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Advancements and Optimisation Strategies in Building Integrated Photovoltaic Thermal (BIPVT) Systems

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Abstract: This paper provides an overview of the current innovations in Building Integrated Photovoltaic Thermal Systems. This paper briefly describes varying performance evaluation techniques, optimisation techniques, and the environmental impact and cost implication of Building Integrated Photovoltaic Thermal systems. The results reveal high energy-pin efficiency with Building Integrated Photovoltaic Thermal systems of over 50% and more efficient than when the two systems are incorporated separately. Exergy analysis is a more insightful means of analyzing system effectiveness than energy analysis. The paper covers the current algorithms for various optimisation algorithms such as Genetic Algorithms and Particle Swarm Optimisation that provide enhanced utilization improvements. An evaluation of the environmental impact of Building Integrated Photovoltaic Thermal in terms of carbon dioxide emission reduction and building energy optimisation is made. The results of the life cycle cost studies show that, even though the initial cost is higher than conventional solutions, the overall economic profit is more significant in the future. Some of the challenges described in the paper include increased initial costs and sophisticated integration procedures. In contrast, possible future developments include new materials, Building Integrated Photovoltaic Thermal system standardization, and integration in smart grids. This review is intended to be a state-of-the-art source of information for researchers, engineers, architects, and policymakers involved in enhancing sustainable building technologies using building-integrated photovoltaic thermal systems.

Keywords: Building Integrated Photovoltaic Thermal (BiPVT), Optimisation Techniques, Smart Grid Integration, Sustainable Building Design.

1 Introduction

THE building and construction sector is progressively embracing environmentally responsible practices as a reaction to the growing environmental concerns and the rising need for energy [1]. BIPVT systems go beyond conventional rooftop photovoltaic (PV) panels by directly incorporating them into the building envelope, acting as building material and electricity producers. Think of the walls capable of producing electricity, windows that can provide shade while at the same time harvesting heat or the roofing shingles capable of converting sunlight into electricity. This dual function opens up the possibility of efficient power generation alongside improving the design and efficiency of the building [2]-[3].

This is an expression that is gaining more and more traction than before. Building Integrated Photovoltaic Thermal (BIPVT) systems are at the forefront of this revolution because of their innovative design [4]-[6]. Integrating the production of renewable energy with architectural design in a seamless manner is made possible by these technologies, which provide a one-of-a-kind solution to the problem [7]-[9].

This paper examines how BIPVT systems respond to several drawbacks that arise from having a separate system for power and heating/cooling requirements. BIPVT enable the utilisation of solar power in both

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electrical and thermal applications and can, therefore, provide a higher overall efficiency of energy use by 20%-50% compared to conventional systems. They also make it possible to minimise redundant structures. Thus, decreasing the building footprint, affording better use of space and adding beauty to the building through the customisation of designs.

This paper intends to use the findings compiled in this paper to present a general idea of BIPVT systems, including different configurations, performance evaluation methods, optimisation methodologies, and environmental and economic concerns. Stated thus, this review offers a rich pool of information and ideas for researchers, engineers, architects, and policymakers, who are invested in the development of sustainable building technologies innovated through BIPVT systems.

Traditionally, buildings relied on separate systems for power and heating/cooling needs. Standalone rooftop PV panels generated electricity, while separate boilers or furnaces handled heating and cooling. This approach, however, had some drawbacks that included inefficiencies, wasted space, and limited design potential. BIPVT systems overcome this challenge by using photovoltaic solar panels to produce electricity and heat. Power production is the main task. Nevertheless, the waste heat is utilised for such purposes as heating of premises, hot water supply, and even air conditioning with the help of absorption chillers [10]-[15].

The key pros of the integrated strategy include the following:

- Improved energy efficiency: BIPVT systems may enable the use of solar energy both in electrical and thermal forms; therefore, they are likely to bring about efficiency increments ranging from 20% to 50% compared with separately studied systems [16]-[20].
- Reduced building footprint: The inclusion of energy generation in the building envelope would reduce the need for extra structures, i.e., rooftop panels. This will maximise not only the space available for use but may also reduce the building footprint [21]-[25].
- Enhanced architectural aesthetics: BIPVT systems, with different materials, colours, and transparencies, can offer various design possibilities and integrate into several architectural styles, contributing to the aesthetics of the building [26]-[28].
- Improved building envelope performance: Depending on the system design, BIPVT panels can be used to insulate, thus enhancing thermal comfort while at the same time reducing the heating or cooling demands [29]-[32].

The move from stand-alone PV systems to the incorporation of BIPVT is a great leap in the design of sustainable buildings. This can totally revolutionise the way of designing and building with the BIPVT system if both energy generation and building materials are put together. This is the kind of innovation that would further open up a much more sustainable and energy-efficient future. A summary of the literature review follows, according to the presentation that is provided in Table 1.

Table 1 Literature Review.

Authors	Brief Summary	Area of Work	Reference Number
Amin Elsafi and P. Gandhidhan	Explored the relationship between thermal and electrical energy conversion in PVT systems, highlighting the efficiency of compound parabolic collectors.	PVT systems efficiency	[33]
Boustead I, Hancock GF	Demonstrated the impact of air mass flow on thermal and electrical efficiencies of PVT collectors.	PVT system's thermal performance	[34]
Tiwari and Sodha	Focused on improving the exergy efficiency of solar modules, achieving increased electrical efficiency.	Solar module's energy efficiency	[35]
Diamante LM, Munro PA	Proposed a mathematical method for analysing thermal and optical features of PV and solar thermal functions.	PV and solar thermal analysis	[36]
Joshi A.S. and others	Examined the conversion formula between thermal and electrical energy, emphasising efficiency and exergy outputs.	PV and PVT systems	[37]
Dubey and Tiwari	Analysed thermal, energy exergy, and electrical energy yields by varying the number of	PVT collectors' efficiency	[38]

	collectors and meteorological conditions.		
Tripathi and Tiwari	Analysed hybrid photovoltaic collectors based on exergy, energy savings, and carbon credits.	Hybrid photovoltaic collectors	[39]
Enescu, Chicco, Porumb, and Seritan	Discussed the applications of thermal energy in various fields.	Thermal energy applications	[40]
Sonveer Singh and Rajiv Gadh	Used single-channel PVT array to calculate thermal and exergy efficiencies and carbon credits using optimisation techniques.	PVT system optimisation	[41]
Hussain, Hafiz and Akramuddin	Researched energy efficiencies and exergy analysis based on the Maisotsenko cycle for new air coolers.	Energy and exergy analysis	[42]
Kanchan Vats and G.N. Tiwari	Discussed the efficiency of monocrystalline vs polycrystalline silicon PV cells.	Silicon PV cell's efficiency	[43]

The given combined table chart is the most comprehensive form of the main topics that were discussed in the sections referring to historical development, challenges, and future directions of research on Building Integrated Photovoltaic Thermal (BIPVT) systems. Each of the themes has a colour, and the height of the bar represents the degree of importance or significance assigned to it by the participant. This visualisation captures the whole odyssey of BIPVT systems, from their evolution in technology to the design issues of a system, optimisation techniques, and the conflicts and trade-offs it has between the environmental and economic impact it encompasses. It also examines current challenges and shining new frontiers of promise within this field.

2 From Photovoltaic Pioneers to Integrated Energy Solutions: The Evolution of BIPVT Systems

The use of solar energy technology is a very close narration to Building Integrated Photovoltaic Thermal (BIPVT) systems. Since the earliest history, the sun, with its huge power, has been a source of great fascination to human beings. However, we actually started exploring possible ways of how to put this form of energy to work for us in the 19th century. From the very beginning, there were a number of experiments with different configurations on behalf of the inventors. These efforts ultimately led to the development of the first practical silicon solar cell in 1954. However, traditionally, these early cells did show remarkable efficiencies; despite this fact, their high cost held them back, allowing usage in space applications only.

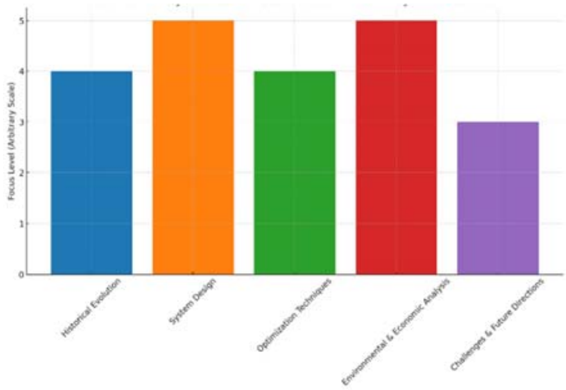

Fig. 1 Overview of Key Themes in BIPVT Systems Research.

Only in the 20th century did development in material science, along with its manufacturing processes, become such that the cost of solar cells reduced and made them more affordable for terrestrial applications. The first oil crisis was also in the 1970s, further speeding up this development and increasing the emphasis on the need for alternative sources of energy. In the 1980s, photovoltaic (PV) panels on rooftops became a feasible source for the generation of electricity both in residential and commercial premises.

However, rooftop installations came with their own limitations. In many circumstances, additional structures needed to be put up, which could again interfere with existing architectural and land use. These systems used only the electrical power of sunlight, leaving an enormous amount of thermal energy unutilised. This realisation encouraged investigation in a direction to find ways by which PV could be incorporated within the building envelope, and thus, the concept of BIPVT emerged. [44]-[49].

In the past, BIPVT systems mainly tried to integrate opaque PV panels into the building facades in such a way that they imitated traditional building materials. However, they were both electrically and thermally limited in performance. Definitely, this was a step forward from the point of view of visibility in comparison to the rooftop panels. Two other semi-transparent PV materials were developed. Both have the advantage of allowing natural light into the building with the added insulation. This has thus brought about configurations of BIPVT to include:

- **Building-integrated photovoltaic (BIPV) systems:** Opaque PV panels seamlessly integrated into roofs, facades, or building elements.
- **Building-applied photovoltaics (BAPV):** Retrofit installations of PV panels onto existing buildings.
- **Translucent and transparent BIPV (T-BIPV):** Semi-transparent or transparent PV materials for windows, skylights, or building cladding, offering daylighting and aesthetics alongside power generation.

The benefits accruing from the integration of PV systems with building architecture:

- **Enhanced energy efficiency:** BIPVT systems maximise solar energy utilisation, capturing electrical and thermal energy, often leading to 20-50% improvement compared to separate systems.
- **Reduced carbon footprint:** By generating renewable energy on-site, BIPVT systems contribute to lower building energy consumption and decreased dependence on fossil fuels.
- **Improved space utilisation:** Getting rid of separate structures, i.e., rooftop panels, optimises space both within and around the building.
- **Enhanced architectural aesthetics:** Diversified material, colour, and transparency of BIPVT systems provide an aesthetic dimension in architecture.
- **Improved building envelope performance:** Depending on the design, BIPVT panels can offer enhanced insulation performance, which shall be useful for enhanced thermal comfort and reduced heating or cooling demands.

The journey of the development of Building Integrated Photovoltaic Thermal (BIPVT) systems has been quite an interesting one from the time that the first practical silicon-based solar cell was developed in the year 1954. This breakthrough triggered an increase in research, particularly after the first oil crisis of the 1970s. This, therefore, brought about the PV panels on rooftops in the 80s, a very paramount evolution on the ladder with regard to solar energy technology. It also considers the development of the BIPVT concept around the turn of the millennium, with the latest development in BIPVT configurations reflecting technological innovation and an increase in penetration of solar technology within building envelope architecture over this period.

The BIPVT systems have experienced technological development that heralds growing technology, as well as growing awareness of the need for holistic building design. The integration of renewable energy generation into building materials is most important for the purpose of making the structures energy-efficient, sustainable, and aesthetically pleasing [16]. There are, however, certain challenges and opportunities that shall be further uncovered and discussed in the following sections.

3 System Design and Configurations: Tailoring BIPVT for Optimal Performance

BIPVT systems offer design options that can fulfil specific requirements and applications [50]-[59]. Understanding these configurations well and their trade-offs is a key factor not only in maximising performance but also in ensuring that it is smooth to integrate with the building. Figure 2 presents a chart summarising key aspects of Building Integrated Photovoltaic Thermal (BIPVT) system design configurations and future directions discussed in this section of the paper. It discusses various benefits that these configurations (Opaque BIPVT, Semi-Transparent BIPVT, BIPV, BAPV, T-BIPV) bring to the system and highlights the needs for material selection, configuration optimisation, and trends for the future. This visualisation clearly demonstrates the wide range of BIPVT systems with the potential for optimised performance and underscores the importance of advancements in this field.

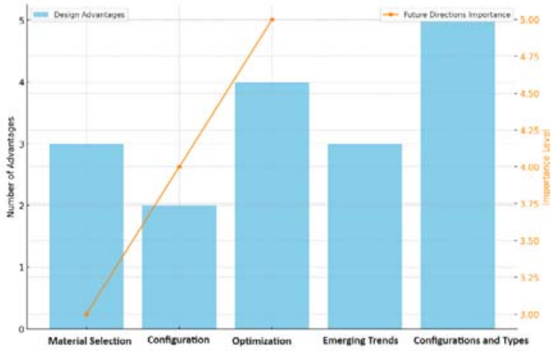

Fig. 2 BIPVT System Design Configurations and Future Directions

3.1 Opaque vs. Semi-Transparent BIPVT: Striking the Balance

The light transparency levels of BIPVT systems vary widely [60]-[67]:

- **Opaque BIPVT:** These use solid PV panels that mimic mostly traditional building materials. They are electrically highly effective since they catch all sunlight but lower natural lighting and increase indoor heat.
- **Semi-Transparent BIPVT (T-BIPV):** These materials allow light penetration using thin-film

PV cells or dyes embedded in glass. They allow the entry of natural light, reduce heat gain, and generate power; however, these systems experience reductions in electrical efficiencies because of the limitations of light absorption. The choice between these systems is based on many factors.

Figure 3 presents the Comparison of Opaque and Semi-Transparent BIPVT Systems.

Fig. 3 Comparison of Opaque and Semi-Transparent BIPVT Systems

Choosing the right type depends on several factors:

- **Energy priorities:** Where the prime focus lies in generating the maximum amount of electricity, then opaque BIPVT is preferable. T-BIPV suits the requirements of buildings that need to maintain a balance between natural light and heat management.

- **Application:** Opaque BIPVT excels for roofs and facades, while T-BIPV finds applications in windows, skylights, and building canopies.

- **Architectural aesthetics:** Both types are flexible in design, which allows the availability of bright colours and the modern transparent effect.

3.1 Beyond Transparency: Exploring Diverse Configurations

Both types are flexible in design, which allows the availability of bright colours and the modern transparent effect [68]-[72]. Figure 4 shows several of the other configurations of BIPVT, each with its unique benefits and considerations:

- **Building-integrated photovoltaic (BIPV):** Building Integrated Photovoltaic (BIPV) is a technology where traditional Photovoltaic (PV) modules are embedded into a building's roof, facade, or structural elements in an aesthetically pleasant manner that creates a balance between good electrical efficiency and material cost savings.
- **Building-applied photovoltaics (BAPV):** Retrofitting existing structures with PV panels allows for energy upgrades without the need for extensive construction. However, there may be some challenges with integration and potential aesthetic dissonance that can arise from the presence of additional structures.

  - **Translucent and transparent BIPV (T-BIPV):** As discussed earlier, T-BIPV offers daylighting with varying degrees of transparency. Thin-film and dye-sensitized solar cells are common choices, requiring careful consideration of spectral filtering and shading strategies.

  - **Building-integrated photovoltaic thermal (BIPVT):** These systems couple PV panels with thermal collectors, capturing both electrical and thermal energy for space heating, water heating, or cooling. Different designs exist, including air-based, water-based, and heat pipe systems, each with specific performance characteristics and complexity.

Fig. 4 Examples of diverse BIPVT configurations

Selecting the optimal configuration requires a holistic approach:

- **Building characteristics:** Orientation, shading, thermal performance, and available space influence suitable options.

- **Local climate:** Temperature, sunlight intensity, and precipitation impact energy demands and system efficiency.

- **Energy requirements:** Electricity generation needs, potential for thermal energy utilisation and desired level of daylighting guide the choice.

- **Aesthetics and budget:** Balancing design aspirations with cost constraints is crucial for successful implementation.

3.2 Unlocking Potential: The Role of Materials and Configuration

Material selection and configuration are critical in optimising BIPVT system performance [71]-[75]. Some key considerations include:

- **PV cell materials:** Crystalline silicon is the most efficient of all the materials. Nevertheless, the T-BIPV applications can be made of lighter and more flexible thin-film technologies such as amorphous silicon or CIGS.

- **Encapsulation materials:** Glass or polymers, for instance, require mechanical properties such as strength, optical properties such as light transmission, and durability such as resistance to weathering. AR coatings can also be used to increase light trapping for opaque systems.

- **Thermal management:** The smooth flow of the heat transfer fluids and proper insulation of the BIPVT systems is essential in systems that seek to capture thermal energy from the solar radiations.

- **Configuration layout:** All these factors, including panel orientation, the space between the panels, as well as the tilt angle of the panels, need to be arranged in the best way possible in relation to the sun exposure as well as the shading patterns to improve the energy capture.

3.3 Emerging Trends and Future Directions

The field of BIPVT is growing and developing as a result of the improvement in material science, manufacturing techniques, and architectural integration of these systems. Key emerging trends and future directions include:

- **Integration with intelligent building technologies:** BIPVT systems are increasingly integrated with building automation systems, enabling real-time monitoring, optimisation, and control of energy generation and consumption.

- **Advanced materials with improved performance:** Research efforts are focused on developing new PV cell materials with higher efficiency, improved durability, and enhanced aesthetic appeal for broader application in BIPVT.

- **Nanotechnology applications:** Nanotechnology offers the potential for creating transparent PV materials with improved light absorption and energy conversion efficiency, paving the way for more aesthetically pleasing and integrated systems.

- **Building-integrated energy storage:** Combining BIPVT with energy storage solutions allows for storing excess energy generated during peak sunlight hours for use during off-peak periods, further enhancing system efficiency and grid resilience.

BIPVT systems assist architects, engineers, and building owners in developing energy-efficient, sustainable, and attractive buildings. Understanding BIPVT's multiple configurations, material issues, and trends lets us maximise its potential. We can then develop buildings that seamlessly integrate renewable energy generation. BIPVT will continue to shape the future of energy-efficient and environmentally friendly buildings as new technologies and design sensibilities evolve.

4 Performance Evaluation: Demystifying the Power of BIPVT Systems

Building Integrated Photovoltaic Thermal (BIPVT) systems generate energy and improve building functionality in a unique way. However, to completely understand their potential, their performance must be compared to other aspects. The following section presents the major conclusions of the energy and exergy efficiency analysis. Thermal analysis, electrical efficiency and environmental considerations are elaborated.

4.1 Energy and Exergy Efficiency Analysis: Unveiling the True Potential

When assessing BIPVT performance, electricity generation alone is insufficient. Integrated energy and exergy analysis provides deeper system efficiency insights [76]-[79].

Energy Efficiency:

- Studies have shown BIPVT systems can achieve combined energy efficiencies exceeding 50%, compared to separate PV and thermal systems typically reaching 20-30% individually.

- This significant improvement stems from the synergistic utilisation of solar energy for electrical and thermal applications.

- However, efficiency varies greatly depending on system configuration, materials, and environmental conditions.

Exergy Efficiency:

- Exergy analysis accounts for the quality and potential work available from energy, providing a more complete picture of system performance.

- Research study shows that the exergy efficiencies of BIPVT systems can vary between 10 – 25 % depending on the type of system and the conditions of use.

- Exergy analysis highlights areas for improvement, such as optimising heat transfer processes and minimising energy losses.

Figure 5 showcases the graphical Analysis for Efficiency of Energy and Exergy in BIPVT Systems: Efficiency up to 50% for energy and 25% for exergy.

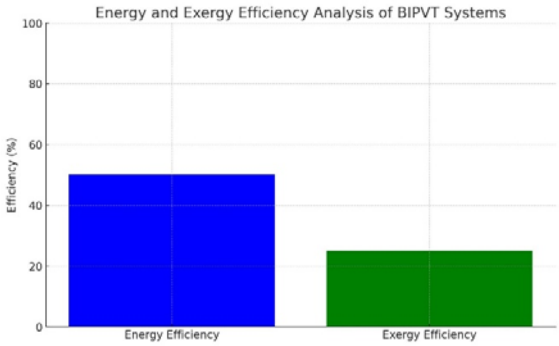

Fig. 5 Energy and Exergy Efficiency Analysis of BIPVT Systems

4.2 Thermal Modelling: Predicting Performance under the Sun

Accurate performance predictions require advanced thermal modelling, depicted in Figure 6. These models simulate heat flow within the system, considering electrical efficiency as a major performance metric.

- **Solar radiation:** Models account for the impact of sunlight's intensity, angle, and spectral distribution on the system.

- **Material properties:** Thermal conductivity, specific heat capacity and other characteristics of PV cells, absorbers and insulation are also taken into account.

- **Airflow and fluid flow:** Air or water flow through the system is modelled, which has an impact on the heat transfer process and temperature distribution.

- **Environmental conditions:** Some of the factors that affect heat transfer and system performance include temperature, wind speed and humidity.

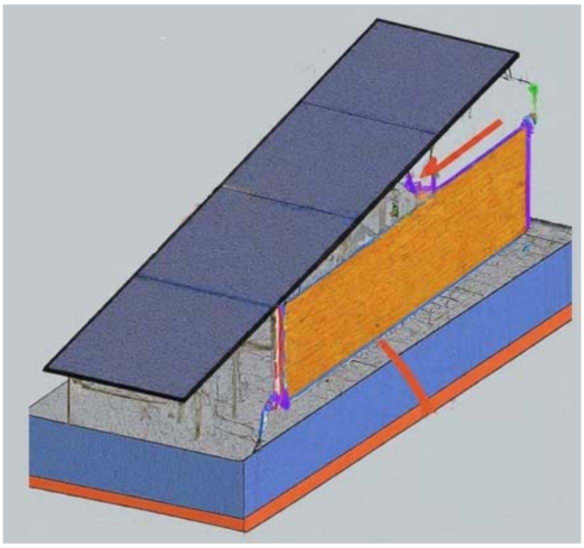

Fig. 6 Schematic representation of a thermal model for a BIPVT system.

By analysing these factors, thermal models predict:

- **Electrical power generation:** Based on solar radiation and PV cell efficiency.

- **Thermal energy output:** Considering heat transfer to the fluid and potential losses.

- **System efficiency:** Combining electrical and thermal outputs for comprehensive evaluation.

4.3 Electrical Efficiency: Unveiling the Power of Sunlight

Efficiency in terms of electrical energy conversion is still a major factor influencing the BIPVT system's performance. Factors influencing it include:

- **PV cell type and technology:** Crystalline silicon is highly efficient; on the other hand, CIGS-based thin films can be easily tuned for specific requirements.

- **Operating temperature:** The BIPVT system also suffers from heat effects as higher temperatures reduce the efficiency of PV cells, which is an indication of the need to control heat.

- **Shading and dust accumulation:** Shading reduces the efficiency of the solar panel by a large extent, whereas dusting needs to be done from time to time.

- **Inverter efficiency:** The aspect of the conversion of DC power from PV cells to AC power by the inverter affects the overall power output of the system.

4.4 The Dance with the Sun: Impact of Environmental Conditions

Environmental factors play a crucial role in BIPVT performance:

- **Solar radiation intensity:** Higher intensity increases electricity generation, but careful thermal management is crucial to prevent overheating.

- **Ambient temperature:** Warmer temperatures negatively impact electrical and thermal efficiency, emphasising the importance of heat dissipation strategies.

- **Wind speed:** Moderate wind can improve heat transfer and system efficiency, while high winds might require additional structural considerations.

- **Humidity:** High humidity affects thermal performance and electrical insulation, requiring proper system design and selection of materials.

Environmental factors also have a great impact on BIPVT performance [80]-[82], which is a critical parameter in determining the best system design for the various climates to achieve the best results in a year, as depicted in Figure 7.

This paper thus provides an understanding of these interactions that is useful in the application of energy and exergy analysis, thermal modelling and other techniques to enhance the performance of BIPVT systems.

These detailed analyses have demonstrated that they can save energy and, therefore, offer opportunities for further improvement and innovation. Even though a series of potential BIPVT issues are at play with material development, cost reduction, and broader market adoption, the obvious thing here is that the systems are great with future potential for application within sustainable building design. This is a game-changer solution, which might change the way energy is produced and consumed. This not only makes it possible for the building to get integrated into its environment but also to harness the potential of the sun's power for less strain on environmental resources.

Fig. 7 Impact of environmental factors on BIPVT performance

5 Optimisation Techniques

BIPVT systems combine style with functionality and, when integrated with the building structure, are able to make power. But to unleash this potential, one needs to harness the power of optimisation. This chapter discusses various techniques for improving efficiency in systems and further explains how mathematical modelling can play a great role in optimising the system performance of a BIPVT system. The comparison in Figure 8 is drawn from different optimisation techniques for Building Integrated Photovoltaic Thermal (BIPVT) systems.

It highlights specific areas of applications and the advantages that are brought by such methods. Normally, Genetic Algorithms and Particle Swarm Optimisation are applied in three basic areas. There are a lot of applications in alternative methods like response surface methodology and artificial neural networks. In view of the potential benefits of these optimisation strategies, the improvement of the system performance can be to a level from 1 to 5. "Other Techniques" are by far the most promising as they are very flexible and have the highest level of prediction. The above diagram also shows the vital role that optimisation plays in effective, low-cost, and environmental BIPVT. Optimisation in BIPVT Optimisation.

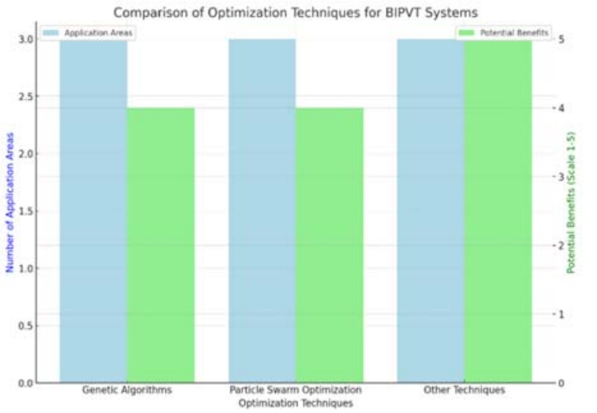

Fig. 8 Comparison of Optimisation Techniques for BIPVT Systems

5.1 Uunveiling the Toolbox: Strategies for a Brighter Future

The data shows that to improve system performance in BIPVT, researchers and engineers apply several techniques of optimisation:

5.1.1 Genetic Algorithms: Genetic algorithms are based on natural selection and are best described as approximating evolution towards a better system design. In the optimisation of a BIPVT design, an example of such is shown in Figure 9.

They could optimise different parameters by simulating very many configurations of different generations and then carefully selecting the best ones that can be used according to some criteria, which could be the optimisation of parameters like panel tilt angle, airflow rate, and material selection:

- **Panel tilt angle and orientation:** For maximising solar radiation capture.
- **Airflow rate and channel design:** For efficient heat transfer within the system.
- **Material selection and thickness:** To balance thermal performance and weight.

A general form of an optimisation problem that GAs can solve may be defined as Where f(x) is the objective function, e.g., energy output, efficiency; x is the design variables, e.g., tilt angle, material properties; and gi(x) are the constraints, e.g., physical constraints, cost constraints.

5.1.2 Particle Swarm Optimisation: This section presents benefits for the environment, life cycle cost analysis, and economic feasibility for BIPVT systems. Individual 'particles' representing different system configurations move through the design space, influenced by their own experience and that of their neighbours.

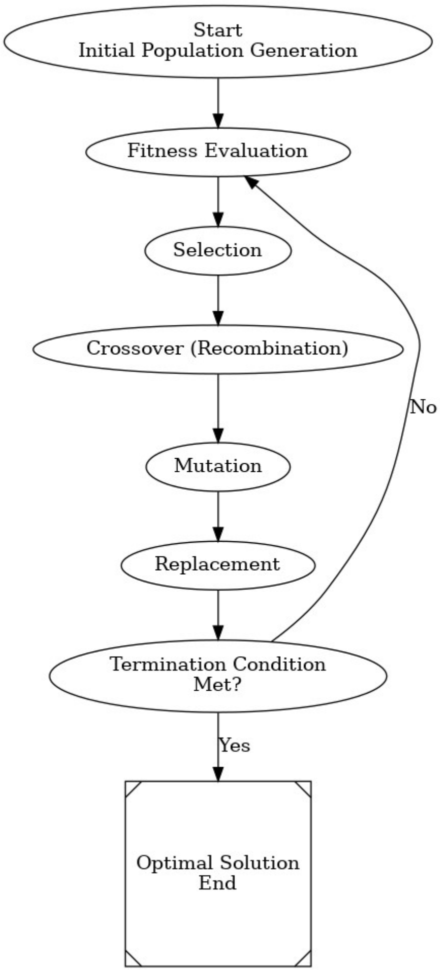

Fig. 9 Genetic Algorithm optimisation Process for BIPVT system design

Individual 'particles' representing different system configurations move through the design space, influenced by their own experience and that of their neighbours. This method could optimise similar parameters by simulating the movements of a flock of birds or a school of fish to find the best solution. The PSO updates the position of each particle based on its own experience and the experience of neighbouring particles. Figure 10 presents Particle Swarm Optimisation for BIPVT system optimisation.

This leads to convergence towards optimal solutions for parameters like:

- **PV cell type and technology:** Choosing the most suitable option based on efficiency, cost, and spectral response.
- **Inverter sizing and efficiency:** Matching inverter capacity to system output and minimising energy losses.

- **Shading mitigation strategies:** Optimising panel placement and incorporating shading devices to minimise efficiency reduction.

5.1.4 Mathematical Modelling: Involves creating equations to represent the physical behaviour of BIPVT systems. This could include equations for energy balance, thermal and electrical efficiency, and environmental impact. For instance, the energy balance equation for a photovoltaic cell might be represented as:

$$Qin=Qelec+Qth+Qloss$$

Qin is the solar energy input, *Qelec* is the electrical energy output, *Qth* is the thermal energy output, and *Qloss* represents losses.

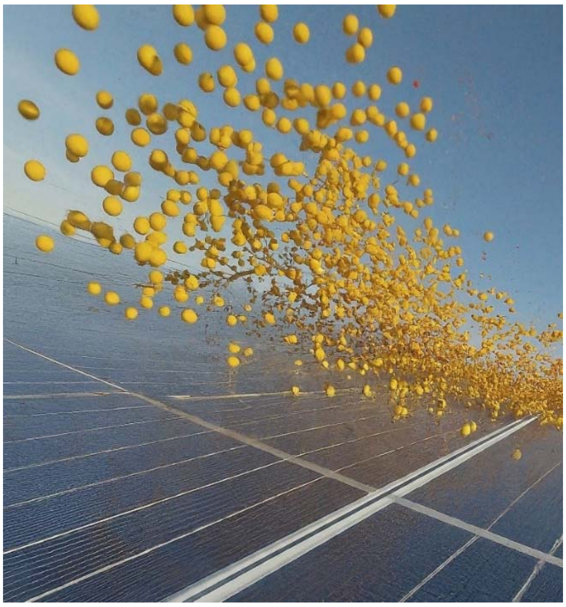

Fig. 10 Particle Swarm Optimisation for BIPVT system optimisation

5.1.4 Other Optimisation Techniques: Additional methods include:

- **Response surface methodology:** To create a mathematical representation of relationships between variables and to find the best settings for the variables.

- **Artificial neural networks:** Applying the machine learning methods for training on the simulated data and for making predictions on the best configurations.

- **Multi-objective optimisation:** Managing to optimise a number of antagonistic goals: electrical and thermal efficiency taken into account with the cost factor.

5.2 The Bridge between Theory and Reality: The Power of Mathematical Modelling

Thus, mathematical models are of great importance in the course of optimisation processes. As shown in Figure 11, These models represent the physical behaviour of BIPVT systems through equations and algorithms, allowing researchers to:

- Assess the capability of various design configurations in terms of their performance without having the need to develop costly physical models.

- Determine the critical parameters which have a strong influence on the performance of the system.

- Understand the effects of system variations in the operating environment and system modes.

- Offer useful information to guide the search for optimisation algorithms for improved solution values.

Fig. 11 Framework for BIPVT systems

Thus, by using various optimisation methods and the possibilities of mathematical modelling, scientists can get the most out of BIPVT systems. Such efforts help in the development of highly effective systems for generating energy while at the same time minimising the negative effects on the environment and thus working towards future sustainability.

BIPVT systems are most effective with the latest methods and equipment. It is possible to design effective systems for the achievement of the intended goals through the application of certain optimisation techniques and mathematical modeling. As BIPVT systems are enhanced, renewable energy generation will be seamlessly incorporated into the built environment and thus frame sustainable architectural design. With the advancement of research and development that is being done in the future, this will only get better.

6 Environmental and Economic Analysis of BIPVT Systems

BIPVT system can be used to produce electricity and heat at the same time, thus providing both economic and social benefits. We use solar power to produce electricity on the premises, thus saving on the use of fossil fuels and promoting sustainability. What are the implications of having these benefits for the environment as well as the economy? In this section, BIPVT systems' environmental impact, life cycle cost, and economic viability will be explained.

Figure 12 compares the environmental and economic benefits of Building Integrated Photovoltaic Thermal systems. The environmental benefits are listed on the left-hand side of the page. Each component has a rating between one and five to measure how important or influential it is to lower CO2 emissions, energy efficiency, better local air quality, and resource conservation.

Right-hand economic elements have similar ratings. These ratings emphasise the balance between the initial investment, operation and maintenance costs, huge energy savings, and end-of-life costs. This visualisation shows that BIPVT systems may require higher initial investments, but they can yield considerable environmental and economic returns, aligning with sustainability and energy efficiency goals.

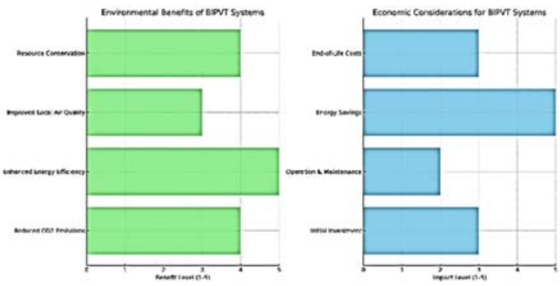

Fig. 12 Environmental Benefits and Economic Considerations for BIPVT Systems

6.1 Hharnessing the Sun for a Greener Future: Environmental Benefits

As illustrated in Figure 13, the environmental benefits of BIPVT systems are unquestionable:

Generating electricity on-site with BIPVT systems leads to significant reductions in CO2 emissions by displacing energy production from fossil-fuel power plants. Research suggests that a standard BIPVT system has the potential to reduce annual CO2 emissions by 2-5 tons, which can vary depending on factors such as system size and location.

- **Improved Energy Efficiency**: When both electrical and thermal energy are produced in one system, the total energy used will be lesser than the sum of the two systems' PV and thermal. Such a case will encourage a reduction in the demand for energy on the grid and reduce dependence on non-renewable resources.
- **Enhanced Local Air Quality:** BIPVT systems improve air quality since there is less dependence on fossil fuels and hence less emission of harmful pollutants, including nitrogen and sulfur oxides.
- **Reduced CO2 Emissions:** The BIPVT systems result in reduced CO2 emission as electricity is generated on-site, which will displace energy generation taking place at the CO2-emitting fossil fuel power plants. According to studies, a regular BIPVT system can replace between 2 to 5 tons of CO2 annually, depending on its size and location.
- **Resource Conservation:** On-site energy generation reduces the need for long-distance electricity transmission, minimising energy losses and conserving valuable resources.

Fig.13 Environmental benefits of BIPVT systems: reduced CO2 emissions, enhanced energy efficiency, improved air quality, resource conservation

6.2 Beyond Green Credentials: Life Cycle Cost Analysis and Economic Feasibility

While environmental benefits are crucial, economic feasibility remains a key consideration for widespread BIPVT adoption (Figure 14). Life Cycle Cost Analysis (LCCA) provides a holistic picture of the costs associated with a system throughout its lifetime:

- **Initial Investment:** Includes costs for materials, design, installation, and permits.
- **Operation and Maintenance:** Covers cleaning, repair, and system monitoring expenses.
- **Energy Savings:** Represents the financial benefit of generating electricity and thermal energy on-site.
- **End-of-Life Costs:** Includes recycling and waste disposal expenses.

While initial investment costs for BIPVT systems may be higher than conventional building approaches, the long-term benefits of energy savings and avoided grid reliance can create a positive economic return on investment (ROI) over the system's lifetime.

Fig.14 Life Cycle Cost Analysis Framework for BIPVT systems

Several factors influence the economic feasibility of BIPVT systems:

- **Government incentives and subsidies:** Government financial support can significantly reduce upfront costs and improve ROI.
- **Energy prices:** Higher electricity and heating costs lead to faster payback periods for BIPVT systems due to larger energy savings.
- **System size and complexity:** Larger and more complex systems may require higher initial investments but can offer more significant energy generation and faster ROI.
- **Technological advancements:** Ongoing research and development reduce the cost of materials and components, making BIPVT systems increasingly cost-competitive.

BIPVT systems offer a compelling value proposition, balancing environmental benefits with economic considerations. While initial costs might be higher than traditional approaches, LCCA reveals significant potential for long-term economic gains through energy savings and reduced reliance on fossil fuels. As technology advances, government incentives increase, and awareness of environmental benefits grows, BIPVT systems can become a financially viable and sustainable solution for the future of building design.

7 Navigating the Path Forward: Challenges and Future Directions of BIPVT Systems

While Building Integrated Photovoltaic Thermal (BIPVT) systems present a promising path towards sustainable building design, challenges remain in realising their full potential [83]-[85]. This section delves into the current hurdles in design, installation, and maintenance and explores exciting future directions for research and development.

As depicted in Figure 15, the chart illustrates the obstacles encountered by Building Integrated Photovoltaic Thermal (BIPVT) systems, as well as the potential consequences of future developments. All challenges will be depicted in red text, with their severity depicted in text size on a scale from 1 to 5. Future directions will be discussed in blue text, as a call to attend to these challenges, to support and drive innovation in BIPV technology. Such a vision will make more tangible the interaction of current challenges and the opportunities innovation is likely to use in turning BIPV systems onto new paths. This would bring further improvements to the efficiencies, more adoptions, and ease of integration into sustainable building designs.

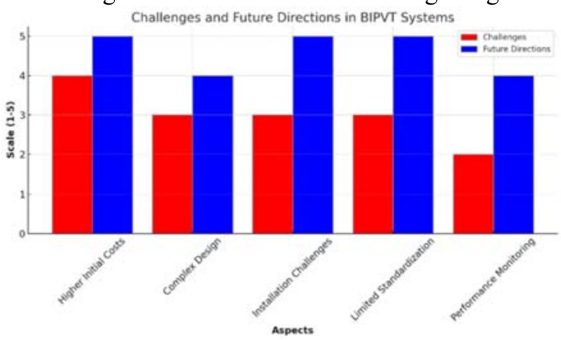

Fig. 15 Challenges and Future Directions in BIPVT Systems

7.1 Facing the Hurdles: Current Challenges in BIPVT Implementation

Although they have many advantages, as seen in Figure 16, BIPVT systems still suffer from a number of challenges in their bid for worldwide acceptance:

- **Higher Initial Costs:** Compared to conventional building materials, the initial investment for BIPVT systems can be higher, hindering widespread adoption, especially in cost-sensitive projects.
- **Complex Design and Integration:** Integrating PV and thermal functionalities into the building envelope requires specialised design expertise and careful consideration of structural, thermal, and aesthetic aspects, increasing design complexity.
- **Installation Challenges:** Installing BIPVT systems can be more complex than traditional building materials, requiring specialised skills and potentially disrupting construction timelines.
- **Limited Standardization:** Diverse designs and materials in BIPVT systems pose standardisation and mass production challenges, potentially hindering cost reduction and broader availability.
- **Performance Monitoring and Maintenance:** Long-term performance monitoring and maintenance needs for BIPVT systems are still evolving, requiring new tools and expertise development.

7.2 Embracing Innovation: Future Directions for BIPVT Systems

Despite the challenges, the future of BIPVT systems holds immense promise. Figure 17 presents a general picture of Future directions for BIPVT systems. Several areas beckon for focused research and development:

- **Advanced Materials:** Research on new materials with improved efficiency, lower cost, and enhanced aesthetics (e.g., transparent and flexible PV cells) can optimise performance and broaden application possibilities.
- **Standardization and Modular Design:** Developing standardised components and modular systems can streamline design, fabrication, and installation, promoting wider adoption and cost reduction.
- **Advanced System Integration:** Integrating BIPVT systems with building automation and smart grid technologies can optimise energy production, storage, and consumption, enhancing overall building performance.

Fig. 16 Challenges in BIPVT implementation: higher initial costs, complex design, installation challenges, limited standardisation, performance monitoring

- **Performance Modelling and Optimisation:** Refining performance modelling tools and exploring new optimisation techniques can improve system efficiency and cost-effectiveness.
- **Life Cycle Assessment and Life Cycle Cost Analysis:** Comprehensive life cycle analysis can better quantify the environmental and economic benefits of BIPVT systems, strengthening their competitive edge.

Building Integrated Photovoltaic Thermal Systems offers a transformative approach to energy generation and sustainable building design. By addressing the existing challenges through innovative materials, standardised designs, and integrated technologies, BIPVT systems have the potential to revolutionise the built environment. This journey requires collaboration between researchers, engineers, architects, policymakers, and building owners, paving the way for a future where buildings seamlessly integrate with their environment, harvesting the sun's power for a more sustainable tomorrow.

Fig. 17 Future directions for BIPVT systems: advanced materials, standardisation, system integration, performance modelling, life cycle analysis

8 Conclusion

This research has analysed the field of Building Integrated Photovoltaic Thermal (BIPVT) systems in detail and has identified the methods by which these systems can revolutionise sustainable construction and energy production. Our analysis has yielded several key findings:

- **Enhanced Efficiency:** We explored how BIPVT systems can achieve combined energy efficiencies exceeding 50%, significantly surpassing traditional separate PV and thermal systems. Advanced modelling tools enable precise performance prediction, and optimisation techniques like Genetic Algorithms unlock further efficiency gains.

- **Environmental Champion:** From CO2 emission reduction to improved air quality and resource conservation, BIPVT systems emerged as champions for environmental sustainability. Their on-site energy generation translates directly into reduced reliance on fossil fuels and a cleaner future.

- **Economic Feasibility:** While initial costs remain a consideration, life cycle analysis revealed the potential for long-term economic benefits through energy savings and reduced grid dependence. As technology advances and costs decrease, BIPVT systems become increasingly viable.

- **Technological Advancements:** Some of the areas of research that were identified to be important in our review include advanced materials, standardisation and integration with smart grid technologies. These are very important in enhancing the effectiveness of BIPVT systems for increased efficiency.

However, several limitations and challenges persist. Such a system has higher initial costs than conventional building materials and has the added costs of separate PV systems.

- They are complicated in design and integration and thus need the services of a professional.

- Possible problems during installation and possible problems with construction timeframes and schedules.

- Currently, there is a low level of standardization which is a drawback in the mass production and the use of the technology.

- Changed requirements related to the persistent assessment and tuning of long-term performance.

Looking to the future, several promising directions emerge:

- Design of new materials with better performances, less expense, and better appearance.

- Standardizations and modularisation of the system to help in the simplification of the fabrication and construction steps.

- Another feature that is integrated with the energy management system includes building automation and smart grid technologies.

- Improvement of the performance modelling tools and methods as well as optimisation approaches.

- Improving the calculations of environmental and economic impacts with the help of life cycle assessments.

Therefore, BIPVT systems are innovative solutions for efficient building design and construction to generate energy, enhance architecture and protect the environment. As we know, there are still some issues that hamper the implementation of BIPVT, but the advantages of doing so are clear. With the increase in research studies and advancement in technology, these systems are expected to have a significant contribution to the development of the energy-conscious and sustainable buildings of tomorrow.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Author Contributions: Conceptualization, M.P.U., A.D. and A.V.; methodology, M.P.U. and A.D.; formal analysis, M.P.U.; investigation, M.P.U., A.D. and A.V.; resources, M.P.U. and A.D.; data curation, M.P.U.; writing—original draft preparation, M.P.U.; writing—review and editing, M.P.U., A.D. and A.V.; visualisation, M.P.U.; supervision, A.D. and A.V.; project administration, M.P.U. All authors have read and agreed to the published version of the manuscript.

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