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Review

A Review on Building Integrated Photovoltaic Façade Customization Potentials

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Abstract: Technological advancement in Building Integrated Photovoltaics (BIPV) has converted the building façade into a renewable energy-based generator. The BIPV façade is designed to provide energy generation along with conventional design objectives such as aesthetics and environmental control. The challenge however, is that architectural design objectives sometimes conflict with energy performance, such as the provision of view and daylight versus maximum power output. In innovative cases, the characteristics of conventional BIPV façades have been modified by researchers to address such conflicts through customization as an emerging trend in BIPV façade design. Although extensive reviews exist on BIPV product types, design integration, adoption barriers and performance issues, research on BIPV customization has not been reviewed as a solution to BIPV adoption. This paper seeks to review the potential of BIPV façade customization as a means of enhancing BIPV adoption. The current paper identifies customization parameters ranging from the customization category, level, and strategies, and related architectural potential along with an assessment of their impact. The findings reflect that elemental and compositional level customization using combined customization strategies provide enhanced BIPV products. These products are well integrated for both energy generation and aesthetic applications with a power output increase of up to 80% in some cases. The paper concludes that a wide range of BIPV adoption barriers such as aesthetics, architectural integration, and performance can be overcome by appropriate BIPV customization.

Keywords: Building Integrated Photovoltaics (BIPV); façade; customization; architectural potentials; barriers

1. Introduction

Buildings are a main source of global energy consumption and CO_2 emissions; accounting for about 40% of global energy consumption [1,2] The international contribution to sustainability has generated a large number of publications in relevant journals and conferences over the last four decades [3] and has established a dire need to reduce greenhouse gas emissions [4–6] as these gases are potential causes of threats to the ecosystem such as global warming [7–10]. From the Kyoto protocol of 1997 to the Paris Agreement of 2015, various policy directions have been motivated to mitigate international environmental pollution. Mitigation in various dimensions is a key factor to improving the environment for future generations [11,12]. At the building scale, the potential of on-site renewable energy generation to optimize energy demand and supply infrastructure has been investigated [13–15]. This provides an opportunity to address environmental pollution; which has frequently been linked with the rising level of nonrenewable energy consumption [5]. Building Integrated Photovoltaics (BIPV) provides such an opportunity through clean micro-energy generation being adoptable to various building designs. Several studies indicate that application of BIPV leads to substantial energy savings [16–18] and thus related gains in energy consumption and reduction of pollution sources. BIPV reduces the damage done to the ecosystem through conventional energy sources [19] and is a promising way of relieving the increasing financial and environmental costs of fossil fuel energy generation [20]. Technological advancements have evolved BIPV into a PV application with the capability of electrical delivery at a comparatively lower cost than grid electricity for certain end users in certain peak demand niche markets [21]. As a contemporary material available to architects, BIPV serves simultaneously as a part of the building envelope and an energy source. BIPV systems can be more cost effective simply because their composition and location replaces a number of conventional components and thus provide multiple gains which are reviewed in details in this paper. These include savings in materials and electricity costs, reduced use of fossil fuels, decreasing carbon and greenhouse gases emissions and improved architectural image of the building [22,23].

However, several studies highlight various barriers which are limitations to the widespread adoption of BIPV [24–34]. They range from general product issues such as performance, aesthetics and technical complexity [26] to specific regional issues such as the need for extensive education on professional and public levels [24,25,27]. Greater attention to research and development in customization and BIPV product designs with good architectural aesthetics and integrality have been suggested by reviewers as potential solutions to these [25,26,28,32]. However, our survey of recent BIPV reviews over the last 5 years (Table 1) shows that there is only limited information on customization as potential driver for BIPV adoption. Only partial attention has been made of custom BIPV; relating to mention of strategies [35,36] and cost limitations [37]. In two other cases [38,39] a descriptive inventory of several market-ready custom BIPV product applications connecting cell technology and architectural integration is given [38]. Also, details on the possibilities, market options, and aesthetic levels of customizability were presented [39].

Table 1. Summary of customization content in recent Building Integrated Photovoltaics (BIPV) reviews.

Reference	Title/Focus	Customization-Related Content
[40]	Recent advancement in BIPV product technologies: a review	-
[41]	Embedding passive intelligence into building envelopes: a review	Reference to a system-based process design
[35]	A critical review on building integrated photovoltaic products and their applications	Brief mention
[22]	Double skin façades (DSF) and BIPV: a review of configurations and heat transfer characteristics	Inference to different design modes
[42]	A comprehensive review on design of building integrated photovoltaic system	Reference made to an energy-conscious process design
[39]	Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector	Possibilities, market options, aesthetic levels; an architectural layering process design approach
[43]	PV glazing technologies	-
[36]	Building Integrated Photovoltaics: a Concise. Description of the Current State of the Art and Possible Research Pathways	Brief mention
[37]	Building Integrated Photovoltaics (BIPV): review, Potentials, Barriers and Myths	Brief mention of the need, possibilities and challenges
[38]	'State-of-the-art' of building integrated photovoltaic products	Details on available custom products in the market
[44]	Building integrated photovoltaic products: a state-of-the-art review and future research opportunities	Possibilities and available custom products in the market
[45]	The path to the building integrated photovoltaics of tomorrow	Brief mention of possible future in product variety
[46]	Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: energy, environmental, and economic evaluations	-
[47]	Photovoltaics and zero energy buildings: a new opportunity and challenge for design	-
[48]	Architectural Quality and Photovoltaic Products	Mention of examples, function and challenges

Source: By Authors.

Furthermore, no information or review of experimental investigations on customization is presented to theorize its description or justify its potentiality. This review paper aims to fill this gap as identified in the literature by investigating the characteristics, strategies and potentials of BIPV customization. In addition, the study seeks to showcase the opportunities provided by customization to address the barriers of conventional BIPV.

1.1. BIPV Customisation: Working Definition

Customization is, "the action of modifying something to suit a particular individual or task" [49]. It can also be described as the configuration of products and services to meet customers' individual needs [50]. These definitions suggest that customization is directly associated with the identification of a function, need or objective. As it relates to BIPV, several customization objectives have been investigated, such as aesthetics [51,52], architectural integration [53,54], thermal management [55–57], and shading [15,41,53]. These objectives consequently determine the added function of the designed custom BIPV façade along with energy production from the solar cells. Ref. [39,58] suggest that BIPV designs can follow a systematic design process. This infers that various levels/stages of customization are identifiable; [39] suggests a cell, module, and façade level activity while [58] presents an elemental, compositional, and integrational level of interest. In both representative cases, the idea is to first customize the cell, then the module, and finally the façade.

1.2. Research Design

The present review is divided into three main sections; first an overview on BIPV façades, then an appraisal of standard BIPV barriers, and finally a review of BIPV façade customization studies. Data collection and analysis steps of relevant studies for all sections of this paper were limited to English-language studies found in the ScienceDirect and Google Scholar database. In Section 1, an assessment of the mention given to BIPV customization in previous state-of-the art reviews was presented to validate the need for this investigation. For Section 2, we identified eleven (11) studies within the past five years which focused primarily on a review of barriers inherent to BIPV in general, BIPV products or to BIPV adoption. The selection was limited to the last five years, as BIPV is an evolving technology and this review seeks to identify current mitigating issues. These studies collectively represent the views of several researchers drawn from surveys involving close to 1000 respondents, based on experiences and findings from professionals and researchers worldwide. In Section 3, keywords such as "BIPV customization", "custom BIPV", "customized BIPV" were used in our search, but at the time of writing this review, no studies with these exact words were found. We expanded our search for related titles on BIPV façade customization and identified 25 representative studies with related abstracts and thus focused our investigation on these. Figure 1 shows a color-coded mind map for this investigation; it reflects the research direction and connections, as well as a basis for deductive reasoning which informs the resulting conclusions made in this review. The blue-coded section groups together the research on BIPV types and potential benefits which are discussed in detail later in Section 2 (Overview on BIPV façades). The red coded section combines the barriers that affect BIPV adoption into the built environment later discussed separately in Section 3 (BIPV barriers). The green coded sections put together the specifics of customization as an approach to enhance BIPV adoption into built environment later discussed in Sections 4.1 and 4.2 (BIPV customization investigations). The detailed discussions on the specific findings of the mind map are discussed in the following Sections 2–4.

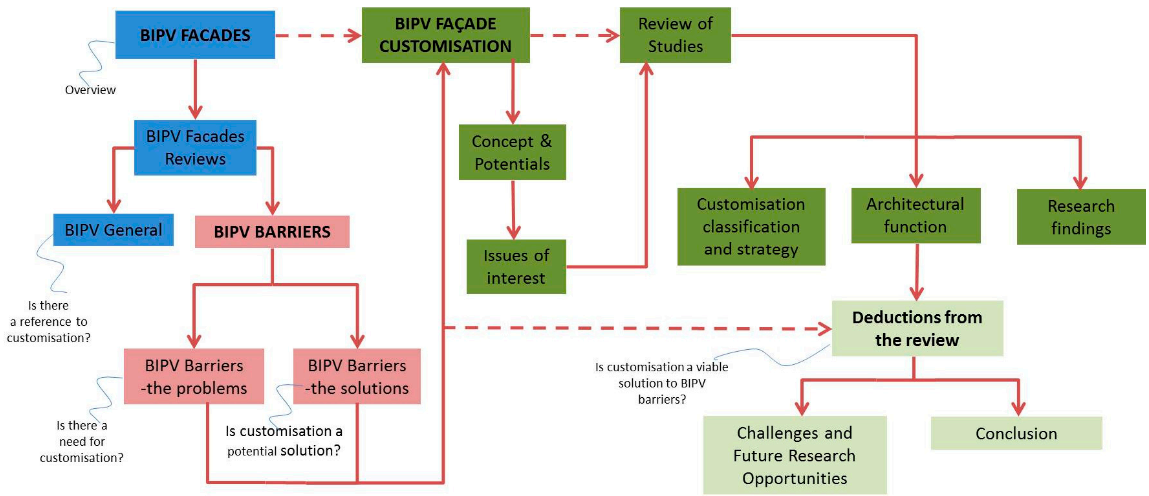


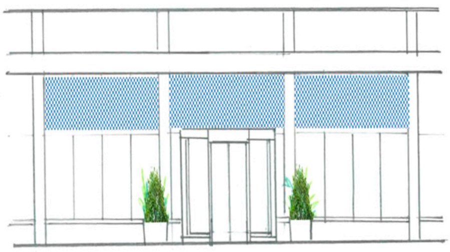
Figure 1. BIPV façade customization review mind map. Source: authors.

2. Overview on BIPV Façade Applications

The building façade is conventionally made up of walls, glazing, cladding and fenestrations; and other structures like shading devices, parapets and balconies. Each of these building components provide opportunities for integrating PVs to the building and by extension, for façade customization [36,37,59–62]. The main BIPV façade applications extracted from literature [39,43,59,61,63] include curtain walls, glazing, external/shading devices, and innovative applications. Table 2 presents an overview of these applications using representative built examples to describe the advantages and disadvantages of each of these types.

Table 2. Design impact of BIPV façade types. Source: authors.

BIPV Façade Type	Design Impact
1. Curtain Wall/Cladding Systems Solar panels integrated as a conventional cladding system for curtain walls and single layer façades [37].  a.	• Advantages – Intelligent way of balancing daylighting and shading [37]. – Iconic importance in the field of architecture [37]. – Different colors and visual effects can be included [61]. – Regulates the internal temperatures of the building by minimizing solar gain in the summer [61]. – Light effects from these panels lead to an ever-changing pattern of shades in the building itself [61]. – Impacts on overall architectural image – Maximizes façade wall for energy generation • Disadvantages – Installation costs can be high [61]. – Potentially less energy than on roof-top [37]. – Requires complex planning and compliance with a great many physical properties [37]. – Properly handling needed to prevent view obstruction by electrical cables
2. Solar Glazing and Windows Applied as semi-transparent/translucent parts of the façade based on solar cell transparency. They can be integrated into windows, glazing panels, for view or daylighting [59].	• Advantages – Allowing for filtered view as well as energy generation [61]. – Potential application as opaque or semi-transparent/translucent glazing [59]



b.

- Special PV elements used thermal insulators in combination with standard double or triple glazing elements [59].
- Added functionality as sun shading
- The patterns from the shading generate a dynamic experience of spatial variety through the day.

• Disadvantages

- Potentially lower efficiencies[37]
- Increase in cell spacing yields less energy due to fewer cells

3. External Devices/Accessories

Sunshades and sunscreens, spandrels, balconies parapets, elements of visual and acoustic shielding [61].

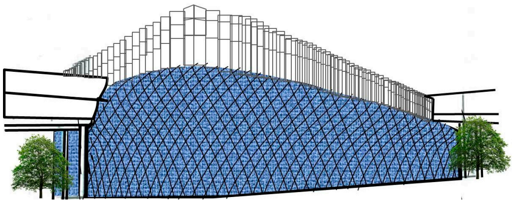
c.

Advantages

- Potential for minimizing both building heat loads and energy consumption [59].
- Vertical or horizontal sun shading provided above windows [61]
- Use of building shading structure as mounting to prevent additional load on façade [61].
- Potential as fixed or adjustable devices [59,61]
- Allows for PV modules of different shapes [61].
- Disadvantages
- Shadows cast from BIPV panels may need filtering to even out light distribution
- Obstruction of view if not transparent or translucent

4. Advanced/Innovative Envelope Systems

Such as double skin façades, active skins, rotating or moving façade parts, etc. [59]



d.

• Advantages

- Integration with advanced aesthetic polymer technologies [59].
- Generation of heat in winter for space heating
- Double skin façades assist in cooling of BIPV panels [64].
- Possible integration with other building elements for performance and aesthetics [53,55–57]

• Disadvantages

- Potentially more expensive than other types
- Energy maybe required for extraction of heat in summer via mechanical means or forced ventilation [64].

a. Curtain Wall of Hanergy Office, Guangdong, China; showing BIPV cladding; b. KTH Executive School AB, Sweden; showing glazing with wide spaced solar cells for daylighting and view; c. Shading devices on Kingsgate House London, UK; showing vertical polycrystalline panels; d. Innovative façade of Hanergy Headquarters, Beijing, China; showing innovative "dragon scale" arrangement of BIPV modules

2.1 Strategic Benefits of BIPV

BIPV is a multifunctional technology and they are therefore usually designed to serve more than one function [36,60,65]. Along with the fundamental function of producing of electricity, the multi-functionality of BIPV thus implies that it can fulfill several other tasks as a façade element such as solar protection and glare protection. Three identified classes of such added function or benefits from literature relate to the building envelope design, economic advantages and environmental impact.

- Design Benefits: relating to architectural integration and function of BIPV as a building component
- Economic Benefits: relating to financial advantages accrued as a result of BIPV application
- Environmental Benefits: relating to micro or macro environment improvements due to BIPV application

The list below contains a categorization of the multiple functions that BIPV modules can perform based on its unique characteristics.

1. Design-related benefits
    a. View and daylighting—semi-transparent options allow for light transmission and contact with exterior [61,66,67].
    b. Aesthetic quality—integration in buildings as a design element [36,61]
    c. Sun protection/shadowing/shading modulation—used as fixed or tracking shading devices [36,37,60,61,67],
    d. Replacement of conventional materials such as brickwork [37].
    e. Public demonstration of owner's green ecological and future-oriented image [61].
    f. Safety—applied as safety glass [61].
    g. Noise protection—reaching up to 25 dB sound dumping [36,37,61,67].
    h. Heat protection/Thermal insulation (heating as well as cooling)—improving the efficiency of cells by cooling through rear ventilation [36,37,61]
    i. Visual cover/refraction—one-way mirroring visual cover [60,61].
2. Economic Benefits
    a. Removal of the need for the transmittance of electricity over long distances from power generation stations [68,69].
    b. Reduction in capital expenditure for infrastructure and maintenance [68,69].
    c. Reduction in land use for the generation of electricity [28,70].
    d. Material and labour savings as well as electrical cost reductions [36].
    e. Reduction in additional assembly and mounting costs, leading to on-site electricity and lowering of total building material costs and significant savings [45]. In addition, ongoing costs of a building are reduced via operational cost savings and reduced embodied energy [71].
    f. Combined with grid connection, FITs; cost savings equivalent to the rate the electricity is close to zero [28,46,72]
3. Environmental Benefits
    a. Reduction of carbon emissions [28]
    b. The pollution-free benefit of solar energy [45].
    c. Reduces the Social Cost of Carbon (SCC) relating to the health of the public and the environment [28].

3. BIPV Façade Applications: Barriers and Strategies

Notwithstanding the stated multi-functionality of BIPV already expressed in several studies, its adoption is globally challenged by certain barriers. It has been argued that sustainability goals of the future can only be achieved if we look beyond new technologies themselves, and account for the complex human factors influencing their adoption and use [73]. Several researchers have investigated these barriers and their studies show that there are various perspectives and issues of concern. These include challenges in the various stages of application [30] such as the design stage and installation stage, and in some regional cases, expertise limitation, lack of promotion, and financial issues [27]. There are also key barriers that are general to BIPV adoption, and in some cases, affect the building integration of other renewable energy technologies. Some of these general issues from a more holistic point of view are sociotechnical, management, economic, and policy-related [29] as well as knowledge and information-related [26]. Others include insufficient presentation of BIPV product and project databases, lack of adequate business models, and insufficient dissemination of BIPV information [24].

In almost all of these studies, strategies for overcoming these barriers have been proposed. These strategies are drivers in various forms with the potential to advance or facilitate the BIPV implementation in the built environment. In some cases, they are proposed solutions to counter one or more barriers when fully applied. Table 3 gives a detailed overview of the findings of these related studies showing a categorization of the barriers and drivers identified to BIPV application; to clearly identify the issues of concern and potential solutions.

Table 3. A detailed overview of identified BIPV barriers and drivers. Source: By Authors.

Barriers	**Drivers**
1. Product efficiency and design	1. Research & Development on product design and design tools
• System performance [25–27,29–31,34] • Design standards, codes and regulations [24,28,30,32,34] • Design tools and software [25,26,30,33] • Aesthetics and architectural integration [25,26,30–33]	• Enhanced product design for architectural integration, innovative manufacturing, customization, standardization and modularity [24,26,28,30,31,33] • Improved product performance [25,26,28,31] • Development and application of Building Information Modelling (BIM), simulation & mathematical software and tools for design, performance monitoring and environmental issues [24,26,28,30,31,33] • International research and design collaborations [24,26,28]
2. Product and project demonstration and databases [24–26]	2. Educational programs and public awareness projects
3. Education	
• Professional training and expertise [24–27,29,30,32–34] • Public awareness and perception [24–29,32–34]	• Professional technical experience, training and development [28–30,32.34] • Development of an international Product and Project database [24,26] • Development of educational material for universities [25,33]. • Increased public knowledge via effective marketing; outreach events; use of specific communication tools for client motivation [24–30,31,34] • Urban demonstration projects on BIPV and energy-related issues [28,32,34]
4. Economy	3. Active governmental interventions
• Material and system costs [25–29,32–34] • Governmental support and policies [26–29,31,33] • International or bank support [27,29,31]	• Dedicated government support and incentives [27,29–34 • BIPV implementation policy formation; [28,29,31] • Non-financial incentives as 'green accreditation' and reduction in lending rates [27,28]
5. Gap between PV and building industry [29,30,32]	4. International professional management and collaborations
6. Management & business and project planning [24,28,29,32]	• Increased collaboration between government, research bodies, manufacturers, building professionals and clients [26,28–32,34] • Development of specific management and business models [24,26,30] • Development of international guidelines, standards and codes for BIPV implementation[24,26,30,31]

The collective information from these 11 studies represents the opinions of close to 1000 international respondents. The summary of these findings was distilled and diagrammatically presented in a force field analysis (Figure 2) for further scrutiny. A force field analysis is a management analytical tool used to conceptualize the forces interacting to promote and oppose change in a given situation [34]. We have applied it to give a visual representation of the barriers, stated as restraining factors and drivers as facilitating factors. Kurt Lewin is often acknowledged as the first to propose this technique in 1951 [74]. The weight of the arrows in this adaptation is shown in percentages, and obtained from the frequency of mention in studies of a barrier or solution.

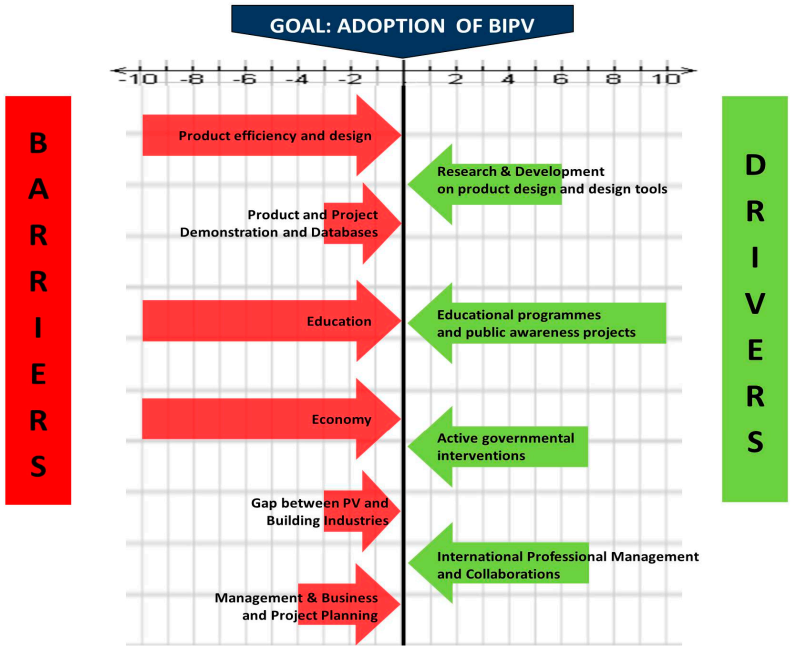


Figure 2. Simplified force field analysis of barriers and drivers of BIPV adoption. Source: By Authors.

3.1 Force Field Analysis: Comparison of Barriers and Strategies

Statistically speaking, six classes of barriers relating to the product, education, economy, and industry were identified in the referred literature with further sub-division of three of these classes. As an example, the product efficiency and design class encompasses related barriers such as system performance, design standards, codes and regulations. It also includes design tools and software, aesthetics and architectural integration issues. As observed from our investigation, the need to address public awareness and perception [24–29,32–34] and the insufficient professional training and expertise [24–27,29,30,32–34] are the most frequently identified barriers to BIPV adoption. This suggests an international agreement that the need for proper education regarding the potentials of BIPV is lacking in both public and professional domains. Comparatively, insufficient product and project demonstration and database, as well as insufficient international or bank support are ranked as the least identified barriers. It may be assumed therefore that client motivation via these latter support schemes may not be directly related to the reluctance to BIPV adoption. Another deduction from this survey is that comparatively, there are potentially more product efficiency and design related barriers, although education issues are deemed more crucial. It may be thus deduced that increase in education, training and expertise can be a tool to address issues with performance.

The analysis shows the combined weight of barriers is 400% (normalized to 40) and the combined weight of the drivers is 300% (normalized to 30). By increasing attention to the drivers, via increased research and development, raising each to a 100%, the combined weight of the drivers will rise to 400% (normalized to 40)—assuming the barriers stay constant. In this scenario, the drivers will effectively cancel out the barriers.

With particular mention to the strategies proposed, our goal was to identify if there was sufficient information to suggest BIPV customization was a potential driver for BIPV adoption. To this end, the need for education related to design integration such as BIPV variety relating to technological choice, aesthetics, color, shape and size has been identified [25]. Improvements in product design with appeal to architects was mentioned as a potential solution; relating specifically to aesthetics [25,26,32,33], directly to customization and variety [25,26], and architectural integration [25,26,28] and innovation [30]. Thus, customization driven by variety, aesthetics and architectural integration has been identified as a potential driver of BIPV adoption. This justifies the need to further investigate BIPV customization studies and the validation of their potential to address these barriers as mentioned.

4. BIPV Façade Customization: Critical Review of Investigations

As architects are saddled with the responsibility of building design; it is pertinent to understand fully the opportunities provided by BIPV in order to communicate them effectively to clients [75]. It has been put forward that the success of the BIPV market will in part be determined by the availability of good customizability and convincing aesthetics [39]. It terms of the need, one aspect mentioned by [76] suggests that standardized products are often not applicable when retrofitting demands flexible dimensions, and custom products have better thermal performance than conventional products [77]. Another research posits that aesthetics, dimensional requirements focused on customization capacity and functionality ought to drive the requirements for the BIPV façade [78]. Thus, this calls for innovative approaches with custom-made products as some have huge potential for energy conservation and thermal comfort [79]. Most manufacturers provide custom-made BIPV services, such as the possibility to produce modules of various power output, form, glass serigraphy/printing and colors, as well as to change the cell arrangement and the glass surface (clear glass, prism, enameled) with different properties (i.e., glare reduction) and finishing [39]. This section however, focuses on BIPV façade customization from the perspective of research investigations to identify the potentials of custom BIPV already mentioned in this review. This perspective was chosen to detail the unbiased results of research experimentation without the inhibition of market performance or worthiness.

4.1. Methodological Approach

This section focuses on the details of the investigative analysis of the 25 selected papers on BIPV customization. As earlier stated, the result of the review was used to check the applicability of BIPV façade customization to address the barriers of standard BIPV. Four (4) aspects of review were selected which are Innovation & custom category, Customisation strategy, Architectural function and Research results. These describe various aspects of BIPV façade customization and form the framework for this evaluation. Figure 3 shows these related aspects as a research guide; with further explanation briefly presented following the figure to explain the definitions and state the importance of each aspect of the review.

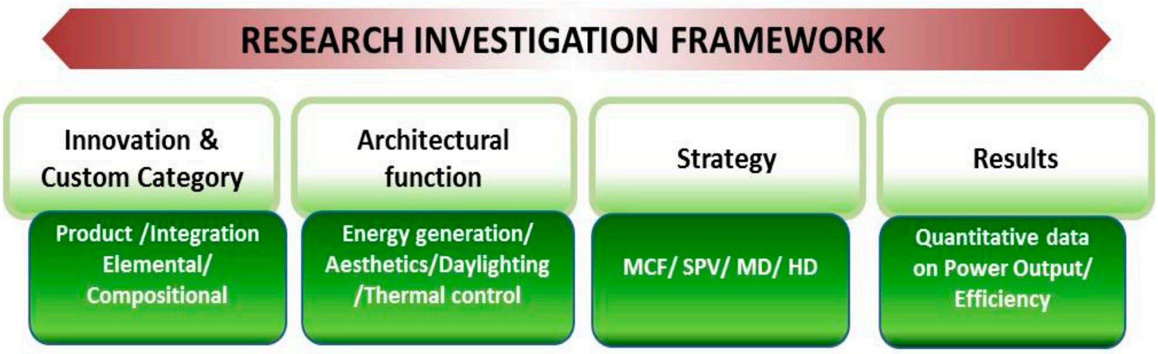


Figure 3. Research investigation framework. Source: By Authors.

1. Innovation and Custom Category: Product/Integration/Elemental/Compositional

This establishes whether customization is the design of a new product or a developed system of integration. Next, the identification of the customization level with regards to the aspect of the BIPV façade for which parametric variation was investigated. In this regard, several other authors suggest that a sub-division of BIPV exists by its constitution, being the elements that make up the modules and the composition that makes up the façade [35,38,39,58,60].

- The Elemental Level: this represents the breakdown of a BIPV module into various components i.e., the solar cells, frame, glass and other protective layers; reflecting customization of cell or glass or layer type; colors or efficiencies.

- The Compositional Level: this represents the composition of the cells of the BIPV module (module-level), relating to cell spacing and the modules of the BIPV façade (façade-level), relating to tilt angle or spacing from wall for example.

2. Customization strategy: Standard/Custom/Module/Façade design manipulation

In each of the studies various strategies have been employed to customize the BIPV façade. This section helps to provide an inventory of various strategies, categorization for further analysis, possible requirements, limitations and challenges, as well as directions for possible improvements.

These groups are;

- Systematic Parametric Variation (SPV): iterative parametric changes to reach an optimum goal
- Modification of Conventional Features (MCF): modification of conventional BIPV parts
- Enhanced Design Modularization (EDM): upgrade of BIPV façade types into unique modules
- Compositional Modification and Hybridization (CMH): combination of special materials with BIPV

3. Architectural function: energy generation/aesthetics/daylighting/thermal control

This section represents the stated, implied and potential functions of the custom BIPV façade in each study. It informs the specific custom function and provides justification to debate the sustained multi-functional advantage of BIPV. It also indicates if a connection exists between the customization category and level, and the potential architectural function.

4. Results: Power Output/Cell efficiency/Heating or Cooling loads

As the focus of this review is to validate the potential of BIPV customization as a solution to standard BIPV challenges, we also extracted the specific qualitative or quantitative data from the studies as made available. In some cases data on power output of BIPV façade output was provided which was;

- A comparison with a base case (standard BIPV);
- Hot climate results as representative of intense scenarios (where multiple climatic data was presented), or
- Highest output (where optimization based on parametric variation was investigated)

Table 4 details the investigated cases based on the research investigation framework explained above. It presents a concise summary to reflect how each study addressed BIPV customization to meet certain pre-defined objectives. All deductions from made from the experimental investigations were synthesized and analyzed in the discussion that follows the table.

Table 4. Research investigations on BIPV façade customization.

Reference	Country of Study (BIPV Location on Façade)	Deductions from Experimental Investigations					Research Results
		Objective	Custom Category/Class of Study	Customization Level Investigated	Strategy (Description)	Architectural Potential	
[51]	Taiwan (Wall)	Development and analysis of a full-colour PV module	Product/Design and fabrication	Elemental (Full-colour and monochromatic coloration of module parts)	Modification of conventional features (MCF) (Color image on backsheetglass with applied grayscale mask)	Energy generation; Aesthetics	Short Current density: 0–14% reduction Cell efficiency : drop to max of 10% Power: 14.2% reduction
[53]	Switzerland (External Device)	Design, fabrication and testing of an adaptive solar façade	Product & Integration/Design and fabrication; Performance Optimisation; Architectural Integration	Compositional @Façade-level (dynamic façade patterns and flexible tilt angle)	Enhanced design modularization (EDM) (Highly modular dynamic BIPV façade with a suitable support structure, tracking and control systems)	Energy generation; Thermal Control; Energy saving; Aesthetics	Power: 36% increase Total energy savings: 31% increase Energy consumption: 8.9% decrease CO_2 offset: 15.3 kgCO_2-eq per year based on the European Union grid mix.
[80]	Austria (Glazing)	Plasmonic coloring on c-Si PV modules	Product/Design and fabrication	Elemental (Cell coloration)	MCF; (Silver film deposition on c-Si modules with Ag thermal annealing.)	Energy generation; Aesthetics	Short circuit current: average of 10.7% reduction Open circuit voltage: average of 1.1% increase Fill factor: average of 3.07% increase Maximum Power/Efficiency: average of 8.3% reduction
[81]	South Korea (External Shading)	Application of layering effects to a BIPV façade	Product/Design and fabrication; Architectural Integration	Compositional @Module-level (Coloration of backsheet and Cell arrangement)	EDM (Layered effects to BIPV module: unique architectural finishing of glass sheets, coloration of backsheet with patterned cell arrangement.)	Energy generation; Daylighting; Aesthetics	Architectural layering and modularization approach enabled application and adaptation of the described effects specifically developed to meet unique requests from clients; No performance data was available.
		Modular retrofitting of a BIPV façade	Integration/Architectural Integration	Compositional @façade-level (tilt angle)	EDM (Modular retrofit and prototyping based on design of conventional façades)	Energy generation; Daylighting; Aesthetics	
[63]	Switzerland (Cladding)	Retrofitting of a prototype residential block with BIPV	Integration/Architectural Integration	Elemental (Cell transparency); Compositional @Façade-level (Module position)	EDM (adaptation of BIPV typologies to blend with convemtional facade prototypes)	Energy generation; Thermal control; Daylighting; Retrofitting; Aesthetics	No extra complexity recorded in application of the method and façade construction. Qualitative assessment of interviewed professional adjudge that aesthetical aspects as positive .
[82]	Korea (Window)	Colored a-Si:H transparent solar cells employing	Product/Performance and Optimization;	Elemental (Electrode and Backsheet	EDM; systematic parametric variation (SPV); MCF (Transparent	Energy generation;	Cell Efficiency: average of 6.36% at 23.5% average

		ultrathin transparent multi-layered electrodes.	Architectural Integration	transparency, Colour variability)	multi-layered electrodes (TMEs) with customizable coloration of optoelectronic controlling layer (OCL)	Aesthetics; Daylighting	transmittance with TME @500–800 nm Ave Open circuit voltage:0.8 V Ave Fill factor: 54.66%
[83]	China (Window & Double Skin Façade)	Comparison of energy performance between PV double skin façades and PV insulating glass units	Product/Design and fabrication; Performance and Optimization; Architectural Integration	Compositional @Module-level (Module Position, Air gap)	MCF; SPV; (Regulation of air gap)	Energy generation; Thermal control; Daylighting; Energy saving; Aesthetics	Ave. SHGCs: 0.152 (PV-DSF) and 0.238 (PV-IGU) Ave. U-value: 2.535 W/m^{2}K (PV-DSF)and 2.281 W/m^{2}K (PV-IGU) Conversion efficiency of PV-DSF is 1.8% better than PV-IGU Approx. power output: 0.01–0.3 kWh (PV-DSF); 0.01–0.32 kWh (PV-IGU) Energy Saving potential: 28.4% (PV-DSF) and 30% (PV-IGU)
[84]	China (Double Skin Façade)	Overall energy performance of an a-si based photovoltaic double-skin façade	Integration/Design and fabrication; Performance and optimization; Architectural Integration;	Compositional @Façade-level (Ventilation mode)	MCF; SPV; (Change in ventilated modes for PV-DSF)	Energy generation; Thermal control	Ave SHGC: 0.14 (Non-Ventilated), 0.15 (Naturally-Ventilated), 0.125 (Ventilated) U-value: 3.3 (Non-Ventilated), 3.7 (Naturally-Ventilated), 4.65 (Ventilated)
[85]	Switzerland (Window & Wall)	Performance investigation of selected BIPV façade types.	Product & Integration/Design and fabrication; Performance and optimization; Architectural Integration	Elemental (Cell technology, cell transparency); Compositional @Module-level & Façade-level (Module Position, Air gap, Tilt angle)	SPV; Variation of BIPV module position and ventilation mode	Energy generation Thermal control Daylighting Shading Aesthetics	Approx. power output: 3–11 kWh (c-Si @30°); 2.5–8 kWh (c-Si @90°); 0.6–2.1 kWh (a-Si @30°); 0.5–1.45 kWh (a-Si @90°); 0.8–2 kWh (a-Si @90°-ventilated)
[86]	China (Window)	Assessment of energy performance of semi-transparent PV insulating glass units	Product & Integration/Design and fabrication; Performance and optimization; Architectural Integration	Elemental (Backsheet); Compositional @Façade-level (Air gap)	MCF; SPV; (Variation of air gap and backsheet material)	Energy generation; Thermal control; Daylighting; Energy saving	Ave. PV temp: 23–42 °C Ave. Daylight illuminance: 0–360 lux Ave. Heat gain: −12.5–165 W/m^2 Power output @ air gap: 67.41 kWh @3 mm; 67.35 kWh @6 mm; 67.32 kWh @9 mm; 67.3 kWh @12 mm; 67.29 kWh @15 mm Power output @backsheet type: 67.32 kWh (Clear glass); 66.84 kWh (Low-e glass); 67.4 kWh (Low iron glass): 67.2 kWh (Tinted glass)

[87]	USA (Window)	Energy benefits from semi-transparent BIPV window and daylight-dimming systems	Product & Integration/Performance and Optimization; Architectural Integration	Elemental (Cell transparency and efficiency); Compositional @Façade-level (Orientation and WWR)	MCF; SPV; (Use of a DOE-2 based calculation algorithm simulations of parameterised vaules)	Energy generation; Thermal control; Daylighting; Shading; Energy savings	Power output range on south façade/month: 35.1–71.9 kWh @6.65 efficiency, 40% transparency, 48 W 46.4–95.4 kWh @8.82 efficiency, 20% transparency, 64 W 52.4–107.2 kWh @9.91 efficiency, 10% transparency, 72 W Approx. Annual Power output @WWR: 1165 kWh @10%; 3496 kWh @30%; 8157 @70%
[88]	Canada (Double Skin Façade)	Patterns of façade system design for enhanced energy performance	Product & Integration/Performance and Optimization; Architectural Integration	Compositional @Module-level (Module placement/arrangement)	MCF; SPV; EDM (Manipulation of planar geometry to induce increase in solar capture)	Energy generation; Thermal control; Aesthetics	Comparison with base case: Power Output: 20–80% increase Heating load: about 200% increase (worst case) Cooling load: about 52% reduction (best case) Peak electricity: peak spread of 4–5 h.
[55]	Pakistan (Wall)	Energy and Cost Saving of a Photovoltaic-Phase Change Material (PV-PCM) System	Product/Design and fabrication; Performance and Optimization; Cost	Elemental (Phase-change materials); Compositional @Module-level (Module design)	SPV;CHM; EDM (Passive cooling of BIPV with solid-liquid PCMs)	Energy generation; Thermal control	Temperature drop: 16% (PV PCM-1); 32.5% (PV PCM-2) Ave energy efficiency increase: 7% (PV PCM-1); 10% (PV PCM-2)
[89]	China (Wall)	Analysis and monitoring results of a BIPV façade using PV ceramic tiles	Product/Design and fabrication; Performance and Optimization; Architectural Integration	Compositional @Module-level (Module Position/Module Arrangement)	MCF(Replacement of module backsheet with ceramic tile)	Energy generation; Thermal control; Aesthetics	Ave. power output: 15–72 kWh (east); 15–65 kWh (West); 1–72 kWh (south); 0–18 kWh (North)
[90]	UAE (Double Skin Façade)	Performance and energetic improvements due to installation of semi-transparent PV cells	Product & Integration/Design and fabrication; Performance and Optimization; Architectural Integration	Compositional @Module-level & Façade-level (Number of glass layers, Ventilation mode)	MCF; SPV; (Application of alternate ventilation modes and number of glass layers)	Energy generation; Cladding	Sensible cooling energy need reduction: 1.5% (DSF forced vs. natural), 1.9% (Single Layer forced vs natural) Peak power drop: 4% (DSF forced vs natural), 2.3% (Single Layer forced vs natural) Annual energy production increased by 2.5 (DSF) 6% (Single Layer)
[17]	USA (Ventilated Double Skin Façade)	Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin façade	Product & Integration/Performance and Optimization; Architectural Integration	Compositional @Façade-level (Air gap, Orientation)	MCF; SPV; EDM (Application of alternate air gaps and orientation in office room prototype room)	Energy generation; Thermal control; Daylighting; Shading	Approx. ave. electricity use: 300 kWh (100 mm); 310 kWh (200 mm); 285 kWh (400 mm); 270 kWh (600 mm) With 400 mm: Max power output range on south façade/month: 10.3 kWh

							(June)–20 kWh (November) Approx. Annual Energy output: 48 kWh/m^2 (East), 64 kWh/m^2 (South), 54 kWh/m^2 (West) Approx. cooling need: 18–270 MJ Approx. heating need: 0–35 MJ Ave. daylighting illuminance/month: 130–300 lux Observed 50% less net electricity that conventional glazing systems
[91]	Slovakia (Ventilated PV Façade)	Thermal Performance of a Ventilated PV Façade Coupled with PCM	Product & Integration/Design, Performance and Optimization; Architectural Integration	Compositional @Module-level (Module design—addition of PCM)	CMH; SPV (Hybridisation of BIPV with PCM layer)	Thermal control	PV temp decrease: up to 20 °C Peak temp. shift: more than 5 h
[92]	France (Ventilated PV Façade)	Experimental evaluation of a naturally ventilated PV double-skin building envelope in real operating conditions	Product & Integration/Design and fabrication; Performance and Optimization; Architectural Integration	Compositional @Module-level (Module arrangement)	MCF; SPV (Utilising the stack effect to cool a prototype pleated PV double façade)	Energy generation; Thermal control; Daylighting; Shading; Aesthetics	Approx. Peak power output per plane: 165 kW (Bloc1); 200 kW (Bloc2); 210 kW (Bloc3) Prismatic configuration was chosen to compensate for façade azimuth—overshadowing in part; improvement in electrical performance by a more favorable orientation of solar cells
[93]	UAE (Window Blinds)	Energy, Cooling and Cost analysis of BIPV blind system	Product & Integration/Design and fabrication; Performance and Optimization; Architectural Integration; Cost	Elemental (cell technology); Compositional (Module position)	EDM; SPV (Prototyping based on conventional façade design component)	Energy generation; Thermal control; Cost issues	Ave. power output: 41.55 kWh/m^2 (c-Si); 43.22 kWh/m^2 (a-Si) Cooling load Energy Saved: 7.11 kWh/m^2 (c-Si); 6.89 kWh/m^2 (a-Si)
[64]	China (PV-Blinds in Double Skin Façade)	Comparative study on thermal performance evaluation of a new double skin façade system integrated with photovoltaic blinds	Product & Integration/Design and fabrication; Performance and Optimization; Architectural Integration	Compositional @Module-level (Module Position/Tilt angle)	SPV (Experimentation on different system ventilation modes and blind parameters)	Energy generation; Thermal control; Daylighting	Approx. SGHC peak (@4.5 cm spacing): 0.75 (30°); 0.95 (45°); 0.97 (60°); (based on ventilation mode): 0.499(Mechanical); 0.531(Natural) About 12.16% and 25.57% compared with reference DSF cases

[94]	China (Ventilated Double Skin Façade)	Thermal performance of a photovoltaic wall mounted on a multi-layer façade	Integration/Performance and Optimization; Architectural Integration	Compositional @Facade-level (ventilation mode)	SPV (Mathematical modelling and variation of ventilation modes)	Energy generation; Thermal control	Ave SHGC: 0.14 (Non-Ventilated), 0.15 (Naturally-Ventilated), 0.125 (Ventilated) U-value: 3.3 (Non-Ventilated), 3.7 (Naturally-Ventilated), 4.65 (Ventilated)
[52]	(Glazing)	Aesthetic improvement of PV for Building integration Encapsulants	Product/Design and fabrication; Architectural Integration	Elemental (Encapsulant material)	MCF (Coloration of encapsulant material using florescence dyes)	Energy generation; Aesthetics	Power output increase: 2.0 %(Clear Sylgard 184); 2.5% (Red 100 ppm Lumogen dye in Sylgard 184)
[95]	Italy (Glassblocks)	Evaluation of prototype BIPV optical performance	Product/Design and Fabrication; Performance optimization	Compositional @Module-level (position of solar cells)	CMH; EDM (Prototyping based on conventional façade design component)	Energy generation; Aesthetics; Daylighting; Thermal Control	Power output reductions: 19.67% (DSSC Part of Surface); 6.01% (All of Surface); 54.09% (Interior of Surface); 69.94% (Middle of Block)
[96]	Netherlands (Wall)	Aesthetics preservation BIPV façade using Zigzag geometry	Product/Design and Fabrication; Architectural integration	Elemental (colour of reflector layer); Compositional @Facade-level (tilt angle)	EDM; MCF; SPV (Concealment of PV via zigzag geometry to enhance solar capture)	Energy generation; Aesthetics	Monthly Power output: 28.6 kWh (Grey), 30.7 kWh (White) Performance ratio increase (ref. vertical panels): 43.75% (Grey), 53.75% (White)

4.2. Assessment of BIPV Customization Parameters

Table 4 shows that all the studies reviewed give focus to energy generation and architectural integration; most also focus on performance and optimization of the BIPV façade; few focus on cost and environmental issues. This is reminiscent of the general fact that a BIPV façade is primarily a building element with energy producing capability. Thus, its integration and optimization of its performance are significantly important. The country of study and BIPV façade type highlight the potentiality in a variety of countries and application in building location. The variety of objective and approach in the various studies was expected, and provided a broad spectrum to carry out the review. However, in order to provide a sensible analysis, categorization was done at each stage without bias to the original intent of the researchers.

4.2.1. Innovation and Custom Category

Statistically, nine of the cases focused on design of a custom BIPV product [51,52,55,80–83,89,95], only four focused on a customization in the integration process [63,81,84,94], while 12 combined both product and integration concerns in their research [17,53,63,64,85–88,90–93]. This suggests that most custom BIPV façade products are designed with attention on the potential for proper architectural integration. Each approach is uniquely different, yet they meet the same goals of energy generation, aesthetics, and daylighting or thermal control. It is important to consolidate at this point the fact that conventional BIPV façades can provide some of these gains along with energy generation. However, these customized BIPV have the potential to out-perform standard types based on pre-design specifications and functionally-driven objectives, which emphasize these other benefits.

Regarding the customization level, four were purely elemental [51,52,80,82], eight were compositional at the module-level [64,81,83,88,89,91,92,95], and five were compositional at the façade-level [17,53,81,84,94]; eight studies combined all of the levels [55,82,85–87,90,93,96]. Comparing elemental versus compositional level, studies can be more easily carried out using conventional PV modules without the requirement of a custom-designed module. As this will require less time to fabricate the test specimens, it is probable that compositional studies are thus preferred, and were thus more numerous. However, using conventional modules for customization suggests innovative and creative applications.

4.2.2. Customization Strategy

The studies showed varying levels of complexity in the strategies used to achieve the objective of customization. It is clear from the examples that this was achieved by an interdisciplinary approach to BIPV product design. It therefore suggests that the accomplishment of custom BIPV modules requires input across several disciplines. While this may be more demanding and expensive, it creates the opportunity for greater novelty and innovative ideas. Enhanced flexibility and variety was noticed in the strategic approach applied in custom BIPV integration studies.

In the investigated cases, three were SPV [64,85,94], four were MCF [51,52,80,89], four were EDM [53,63,81], and 14 combined two or more strategies [17,55,82–84,86–88,90–93,95,96]. Clear evidence thus presents a combination of various strategies is required to achieve BIPV façade customization. In the cases of combined strategies, most of the studies addressed customization at both an elemental and compositional level, reflecting a holistic approach. Furthermore, most of the studies in this class were carried out to address aesthetic or thermal control objectives. Deductively therefore, the combined strategy approach is preferred for BIPV façade customization as it covers various multi-dimensional issues in the design.

4.2.3. Architectural Function

All the studied cases showed interest in energy generation potential of the custom BIPV, but to varying degrees. With regards to the added functions, [17] studies addressed thermal control [17,53,63,83–89,91–95], [15] addressed aesthetics [17] and, [11] addressed daylighting functionality based on research objective or cell type selection as all a-Si applications permit some degree of light transmission [7,63,64,82,83,85–87,92,95]. Also, three addressed energy savings [53,83,87], four specifically on shading [85–87,92], and one on cladding [90] and cost [93].

The review shows that although all focused on energy generation of the custom BIPV façade, all focused also on at least one or more added function. More than half of the studies were on thermal control—in terms of added BIPV function; proving capture and reuse of PV thermal energy, as well as reduction of direct solar radiation to the interior. A sizeable number of the studies show a connection with the goal of improving the thermal control or aesthetic appeal of the product. It suggests that customization of BIPV products is in some way primarily driven by these two objectives. We observed that the architectural functions were achieved by all the classified strategies. The import of this finding is that categorization developed for this review of customization strategies for BIPV façades is justifiable, flexible and versatile in applicability.

4.2.4. Results

Performance data from the studies were varied and not reflective of comparisons with a conventional BIPV or a reference case in most cases. Were available, a 4–70% reduction related to power output was observed [51,80,90,95] and a 2–80% increase [52,53,55,96]. It is important to observe that these studies used different strategies with different reference cases. As these studies were also in different climates it is not possible to make a general conclusion on these results. They are however representative of the fact that BIPV façade customization has potentials for performance improvements or otherwise based on the design and specifications

Of the studies related to thermal control with reference cases, 3 showed improvements in relation to power output while 1 showed reductions. Of the studies related aesthetics with reference cases, 4 showed improvements in relation to power output while 2 showed reductions. This suggests the in comparative situations, the process of customization can enhance thermal control and aesthetics with satisfactory performance related to power output.

5. Challenges and Future Prospects

Several challenges exist with the concept of BIPV customization in general and specific terms and several studies have outlined these barriers [24–34,97]. Firstly, BIPV itself is still in a technological developmental phase. Its full potential is yet to be maximized and studies argue that there are still design codes and standards for application that are not full developed [24,28,30]. This review has further brought to light the vast variations in strategies and approaches with BIPV façade customization. Developing a framework for analysis is thus potentially challenging and requires certain generalizations.

Specific to BIPV façade customization objectives, thermal control and aesthetics were identified as the most frequently studied. However, the several of strategies used in both cases required special manufacturing processes which are not yet standardized on a large scale. Thus, problems with cost, machinery, and standards exist. This scenario is worsened by the identified gap between the PV and building industry [29,30,32]; as the lack of willingness to adopt new technology can be a drawback for custom applications. Further research is required to standardize the assessment of custom BIPV and develop a model for evaluation of strategies. This review intended to identify the potentiality of BIPV customization but does not answer questions related to climatic or regional applications. Customization in relation to cost issues is another area that presents further research potential to yield clear evaluative data. The cost and efficiency of a BIPV system can be lowered by reducing PV module and component manufacturing costs, improving PV and other component efficiencies, and understanding whole life cycle costs [21,98] in relation to local factors and the context when used a building skin[99].

A comparative analysis between research driven BIPV customization and commercial custom BIPV products is also required to reflect the quantitative and qualitative dimensions of the variations in performance and perception. The main bottleneck discovered during a BIPV study conducted in an European research project, was in the ability to communicate this enhanced value and the new possibilities to customers and thus justify the higher cost -generally an increment around 20% [66].

Thus, custom BIPV potentials require proper communication of potentials to both the public and professionals.

6. Conclusions

This review strategically raises a theoretical background for a renewed focus on BIPV customization. It is clear that there are several experimental studies which engage in this strategy at one level or the other. Our findings indicate that BIPV façade customization can be carried out with significant advantages which include:

1. Flexibility and applicability at an elemental and compositional level
2. Versatility in development of both custom BIPV products and custom BIPV integration schemes
3. Multiple type strategies in single or combined scenarios can be used to achieve objectives
4. Increase in power output and performance is possible in a range of 2–80% based on design
5. Although, reduction in power output and performance occurs also at a range of 4–70% based on design

In summary, we conclude that BIPV façade customization can address some of the barriers with conventional BIPV façades relating to product efficiency and aesthetic design. It can also be a driver of enhanced innovative product design for architectural integration. The extensive research and global interest in BIPV over the last one decade is not likely to abate. Areas such as daylighting, self-cleaning PV glazing, aesthetics using color, form or shapes, concentrating BIPV, perovskite-based solar cells and solar trees are some of the emerging areas [36,45,100–103]. With shifting policies, government tariffs and policy changes, it will also be interesting to investigate the possibility of using demonstration projects in certain regions as a push for BIPV-wide acceptance. Such projects will be opportunities to communicate the significant benefits of BIPV customisation and advance its adoption.

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