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Review on application of BIPV technology into the modern buildings

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ABSTRACT

Over the past few decades, there has been a noticeable increase in global energy consumption, which represents a significant problem caused by unsustainable and harmful methods of energy production. This issue leads to an emission of harmful greenhouse gases and environmental pollution on a global scale. By considering the reasons that lead to the mentioned problems, emphasis has been placed on the technologies of the renewable energy sources, as a key solution for reducing harmful environmental consequences. As a contribution to the transition to a more sustainable energy system, solar photovoltaic technology is of great importance. In addition, special attention is paid to the integration of solar photovoltaic systems into building structures (building integrated photovoltaics - BIPV). The advantage of this technology is in the balance of efficient energy saving and generation, with aesthetic and visual comfort. By analyzing the implementation of BIPV, the study provides an insight into the potential of this technology, its contribution to the global energy sustainability, as well as the results achieved through the implementation of various solutions.

KEYWORDS

Building integrated photovoltaics, Building, Application.

1. INTRODUCTION

Solar energy is the most abundant renewable energy source, available in both direct and indirect forms. Solar energy utilization can be categorized into two primary areas: solar thermal and photovoltaic systems. Solar thermal applications focus on harnessing solar radiation to produce useful heat. In contrast, photovoltaic (PV) technology is designed to convert solar energy directly into electricity, using PV cells, with conversion efficiencies ranging from 7% to 40% [1].

Photovoltaic modules are building-integrated when designed to meet essential construction requirements and replace conventional building materials. Figure 1 provides an initial overview of BIPV systems through examples. Key considerations include the type of structural integration of the modules, the flexibility in adjusting module size, and how aesthetic features can be achieved using colors, surface textures, or partially transparent designs. If the integrated PV module is removed, it will be substituted with a suitable conventional building material [2, 3].

Reducing carbon dioxide (CO2) emissions from the building sector is an urgent priority. One strategy to address this challenge is by harnessing on-site solar energy. In 2021, the growth in renewable energy generation reached its highest level in recent years, with solar PV modules contributing over 60% of this increase. More than 60% of the growth in PV usage came from utility-scale installations, while the rest was attributed to smaller systems such as commercial and residential PV modules. However, to meet global energy goals, the annual solar PV power generation will need to double over the next five years. In this context, the application of building-integrated photovoltaic (BIPV) modules into the building envelope has garnered significant research interest in enhancing building energy efficiency [4-6].

module geometry	standard size	custom size	standard width, adaptable length	custom size
appearance	close to conventional appearance, frameless modules, mounted with clamps	partially transparent, close to conventional appearance	surface texture, uniform color	sophisticated artistic design
constructional integration	additional ventilated layer	glazing-integrated	module-integrated backrail system for ventilated facades	glazing-integrated

Figure 1: Overview of BIPV systems through examples [2]

Urban morphology significantly affects the PV potential as it dictates the amount of solar radiation that can reach various parts of a building's surface. Li et al. [7] performed an analysis using a model comprising nine rectangular solids and demonstrated that buildings with higher aspect ratios and greater site coverage exhibited increased PV potential. They also found that by selecting the appropriate urban form, it is possible to achieve the annual electricity demand of a residential building. The photovoltaic (PV) potential of building facades with installed BIPV modules is significantly influenced by the pursuit of economic efficiency. Fath et al. [8] conducted an urban-scale study revealing that building façades contributed to 13% of the PV capacity necessary for achieving profitability in PV installations. In a study, Brito et al. [9] found that the PV potential of facades represented approximately 50% of the total potential when economic efficiency was not considered. However, this potential can be reduced to around 5%, 15%, and 30% if the payback period for the facade system investment is less than 17.9, 23.0, and 32.2 years, respectively.

2. CHARACTERISTICS OF BIPV

In BIPV systems, photovoltaic panels are embedded within building elements like walls or roofs. To mitigate heat buildup on the PV panels, BIPV approach involves ventilating the wall [10]. This method allows air to flow between the PV panel and the building wall, driven either by natural ventilation or forced convection, and then be expelled into the surrounding environment, as illustrated in Figure 2. Before designing a BIPV system, a thorough investigation into the different types of solar modules and the materials used in PV cells is essential to determine which module offers the best suitability, reliability, and benefits based on design, cost, and environmental factors. Additionally, an analysis of solar radiation and climatic conditions is necessary for effective integration [11-13].

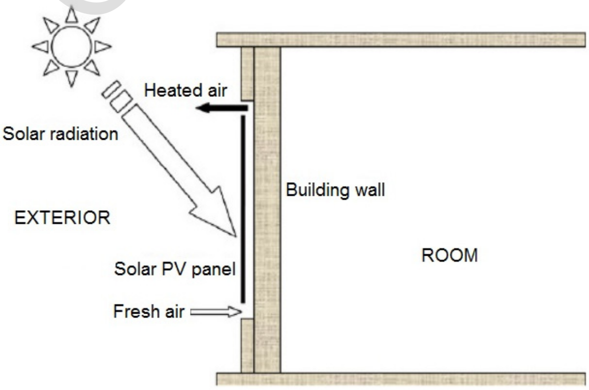

Figure 2: Schematic diagram of BIPV

The concept of BIPV has been developing over several decades. Various research groups and companies worldwide have contributed to the development of these technologies. Today, there are numerous companies and research institutions dedicated to innovating in the field of BIPV, providing new design and technological approaches to improve the efficiency and integration of solar systems into building structures.

In the early 1970s, the first initiatives and experiments related to the integration of solar systems into building structures began. The Wohnanlage Richter residential complex in Munich, Germany, designed in 1982 and featuring polycrystalline cells on its curtain walls, is recognized as one of the earliest examples of photovoltaic systems integrated into building design [14-16]. The initial attempts involved solar equipment that was added onto or installed onto existing structures. However, the real development of the BIPV concept began with the advancement of thin-film and flexible photovoltaic technologies, enabling greater adaptability and integration into various building materials. In Figure 3, a continuum of solar system designs for residential buildings is depicted, showing increasing integration (from left to right) with the architecture and materials of the building.

Figure 3: Examples of increasing integration of PV Panels [14]

BIPV systems offer exceptional long-term reliability, with typical warranties ranging from 20 to 25 years [17]. There are many advantages associated with BIPV solutions:

- innovative design,
- sun protection and electricity generation,
- minimize the building's carbon footprint,
- thermal insulation properties,
- soundproofing and enhanced comfort,
- enhance the building's value,
- eco-friendly,
- sustainability.

When considering the advantages of BIPV compared to other materials, the aesthetic appearance of these panels can be seen as both an advantage and a disadvantage. In many cases, aesthetics are crucial and significant for the adoption of BIPV in the market. Research has shown that BIPV offers improved aesthetics compared to traditional solar panels. With various BIPV technologies available, such as solar tiles, facades, glass, and solar fabrics, which are more visually appealing to architects, builders, as well as homeowners and building owners, due to their adaptability to the roofs of houses and buildings they are installed on. Aesthetic appearance is not the only important factor; it's also essential for the panels to be functional.

Although the advantages of BIPV are evident, sometimes it can be challenging to identify all the obstacles and barriers to adopting these technologies. One of the main disadvantages, according to research, is the cost. Solar tiles are more expensive than solar panels, making panels a more affordable solution for building construction. Especially when considering that the cost depends on the pitch and size of the roof on which they are installed. Another disadvantage of solar tiles relates to energy efficiency. Solar tiles sometimes have lower energy efficiency than regular solar panels, and buildings require a certain roof pitch with high sun exposure [18-19].

BIPV installations require a significant initial investment, although ongoing maintenance costs are very low. Each installation must be assessed in its unique context, especially considering the generated electrical energy, installation duration, alternative costs, etc. The cost of a BIPV installation depends on factors such as roof pitch, size, modules, design, etc. For a standard-sized single-story house, the installation cost averages around $25 per square foot. The total installation costs for solar tiles are approximately three times higher than those for solar panels, including roof reconstruction.

Many BIPV manufacturers produce custom modules manually with limited automation, leading to higher costs for solar building envelope components compared to non-solarized alternatives. This is reflected in the investment costs associated with 'handcrafted BIPV modules,' as shown in Figure 4. Currently, only a few manufacturers offer standardized BIPV products with fixed dimensions. The green dotted line at €131/m^2 represents the maximum additional cost at which solar building products remain cost-effective. If BIPV system prices fall below this line, the solar building envelope proves to be more economical over its lifespan compared to conventional options. A highly automated, flexible production process capable of producing approximately 55 MW annually, would enable pricing below €131/m^2 (including components like cabling, inverters, brackets, mounting systems, grid connections, meters, and installation). Such advancements in BIPV facade production could provide attractive profits for end users, manufacturers, and investors, and offer significant opportunities for smaller local production facilities in Europe due to the benefits of proximity and coordination with end customers [2].

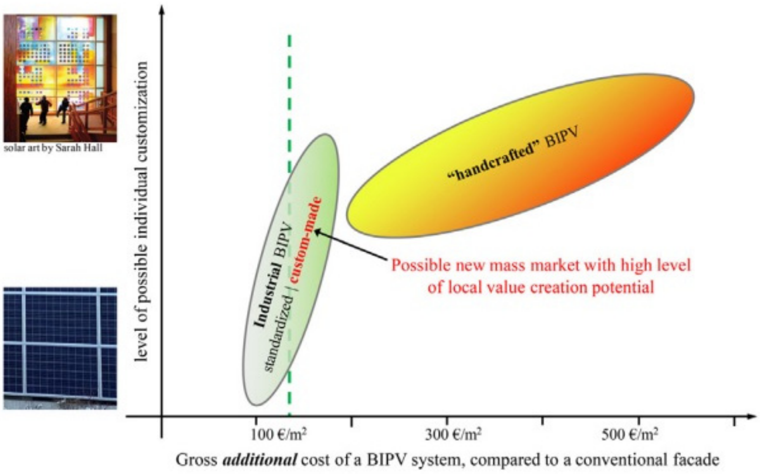

Figure 4: Additional price for a BIPV installation versus a conventional facade, depending on the degree of customization [2]

3. MAIN CATEGORIES OF BIPV

Different classifications of BIPV can be found in literature, depending on their purpose and criteria. One of the main divisions is based on the location of the installation on the building itself, so these systems can be on the roof, in the facade, or on external integrated devices. Each of these groups corresponds to application categories according to the EN 50583 standard. Roof installations correspond to categories A and B, facade installations to categories C and D, and external integrated devices to category E. Examples of BIPV systems in the building applications are shown in Figure 5.

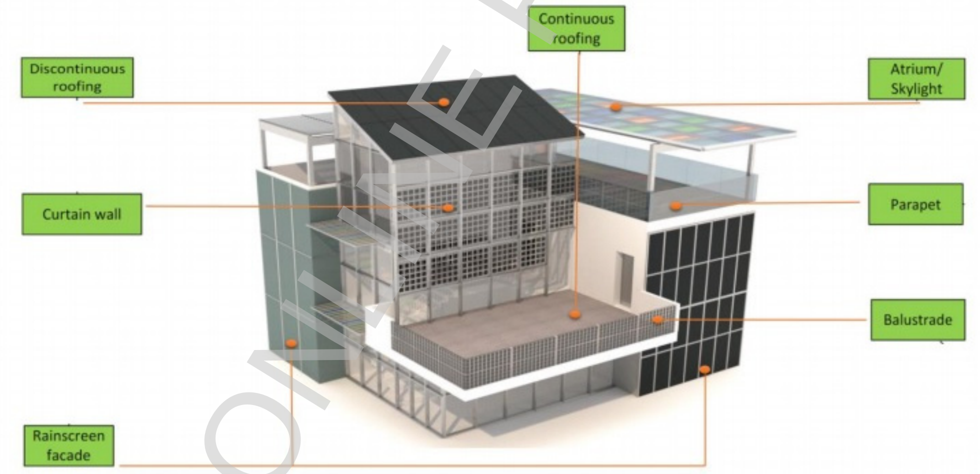

Figure 5: Examples of BIPV systems in actual building applications [20]

3.1. BIPV roof installation

Roofs unequivocally have the greatest potential for collecting solar energy, thus making them ideal for the implementation of BIPV technology. Sloped roofs, for instance around 30°, offer the best energy collection, although flat roofs, also known as continuous roofs, can be well utilized too. One of the challenges in optimizing energy collection through solar panels is the suboptimal angle of inclination, which reduces energy production. This issue affects both types of roofs but is particularly significant for flat roofs where the inclination is inflexible or limited. Examples of BIPV installation on roofs are shown in Figure 6.

As mentioned earlier, solar roof tiles represent one of the most common ways of integrating BIPV technology. They are synonymous with traditional roof tiles. Each solar tile covers an area larger than 0.5 m^2 and can be made of foil or glaze. The resemblance of solar tiles to traditional tiles negates aesthetic challenges, seamlessly blending in with conventional flat roofs. Unlike large solar tiles, smaller ones have modules smaller than 0.5 m^2 with a configuration that does not affect their application. Roofs equipped with BIPV technology can also be (partially) transparent. These elements can cover the roof entirely or partially. Their purpose is to provide illumination to the space, along with additional thermal, sound, and water-resistant functions [20 - 23].

Figure 6: Examples of BIPV installation on roofs [24]

3.2. Façade installation of BIPV

The second significant application area of BIPV is the facade, where solar panels of all technologies can be integrated as conventional wall cladding with multiple layers and single-layer facades. Integration of solar modules into building facades can preserve the original function, security, aesthetic requirements, and facilitate electricity production throughout the year. Additionally, such a facade can reduce thermal losses from the interior of the building .

The first method of installing BIPV on the facade of a building is as a wall curtain. It involves a continuous and external system of facade openings, which can be fully or partially glazed. The term "wall curtain" refers to its construction, as the facade is suspended like a curtain from the upper edge of the building and attached at various points to prevent water and air infiltration. The construction itself is made of aluminum frames filled with glass panels. This meets various requirements such as structural support, acoustic properties, thermal insulation, water resistance, etc. This method of integrating BIPV is most common in commercial buildings. In Figure 7, an example of a commercial building with such a system installed is shown.

Figure 7: Curtain wall [21]

When installed as a "warm facade," this method separates the external and internal environments. It can be implemented according to various construction systems such as stick systems, unitized curtain walls, structurally glazed facades, point-fixed suspended facades. In their most basic form, these systems are windows but can also be integrated into more complex facades. Another way to install this system on the facade of a building is as a "cold" or ventilated facade. This system consists of a supporting substructure, an air gap, and cladding. It's possible to categorize them as "transparent" with openings at the top, "ventilated" with openings at the bottom and top, and "pressure-equalized" rain screen facade with barriers in the air gap. The panels are often clad in aluminum and installed a short distance from the building to allow for ventilation and drainage. The ventilation gap should be a minimum of 100mm and helps improve performance by reducing temperatures, and it can also be used as a space for cable routing. Another method is the double-skin facade, which consists of two layers, typically made of glass, with air flowing between them. The space between can range from 20mm to several meters and serves as insulation against extreme weather conditions, sound, etc. The PV is the same as in the curtain wall, but in this case, thermal insulation is not needed. One of the more intriguing methods of integrating BIPV is into the building's windows. Solar cell products designed for glazing are used for this installation method. They can come in different colors and levels of transparency, allowing for various aesthetic outcomes. The spacing between solar panels ranges from 3 to 50 mm, depending on the level of transparency and criteria for electricity production. Through this gap, daylight passes, contributing to lighting while electricity is generated. This installation method is more suitable for colder climates because in warmer regions, there might be overheating due to the greenhouse effect.

3.3. Installation of BIPV on external integrated devices

External integrated devices include building elements that come into contact only with the external environment. Therefore, BIPV can be installed on terrace railings, atriums, roller shutters, awnings, etc. Integration of PV in this manner represents one of the most effective ways to control internal daylighting and thermal conditions of the building. This reduces the penetration of solar heat into the building, leading to less need for ventilation and reducing the cooling load while providing additional electricity production. If a controllable system is installed, the louvers can track the movement of sunlight to achieve greater efficiency. Another option is to position the louvers in winter so that they collect energy during the day and close them at night to reduce heat loss [22, 23]. Examples of BIPV systems on external integrated devices are shown in Figure 8.

Figure 8: BIPV systems on external integrated devices [20]

PV panels can be integrated as multifunctional components in transparent roof structures or atriums, allowing for controlled light to enter the building's interior. As semi-transparent roof units, they provide protection from heat, sunlight, glare, and weather conditions. One integration method involves placing small PV cells on atrium glass, creating transparent gaps between them to permit controlled daylight inside. Well-designed PV-integrated atriums can also enhance the building's aesthetic from the inside. While these glazing systems are typically best suited for smaller PV installations, they can be visually appealing and offer excellent visibility. Since skylight, atrium, and greenhouse glass are often heavily tinted to reduce glare, semi-transparent PV glazing can serve as an effective alternative.

4. APPLICATION OF BIPV IN A MODERN BUILDING SECTOR

Europe used to be the largest market for PV systems worldwide, but it was recently surpassed by China. However, Europe remains the region with the highest installed PV capacity. Nevertheless, the installation rate in Europe is slowly declining while it is increasing in other leading countries worldwide. Europe continues to represent a consistent market opportunity, primarily due to the construction materials used. One of the obstacles has been the installation on historically significant buildings, concerning the color of the cells and their integration into valued facades. The problem has been solved, and on the market, cells with high integration levels and minimal visual impact are readily available. Leading the list of European countries offering the best opportunities for BIPV is Germany [25]. Projection for Europe market for the 2025th year is shown in Table 1.

Table 1: Europe market for BIPV with projection for the 2025th [25]

Application	2020	2021	2023	2025	CAGR (2020-2025)
Roofs	539.7	656.9	1,056.7	1,827.1	27.6%
Facades	321.0	366.1	516.2	780.9	19.5%
Glazing	136.3	156.1	220.6	332.2	19.5%
Shading	92.7	102.5	134.4	184.2	14.7%
TOTAL	**1,089.7**	**1,281.6**	**1,927.9**	**3,124.4**	**23.5%**

Countries in the Asia-Pacific region have recently made significant contributions to the BIPV market and have become leading markets worldwide. The reason for this is the prevalence of tiled roofs, which are common in densely populated areas of these countries, and concrete roofs, which are also very popular in this region and suitable for installing these systems. These regions host some of the leading industries for BIPV production. Looking at individual countries in this region, China stands out significantly as the largest PV consumer in recent years. Due to severe air pollution, China implemented changes to renewable energy industry laws as early as 2005. By taking such actions, the government shut down thousands of coal factories. There are also various programs for installing solar systems on a large number of government-owned houses in rural areas. Additionally, in Shanghai, every building must have a green roof, and in China, buildings must significantly reduce their energy footprint [19, 25]. Projection for Asia-Pacific region for the 2025th year is shown in Table 2.

Table 2: Asia-Pacific market for BIPV with projection for the 2025th [25]

Application	2020	2021	2023	2025	CAGR (2020-2025)
Roofs	668.6	804.3	1,264.3	2,138.7	26.2%
Facades	536.9	625.6	920.7	1,453.3	22.0%
Glazing	228.2	265.1	387.8	608.2	21.7%
Shading	87.6	97.3	129.9	184.5	16.1%
TOTAL	**1,521.3**	**1,792.3**	**2,702.7**	**4,384.7**	**23.6%**

On the American market, which includes both North and South America, roof-mounted BIPV systems have the highest usage, accounting for 80.4%, while other installation methods are represented at less than 10%. BCC Research, which analyzed the American market, highlights California, New York, New Jersey, New Mexico, Massachusetts, Pennsylvania, Maryland, Connecticut, Arizona, and Nevada as the states with the most incentives for PV systems [19, 25]. Projection for American market for the 2025th year is shown in Table 3.

Table 3: American market for BIPV with projection for the 2025th [25]

Application	2020	2021	2023	2025	CAGR (2020-2025)
Roofs	696.6	844.8	1,349.3	2,317.4	27.2%
Facades	84.3	96.0	135.3	204.3	19.4%
Glazing	27.7	30.6	39.7	53.9	14.2%
Shading	57.8	65.2	89.6	131.2	17.8%
TOTAL	**866.4**	**1,036.6**	**1,613.9**	**2,706.8**	**25.6%**

According to Aaditya et al. [26], most studies on BIPV have been conducted in controlled indoor environments or simulations, which may not accurately reflect real-world performance. The following sections explore on-site case studies of BIPV systems under actual climate conditions.

In a studies conducted by Chow et al. [27-29] in Hong Kong, a 260 m^2 BIPV wall was installed on a 30-storey subtropical hotel building, mounted on the west facade. An air gap of 250 mm was maintained between the wall and the PV panels, allowing natural ventilation through this space. Three ventilation configurations were examined: (a) PV/C, where all sides were open for ventilation; (b) PV/T, where only the top and bottom ends were open; and (c) BIPV, where PV panels were directly attached to the external wall. The PV/C configuration performed best in hotter months (April to August and October), while the PV/T configuration showed superior results during colder periods (November to February). The BIPV system excelled in September. Overall, the electrical efficiency for PV/C, PV/T, and BIPV configurations was 10.2%.

Leite, Didone and Wagner presents investigation at small section of an office building in Brazil, which was equipped with semi-transparent BIPV panels [30]. This study compared the performance of BIPV systems in Brazil with those in northern hemisphere locations. The findings revealed that the annual energy production from the semi-transparent PV system in Brazil was significantly higher than the peak energy output recorded in a German city, reaching 750.3 kWh/year, which is 39–43% greater than the highest figures reported in Germany.

Gaillard et al. [31] in France, conducted a study with three prototype building envelopes with naturally-ventilated double-skin configurations were tested on various buildings. Two of these systems were implemented on individual houses, while one was installed on an office building. The average thermal efficiency of these systems ranged from 16% during the autumn and winter months to 25% in spring and summer. For the office building façade, a temperature difference of approximately 10°C was observed, even when solar irradiation was absent.

In a study by Sadineni et al. [32] in the United States, conducted in a residential area with approximately 200 houses, the impact of photovoltaic (PV) installation orientation on peak load was investigated. The research determined that a 40° south-west orientation was the most economically favorable for consistent electricity usage and pricing. The total annual energy consumption in homes with this PV orientation was reduced by 38% compared to similarly sized homes without PV systems. Additionally, the peak energy demand for homes with PV installations decreased by 62%. In Switzerland, Jayathissa et al. [33] examined an Adaptive Solar Façade (ASF) for BIPV systems in a cold climate. The ASF significantly reduced the building's energy load, including lighting, heating, and cooling, by nearly 50% compared to a system without shading. The total energy consumption with the ASF was approximately 700 kWh.

In a study by Chatzipanagi et al. [34] in Switzerland, BIPV systems were demonstrated as both window and roof installations, with variations including systems with and without air gaps for ventilation. The study focused on how PV cell operating temperature affected performance, using models such as NOCT and Equivalent Cell Temperature (ECT). It was found that a c-Si module inclined at 30° outperformed one inclined at 90° across all seasons, primarily due to shadow effects impacting the latter. This highlights the significant role of installation angles and seasonal variations in the performance of BIPV systems.

The following examples are not necessarily the most aesthetically pleasing or functional building solutions, but they illustrate the successful application of PV systems across various geographical, cultural, and climatic contexts.

On the southern side of the Meier Hospital in Florence, a photovoltaic glass tower was constructed to maximize solar energy collection, particularly during the winter months. This project was designed by the firm CSPA Firenze, led by architect Paolo Felli. Besides considering energy and environmental aspects, attention was also given to social impact. Figure 9 depicts the glass tower.

Figure 9: PV glass tower of the Meier Hospital [21]

The aim was to create a pleasant space without additional energy usage that would be in use for various activities throughout most of the year. Integrating PV installations into the facades of the glass tower building allows for combining energy production with other functions of the building envelope. Electrical energy is generated on-site, avoiding losses in transmission and distribution and reducing capital and maintenance costs for the electricity distribution company. The PV system has a capacity of 30 kWp and is implemented with glass/glass PV modules.

The Greeting to the Sun monument is located in Zadar, next to the sea, and it was designed by Nikola Bašić. The monument has a diameter of 1102 mm and symbolizes the sun, which absorbs sunlight through solar panels during the day and then transforms that energy into visual effects during the night, as shown in Figure 10. This artistic installation contains over 300 multilayered glass plates, with a photovoltaic solar module [21].

Figure 10: Monument „Greeting to the Sun" in Zadar [21]

Below the glass, there are over a thousand lights that can illuminate with different intensities and colors. Using a computer, various messages, graffiti, words, etc., can be displayed here. In the future, it is planned that entering the circle would trigger a light reaction, which would interact further if more people are present within the circle.

The Sheikh Zayed Learning Center is located in Abu Dhabi and had to meet a series of requirements set by the urban planning council. By fulfilling all these requirements, this center became the first state building to achieve the highest possible sustainability rating. The building was designed to be energy-independent, achieved through a combination of the best available lighting and ventilation techniques. Sheikh Zayed Learning Center is shown in Figure 11.

The building is designed to facilitate airflow circulation through and around the courtyard, as well as to maximize the use of sunlight. Small windows allow for natural light while avoiding excessive solar radiation. The structure is predominantly embedded in the ground to reduce temperature differentials between the interior and exterior. BIPV collectors are installed across the entire roof surface, generating 150 kW. This way, the building produces 95 percent of its required energy [21].

Figure 11: Sheikh Zayed Learning Center in Abu Dhabi [21]

5. CONCLUSION

Excessive energy consumption represents a key challenge in sustainability and environmental protection. To combat this, measures need to be taken to increase energy efficiency, promote renewable energy sources, and reduce unnecessary energy waste. The use of solar energy, as a form of renewable energy, has proven to be particularly effective. Special emphasis has been placed on integrating BIPV into structures to achieve efficiency and aesthetic value.

BIPV technology has significant potential to transform the construction industry and contribute to the sustainability of urban development. The integration of solar panels into buildings enables the production of clean energy on-site, reduces emissions of harmful gases, and decreases dependence on traditional energy sources. Additionally, BIPV systems offer aesthetic and functional benefits, contributing to modern and innovative building design. These systems have the potential to greatly enhance building performance while also reducing harmful emissions. It is important to assess the energy loads required by type during both the design and operational phases of a building. Additionally, choosing appropriate materials and determining the optimal placement of systems within the building are crucial steps for maximizing the effectiveness of this technology.

However, despite numerous advantages, several challenges limit the wider implementation of BIPV technology, including high initial costs, lack of standardization, regulatory barriers, and insufficient awareness of potential benefits. To overcome these challenges, further research and development in the field of BIPV are necessary to enable wider implementation of these innovative systems.

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