# LIFE CYCLE COST ANALYSIS OF BUILDING INTEGRATED PHOTOVOLTAIC THERMAL (BIPVT) SYSTEMS: A REVIEW

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*ABSTRACT*

*The building-integrated photovoltaic thermal (BIPVT) system can be considered a powerful and versatile technology that is being used to meet the growing demand for energy in the modern world. Nowadays its use is not only limited to urban areas, but due to its affordable and pollution-free nature, it is becoming popular among rural people as well. Since it is much cheaper than the systems associated with energy-producing grids in the traditional way, nowadays its popularity is not limited to industrial applications; nowadays it is also used in residential buildings for solar heaters and other applications in the winter season. This paper reviews the current state-of-the-art technology of BIPV, including BIPV Foil, Tile, Module, and Solar Sale Glazing products. AI techniques such as artificial neural networks (ANN), fuzzy logic, and machine learning are being used to customize energy production, improve thermal management, and predict system behavior. This review paper has analyzed cost analysis for the proposed system based on various factors. Life cycle cost analysis is calculated based on the initial and current costs spent during the use of PV modules. Various PVs are used worldwide. Technology has been analyzed, and conclusions have been made about material and savings based on it. Building Integrated Photovoltaic Thermal (BIPV/T) systems combine solar photovoltaic with thermal energy recovery, allowing building elements (such as roofs or facades) to generate both electricity and useful heat. Life cycle cost analysis (LCCA) evaluates the total cost of these systems over their operational lifespan-including initial investment, operation, maintenance, component replacement, and end-of-life costs-providing insight into long-term economic feasibility.*

*Keywords: BIPVT, Solar Energy, Thermal Management, Energy Payback.*

## INTRODUCTION

The abundant availability of solar energy on Earth during the day makes it popular as the most acceptable renewable energy source. The function of a photovoltaic (PV) module is to absorb solar energy and convert it into electricity using the principle of light-electrical effects. A PV module converts about 10–20% of the solar radiation obtained into electrical energy; the remaining energy is reflected in the atmosphere or is absorbed as heat, which increases the temperature of the PV module and reduces its electrical efficiency (He et al., 2020; Skoplaki & Palyvos, 2009). Flowing air or water under a PV cell or module reduces its temperature and can improve its electrical efficiency (Sharafeldin & Gróf, 2019). This fluid can be used to heat space in hospitals, hotels, and kitchens or to dry medicinal plants. Building-integrated photovoltaic thermal (BIPVT) systems are formed when a hybrid photovoltaic thermal (PVT) (Al-Waeli et al., 2017) unit is installed on the front, windows, and roof of a building. Integrating such PV modules in the outer part or roof of the building improves its efficiency.

The solar radiation entering the terrestrial region of the

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Earth is about $1.2 \times 10^{17}$ watts, of which only 2/3 is available for sensory warming, as can be seen in Figure 1. In addition, we know that 71% of the Earth's surface is covered with the sea, where there are no buildings. The forests are about 10% of the Earth's surface or about 35% of the total land area (Figure 2). Therefore, the solar flow available on the flat area of the land is about $2.3 \times 10^{16}$ watts that can be used to produce warming or electric energy using PV modules.

Building Integrated Photovoltaic Thermal system is a new approach by Lu et al. (2019) and the latest technology in the application of PV cells, as it also uses thermal energy emanating from solar cells (Fudholi et al., 2018), in addition to converting solar energy into electrical energy (Shukla et al., 2017). Table 1 provides a summary of the literature and contributions of existing literature. The use of forced or natural convection cooling in solar systems increases overall electrical efficiency. Table 2 discusses the overall efficiency recorded in the past by various researchers.

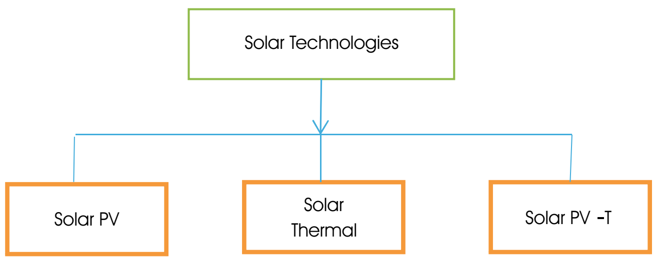


Figure 1. Classification of Solar Technologies

Data-operated BIPV systems have been identified, which must have the following four features. These four characteristics can be described in detail in this way:

*Data Sensing:* Traditional supply-side data and daily demand, price, etc., including weather, roof angle, etc., also show a huge increase. These directly measurable supply and demand data are the most basic features of BIPV.

*Data analysis:* Analysis of data obtained from direct or indirect measurement of data sensing is the second feature of BIPV. Data analysis of BIPV can not only detect residential behavior in the demand party but can also show various shading and various electrical consumption on the supply side.

*Data-powered Forecast:* Information obtained from data analysis and data sensation can be used to predict the future trends of the supply side and the energy change of the demand side (Gul et al., 2016). Data-managed forecast forecasts are affected by long-term and short-term production forecasts and load changes on the demand side.

*Data-Removed Adaptation:* This adaptation policy guidance, Li et al. (2020), distributed energy system design, and high-to-peer-to-peer (P2P) keep the higher requirements for trading. SBIPV systems will be able to effectively connect the supply-side and demand-side as an interface through data-driven adaptation.

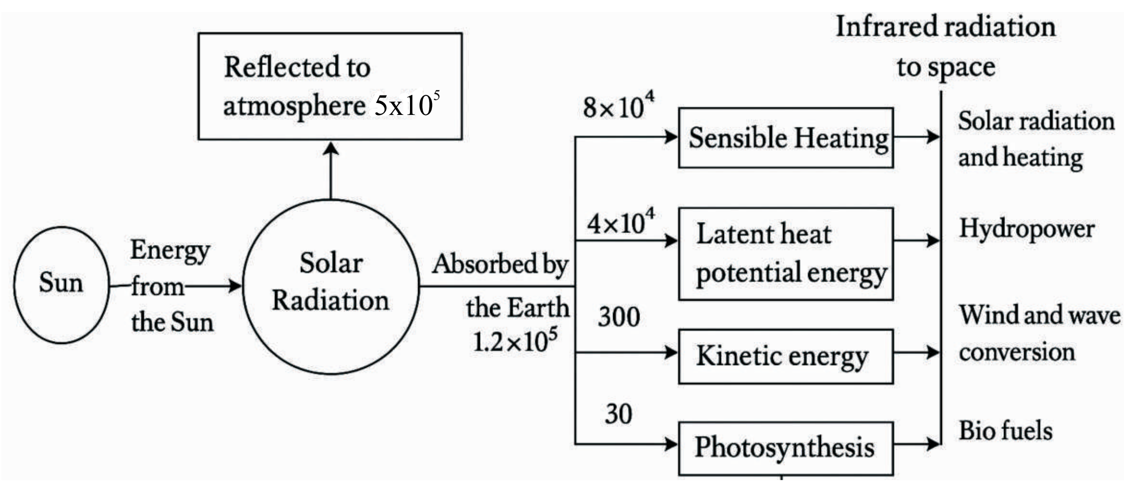


Figure 2. Solar Energy Available for use in Heating Devices

| Authors | Brief Summary | Area of Work | Reference Number |
|---|---|---|---|
| Amin Elsafi and P. Gandhidhan | PVT systems detected the relationship between thermal and electrical energy conversion, and highlighted the efficiency of the compound eminent collectors. | PVT systems efficiency | Elsafi & Gandhidasan (2015) |
| Boustead I, Hancock GF | PVT The effects of air mass flows on the thermal and electrical efficiency of the collectors were demonstrated. | PVT system's thermal performance | Upadhyay et al. (2025) |
| Tiwari and Sodha | The focus was on improving the energy efficiency of the solar module, increasing electricity efficiency. | Solar module's energy efficiency | Joshi & Tiwari (2007); Sarkodie et al. (2021) |
| Diamante LM, Munro PA | P.V. And a mathematical method was proposed for analysis of thermal and optical characteristics of solar thermal functions. | PV and solar thermal analysis | Diamante & Munro (1991) |
| Joshi A.S. and others | The conversion formula between thermal and electrical energy was examined, which emphasized efficiency and exergy output. | PV and PVT systems | Joshi & Dhoble (2018) |
| Dubey and Tiwari | The thermal, energy energy and electric energy yields were analyzed by changing the number of collectors and meteorological conditions. | PVT collectors' efficiency | Dubey & Tiwari (2009) |
| Tripathi and Tiwari | Hybrid photovoltaic collectors were analyzed based on exercise, energy savings and carbon credit. | Hybrid photovoltaic collectors | Tripathi et al. (2016); Herez et al. (2020) |
| Enescu, Chicco, Porumb, and Seritan | Applications of thermal energy were discussed in various fields. | Thermal energy applications | Enescu et al. (2020) |
| Sonveer Singh and Rajiv Gadh | Single-channel PVT array was used to calculate thermal and exercise competencies and carbon credits using adaptation techniques. | PVT system optimisation | Singh et al. (2015) |
| Hussain, Hafiz and Akramuddin | Research was conducted on the Mesoscale cycle -based energy efficiency and exercise analysis for the new air coolers. | Energy and exergy analysis | Hussain et al. (2020) |
| Kanchan Vats and G.N. Tiwari | The efficiency of monocrystalline vs. polycrystalline silicone PV cells was discussed. | Silicon PV cell's efficiency | Vats & Tiwari (2012) |

Table 1. Literature Review

| Sr. No | Location of Instalment | Material Used | Efficiency | Country | Reference |
|---|---|---|---|---|---|
| 1 | Roof-top of building | Amorphous silicon | 33.54% | New Delhi, India | Agrawal & Tiwari (2010) |
| 2 | Building- integrated heating system | Water-based polycrystalline-based Silicon PV module | 73-81% | Malaysia | Ibrahim et al. (2014) |
| 3 | Naturally Ventilated BIPVT system | NA | 26.5-33.5% | Slovenia | Agathokleous et al. (2018) |
| 4 | Roof-sized PV/thermal array combined with a ground-coupled heat pump | Crystalline Silicon | 55-62% | Canada | Bakker et al. (2005); Tsai (2015) |
| 5 | Window | Semi-transparent amorphous Silicon | 45-63.4% | USA, South Korea | Chae et al. (2014) |

Table 2. Presents the Efficiency of Various Types of BIPVT Used by Various Researchers

PV with building architecture Benefits received from integration of systems:

*Advanced Energy Efficiency:* BIPVT systems (Figure 3) maximize solar energy use and collect electrical and thermal energy (Phongsitong, 2006), which usually improves 20–50% compared to different systems.

*Low Carbon Emissions:* By generating renewable energy on the site, BIPVT systems contribute to reducing the energy consumption of the building and reducing dependence on fossil fuels (Mamat et al., 2019).

Better Location Uses: Get rid of different structures, i.e., roof panels, and adapt the space both inside and around the building.

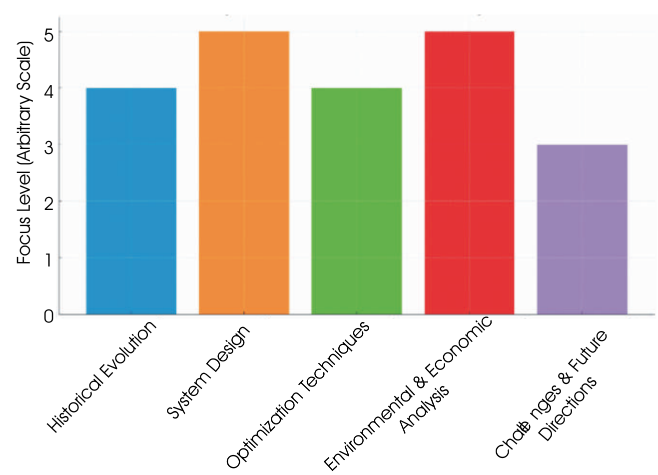


Figure 3. Overview of Key Themes in BIPVT Systems Research

*Advanced Architectural Aesthetic:* The diverse material, color, and transparency of BIPVT systems provide an aesthetic dimension in architecture.

*Better building cover performance:* Based on design, BIPVT panels can provide advanced insulation performance, which will be useful for better thermal comfort and low heating (Othman et al., 2016) or cooling demands.

### 1. Exergy Analysis and Optimization of the BIPVT System

Various BIPVT systems are based on either silicone-based PV techniques or non-silicon-based PV techniques. So far, 46 percent mono-crystalline silicon (m-Si), 43.7 percent multi-crystalline silicon (p-Si), 2.2 percent ribbon silicon (r-Si), 5.2 percent amorphous silicon (a-Si), 4.7 percent cadmium telluride (CdTe), and 0.5 percent copper indium gallium selenide (CIGS) are used in consumer PV modules.

These PV systems are becoming increasingly reliable and durable. PV manufacturers currently provide 5 to 30 years of service life warranty based on the production process used. This category is created according to the concept of silicon- and non-silicon-based and new generations to be implemented nowadays in the modern world (Figure 4).

Exergy transfer in the solar power system occurs through mass flow and heat contact. Exergy is emerging as a powerful tool for researchers in the design and adaptation process of new systems. In fact, nowadays many academics are also taking advantage of these methods for the development of systems. In addition to use in thermodynamic processes, according to Chialastri & Isaacson (2017), it can also be used in the overall electrical performance or efficiency of any system related to PV energy.

Various losses in the system can be calculated easily using qualitative and quantitative methods. Exercise analysis is used to predict thermal performance of the energy system and gain better understanding of energy losses in the system. As a result, the Sardarabadi & Passandideh-Fard (2016) exercise assessment can estimate what and how much efficient thermal systems can be designed by reducing the sources of existing disabilities.

The maximum function produced by heat sources and sinks can be expressed in this way:

$$W_{\max} = exergy = (1 - \frac{T_0}{T_1}) \times Q_1$$

Where $T_1$ is the heat source (degree Kelvin) and $T_0$ is the heat sink at ambient temperature (degree Kelvin).

Where $Q_1$ is the heat energy supplied at $T_1$.

For similar heat energy input, the increase in the source temperature $T_1$ produces more energy, and less energy is generated at the given environment temperature $T_0$. As the quality of the process decreases, the exercise of the system also decreases.

### 2. Carbon Credit Earned

Pollutants from the PV system during energy production

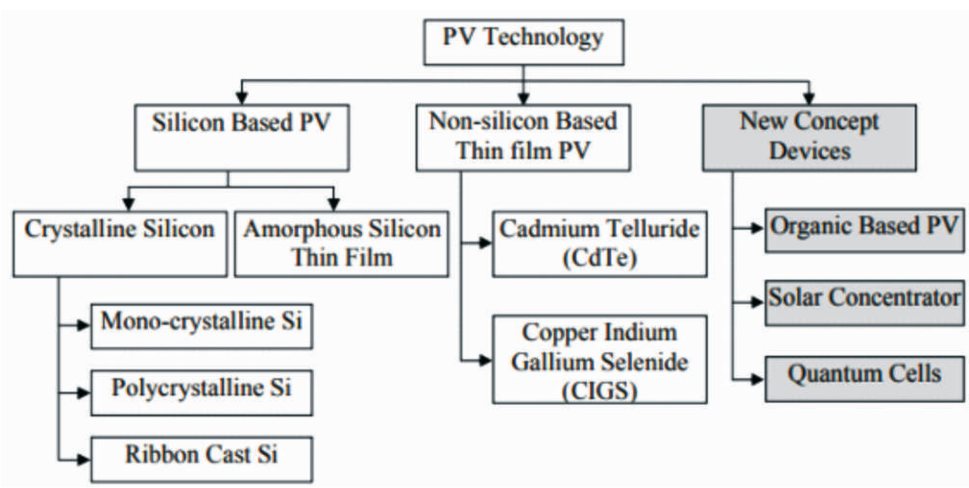


Figure 4. Classification of PV Cells Based on Various Technologies

are not emitted into the atmosphere; however, pollution can occur during the manufacturing process of PV systems. It is necessary to keep an account of pollution (mainly $CO_2$) during the lifetime of the PV system. A method can be used similar to EPBT to calculate pure $CO_2$ return time in relation to climate change mitigation capacity of PV production systems (Pielke Sr, 2013). Cumulative $CO_2$ mitigation per kWh is calculated and compared to pure $CO_2$ emissions with alternative power generation methods (Belyakov, 2019). Such parameters related to $CO_2$ mitigation are an important component of international trade of national as well as emission programs that have been adopted to combat global warming. Calculation of earned carbon credits gives an idea of how much damage the greenhouse effect does to the system.

Whenever energy is produced by non-traditional methods, the most important factor is carbon dioxide emission. The amount of carbon being saved for energy production in the traditional way is the original carbon credit earned. This analysis is performed by every manufacturer or researcher, as it is one of the major methods of controlling pollution by giving small economic incentives or freedom to reduce the amount of pollutants in the atmosphere.

### 3. Life Cycle Cost Analysis and Thermal Modeling

In BIPVT systems, solar cells have been classified into six technologies for analysis (Figure 5): mono-crystalline Silicon, poly-crystalline Silicon, EFG ribbon crystalline silicon, amorphous Silicon, Cadmium Telluride, and Copper Indium Gallium Selenide.

Cost analysis is calculated on the basis of the life cycle concept, which is a gradual approach to cost analysis. For effective calculation and analysis of the entire BiPVT system, a device called the life cycle cost analysis (LCC) is selected, which provides cost effectiveness. It is mandatory to maintain a system to run in a proper position, including procurement, operational costs, maintenance costs, and disposal of unwanted items. From installation to future maintenance, the amount spent on the entire system is included in the analysis of cost evaluation, called LCC. We have to develop a system that provides proper production without more operational costs. The system should give us a lifetime assurance of proper quality and good work. The objective is to reach a system that can provide a quality and effective system to implement it in a cost-effective manner and adopt this design for future use. The LCC evaluation of the BiPVT system includes initial cost, maintenance cost, operational cost, and depreciation and replacement costs.

By application of thermal (mathematical) modeling and heat transfer relationships, different systems were taken into consideration to calculate the energy, energy efficiency, and temperature of the outlet heat (Figure 6). Since all the ducts are connected among themselves,

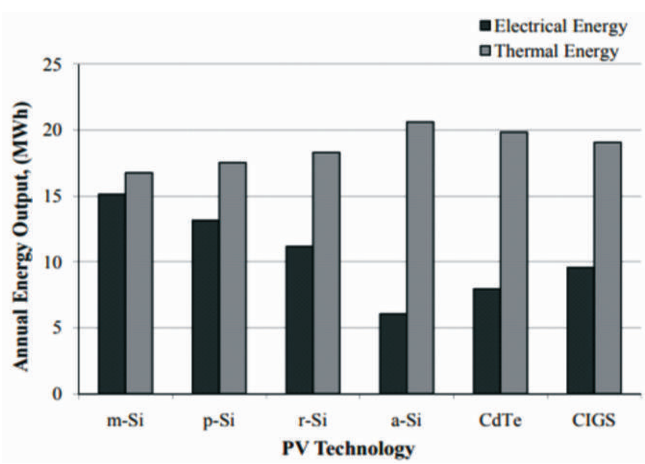


Figure 5. Annual Energy Production for various BiPV/BiPVT technologies

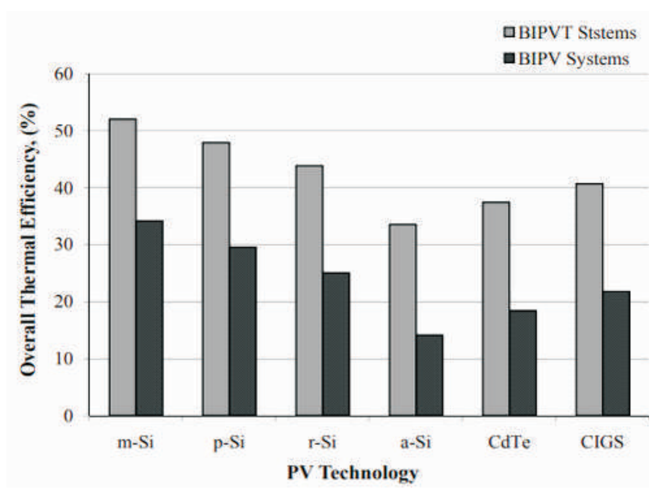


Figure 6. BIPV/Overall Thermal Efficiency for BIPVT Technologies

the outlet of one system is connected to the inlet of another system in the respective columns. The input of the BiPVT system in the first duct has a combined effect of room temperature and ambient temperature (Sani et al. 2022). The velocity of air flowing from the channel is 3 m/second at a mass flow rate of 1 kg/second.

Mono crystalline silicon-based BiPVT produces the most electrical energy, while amorphous silicon (a-Si) produces the lowest energy. This is because the electrical conversion efficiency of m-Si BiPVT is better than other systems. The system that absorbs most solar radiation and converts a large amount of electrical energy produces a small amount of heat energy on the output.

### *3.1 Key Components of Life Cycle Cost Analysis for BIPV/T Systems*

*Initial/Capital Cost:* Cost of PV/T modules Jarimi et al. (2016), inverters, installation (labor, mounting), electrical and mechanical components.

*Operation and Maintenance (O&M) Cost:* Regular cleaning, inspections, monitoring, and minor repairs make up a significant share of the lifetime costs.

*Replacement (Failure) Cost:* Mainly inverter and, less frequently, module replacements.

*Decommissioning/Salvage Value:* Value recovered or expense incurred at system end-of-life.

*Discount Rates and Inflation:* Used to estimate the present value of future costs.

| Cost Category | Share of Total LCC (approximate) |
|---|---|
| Initial/Capital | 26% |
| O&M | 63% |
| Failures/Replacements | 11% |

Table 3. Typical Cost Distribution

According to a recent analysis, the breakdown for rooftop solar PV systems (and similarly for BIPV/T) is given by Table 3.

The major expenses over the life cycle are operation and maintenance (O&M), which includes cleaning (especially for urban dust), inspections, and occasional component replacements (mainly inverters). Inverters have a typical operational life of 10 years (replacement cost estimate included), while panels generally last 25+ years with low failure rates.

### *3.2 BIPV/T-Specific Findings*

Initial installation costs for BIPV/T systems are generally higher than conventional PV or traditional heating/cooling solutions, largely due to integration with building envelopes. PV module expenses constitute 43–77% of construction costs, with significant costs also attributed to the balance of system (10–16%) and structural supports (3–18%). Ongoing maintenance and inverter replacement costs are crucial factors for long-term economics. For insulated BIPV roofs, the Levelized Cost of Electricity (LCOE) can be as low as 3.38 ₹/kWh, with payback periods around 6.3 years and a high internal rate of return (IRR) of 29.4% (compared with conventional roofs).

A comparison (Table 4) focuses on the key life cycle cost factors for silicone-based (crystalline silicon, c-Si, or mc-Si) and non-silicon-based (such as CdTe and other thin-film) PV technologies in Building Integrated Photovoltaic/Thermal (BIPV/T) applications.

Silicon-based PV systems (mono- or multi-crystalline) dominate BIPV/T installations due to their maturity, reliability, and long operational life (Debbarma et al., 2017). Their initial and overall life cycle costs are somewhat higher-but improving-due to manufacturing

| Aspect | Silicon-Based PV (c-Si/mc-Si) | Non-Silicon-Based PV (CdTe, etc.) | Reference |
|---|---|---|---|
| Initial/Capital Cost | Moderate to High | Generally lower than silicon | Pimpalkar et al. (2025) |
| O&M Cost (% of LCC) | About 63–74% | Similar share; O&M is dominant for both | Pimpalkar et al. (2025) |
| Failure/Replacement | Inverters often need replacing ~10yr | Inverters similar; panel failure rates vary | Pimpalkar et al. (2025) |
| Panel Replacement | Typically low, <1%/yr | Typically low, varies by tech | Pimpalkar et al. (2025) |
| Life Cycle (years) | 20–25+ (modules), 10 (inverters) | 20–25+ (modules), 10 (inverters) | Pimpalkar et al. (2025) |
| Payback Period | 6–8yr, can vary by region/system | Often shorter due to lower initial costs | Pimpalkar et al. (2025) |
| Energy Payback Time | ~1yr (Europe, sunny climate) | CdTe can be lower, i.e., <1yr | Pimpalkar et al. (2025) |
| GHG/Env. Impact | Moderate; higher for multicrystalline | Often lower for thin-film (CdTe, a-Si) | Pimpalkar et al. (2025) |

Table 4. Life Cycle Cost Comparison of BIPVT Systems

efficiencies. Non-silicon-based PV (CdTe, a-Si, etc.) often offers lower initial costs, faster energy payback times, and slightly lower environmental impacts, but may have shorter module lifespans or lower conversion efficiencies, impacting total LCC. However, modern thin-film tech like CdTe is closing these gaps for selected climates (Samimi et al., 1997).

### 4. Challenges and Future Directions of BIPVT Systems

Although the building integrated photovoltaic thermal systems offer a promising route towards the sustainable building design, there are challenges in realizing their full potential (Psomopoulos, 2013). This section deeply considers the current obstacles in design, installation (Arpino et al., 2015) and maintenance and examines the exciting future directions for research and development.

As depicted in Figure 7, the chart building refers to the integrated photovoltaic thermal systems as well as the possible results of future development. All challenges will be represented in red, and their severity will be shown in the shape of the text on a scale of 1 to 5. The directions of the future will be discussed in blue, so that these challenges can be resolved, BIPV technology can be called to support and promote innovation. Such an approach will give more embodiments to the interaction between current challenges and occasions that innovation can use BIPV systems to turn on new paths. This will further improve efficiency, will be more adopted, and integration in sustainable building designs will be easier.

BIPVT systems are still facing many challenges for worldwide approval:

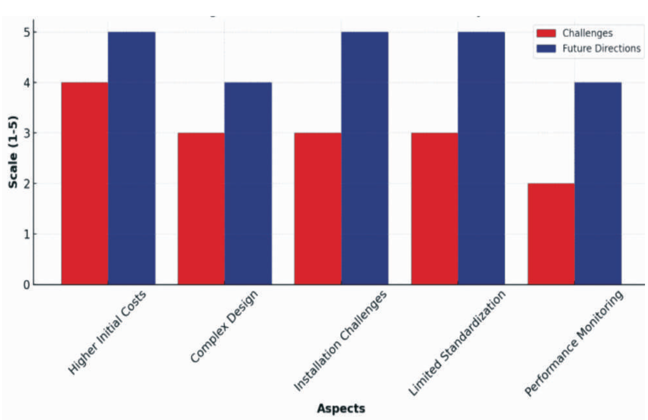


Figure 7. Challenges and Future Directions in BIPVT Systems

- *High early costs:* Compared to traditional construction materials, the initial investment for BIPVT systems may be higher, which leads to extensive adoption, especially in cost-sensitive projects.
- *Complex Design and Integration:* Integrating PV and thermal functionalities into the building envelope requires specialized design expertise and careful consideration of structural, thermal, and aesthetic aspects, increasing design complexity.
- *Installation challenges:* Establishing BIPVT systems can be more complex than traditional construction materials, which require special skills, and this can lead to an obstruction of the construction time limit.
- *Limited standardization:* Miscellaneous designs in BIPVT systems offer challenges of standardization and mass production, which potentially hinder cost reduction and comprehensive availability.
- *Performance Monitoring and Maintenance:* Long-term performance monitoring and maintenance requirements for BIPVT systems are still developing, requiring new equipment and expertise development.

The manufacture of integrated photovoltaic thermal systems provides a transformative approach to energy production and durable building design. By solving existing challenges through new materials, standardized designs, and integrated techniques, BiPVT has the ability to revolutionize the environment created. The trip requires cooperation between researchers, engineers, architects, policymakers, and building owners who will pave the way for a future where buildings will be easily integrated with their environment and will use the sun's energy for a more durable tomorrow.

### Conclusion

This research has analyzed the area of the Building Integrated Photovoltaic Thermal systems in detail and identified methods by which these systems can revolutionize sustainable construction and energy production. BIPV/T systems, while requiring a higher initial investment than traditional systems, can be economically competitive over their lifetime if properly maintained and supported by favorable policies. O&M

and inverter replacement dominate lifetime expenses, making efficient maintenance practices and high-reliability components key to economic success. Building-Integrated Photovoltaic is an intelligent energy production system incorporating solar PV panels as part of the roof, windows, facades, and shading devices. When active heat recovery is combined with BIPV systems, either in a closed loop (like PV-T with a liquid loop) or in an open loop with forced air, they are known as building-integrated photovoltaic-thermal systems. Building-Integrated Photovoltaic is an intelligent energy production system consisting of solar PV panels as part of roofs, windows, facades, and shading devices. When active heat recovery is accompanied by BIPV systems, either in closed loops (like PV-T with liquid loop) or forcefully combined into open loops with air, they are called building-integrated photovoltaic-thermal systems. BiPVT modules are designed for solar energy and thermal air collectors that provide heat and electrical consumption similar to heat pumps for space/water heat applications. It can be concluded that the BIPVT system located on the sloping roof produces more power than the BIPVT system on the front of the building. For the purpose of calculating thermal and electrical benefits, fourteen different possible combinations of the roofing BiPVT system have been examined. The use of the proposed BiPVT method helps reduce the cost of traditional roof and cover material in the construction of the outer structure of a building. A part of solar energy is converted into electrical energy with better efficiency by reducing the use of fossil fuels. In addition, useful thermal energy is also produced, which is necessary to heat the room and thus reduces peak load in cold weather.

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