_{mp}$, and voltage at the maximum power $V_{mp}$. Then, the fill factor (FF) and power conversion efficiency $\eta$ are calculated from equations (1) and (2), respectively.

$$\mathrm{FF} = \frac{P_{max}}{V_{OC} \times I_{SC}}, \quad (1)$$

$$\eta = \frac{P_{max}}{G \times A}, \quad (2)$$




(a) (b)

Figure 12: (a) Semitransparent PV modules integrated into a greenhouse roof. (b) Opaque and semitransparent PV used as shading in the Energy Research Centre in Northland Power [69, 71].

where $G$ is the incidence irradiance (W/m$^2$) and $A$ is the window surface area (m$^2$).

Thermal parameters include a solar heat gain coefficient (SHGC) and $U$-value. The SHGC is the fraction of incident solar radiation admitted through a window, including radiation directly transmitted and absorbed and subsequently released inward. The $U$-value or thermal transmittance is the rate of heat transfer through a structure (which can be a single material or a composite), divided by the difference in temperature across that structure. These parameters are often used for the determination of the thermal effectiveness of traditional glazing systems. The $U$-values and SHGC are calculated from formulas (3), (4), and (5).

The $U$-value of the glass is

$$U_g = \frac{1}{1/h_o + 1/h_i + L/K}. \quad (3)$$

And the overall $U$-values of the entire window is given by

$$U = \frac{U_g A_g + U_f A_f}{A_g + A_f}, \quad (4)$$

$$\text{SHGC} = \tau + N\alpha, \quad (5)$$

where, $h_o$ and $h_i$ are the outdoor and indoor glass surface heat transfer coefficients, respectively, in Wm$^{-2}$K$^{-1}$; $L$ is the glass thickness, in m; $K$ is the thermal conductivity of the glass, in Wm$^{-2}$K$^{-1}$; $U_g$ and $U_f$ are the $U$-values of the glass and the frame, respectively; $A_g$ and $A_f$ are the areas of the glass and the frame, respectively, in m$^2$; $\tau$ is the total solar transmittance of the semitransparent PV; $N$ is the inward flowing fraction of the absorbed radiation; and $\alpha$ is the solar absorption of the semitransparent PV.

The optical properties include visible light transmission (VLT), light-to-solar gain ratio (LSGR), and window-to-wall ratio (WWR). To measure VLT, daylighting is introduced to an indoor room by using a semitransparent PV to allow daylight into building interiors. This reduces the need for artificial lighting during the day according to Gueymard [76]. LSGR is the ratio of VLT and SHGC that highlight the importance in characterizing the spectral selectivity and performance of glazing systems. VLT, LSGR, and WWR are given by formulas (6), (7), and (8), respectively:

$$\tau = \sum \tau_i, \quad (6)$$

$$\text{LSHG} = \frac{\text{VLT}}{\text{SHGC}}, \quad (7)$$

$$\text{WWR} = \frac{\sum \text{glazing area}}{\sum \text{gloss exterior wall area}}, \quad (8)$$

where $\tau$ is the total visible transmittance of semitransparent PV glazing; $\tau_i$ is the visible transmittance of the different layers from different days; $\sum \text{gloss exterior wall area}$ is the total area of the walls that separate the outside from the inside of the building.

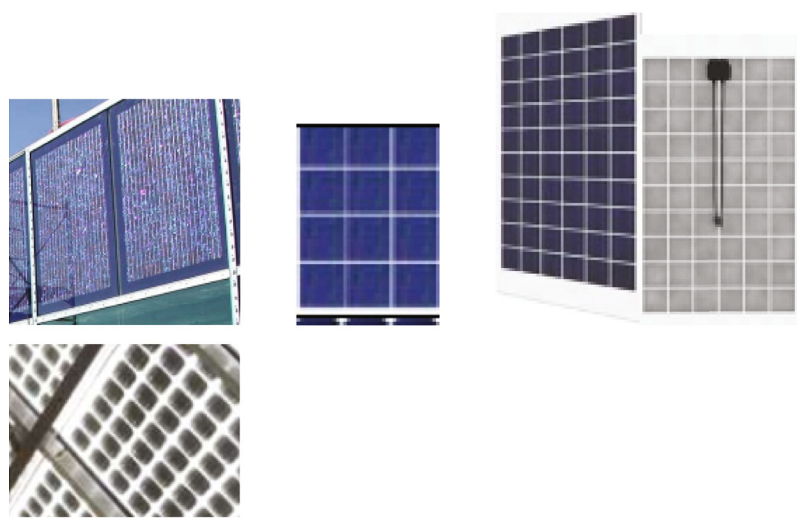
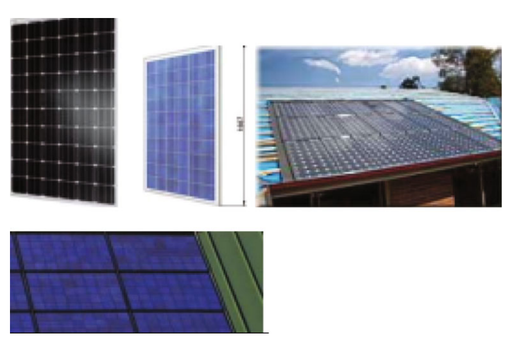
Furthermore, studies show that temperature, orientation, design of the solar cell, and optimal window-to-wall ratio (WWR) are important parameters affecting the performance of semitransparent BIPV. According to Jiang et al. [77], Wong et al. [78], and Xu et al. ([21]), these parameters show a greater impact on the overall energy consumption of buildings, through effects on PV electricity generation, lighting, cooling, and heating. WWR is an essential building envelope element that decides the indoor luminous and thermal environments.

## 4. Analysis of the Semitransparent BIPV System Performance

In this section, semitransparent BIPV have been described in terms of the amount of energy generated, energy saved, daylight saved, and general performance assessment basing on the electrical, thermal, and optical properties. Tables 4 and 5 depict semitransparent BIPV case studies under different parameters and locations.

*4.1. Electrical and Thermal Performance of the Semitransparent BIPV.* Electrical and thermal performances are considered as the effects on power generation of different factors such as photovoltaic technologies, solar heat gain coefficient, heat transfer coefficient, and $U$-values or when the module is exposed to different irradiance (geographical location) and other factors such as air ventilation.

Table 2: Market names according to the products.

| Type of product | Description | Examples |
|---|---|---|
| Foil | They are adhesive mounted, require no frame, and have low mounting cost. They are good for large roof expanses. Their big advantage is that they are flexible to any shape you need. |  |
| Tiles | These are mostly PV products installed on the whole roof or part of the roof. They can be installed by a roofer with little training. |  |
| Glazing product | These are used as shading devices, windows, roofs, facades, and green houses. Also, they have the ability to transmit daylight for the options of using natural lighting while producing electricity. |  |
| Module | These are the cheapest form of integration, and have improved appearance over external frames. They are normal PV modules. Most are opaque PV used for roofing purposes. |  |

Source: Jelle et al. [74]; Debbarma et al. [42]; Shukla et al. [24, 25].

In the work by Vats and Tiwari [79], evaluation of the energy performance of a semitransparent BIPVT integrated to the roof of a room was performed. Energy has been compared for six different PV modules. It was observed that the maximum annual electrical energy was 810 kWh for a heterojunction over the crystalline silicon cell, while the annual thermal energy was 464 kWh for amorphous silicon. The study concluded that the heterojunction PV module is more suitable for producing electrical power compared to amorphous silicon.

Table 3: Summary of the basic parameters of the semitransparent BIPV.

| Electrical | Thermal | Optical |
|---|---|---|
| Solar PV efficiency ($\eta$) in % | Solar heat gain coefficient (SHGC) in % | Visible light transmittance (VLT) in % |
| Open circuit voltage ($V_{OC}$) in V<br>Short circuit current ($I_{SC}$) in A<br>Maximum power point ($P_{max}$) in W<br>Fill factor (FF) in % | $U$-value or heat transfer coefficient in W m$^{-2}$K$^{-1}$ | Light-to-solar gain ratio (LSGR) in %<br>Window-to-wall ratio (WWR) in % |

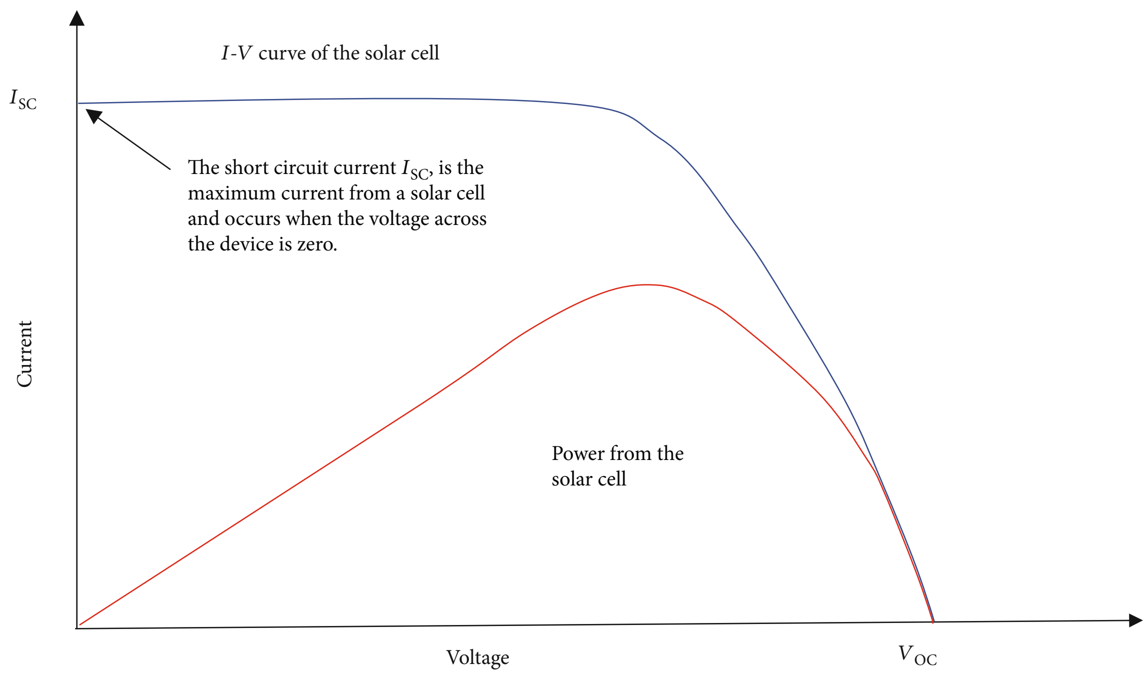



Figure 13: Typical $I-V$ and $P-V$ curves [72].

Peng et al. [80] developed a numerical simulation model using EnergyPlus to predict the overall energy performance of a photovoltaic double-skin facade (PV-DSF). The energy-saving potential was compared with other technologies, while sensitivity analyses of air gap depths and analyses of the optimal air gap were conducted in Berkeley. In comparison to other technologies, the naturally ventilated saved electricity by PV-DSF per year was about 35%. The PV-DSF method enabled generating 65 kWh/year per unit area, while 50% of lighting electricity could be saved in the winter. The study concluded that thicknesses between 400 mm and 600 mm could be recommended as the optimal air gap range for a PV-DSF installation while 15% of the annual net electricity use could be saved and could produce good thermal performance and day lighting if an air gap depth of 600 mm was chosen.

According to Yang [81], open-loop air-based BIPVT systems were experimentally investigated. The experimental approaches in this study were indoor tests in the built environment, outdoor tests in specially designed test cells, and building size experiments and demonstrations. This was also studied by Yang and Athienitis [82] on the indoor tests using a solar simulator. Experimental results confirmed that the two-inlet BIPVT concept improved thermal efficiency by 5% compared to a conventional single-inlet system. Comparisons of prototypes were conducted on monocrystalline opaque PV and semitransparent monocrystalline PV modules. Results showed that applying semitransparent PV modules with 80% of the module area covered by solar cells in BIPVT systems increased energy efficiency by up to 7.6% compared to opaque ones.

Ekoe et al. [83] studied the semitransparent BIPVT system, and simulation was done for the investigation. The parameters found were electrical and thermal. In this study, 30 PV modules were used and results reported that annual thermal energy output was 76.66 kWh, while total thermal efficiency was 56.07%. Maximum heat taken from fins to the air stream was 25.49 Wh, and annual heat extracted was 55.44 kWh.

*4.2. Electrical and Optical Performance of Semitransparent BIPV.* The BIPV electrical and optical performance concerns parameters such as current and voltage, visible light transmittance, light-to-solar gain ratio for both single and glazed modules, and the window-to-wall ratio. Kha [72] experimentally investigated the performance of semitransparent BIPV

Table 4: Electrical and thermal properties of semitransparent BIPV: case studies from different locations.

| Location | Description | Results | Reference |
|---|---|---|---|
| California | Evaluation of the energy performance of a photovoltaic double-skin facade (PV-DSF) was conducted. | 50% of lighting electricity was saved in the winter, and 15% of the annual net electricity was saved. | [80] |
| Canada | Air-based building-integrated photovoltaic-thermal (BIPVT) systems were investigated. | Thermal efficiency was improved by 5% compared to a conventional single-inlet system. | [81] |
| Cameroon | Building-integrated semitransparent photovoltaic thermal systems (BISPVT) were simulated. | The system area of 36.45 $m^2$ can annually produce an amount of thermal energy of 76.66 kWh at an overall thermal efficiency of 56.07%. | [83] |
| Germany | Calculation of the thermal impact on building performance of an integrated PV facade was conducted. | 12% of heating energy was saved. | [84, 85] |
| India | A building semitransparent PV thermal system was integrated into the roof and facades. | Energy efficiencies were 11-18% at the roof and 13-18% at the facade, respectively.<br>Electrical efficiencies were 85% at the roof and 72% at the facade, respectively. | [22] |
| India | Evaluation of the energy performance of a semitransparent BIPVT integrated to the roof of a room was performed. | The annual electrical energy generated was 810 kWh for a heterojunction, while the annual thermal energy was 464 kWh for amorphous silicon | [79] |
| Japan | Evaluation of electrical and solar heat using a BIPVT hybrid was done. | Thermal efficiencies were 20-22% for glazed systems and 29-36% for unglazed systems, respectively. | [86] |
| Japan | A semitransparent BIPV was evaluated by simulation. | 5.3% of heating and cooling were reduced.<br>Net energy savings of 3.0–8.7% were achieved. | [78] |
| Korea | Evaluation of electrical thermal energy from different conditions was done, as the sun shading module was rated at 40 kWp and the rooftop modules were rated at 60 kWp | On a cloudy day, the energy generated was 40.8 kWh, while solar irradiation was 2513 Wh/$m^2$.<br>On a normal day, the energy generated was 69.8 kWh, while solar irradiation was 4458 Wh/$m^2$.<br>On a sunny day, the energy generated was 68 kWh, while solar irradiation was 6554 Wh/$m^2$. | [87] |
| Turkey | The energy of the semitransparent a-Si solar cells integrated to a Tromble wall was evaluated. | Average electrical efficiency was 4.52%, and thermal energy was 27%. | [88] |
| USA | Semitransparent BIPV windows were studied for the overall energy of commercial buildings in various tropics. | The system can save 30% of the total heating and ventilation system energy compared with the clear glass system. | [29] |

Table 5: Electrical and optical properties of semitransparent BIPV: case studies from different locations.

| Location | Description | Results | Reference |
|---|---|---|---|
| Brazil | The energy-saving potential of semitransparent PV windows was investigated. | 30% of the total HVAC was saved using daylight.<br>18%-59% of NEB was achieved. | [29, 91] |
| Brazil | Semitransparent photovoltaic panels in windows were evaluated. | The reduction in the final energy consumption ranged from 19% to 43%. | [90] |
| Canada | Potential benefits of semitransparent photovoltaic windows were evaluated by simulation. | The STPV module with 10% visible effective transmittance resulted in the lower electricity consumption of 5 kWh/$m^2$/yr. | [89] |
| India | The three semitransparent BIPV on power and optical properties were evaluated. | The values of VLT for the three PV modules were in the 7.09%–23.49% range, and power generation and efficiency increased by around 0.01–0.13%. | [92] |
| Italy | A comparison of BIPV facade semitransparent modules for the human comfort conditions was conducted. | A room with semitransparent PV performs better than that with a-Si PV module. | [93] |
| Spain | Impacts of optical characteristics on the energy performance of semitransparent PV windows were investigated. | Net energy savings of 3.0–8.7% were achieved. | [78] |
| Spain | Energy performance of the WWR of five STPV elements was evaluated. | Energy saving potential ranges between 18% and 59% compared to the normal glass. | [91] |
| Singapore | Performance of semitransparent BIPV windows in a tropical climate was conducted. | The NEBs vary from 1.79 to 23.26 kWh/$m^2$/yr and increase steadily with the increase in WWR. | [72] |

Table 6: Semitransparent BIPV analysis software.

| Software | Description | Reference |
|---|---|---|
| TRNSYS | Analysis and simulation of BIPV/BIPVT | [31, 95, 96] |
| EnergyPlus | Analysis and simulation of BIPV | [72, 90, 96–99] |
| PVSYST | Computing and modeling of the BIPV with data analysis | [18, 100] |
| RETScreen | Annual energy generation | [101] |
| THERM | Power and energy simulation | [102] |
| FLUENT/CFD | Electrical energy simulation | [67, 103] |
| PHOENICS | BIPV analysis and simulation | [96] |
| PVSYST | Analysis and simulation | [104] |
| SOLCEL | Modeling of the BIPV | [51] |

windows in Singapore. The overall energy performance was evaluated by calculating net electrical benefits (NEB) including the generation of electricity and the reductions of cooling energy and artificial lighting energy, through parameters of thermal, electrical, and optical properties. Six semitransparent BIPV modules were tested. The results showed that the NEB of the BIPV depended on the WWR and when compared with other commonly used glazing systems, semitransparent BIPV windows were found to be the best in terms of overall energy-saving performance. In conclusion, the study demonstrated the good energy saving potential of the semitransparent BIPV windows to be used for the natural light.

Kapsis and Athienitis [89] observed the effect of optical properties by simulation on semitransparent PV windows. The parameters evaluated were the orientation of facades, window-to-wall ratio, and electrical lighting. It was reported that semitransparent PV windows with 10% visible active transmittance had the best energy-saving potential. The study concluded that to maximize the energy-saving potential of semitransparent PV windows, the selection of optical properties is necessary due to daylight and lighting controls applied to the building.

Didoné and Wagner [90] conducted an evaluation of the potential energy savings and energy generation of semitransparent PV windows in two Brazilian cities of Fortaleza and Florianopolis. The result shows that energy savings were 19% to 43% for these cities of Fortaleza and Florianopolis, respectively. Also, in Fortaleza, a higher energy of 493.6-798.6 kWh/year was achieved in PV windows compared with that of 591.8-750.3 kWh/year in Florianopolis City. The study concluded that it is possible to reduce the energy consumption for artificial lighting and cooling utilizing suitable control frameworks and to generate more energy using semitransparent photovoltaic panels in windows.

There is a different software that is used for experimentation, analysis, and design as shown in Table 6. In fact, the use of software as tools for simulation and modeling is primarily to simplify the determination of different BIPV performances under various conditions [94].

To conclude this section, we see that the outdoor performance of the BIPV module is influenced by many factors. Some of these issues are related to the module itself and others to the location and environment. Hence, in the installation of BIPV, the selection of the geographical location is important because it determines temperature, irradiance, wind speed, and location of the building itself to harvest higher energy.

### 4.3. Semitransparent BIPV Challenges and Future Technology Prospects

As described in Shukla et al. [24, 25] and Shukla et al. [27], studies investigated and determined that small economies of scale, long payback period, high initial capital costs and installation costs, and limited information on market potential are the big challenges facing BIPV development as summarized in Figure 14.

BIPV challenges were discussed in detail by authors Goh et al. [105], Mousa [106], and Baljit et al. [66] to include among others, technological limitations, poor financial support, high initial investments, low acceptance level to the community and low level of awareness of the architect who lacks essential practical knowledge, and general lack of public awareness of government policy. These challenges need to be addressed for the purpose of increasing the market and increasing the volume of installations of BIPV.

Furthermore, aesthetic, technical, economic, and social challenges have been determined to face PV cell operations as detailed in Defaix et al. [102], Nasr [58], and Sai et al. [63]. In the aesthetic challenge, the studies discussed that many architectural designs make it very difficult for building stakeholders to install a PV module to an existing structure of a building since it is not an integral part of the building. Technically, the PV modules need a large space for installation and it is difficult to get a good orientation. In the economic challenge, the studies show that the cost of installation and its implementation is high rather than the normal PV system. In the social challenge, most of the people are not familiar with the new technology and it is difficult to accept the technology as a reliable source of energy; hence, awareness to stakeholders is needed and different trainings also need to be conducted to give awareness to the BIPV system.

### 4.4. Semitransparent BIPV Future Research Opportunities

In various countries such as Germany, Japan, China, Spain, India, and the United States, the BIPV are widely implemented due to government support and awareness; hence, there is a great need for government support to get the industry started as it has been carried out with accomplishment in European countries. However, in Tanzania and other tropical

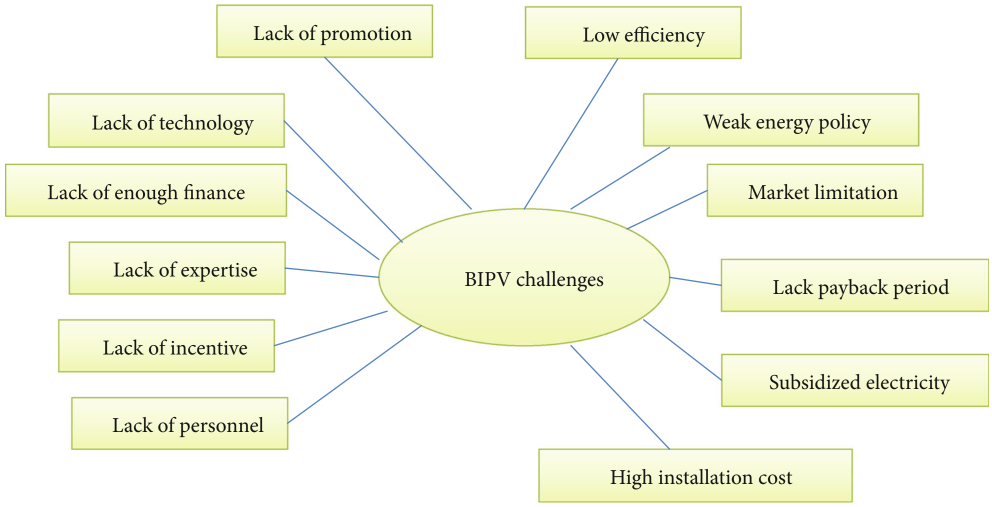



Figure 14: Challenges of the semitransparent BIPV [27].

countries, the BIPV are rarely used up to now. Due to the large amount of solar radiation, BIPV systems are very well suited for energy generation and they will possibly play a significant role in future energy generation. New technologies under improvement will in the future provide semitransparent BIPV with better efficiencies and decreased production costs. Some of the new concepts relate to the third generation of organic-based PV, consisting of dye-sensitized and $TiO_2$ solar cells; and solution also concerns the awareness of stakeholders and the growth of the market share.

## 5. Conclusion

Semitransparent BIPV is a smart energy generation approach that integrates photovoltaic technologies into buildings to harvest abundant solar energy in various forms. It is considered to be among the most promising renewable energy technologies of the future since its discovery in the 1970s. The present work provided a comprehensive review of the semitransparent BIPV state-of-the-art technology and energy performance and considered its future technological challenges. The review has shown essential factors such as window-to-wall ratio, transmittance, solar irradiation, shadowing effect, ambient temperature, the direction of the building, and the PV tilt angle in the determination and improvement of output power. The semitransparent BIPV was demonstrated to have many advantages as a replacement of the conventional materials of building facades, while at the same time providing clean energy, thus reducing unclean external source dependency.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this review.

## Acknowledgments

The authors would like to acknowledge the African Centre of Excellence Water Infrastructure and Sustainable Energy Futures (WISE-Futures) of the Nelson Mandela African Institution of Science and Technology (NM-AIST) for enhancing and stimulating the learning and research environment, which contributed immensely in completing my research article.

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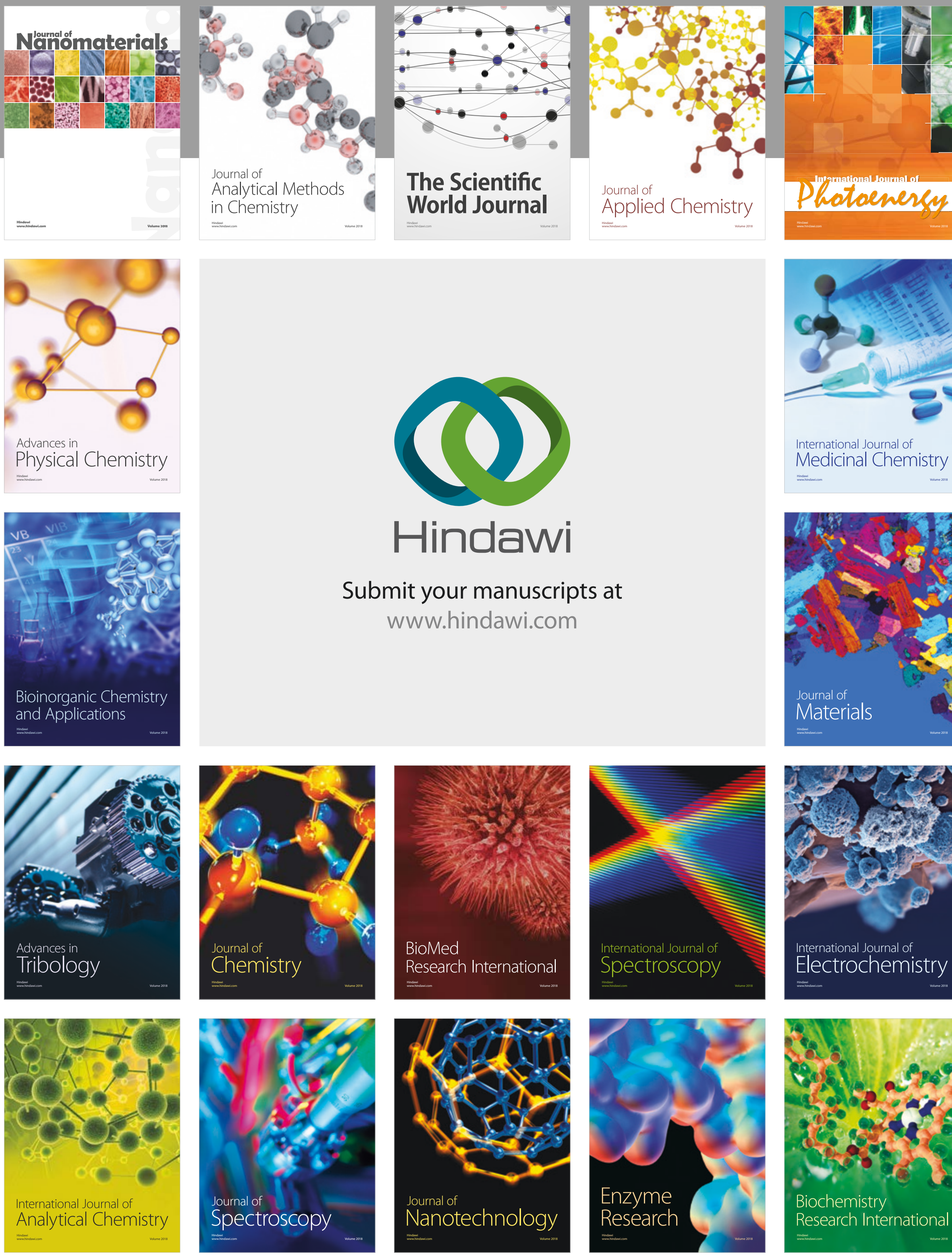

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