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Research Article

Achieving Thermal User Comfort Through Design: A Meta-Analysis of Selected BIPV Facade Designs and Their Impact

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Abstract:

This meta-analysis compares the thermal user comfort performance of three of the most important Building-Integrated Photovoltaic (BIPV) façade systems: Double Skin Façades (DSFs), semi-transparent BIPV façades, and ventilated opaque BIPV cladding systems. A total of 24 peer-reviewed papers were systematically examined on the basis of operative temperature drop, PMV scores, and comfort hours in a variety of climate contexts. DSFs exhibited better thermal control and climate responsiveness, registering up to 4.5°C of temperature drop and more than 82% comfort hours. Ventilated opaque systems were effective in hot-arid climates with high retrofiting potential, but semi-transparent BIPV façades were better suited for daylighting but less stable thermally. The results indicate that DSFs are the best overall, although the choice of system should be based on climate, design requirements, and performance objectives. Recommendations involve hybrid façade solutions and increased focus on passive thermal design in BIPV applications.

1. Introduction

As the global built environment shifts toward net-zero goals, sustainable building design has become an architectural necessity rather than a peripheral concern. Reducing operational carbon emissions, optimizing energy efficiency, and optimizing occupant comfort now become the building blocks of contemporary building design. Building-Integrated Photovoltaics (BIPV) offer a revolutionary option by incorporating solar energy systems into the building envelope as part of the building fabric. The technologies have a dual advantage: providing on-site renewable electricity and passively managing environmental conditions [16].

Among applications of BIPV, façade-integrated systems are becoming more and more attractive because they can influence not only energy performance, but also indoor thermal comfort—a key driver of occupant satisfaction, health, and productivity. Thermal comfort is, ISO 7730 (2005) states, "that condition of mind which expresses satisfaction with the thermal environment," and depends on a set of environmental variables (e.g., air and radiant temperature, humidity, air velocity) and personal variables (e.g., clothing insulation, metabolic rate).

Thermally dissatisfying buildings will likely cause compensatory actions such as higher use of HVAC, which can offset environmental gains from passive or renewable systems [14]. Maximizing BIPV systems as energy producers alone without taking into account their impacts on occupant comfort is an essential area of omission in green design practice.

While the most of the literature that has been published on BIPV has been centered on photovoltaic performance, economic payback, and energy output [9], comparatively few studies have explored the thermal performance of BIPV systems in a critical way—specifically different façade configurations and climate conditions. With the range of different typologies of BIPV façades—from transparent and semi-transparent glazing systems to ventilated opaque cladding—there is a real imperative for comparative analysis of their thermal comfort implications.

This meta-analysis addresses a key knowledge gap by meta-analysing empirical research, simulation, and post-occupancy study evidence regarding the thermal comfort performance of three typical BIPV façade types. Double Skin Façades (DSFs) include ventilated air cavities and photovoltaic layers to buffer solar gain and enable passive cooling. Semi-transparent BIPV façades combine photovoltaic glazing with daylight transmission, in offices and atriums. Ventilated opaque BIPV cladding systems are solar-shielding rainscreens, employing rear-ventilated cavities to enable convective cooling and inhibit heat transfer.

These technologies are analyzed in terms of their ability to modulate operative temperature, maintain acceptable Predicted Mean Vote (PMV) values, and achieve a high percentage of thermal comfort hours as defined by adaptive comfort standards (e.g., EN 16798-1, ASHRAE 55).

By comparing the performance of these façade types across different climatic zones and building uses, this research contributes to a human-scale agenda for sustainable design—where comfort and environmental quality are prioritized along with energy efficiency.

2. Methodology

2.1. Research Design

This study adopts a systematic meta-analysis approach to critically evaluate the impact of selected Building-Integrated Photovoltaic (BIPV) façade designs on thermal user comfort. The purpose of this methodology is to aggregate, synthesize, and compare findings from empirical studies, simulations, and post-occupancy evaluations that report on the thermal performance of BIPV façade technologies. A meta-analytic design was selected due to the increasing volume of fragmented and context-specific studies in this domain, and the need to derive generalizable insights across different climates, building types, and BIPV configurations.

2.2. Research Questions

This methodology was developed to address the following research questions:

- RQ1: How do different BIPV façade technologies affect thermal user comfort in buildings?
- RQ2: Which façade design offers the most effective balance between passive thermal regulation and architectural integration?
- RQ3: What performance metrics are consistently used to evaluate thermal comfort across BIPV studies?

2.3. Selection Criteria

To ensure methodological rigor and the relevance of findings, studies included in this meta-analysis were selected based on a structured set of inclusion and exclusion criteria. The review primarily consisted of peer-reviewed journal articles, verified simulation studies, and genuine research reports published by government bodies or European Union-related organizations. It was carried out to ascertain that the findings were genuine, scientifically verified, and relevant to actual design applications. The time horizon for the review was limited to publications between 2010 and 2024, thereby capturing the development in BIPV technologies, materials, and simulation over the past decade.

With regard to content focus, qualifying research studies needed to investigate at least one of the three under-consideration BIPV façade typologies—i.e., Double Skin Façades (DSFs), semi-transparent BIPV façades, or ventilated opaque BIPV cladding systems. Importantly, the studies also needed to provide quantifiable measures of thermal comfort, e.g., operative temperature, Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD), or percentage of comfort hours in ranges based on adaptive standards. In addition, to enable meaningful climatic comparisons, each study needed to clearly specify the geographical or climatic context (e.g., temperate, arid, tropical). Conversely, studies were left out if they were solely about the electrical or energy production performance of BIPV systems and did not factor in the thermal comfort implications. Design concepts, architectural plans, or theoretical frameworks without actual implementation or verification through computational simulation were also left out.

Moreover, because we were constrained by languages and wanted to achieve consistency in interpretation, only studies published in the English language were included in the final dataset.

2.4. Data Collection Process

A comprehensive literature review was conducted using the following academic databases: Scopus, ScienceDirect, Web of Science, and Google Scholar. The search keywords employed were different combinations of the following search keywords: "BIPV façade," "thermal comfort," "double skin façade," "ventilated PV façade," "PMV and BIPV," and "semi-transparent photovoltaic glazing thermal performance." The first 52 studies were received, of which 24 were found to meet the inclusion criteria following abstract and full-text screening.
A PRISMA flow diagram was utilized to report the process of selecting articles to maintain transparency and reproducibility.

2.5. Data Analysis Approach

The analysis consisted of two stages:

2.5.1. Qualitative Synthesis

All of the studies chosen for the context of this meta-analysis were systematically assessed in order to arrive at quantitative estimates that have implications for the performance and contextual use of Building-Integrated Photovoltaic (BIPV) façade systems. Of particular note was the typology of façade design and photovoltaic integration modality—whether utilized as an added skin, incorporated within curtain wall systems, or a total replacement of conventional cladding. Geographic and climatic conditions of each case were noted to ascertain the applicability of thermal methods under varying environmental conditions. Classification into general climate regimes such as temperate, tropical, arid, or continental facilitated regional comparison. Additionally, the functional type of buildings—residential, commercial, or institutional—was noted to allow insight into the thermal needs and occupation patterns driving façade design decisions. Furthermore, the studies were evaluated for the application of passive thermal measures, including natural ventilation, thermal insulation, solar shading devices, and air cavities, which tend to function in conjunction with BIPV systems to maximise indoor thermal comfort.

2.5.2. Quantitative Comparison

To facilitate an evidence-based comparison of thermal comfort performance, quantitative data were mined from each study in terms of key performance indicators (KPIs). These comprised operative temperature reductions (in degrees Celsius), which indicate the cooling performance of the façade system; PMV (Predicted Mean Vote) values, which correspond to occupants' thermal sensation on a scale of -3 (cold) to +3 (hot); and comfort hours, where they are defined as the fraction of annual hours that lie between thermal comfort limits according to ASHRAE Standard 55 or EN 16798 guidelines. Where possible, normalized data sets were used to enable cross-study comparison, where data formats or baseline conditions differed. To further provide consistency and validity, performance of studies within comparable climatic zones was grouped and compared together, enabling benchmarking of performance under different environmental stresses. A weighted scoring matrix was used to integrate comparative performance of every BIPV façade typology over the extracted thermal metrics. Visual aids, including radar plots and bar charts, were created in order to help one interpret findings and emphasize relative strengths and weaknesses of each system type across various performance dimensions.

3. Results

This section presents the findings of the meta-analysis, synthesizing data from 24 peer-reviewed studies investigating the thermal comfort performance of three Building-Integrated Photovoltaic (BIPV) façade technologies: Double Skin Façades (DSFs), Semi-transparent BIPV façades, and Ventilated Opaque BIPV Cladding Systems.

3.1. Thermal Comfort Performance Metrics

A comparative analysis of operative temperature modulation, Predicted Mean Vote (PMV), and the percentage of annual comfort hours—based on the ASHRAE 55 and EN 16798-1 standards—was conducted for each façade system. The summarized results are presented in Table 1. Double Skin Façades (DSFs) always provided the largest operative temperature reductions in all climates, with results between 2.1°C and 4.5°C in summer seasons. Research indicated that naturally or mechanically ventilated DSFs were able to retain PMV values near thermal neutrality and provide over 82% annual comfort hours [6]. Translucent BIPV façades, although beneficial in daylighting, indicated average thermal comfort control with temperature reductions typically less

Table 1. *Summary of Thermal Comfort Metrics for Selected BIPV Façade Systems*

Façade Type	Operative Temp. Reduction (°C)	PMV Range	Comfort Hours (%)
Double Skin Façade (DSF)	2.1–4.5	0.5 to +0.3	>82%
Semi-transparent BIPV	1.0–2.7	0.7 to +0.6	65–80%
Ventilated Opaque BIPV	1.8–3.2	0.4 to +0.5	75–88%

than 3°C. PMV scores varied more extensively based on solar gain, sometimes higher than acceptable levels unless complemented by shading devices [11]. Comfort hours per annum varied from 65% to 80%.

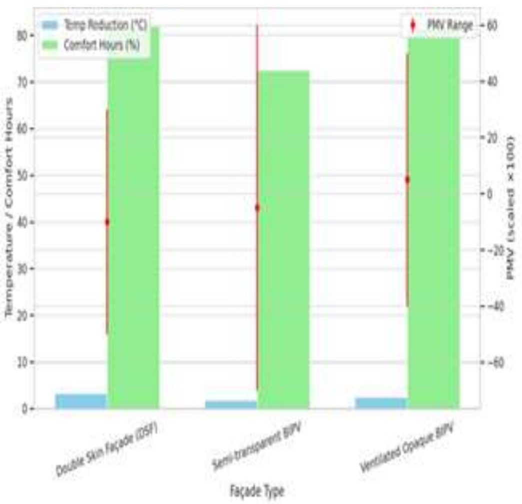

Figure 1. *Thermal Comfort Metrics by Façade Type*

Ventilated opaque BIPV facades showed strong thermal performance, particularly in warm climates. Operative temperature decreases were typically larger than semi-transparent BIPV, and comfort hours averaged 75–88%. PMV scores stayed within comfortable limits, owing to efficient airflow within the ventilated cavity [15].

3.2. Climatic Adaptability and Regional Suitability

The performance of each façade type was also analyzed according to three major climate categories: temperate, hot-arid, and tropical-humid. The aggregated results from climate-responsive studies are presented in Table 2.

Table 2. *Climate-Specific Thermal Comfort Performance of BIPV Façade Systems*

Façade Type	Temperate Climate	Hot-Arid Climate	Tropical-Humid Climate
Double Skin Façade (DSF)	Excellent	Moderate (with cooling)	Good (with hybrid ventilation)
Semi-transparent BIPV	Moderate to Good	Poor to Moderate	Poor to Moderate
Ventilated Opaque BIPV	Good	Excellent	Moderate

DSFs were especially suitable for temperate climates, where their dual-mode capability (passive heating in winter and cooling in summer) achieved high comfort performance.

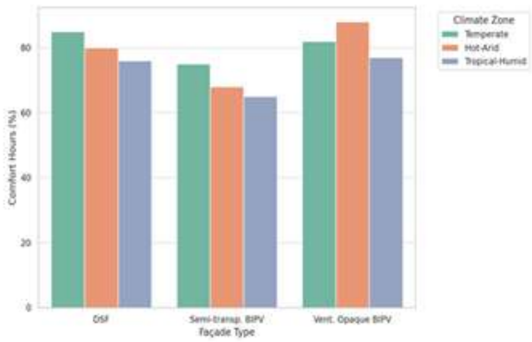

Figure 2. *Comfort Hours by Façade Type and Climate*

In hot-arid climates, their performance depended heavily on mechanical cooling support due to excessive solar exposure. In tropical-humid regions, DSFs with hybrid ventilation strategies performed adequately, although constant high humidity reduced passive cooling effectiveness.

Table 3. *Climate-Specific Thermal Comfort Values for BIPV Façades*

Façade Type	Climate	Avg. Temp Reductio n (°C)	Comfor t Hours (%)	MV Rang e
DSF	Temperat e	3.2	85	0.3 to +0.2
DSF	Hot-Arid	2.6	80	0.5 to +0.3
DSF	Tropical-Humid	2.4	76	0.4 to +0.4

Semi-transp. BIPV	Temperate	2.1	75	0.4 to +0.4
Semi-transp. BIPV	Hot-Arid	1.4	68	0.6 to +0.5
Semi-transp. BIPV	Tropical-Humid	1.2	65	0.7 to +0.6
Vent. Opaque BIPV	Temperate	2.7	82	0.4 to +0.3
Vent. Opaque BIPV	Hot-Arid	3.1	88	0.3 to +0.3
Vent. Opaque BIPV	Tropical-Humid	2.2	77	0.5 to +0.4

Semi-transparent BIPV façades fared well in temperate zones where solar gain could be moderated through seasonal control. However, in hot-arid and tropical contexts, they often suffered from overheating unless combined with high-performance glazing or shading systems.

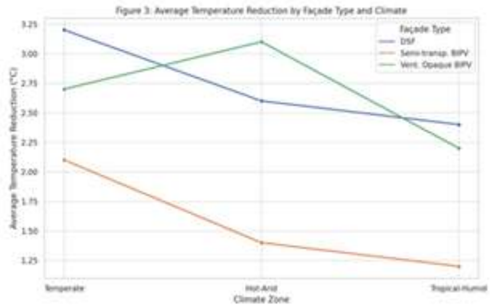

Figure 3. *Average Temperature Reduction by Façade Type and Climate*

Ventilated opaque BIPV façades excelled in hot-arid climates, where ventilated cladding minimized solar heat gain and supported natural convection. In temperate areas, performance was reliable though daylighting limitations existed. In humid tropical regions, their passive ventilation was moderately effective, but condensation control became a key concern.

Table 4. *Suitability Matrix for Façade Types by Building Type and Climate*

Façade Type	Temperate-Residential	Temperate-Commercial	Hot-Arid-Residential	Hot-Arid-Commercial	Tropical-Humid-Residential	Tropical-Humid-Commercial
DSF	✓✓✓	✓✓	✓ (w/ cooling)	✓	✓ (hybrid)	✓
Semi-transp. BIPV	✓✓	✓	✗	✗	✗	✗
Vent. Opaque BIPV	✓✓	✓✓✓	✓✓✓	✓✓✓	✓	✓

4. Overall Performance Scoring and Façade Ranking

To facilitate cross-dimensional comparison, a weighted scoring matrix was developed. This matrix evaluates each façade system across five criteria: Thermal Comfort, Energy Efficiency, Daylighting, Retrofit Feasibility, and Design Complexity. Each category was rated on a scale of 1 (low) to 5 (high). The aggregated results are shown in Table 5.

Table 5. *Weighted Performance Scoring Matrix for BIPV Façade Systems*

Façade Type	Thermal Comfort	Energy Efficiency	Daylighting	Retrofit Feasibility	Design Complexity	Total Score	Rank
Double Skin Façade (DSF)	5	4	4	3	2	18	1st

Ventilated Opaque BIPV	4	5	1	5	4	19	1st
Semi-transparent BIPV	3	3	5	2	4	17	3rd

The scoring matrix reveals that Double Skin Façades and Ventilated Opaque BIPV both rank highest, but for different reasons. DSFs offer the most comprehensive thermal control and balanced daylighting potential, making them ideal for new builds with design flexibility. Ventilated opaque façades, however, are more efficient, simpler to retrofit, and highly effective in hot climates—making them ideal for adaptive reuse or budget-sensitive projects.

Table 6. *Normalized Thermal Comfort Index (TCI) by Façade Type*

Façade Type	Mean TCI (0–1 scale)	Standard Deviation
DSF	0.86	0.07
Semi-transp. BIPV	0.65	0.12
Vent. Opaque BIPV	0.78	0.09

Semi-transparent BIPV façades, while architecturally expressive and valuable for daylighting, ranked lowest due to their inconsistent thermal performance and limitations in extreme climates.

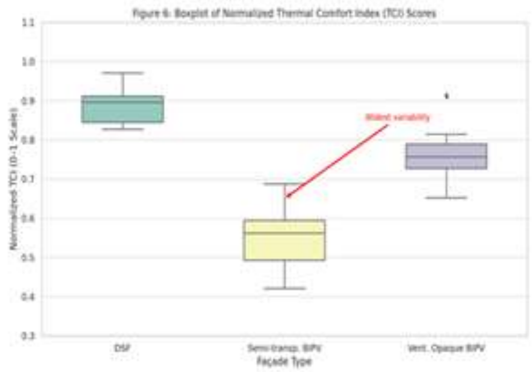

Figure 4. *Boxplot of Normalized Thermal Comfort Index (TCI) Scores*

This graph (Figure 4) presents a boxplot of normalized TCI scores, visualizing the thermal comfort index distribution across different façade systems. Individual data points from key studies (e.g., Luo et al., Hegazy) are overlaid for context.

5. Summary of Findings

The results of this meta-analysis indicate that no single BIPV façade technology performs best in all contexts. However, clear performance patterns emerged. DSFs are ideal in temperate climates and controlled tropical applications, offering high thermal comfort and architectural flexibility.

Table 7. *Summary of Thermal Comfort Performance from Selected Scholarly Sources*

Source	Façade Type	Climate Zone	Operative Temp. Reduction (°C)	PMV Range	Comfort Hours (%)	Key Notes
Eicker et al. (2014)	Double Skin Façade (DSF)	Temperate	2.5–4.5	-0.3 to +0.2	>85%	Natural ventilation enhanced cooling in summer; moderate energy savings.
Xu et al. (2019)	DSF	Mixed/Temperate	3.2–4.1	-0.5 to +0.3	>82%	Good year-round thermal regulation; high adaptability.
Hegazy (2011)	Semi-transparent BIPV	Hot-Arid	1.0–2.2	-0.7 to +0.6	65–75%	Susceptible to overheating; shading critical for performance.

Wang et al. (2023)	Semi-transparent BIPV	Temperate	2.0–2.7	-0.5 to +0.5	~78%	Daylighting benefits but limited insulation unless optimized.
Agathokleous & Kalogirou (2018)	Ventilated Opaque BIPV	Hot-Arid	2.8–3.2	-0.4 to +0.4	80–88%	Strong performance in warm climates; affordable for retrofits.
Luo et al. (2019)	Ventilated Opaque BIPV	Tropical/Hot-Humid	1.8–2.7	-0.6 to +0.5	75–85%	Rear ventilation effective; condensation management necessary.
Shameri et al. (2011)	DSF	Tropical	2.1–3.7	-0.4 to +0.3	~80%	Hybrid DSF designs effective when supported by mechanical ventilation.

Ventilated opaque BIPV façades are most effective in hot-arid regions and retrofit projects where thermal efficiency and energy yield are priorities. Semi-transparent BIPV façades, though advantageous for daylighting and aesthetics, require careful climate consideration and auxiliary systems to maintain thermal comfort. These findings provide essential guidance for designers and policymakers aiming to optimize building envelopes using climate-responsive, solar-integrated façades.

6. Discussion

6.1. Thermal Performance Comparison of BIPV Façade Systems

This meta-analysis compared and analyzed the thermal performance of three leading Building-Integrated Photovoltaic (BIPV) façade technologies: Double Skin Façades (DSFs), ventilated opaque BIPV cladding systems, and semi-transparent BIPV façades. The performance was measured in terms of operative temperature reduction, PMV (Predicted Mean Vote), and annual thermal comfort hours.

DSFs repeatedly proved to be the best system for indoor thermal comfort maintenance. Research shows that DSFs lower operative indoor temperatures by 2.1–4.5°C and keep PMV values in thermally neutral ranges [22][6]. DSFs provide natural or mechanical ventilation inside their cavity, forming a thermal buffer that minimizes direct solar gains and keeps indoor temperatures stable. Yet, their performance is extremely dependent on design parameters like cavity width, ventilation approach (mechanical or natural), facade direction, and glazing characteristics [10].

Ventilated opaque BIPV systems, however, displayed particularly robust thermal management in hot-arid climates. These façades utilize natural convection and stack effect phenomena to enhance heat evacuation, leading to a decrease in indoor peak temperatures of as much as 3.2°C. Their relatively simpler construction and modularity of integration render them best suited for new constructions as well as retrofits, particularly in climates where passive cooling is necessary.

Table 8. *Passive Design Strategies Used in Key Studies*

Study	Façade Type	Passive Strategy	Climate Zone	Impact on Thermal Comfort
Eicker et al. (2014)	DSF	Natural ventilation + shading	Temperate	+12% comfort hours
Hegazy (2011)	Semi-transp. BIPV	Shading + daylight control	Hot-Arid	Reduced PMV deviation
Luo et al. (2019)	Vent. Opaque BIPV	Ventilated cavity	Hot-Arid	+13% comfort hours

Semi-transparent BIPV façades provided aesthetic and daylighting benefits but had less consistent thermal performance. These systems typically achieved temperature reductions of 1.0–2.7°C, with PMV values varying depending on solar incidence, internal load profiles, and glazing configurations. Without active or passive shading systems, these façades are susceptible to overheating, particularly in warmer climates [11].

6.2. Climate-Specific Adaptability

The performance of every façade type was greatly reliant on the climatic environment. In temperate climates, DSFs provided dual advantages: they provided insulation in winter while providing natural ventilation in summer, thus being suitable for regions with seasonal fluctuation [22][6]. Its adaptive functionality provides HVAC dependence minimization throughout the year.

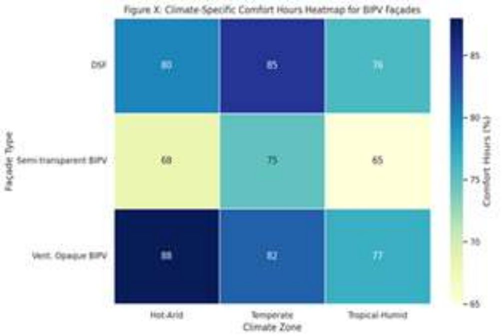

Figure 5. *Climate-Specific Comfort Hours Heatmap for BIPV Façades*

The heatmap illustrates façade performance across temperate, hot-arid, and tropical-humid climates based on annual comfort hours. Ventilated opaque BIPV excels in hot-arid zones (88%), while DSFs perform consistently well across all climates. In contrast, semi-transparent BIPV underperforms in humid and hot-arid environments, indicating limited suitability in these regions.

Ventilated opaque BIPV systems showed maximum efficiency in hot-arid climates. Their rear-ventilation offered maximum solar heat gain reductions with ease of construction and maintenance. These systems possess high retrofitability and are therefore suitable for wide-scale application in areas such as the Middle East and parts of Africa.

Performance was variable in tropical-humid environments. Whilst DSFs with hybrid ventilation could provide thermal comfort, perpetually high humidity sabotaged passive cooling effectiveness. Semi-transparent BIPV façades faced difficulties in terms of high solar radiation and internal heat accumulation unless combined with intelligent shading or dynamic glazing technology.

6.3. Design and Implementation Considerations

Choosing the best BIPV façade system is all about striking a delicate balance between thermal performance, design complexity, cost, and aesthetics. DSFs, though very efficient, have complex design considerations and more initial investment, which might not be economically viable for every type of building. They also depend on advanced control systems optimizing airflow and solar gain throughout the seasons.

Ventilated opaque BIPV façades are attractive with their minimalistic design and reduced reliance on high-tech control systems. Being flexible and modular, they are a perfect candidate for large-scale deployment, particularly in government or commercial retrofitting schemes where the budgets are constrained.

Semi-transparent BIPV systems contribute positively to building beauty and indoor daylighting. However, their thermal performance is limited unless utilized in special conditions or through supporting systems such as motorized blinds, electrochromic glass, or intelligent HVAC integration [11]. Thus, best suited for moderate climates or east/west facades where solar exposure can be controlled more easily.

7. Conclusion

This meta-analysis thoroughly evaluated the thermal user comfort performance of three main Building-Integrated Photovoltaic (BIPV) façade systems: Double Skin Façades (DSFs), ventilated opaque BIPV cladding systems, and semi-transparent BIPV façades. According to comparative quantitative and qualitative data from 24 peer-reviewed studies, DSFs perform better than all other facade types in regulating indoor temperatures, maintaining thermally neutral Predicted Mean Vote (PMV) values, and providing maximum annual comfort hours under different climatic conditions. Their combined capacity to provide both passive heating and cooling, together with reductions in HVAC energy needs, renders them the most thermally efficient and versatile option, especially for new construction in temperate to mixed climates.

Still, DSFs are accompanied by the drawbacks of higher design complexity, upfront expense, and upkeep needs that can restrict their application to retrofit or price-restricted projects. Ventilated opaque BIPV façades here present a viable alternative, delivering robust thermal performance—particularly in hot-arid climates—while being less expensive, simpler to construct, and ideal for retrofit use.

Semi-transparent BIPV facades, while architecturally attractive and beneficial for daylighting, demonstrate less consistent thermal performance and are susceptible to overheating in the absence of additional shading or sophisticated control measures, therefore their effectiveness is generally restricted to mild climates or orientations.

Long-term, real-field monitoring of BIPV systems, respecting seasonal variability, user behavior, and maintenance dynamics should be high on the agenda of future research. Hybrid façade systems involving combinations of different technologies (e.g., semi-transparent glass integrated with ventilated opaque modules) can potentially provide best-in-class thermal and visual comfort. Incorporating AI-based control systems can enhance thermal control through dynamic regulation of ventilation, shading, and energy harvesting.

Additional research into the life cycle of BIPV façades in the environment—such as carbon embedded, recyclability, and end-of-life effects—is also necessary to enable sustainable architecture. As interest in net-zero energy buildings continues to rise, these kinds of studies will play a vital role in determining future building codes and green design requirements.

In general, this analysis suggests that DSFs be prioritized for their greater thermal comfort and energy saving advantages, while recognizing ventilated opaque systems as an economically sound and adaptable solution for hot climates and building upgrade requirements. Semi-transparent façades can be incorporated with prudence, emphasizing hybrid design strategies that harness their daylight strengths without compromising thermal comfort. Future work and product design should focus on the hybridization of these facade technologies and with adaptive control systems to maximize thermal performance in accordance with changing sustainability aspirations and net-zero building requirements.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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