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Review

Paper Review of External Integrated Systems as Photovoltaic Shading Devices

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Abstract: The building sector contributes to 40% of the total final energy consumption and 36% of CO2 emissions in Europe, and these are set to increase in the coming years. International directives are pushing towards a decarbonisation roadmap to improve the quality of cities and the health of citizens. Buildings have a potentially central role in terms of energy transition as a means to produce and save energy. Photovoltaic shading devices (PVSDs) protect buildings from direct solar radiation and overheating while producing renewable electricity onsite and increasing the users' thermal comfort. Even though the potential of the PVSD is considerable, the sector is still unexplored, and few studies on the topic are available in the literature. This systematic review aims to present an exhaustive overview of the current literature on state-of-the-art PVSDs by analysing the scientific framework in terms of the status of the research. It presents a performance-based approach focusing on innovative products, PVSD design strategies, and energetic performance in distinct climate conditions and configurations. In particular, 75 articles and about 250 keywords were identified, selected, and analysed. The literature review serves as a basis for further R&D activities led by both the industrial and the academic sectors.

Keywords: building integrated photovoltaic (BIPV); photovoltaic shading device (PVSD); literature review

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1. Introduction

The world energy consumption is expected to grow by up to 50% by 2030 compared with 1990 due to urbanisation and population growth [1,2], and the building sector contributes to 40% of the total final energy consumption and 36% of CO_2 emissions in Europe (EU Science Hub). To achieve carbon neutrality by 2050, all the new and 20% of the existing building stock would need to be zero carbon by 2030 [3]. The international directives push towards a decarbonisation roadmap to increase citizens' and cities' long-term quality of life. To achieve the building industry's decarbonisation, solar energy is one of the most reliable, environmentally friendly, and promising technologies [4]. A PV system is defined as a building integrated photovoltaic (BIPV) when it replaces the functions of conventional building envelope solutions, including the essential requirements of construction products, such as mechanical rigidity, fire or noise protection, primary weather impact protection, thermal insulation, shading, etc. A BIPV module is a PV module and a construction product simultaneously [5,6]. When a PV system is installed in the building skin, it can increase the proper surface dedicated to energy production, contribute to land savings, and minimise the environmental impact [7]. In this regard, photovoltaic shading devices (PVSDs) are considered building integrated solutions. A PVSD is a BIPV external integrated device classified as an element of the building skin, even though it is in contact only with the outdoor environment due to its main functionality [8]. In particular, a PVSD contributes to a reduction in the energy consumption of buildings by protecting them from direct solar radiation and overheating while producing renewable electricity onsite and increasing the thermal comfort of the users [9–11]. Finally, the use of PV panels in buildings could reduce capital costs (e.g., material savings) and running costs (e.g., maintenance—cleaning of panels) and improve the design solution profit rate [12].

1.1. The Aim of the Study

The motivation behind this paper is to analyse the current (up to the present year, 2023) status of PVSDs in the literature by analysing the framework in terms of the existing technologies, the status of the research, the energetic performance, and the design strategies in order to provide the basis for further R&D activities led by both the industrial and the academic sectors. It provides an integrated and synthesized overview of the current state of knowledge on PVSDs by presenting a performance-based approach focusing on energy performance in distinct climate conditions and configurations (energy savings and energy generation) and on additional information related to the PVSD design. This paper does not investigate design strategies, technical solutions, or energy and comfort performances that are not included in the papers selected here. Future considerations might include a validation of PVSDs in relevant environments. The research focuses on external BIPV integrated devices used as solar shading systems. Thus, semi-transparent photovoltaic systems used in the glazing units of windows have not been included within the analysis, even though they occupy a large share of the BIPV market. The analysis of semi-transparent BIPV solutions could be an objective of further studies.

1.2. Previous Literature Reviews Based on PVSDs

Literature reviews on PVSDs were performed in 2018 and 2017, and in 2022 on control methods for PVSDs. In particular, in [4], an accurate analysis of PVSDs is presented, in which it is highlighted that there are few PVSD products and that there exists a lack of knowledge about the theme. For a successful application of PVSDs, a comprehensive approach is suggested in [13]. It sets out to review the state-of-the-art integrated PV shading devices and their application to highly and fully glazed façades. The results highlight the fact that few studies on the topic are available. In that analysis, a comprehensive method regarding how the calibration of the parameters influences the system's performance is missing. In [14], a very detailed summary of PVSDs and the related control systems are presented. The analysis is focused on current control methods for PVSD systems in buildings. An overview of the geometrical and architectural features of PVSDs is presented in [15], as a small part of a study which is focused on BIPV systems. As mentioned in [10], two methodologies to approach dynamic PVSDs have been identified: the theoretical method based on computer simulations and the experimental process. The second method is more reliable, but not many systems have been analysed accordingly. Few literature reviews on PVSDs have been presented so far, and those which are available are not focused.

The presented investigation differs from those of [4,13–15]. Specifically, this literature review presents a performance-based analysis of the main results that have emerged from the research journals analysed.

2. Methodology

Even though the interest in PVSDs has been increasing over the last few years, the sector is still unexplored, and few studies on the topic are available in the literature. This review paper, by including both quantitative and narrative or more qualitative components, is intended to provide the conceptual frameworks, the state of the art, the missing gaps, and the inconsistencies and to synthesize the diverse results in the extant body of research and the "state-of-the-art" by analysing papers on PVSDs.

2.1. Source of Information and Eligibility Criteria

The investigation of PV shading devices for transparent facades was conducted to present an exhaustive overview of the current state-of-the-art PVSDs in the literature.

The research was performed using the bibliographic databases of scientific publications, Science Direct and Scopus. The field of research was limited by identifying keywords for PVSDs, which were clustered into three parameters: photovoltaic, shading system, and building, as shown in Table 1 [4]. According to the selected parameters and the relevance to the key topic "photovoltaic shading device" and the sub-topics "design strategies", "energetic performance", "energy savings", and "innovative solutions", 75 journal papers were identified, selected, and analysed. The selection of scientific publications represents the core of the literature review and the representative state-of-the-art PVSDs.

Table 1. Field of research clustered into parameters and keywords.

Parameter	Keyword
Photovoltaic	PV, BIPV, building integrated photovoltaic, solar, renewable energy, energy production, module, electricity
Shading system	Blind, venetian blind, shading device, louver, louvre, overhang, canopy, fin, eggcrate, innovation, design strategies
Building	nZEB, nearly zero energy building, construction, energy demand, renovation, energy-saving

2.2. Data Analysis and Reporting Methodology

Seventy-five papers, published in the past eleven years (2011–2023), were selected. The status of the research, in terms of identification of the study typology, location, and working group, was defined by analysing the 75 identified research journals. The type of technology was defined on the basis of the insights presented within the analysed papers, and the authors provided a universal terminology and a schema of the analysed technologies to classify the technological systems and to align the terminology registered within the papers analysed.

2.3. Additional Analyses

Certainly, the large number of stakeholders included within the value chain of BIPVs can create complexity [7]. The presented literature review also aims to collect key information identified within the analysed articles to provide helpful information for the stakeholders of the BIPV value chain. The presented literature review offers an overview of the main information identified within the articles analysed, including (i) design strategies; (ii) energy performance: PV generation and savings; and (iii) innovative solutions. The abstract, the main results, and the conclusions and the identified papers have been read in depth, and the principal insights have been registered. As innovative solutions are presented in detail, some PVSDs are defined as innovative because of their stage of development and distinctiveness within the BIPV framework.

3. Results and Discussion

The 75 research journals are shown in Table 2 and are classified based on specific parameters, including (i) year of publication, (ii) working group and study location, (iii) author keywords and validation method, and (iv) type of technology adopted. Within the following paragraphs, the analysis of the parameters is presented.

Table 2. Research journals selected for the literature review.

Reference Number	Study Location	Keywords	Validation Method	PVSD
[16]	Thailand	Diffuse radiation reflection; Exterior wall; Shading device integrated photovoltaic; Thailand building	Simulation	PV panel
[17]	South Korea	BIPV; CFD; Efficiency; Power generation; Remodelling	Simulation	PV panel
[18]	South Korea	Optimization of a PVSD in office building	Simulation	PV louver
[19]	South Korea	Heat exchange network analysis; Photovoltaic module; Photovoltaic module integrated blind; Shading effects; Venetian blind	Simulation	PV Window blind
[20]	Greece	BIPV; Daylight availability; Electricity production; Photovoltaic panel; Shading device; Thermal comfort	Mock-up—outdoor	PV panel; PV louver; PV eggcrate
[21]	Hong Kong	BIPV; Energy saving; Optimum design; Shading-type building integrated photovoltaic cladding; Surface azimuth angle	Simulation	PV panel
[12]	South Korea	Assessment methodology; PV blinds; Renewable energy; Sustainability	Simulation	PV panel
[22]	South Korea	BIPV (building integrated photovoltaic) system; Daylight responsive dimming system; LED lighting system; PV system; Venetian blind	Real building	PV Window blind
[23]	Greece	Energy production PVSD	Simulation	PV panel; PV louver; PV eggcrate
[24]	Greece	Electricity production; Shading devices	Mock-up—outdoor	PV panel
[2]	Hong Kong	Dynamic performance; Energy saving; Optimum design; Shading-type building integrated photovoltaic clad	Simulation	PV panel
[25]	Switzerland	Shading optimization	Simulation	PV louver; Other PV system
[26]	South Korea	Hybrid solar tracking method; Indirect tracking method; Smart photovoltaic blind; Solar tracking system	Theoretical	PV window blind
[27]	NA	Amorphous silicon; Copper indium gallium selenide; Smart photovoltaic blind	Theoretical	PV window blind
[28]	Switzerland	BIPV; Dynamic facade; Facade engineering; Photovoltaics; Responsive architecture	Simulation	Other PV system
[29]	South Korea	Building integrated photovoltaic blind; Energy simulation; Finite element method; Grid-connected utilization plan; Lifecycle cost analysis	Simulation	PV Window blind
[30].	Greece	BIPV systems; Multicriteria analysis; PROMETHEE method; Shading devices	NA	PV panel; PV louver; PV eggcrate
[31]	Turkey	Building retrofit; Energy efficiency; Office building; Photovoltaic optimization; Responsive shading devices	Simulation	Other PV system

Table 2. *Cont.*

Reference Number	Study Location	Keywords	Validation Method	PVSD
[32]	Indonesia	BIPV; Building envelope; Building simulation; Energy efficient; Shading device	Simulation	PV panel
[33]	Thailand	Assisted natural ventilation; DC fan; Domestic hot water; PV blinds; Tropical climate of Thailand	Mock-up—outdoor	PV Window blind
[34]	China	NA	Simulation	PV louver
[35]	Egypt	Building integrated photovoltaic; Office Buildings; Retrofitting	Simulation	PV panel
[36]	South Korea	Bidirectional blind; Daylight; PV Module; PV blinds	Mock-up—outdoor	PV Window blind
[37]	South Korea	Building integrated photovoltaic blind; Electricity generation; Lifecycle cost analysis; Nonlinearity; Shading effect	Simulation	PV Window blind
[38]	China	Comparative experiments; Electricity generation; Heat gains; PV blind; The total efficiency; Trombe wall	Mock-up—outdoor	PV Window blind
[39]	China	BIPV Trombe wall; Cooling/heating load reduction; Electricity generation; PV blind; Total electricity saving	Simulation	PV Window blind
[13].	-	Fully glazed façades; Highly glazed façades; Integrated façade systems; Intelligent façades; Photovoltaic integrated shading devices	NA	Multiple
[40].	Switzerland	Adaptive shading; BIPV; Dynamic photovoltaics; Multifunctional envelope	Simulation	Other PV system
[41]	Switzerland	Adaptive shading; BIPV; Dynamic photovoltaics; Multifunctional envelope	Simulation	Other PV system
[42]	South Korea	Monitoring system; Photovoltaic panel; Prototype model; Smart photovoltaic system blind; Tracking system	Small scale demonstrator	PV Window blind
[43]	South Korea	Energy self-sufficiency rate; Grid-connected utilization plan; Lifecycle cost analysis; Smart photovoltaic system blind; Spatial footprint	Simulation	PV Window blind
[44]	China	EnergyPlus; Net energy consumption; Optimum tilt angles; Photovoltaic shading system	Simulation	PV panel
[45]	China	Comparative study; Double-skin façade; Photovoltaic blinds; Solar heat gain; Thermal performance	Mock-up—outdoor	PV Window blind
[46]	South Korea	Building integrated photovoltaic blind; Economic impact analysis; Finite element method; Grid-connected utilization; Residential progressive electricity tariffs	Simulation	PV Window blind
[47]	Norway	BIPV; Continuous daylight autonomy; Daylight autonomy; Parametric analysis; Shading system; Useful daylight autonomy; Visual comfort	Simulation	PV louver

Table 2. *Cont.*

Reference Number	Study Location	Keywords	Validation Method	PVSD
[48]	Hong Kong	Building integrated photovoltaics (BIPV); Energy saving potential; Optimum design; Solar photovoltaic (PV) shading	Simulation	PV panel
[49]	Cyprus	Nearly zero energy buildings (nZEB); Autonomous solar electricity; Adaptive thermal comfort; Passive design strategies; Photovoltaic integrated shading devices (PVISD)	Simulation	PV panel
[50]	Saudi Arabia	Architecture; Building integrated photovoltaics (BIPVs); Saudi Arabia; Shading devices; Solar energy	Simulation	PV panel; PV fin
[51]	Worldwide (multiple)	BIPV; Partial shading effects; Photovoltaics; Solar energy; Sun-tracking methods	Simulation	Other PV system
[52]	South Korea	Airconditioning; Bidirectional blinds; Daylight; Lighting	Mock-up—outdoor	PV window blind
[53]	South Korea	Daylighting; Double-skin façade; Energy-saving; PV façade; Shading device	Mock-up—outdoor	PV Window blind
[54]	China	Comparison analysis; Double-skin facades; Experiment study; Photovoltaic blinds; Thermal performance	Mock-up—outdoor	PV window blind
[55]	Greece	BIPV (building integrated photovoltaic); Energy performance; EnergyPlus; Office buildings; Simulation; Thermal comfort	Simulation	PV louver
[4]	-	Paper review of PVSD	NA	Multiple
[10]	-	Control systems; Dynamic shading systems; Geometries; Mechanisms; Responsive architecture	NA	Multiple
[56]	Egypt	Building attached photovoltaic (BAPV); Photovoltaic integrated shading (PVIS); Regression analyses; Zero energy building (ZEB)	Mock-up—outdoor	PV panel
[57]	South Korea	Building façade; multifunction smart window; Photovoltaic blinds; Real-time operation system; Ventilation system	Simulation	PV Window blind
[58]	South Korea	Climate factor; Correlation analysis; Solar photovoltaic blind; Solar tracking method; Technical performance	Mock-up—outdoor	PV Window blind
[59]	South Korea	Feasibility study; Photovoltaic panel type; Solar photovoltaic blind; Solar tracking method; Techno-economic performance analysis	Real building	PV Window blind
[60]	China	Cost of Benefit; Net electricity consumption; Numerical shading model; Photovoltaic shading systems	Simulation	PV panel
[61]	China	Complex shading effects; Glazing façade; PV blind; Thermal–electrical–optical simulation	Mock-up—outdoor	PV Window blind

Table 2. *Cont.*

Reference Number	Study Location	Keywords	Validation Method	PVSD
[62]	Cyprus	BIPV; Energy consumption; Northern Cyprus; Renewable energy integration; Shading devices; Thermal comfort	Simulation	PV panel; PV fin
[63]	Norway	NA	Simulation	PV louver
[64]	Norway	Building integrated photovoltaic shading device; Daylighting; Multi-objective optimization; Parametric design; Passive solar energy technologies; Solar building envelope	Simulation	PV louver
[65]	Iran	Building energy simulation; Building integrated photovoltaic (BIPV); Movable BIPV shading; Optimization	Simulation	PV panel
[66]	Iran	Energy; Photovoltaic; Solar blind system; Solar greenhouse; Thermo-environomic	Simulation	PV panel
[67]	Iraq	Base-case model; benchmarking; building energy simulation (BES); Energy production; Fully glazed façades; Highly glazed façades; Office buildings; Sensitivity analysis	Simulation	PV louver
[68]	USA	Artificial neural networks; Electricity production; Optimum louver slat angle; PV integrated shading device; Visual comfort	Mock-up—outdoor	PV Window blind
[69]	South Korea	Climate factor; Data mining techniques; Decision tree (DT); Efficiency of electricity generation; Hybrid sun-tracking method; Photovoltaic blind (PB)	Real building	PV Window blind
[70]	Japan	Food; Renewable energy; Shading; Solar cell; Sustainability	Real building	PV panel
[71]	USA	Automatic control; Energy equilibrium design; Energy harvesting; Smart building envelope; Window blinds	Mock-up—indoor	PV Window blind
[9]	Saudi Arabia	Energy saving; Hot desert climate; Overall energy; Photovoltaic shading device (PVSD); Tilt angle; Visual comfort	Simulation	PV louver; PV panel; PV fin
[72]	Brazil	Cooling loads; Energy efficiency; Energy generation; Photovoltaic; Shading devices	Simulation	PV louver
[73]	Europe (multiple)	Energy savings; Multi-objective optimization; Shading systems; Visual comfort	Simulation	PV louver
[74]	-	BIPV windows; PV blinds; PV glazing; Performance	NA	Multiple
[75]	Norway	Multi-objective optimization; Genetic algorithms; Genetic operators; Performance-based design; Shading devices	Simulation	PV louver
[76]	Brazil	PV building integration; Architectural integration quality; Energy performance improvement; PV system performance; Economic viability; Aesthetical evaluation	Simulation	PV panel

Table 2. *Cont.*

Reference Number	Study Location	Keywords	Validation Method	PVSD
[15]		Active solar energy systems; Building integration; BIPV; BIPV/T; BISTS	NA	Multiple
[14]		PVSD; Control; Building; Review	NA	Multiple
[77]		PV–OLED blind system; Organic light-emitting diodes (OLED); Daylight	Mock-up—outdoor	PV window blind
[78]	South Korea	BIPV; PV blinds; PV louver; Experimental study; PV simulation; Ladybug	Simulation	PV panel
[79]	China	BIPV; PVSDs; Adaptive façade; Machine learning; Solar energy	Simulation	PV panel
[80]		Solar PV blinds; BIPV; Slat mutual shading; PV; Venetian blinds	Simulation	PV window blind
[81]		Louvered PV window; Natural lighting; Evaluation index; Electricity; Regulation strategy	Simulation	PV louver
[82]	London, Teheran, Los Angeles, Berlin, Singapore	BIPV; PV solar shade; Multi-objective optimisation; PV design; Computational modelling	Simulation	PV louver

3.1. Year of Publication

The year 2017 represents the year with the highest number of publications on photovoltaic shading devices (19). The number of publications on the subject has been about six publications per year in recent years. The exception is the year 2021, in which the pandemic situation probably contributed to reducing the number of publications. Figure 1 shows the annual publications of papers on the topic of PVSDs in the last twelve years.

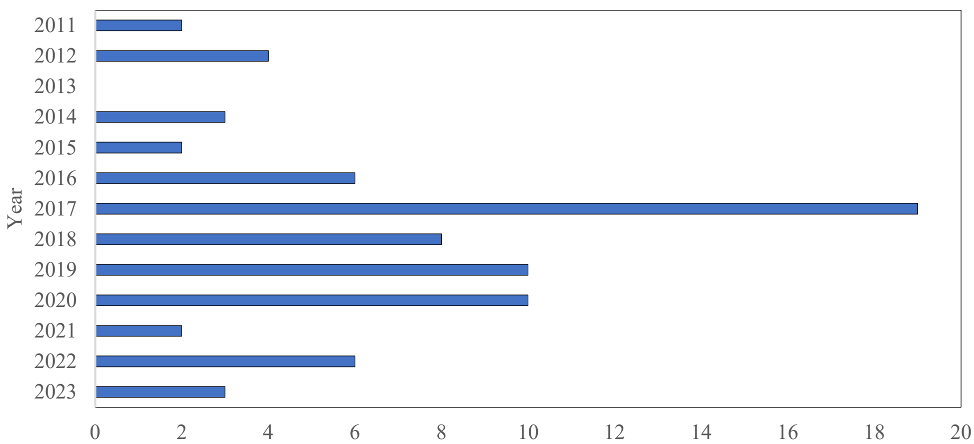


Figure 1. Number of articles on PVSDs from year 2011 to 2023.

3.2. Working Group and Study Location

The universities in which studies on PVSDs have been performed were identified as working groups. In total, 86 institutes were counted. As Figure 2 shows, China was the most active country with regard to the conducting of academic research on PVSDs, with 17 institutions, including universities and state laboratories, involved. The Republic of Korea had ten spots, followed by the UK (8), the USA (8), and Egypt (5). The European Union (including Norway, Switzerland, and the UK) had 29 active academic centres, while the MENA area had 16 spots. The Department of Architectural Engineering at the Yonsei University, Republic of Korea, with authors or co-authors in 12 research journals, was the institution with more publications on solar shading systems. The Korean university was followed by the College of Civil Engineering at Hunan University (China), the Technical University of Crete in Greece (5), and the Division of Construction Engineering and Management at Purdue University (USA). Figure 2 and Table 3 represent the distribution by country of the studied PVSD cases. The study location means the climate condition simulated or tested in the appropriate environment. In particular, when applicable, the study location is represented in Table 3. A multiple study location was conducted in the study in only two cases. It included a multilevel European [73] and worldwide [51] analysis. The spots in which the studies were performed were more frequent in the Republic of Korea (19), Europe (including Norway, Switzerland, and the UK) (15), and China (12). The Department of Architectural Engineering at the Yonsei University in the Republic of Korea, with authors or co-authors in 14 research journals, was the institution with more publications on solar shading systems.

Figure 2. Identification of number of papers in different countries.

Table 3. List of research institutes and study locations for the selected research journals by country.

Country	Institutes	Location
China	17	12
Republic of Korea	10	19
United Kingdom	8	1
USA	8	3
Egypt	5	2
Saudi Arabia	3	2
Greece	3	5
Norway	3	4
Cyprus	3	-
Italy	3	-
Switzerland	2	4
France	2	-
Iraq	2	1

Table 3. *Cont.*

Country	Institutes	Location
Belgium	2	-
The Netherlands	2	-
Iran	2	3
Japan	2	1
Thailand	2	2
Brazil	2	2
Indonesia	1	1
Turkey	1	3
Singapore	1	1
Malaysia	1	-
Germany	1	1
Lebanon	1	-
Sweden	1	-
Czech Republic	1	-
Slovakia	1	-

3.3. Author Keywords and Validation Method

The 243 recorded keywords were grouped into 25 clusters by the software VOSviewer. The analysis was based on the co-occurrence of keywords. The relatedness of the items was determined based on the number of documents in which they occurred together. Each co-occurrence link had the same weight. The keyword with the highest link strength was "BIPV" (47), followed by "Shading device" (23) and "Visual comfort" (18). Some of the 243 keywords in the network were not connected to each other; the largest set of connected items consisted of 152 items, and it was represented by the main keyword "BIPV" and is visible in the centre of the map in Figure 3.

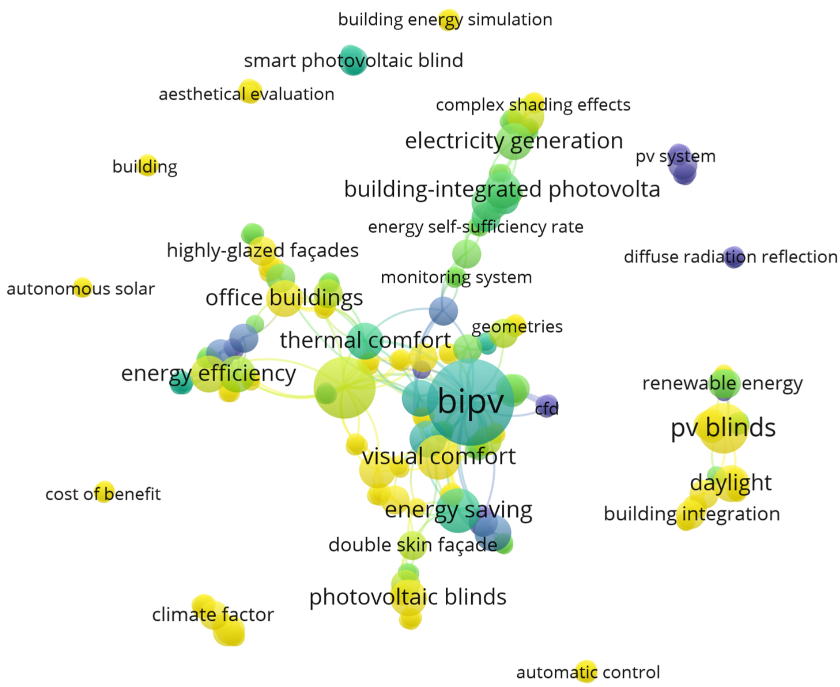


Figure 3. Keyword network map. Source: VOSviewer.

Simulations are the most used systematic analysis methods, especially for external PV blinds, including PV louvres and PV panels (see the next paragraph for a detailed description). The validation/demonstration of PVSDs occurred mainly in outdoor mock-ups for PV window blinds. Few analyses for PVSDs were conducted on demo cases even though outdoor activities were favoured in comparison to indoor tests.

3.4. Type of Technology

PVSDs define the architectonic language of the building skin and curtain walls. They allow the reduction of cooling loads and protect privacy [19]. PVSDs are shading devices substituted by or coated with PV elements [4] that can improve the building's energy efficiency when designed to consider site-specific factors such as orientation and climate [72]. In other words, they are PV modules combined with shading devices that produce electricity and at the same time reduce the energy demand of buildings [74]. In [27], PV blinds are defined as "smart" when they combine the functions of automatic control, real-time monitoring, and management with electricity generation. Integrating PV solutions in shading systems opens new opportunities for the BIPV sector and the BIPV stakeholders.

The power generation of PV blinds is affected by façade orientation and blind arrangement [61]. The architectural component is an influential aspect in the design of dynamic solar shading; it not only improves the aesthetic and cultural values of building façades but also further enhances their performance. It also directly affects the design of other components [10]. Despite not being as common as rooftop PV modules, PVSDs could enhance the performance of existing and new buildings by reducing the thermal loads and generating energy. The net energy demand is essential for deciding which photovoltaic shading device to build [72]. In [4], 24 types of PVSD were defined based on the quantitative analysis of 43 journal papers. In [20], thirteen types of traditional shading devices used mainly for office buildings were examined. The authors believe that a more structured classification of PVSDs, which is partially referred to in [4,20], could ease the reading. The proposed classification also defines the PVSDs examined within the following research. For the original terminology, refer to the related journal paper.

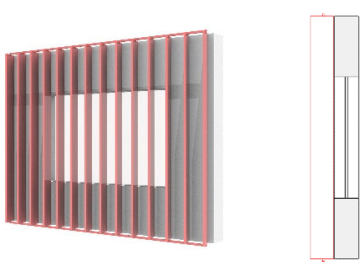
- PV louvre: defined as any similar arrangement of PV slats or PV fins, attached in mechanical systems, often adjustable, used to control ventilation, light intensity, and energy efficiency in general.
- PV window blind: a lightweight system that permits control of the light and privacy and produces energy. The window blind is retractable and includes venetian blinds and roller blinds. This analysis includes embedded PV window blinds as external integrated systems.
- PV panel or PV shading overhang: roof projection, an upper story, or a solid panel of a building beyond the building envelope of the lower part, on which a PV module is integrated.
- PV fin: little static wings that produce energy and are projected perpendicularly or not from the façade and used randomly across the façade, creating rhythm and scale on otherwise soulless cartesian curtain wall grids. PV fins are used to control ventilation, light intensity, and energy efficiency in general. PV fins, unlike PV louvers, are not attached in mechanical systems.
- PV eggcrate: horizontal construction divided vertically into cell-like areas, used primarily to direct downward rays of overhead light and produce electricity (dictionary.com).
- Other PV systems: PV shading systems not included in the previous categories.
- Composite PV systems: PVSD combining multiple simple techniques.

Table 4 shows eight PVSDs, their classification based on the systematic review of 75 journal papers, and a representation.

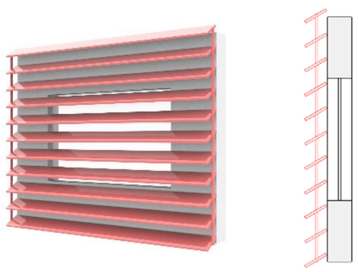
Table 4. PVSD: classification and representation.

SIMPLE SYSTEM								
PVSD	**Position**		**Control**		**Direction**		**Repetition**	
Name	**Outside**	**In between**	**Dynamic**	**Static**	**Vertical**	**Horizontal**	**Single**	**Multiple**
1. PV Louver	x		x	x	x	x		x
2. PV Window Blind	x	x	x	x		x		x
3. PV Panel (overhang)	x			x		x	x	x
4. PV Fins	x			x	x		x	x
5. PV Eggcrate	x			x	x	x		
6. Other PV systems	x		x	x	x	x		x
COMPOSITE SYSTEM								
PVSD	**Position**		**Control**		**Direction**		**Repetition**	
Name	**Outside**	**In between**	**Dynamic**	**Static**	**Vertical**	**Horizontal**	**Single**	**Multiple**
7. PV Panel + Louvers	x			x		x	x	
8. PV Eggcrate + Louvers	x			x	x	x		

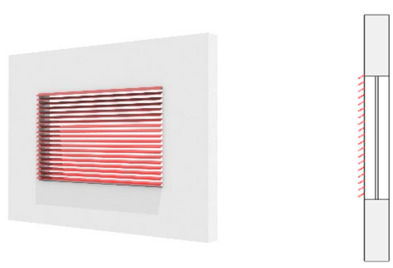
PV Louver, vertical



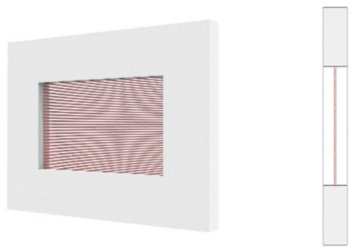
PV louver, horizontal



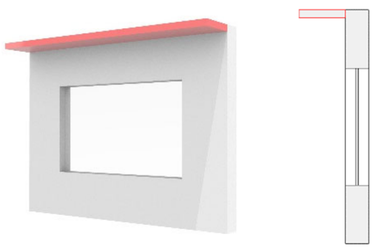
PV Window Blind, external



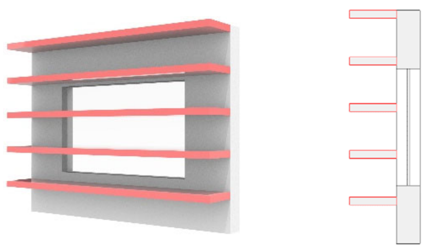
PV Window Blind, embedded



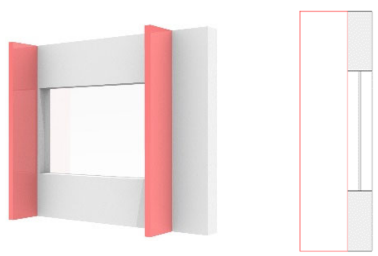
PV Panel, single



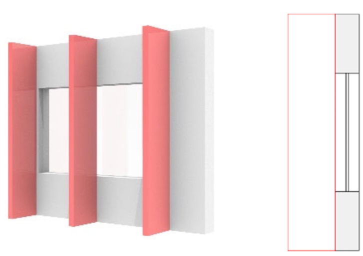
PV Panel, multiple



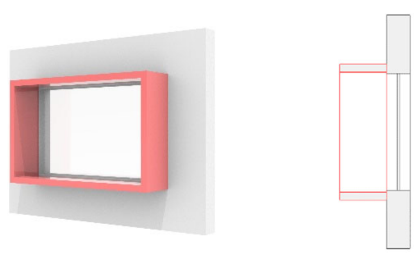
PV Fins, single



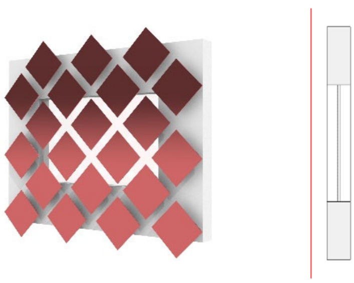
PV Fins, multiple



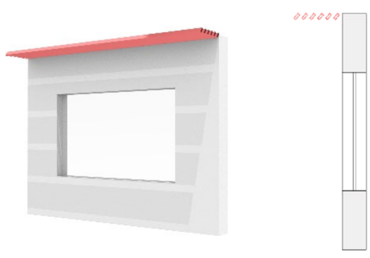
PV Eggcrate



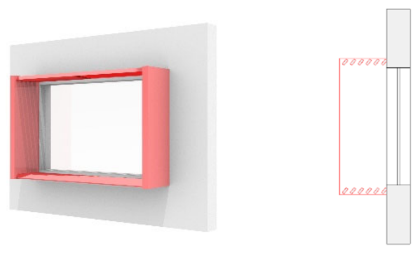
Other PV System



PV Panel + Louver



PV Eggcrate + Louver



3.5. Design Strategies

The design strategies for PVSDs can ease the building process by simplifying the activities and the interactions between the stakeholders, especially the designers, manufacturers, and installers. The exposed analyses have been conducted in distinct locations and climate conditions, classified by [83] as cool temperate, warm temperate, subtropical, and tropical regions. The results show that each climate and environmental condition is best suited to specific PVSD types and requires a customised design between the tilt angle, the blind spacing, and the width to maximise the benefits of the PVSD in each location. An overview of the analysis is presented below.

In [48], the analysis is based on a typical subtropical city in a cooling-dominated climate. PV panels installed in sub-tropical regions achieve more annual electricity than the widely used interior blinds. The optimum tilt angle to maximise energy production is 30°. However, PV panels installed with smaller tilt angles (20°) could achieve more overall electricity benefits than those with larger tilt angles. The solar PV shadings' energy-saving potential is more significant than that of the widely used interior blinds. However, the annual increased lighting electricity decreases with the increase in the tilt angles of solar PV panels. The impact of the tilt angles, surface azimuth angles, overhang lengths, and window-to-wall ratios on the energy performances of the PV panels was assessed in the subtropical city of Hong Kong and has also been analysed in [2].

A multi-objective analysis on PV louvres [73] shows that the shading device needs to be optimised for the climatic conditions to find the best compromise between the heating and cooling demands and the energy required by the artificial lighting system. The analysis was performed at three different latitudes across Europe (north, middle, and south). A larger slat width (60 cm) allowed considerably more energy savings in the analysed three locations. For the surfaces oriented towards the northern direction (in the northern hemisphere), vertical slats with different tilt angles represented the optimal solution with which to optimize the heating and cooling demand. In contrast, horizontal slats were recommended for the surfaces oriented towards the south, east, and west. In a manner consistent with this research, horizontal PV panels were used on the south façade in the Mediterranean regions, while on the east and west facades PV panels and fins were employed [62]. The study in [50] reveals that PV fins are recommended on east and west facades in hot climatic conditions. Increasing the PV inclination angle when considering horizontal shading systems helps to reduce the impact of the self-shading effect without compromising the required window shading. A monthly optimum tilt angle installation permits better results than an annual optimum tilt angle installation, according to the analysis performed in China by [44].

According to [32], the amount of energy produced and saved in a tropical region is not directly proportional to the number of PV panels installed in the building façade. Indeed, it emerged in this research that installing a few PV panels per floor at a higher distance is more effective. The investigation results in [63] show that PVSDs with a higher number of slats performed better as multi-material systems, combining PV or reflective materials on the slats. Certainly, they increase daylighting compared to classic, fully PV-coated systems without increasing energy use. This analysis was performed in Oslo, Norway. However, systems with a lower number of slats provide more daylight and require less energy than systems with a higher louvre count. The results in [37] on PV window blinds installed in South Korea highlight that when the solar blind's width increases, the normalised energy output decreases due to the mutual shading effect between slats. The width of the slat is represented in Figure 4 with "d", while the spacing between the slats is represented with "l". As also demonstrated by [42] in a small-scale demonstrator, the slat's width largely influences the energy production. The definition of the optimal width is necessary to maximise the energy harvested by a PV window blind, and the distance between the indoor/in-between blind and the external glass influences the energy production. Indeed, a greater distance corresponds with a lower energy generation due to reduced solar radiation. A small blind spacing and a large blind width would result in less solar transmission, decreasing the cooling load in summer [53,61]. The same blind configuration increases the power production by 71% compared to systems with large blind spacing and small width. In addition, the power production is greatly influenced when the length of the eave and façade depth increases. The wider PV blind and short blind spacing will capture more solar energy, increasing the air temperature in the cavity. This will help keep the internal glass warm and keep the heat loss low in winter. For the southern façade, the PV blind layer is shaded in large part (60%) at noon in summer. According to the analysis presented in [80], in which is presented a method to assess the electrical power produced by a PV venetian blind, the slat distance/width ratio that maximizes the annual electricity produced is about 0.6 for energy optimizing methods and 0.7 for standard uses. In addition, the reflectivity of the back of the slats has a small influence on the annual production (up to 5%). According to [78], it is crucial to improve the design to eliminate the self-shading effects inside PV blinds.

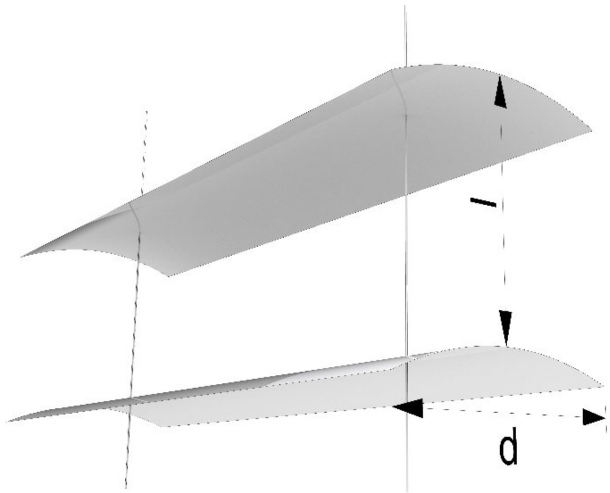


Figure 4. Representation of the slat width (d) and spacing (l).

Ref. [25] presents a technical analysis and reveals that careful planning of module string configuration, PV cell orientation, and location of the bypass diodes reduces the electrical mismatch losses induced by partial shading and can result in more than 50% higher energy yield compared to uninformed design strategies. The research shown in [80] reveals that for PV venetian blinds, the southeast (or -west) orientation provides maximum electrical production, and the automated closing of PV blinds in summer, when the room is unoccupied, allows an increase in electricity production of approximately 9% for the south, east, and west exposures and 16% for the north exposure.

3.6. Energy Performance: PV Generation and Savings

The unique multifunctionality of BIPV systems is also reflected in PVSDs. Indeed, those systems behave as building components by replacing the conventional building envelope solutions [7]. PVSDs produce renewable energy by protecting buildings from solar radiation and glare simultaneously. PVSDs could mitigate the energetic impact of buildings that nowadays are responsible for about 40% of the CO2 gas emissions [84]. As an alternative or in addition to PV rooftop systems, the installation of PV and non-PV systems on facades or as shading devices contributes to achieving the net zero energy target [49,56,85]. However, a combination between renewable power generation and building energy demand reduction should be considered to optimise BIPV systems [17] as well as to guarantee perfect visual and daylight comfort [86]. Indeed, PVSDs offer a relevant improvement in the energy yield harvested in and by buildings [87].

The following paragraph focuses on the performances of PVSDs from the perspective of energy production and energy savings by analysing PVSDs according to the data offered by the literature. A key parameter to guarantee high performance in energy production is the ratio between the slat width and distance and the mutual shading between cells. However, since PVSDs are conceived as multifunctional components, the energy production performance has to be related to the energy savings. For either heating- or cooling-dominated climates, shading systems can facilitate the achievement of the target of energy reduction, with savings up to 80% in specific case studies.

(i) Energy production: The analysis of [20] on PVSDs, conducted in Mediterranean warm, temperate, dry regions, revealed that the most energy-efficient systems were PV eggcrates and inclined PV panels. Horizontal PV louvres performed the worst even though they are one of the most commonly used systems in office buildings. A simple method to evaluate the electrical power produced by PVSDs is proposed in [80]. The method allows the assessment of slat mutual shading and view factors. It is applicable to any slat inclination, orientation, and geometry. In [23], the difference in energy production per m^2 between inclined PV louvres and inclined PV panels was more than 40% (higher for the case of inclined PV panels). However, inclined PV panels and horizontal PV louvres seemed to be less suitable than PV eggcrates [30]. The latter analysis considered a series of criteria, including the PV panels' energy production, the buildings' energy optimisation criteria (heating–cooling–lighting loads), and the users' comfort criteria (outdoor view–glare–aesthetic aspects). In Korea, at a latitude very close to that of Athens, it has been noticed that simple geometry shading systems do not differ in efficiency compared with standard photovoltaic roof solutions [18]. The research in [68] proposes a BIPV device and optimal control method that increases the PV efficiency, maintaining visual comfort. The analysis was performed on a small-scale prototype of a PV louvre. The sensitivity analysis conducted in [67] for hot and arid climates revealed that parameters at the sub-system level, which involve the building façade and its associated compartments and elements, have a greater influence on energy production than those at the system level, which affect the building itself. In particular, the ratio d/l (ratio between the slats' width (d) and the distance (l)) of the PV louvres and the building orientation scored the first and the second influential variable on PV-generated electricity, respectively. In particular, a lower d/l ratio will result in a more significant amount of sunlight [18]. Still, it is not proportionate to the amount of power generated due to a decrease in the area of power generation. Thus, in Korea, it is recommended to set the d/l ratio between 1 and 0.3. A simulation on PV panels performed in different climates in China revealed that the mutual shading on PV cells can significantly reduce PV system efficiency. At high latitudes (Harbin and Beijing), there is no shading effect. A significant shading effect was found at lower latitudes (Guangzhou, Changsha, and Kunming), approximately near the Tropic of Cancer. By decreasing the tilt angle of the PVSD, the shading effect increases [60]. In a typical Greek office building, like those analysed in [55], the amount of electricity produced by a movable vertical or horizontal PV louvre can meet 65% of the building's annual electricity requirements. The researchers conducted a holistic analysis of the technical, economic, and political aspects to investigate the impact of PV window blinds in between the glazing units on nZESBs in South Korea. A two-axis tracking photovoltaic blind with CIGS performed better in terms of the energy self-sufficiency rate in comparison with CIGS and an a-Si fixed solution and a-Si two-axis blinds [43].

(ii) Energy savings: In [45], the performance of PV window blinds placed between the double-glazing unit and measured in China's hot summer and cold winter zones was assessed. The analysis simulated on a physical model revealed that the PV systems were less sensitive to PV blind angle than PV blind spacing, and smaller PV blind spacing increased the energy performance of the building by reducing the solar heat gain. Regarding the specific analysis, the PV system permitted a saving of about 12% of indoor cooling power consumption in summer compared with a similar system non-PV by taking into account the energy production in the energy balance. Non-PV fixed shading devices like eggcrates and inclined panels achieved the lowest energy need for heating, cooling, and lighting in the Mediterranean warm, temperate, dry region [20]. In the same climate, in contrast with other studies, PV vertical louvres oriented to the south, east, and southeast, reduced the energy demand for cooling and heating up to 33% and behaved better than the horizontal PV louvres. However, the latter could achieve better results in cooling reduction. The analysis was conducted on a 9-storey building in Greece. Furthermore, for PV louvres, movable shading systems performed better than those that were fixed in terms of energy demand reduction [55] and daylighting performance in terms of illuminance and glare protection [34]. In [65], a study is presented on movable PV panels in which their energy efficiency is simulated within the climate conditions of Tehran (Iran), and different conclusions are highlighted. Also, in [41], dynamic shading systems assessed in a Swiss case study permitted savings of about 20%-80% of the energy depending on the cooling efficiency heating system in use. However, to be properly used, dynamic shading systems have to implement intelligent algorithms that are able to orientate the blinds to the most energy-efficient position by balancing the energy productions and the energy savings [86]. In all the climate configurations analysed in [73], a reduction of up to 42% of the energy demand was achieved in the optimal shading configuration of PV louvres. In hot desert climates [9], PV eggcrates performed better than horizontal PV louvres in energy production and visual comfort. Still, the eggcrate solution performed worse than PV louvres in cooling energy consumption. On the other hand, for the Nordic countries, the effect of the shading system on the heating demand was more relevant than on the cooling demand and was very sensitive to the tilt angle of the blades [47]. Embedded PV window blinds could achieve better thermal performance than the reference semi-transparent PV systems in China [54]. In [76], a simulation analysis performed in Brazil revealed that PV panels installed vertically on a multistorey building façade allowed a reduction in the building's annual energy consumption. In comparison with a tilted PV system installed on the roof, the performance simulated in terms of energy yield and the performance ratio were very similar. An optimal design method to maximise the energy performance for PVSDs is proposed in [79]. The results showed that by using an optimised PVSD, the cooling and lighting demand in an office in Guangzhou was reduced by up to 48.7%.

3.7. Innovative Solutions

Within the next paragraphs are presented the most representative innovative solutions, according to the author's knowledge. An intense research activity on individual multi-oriented PVSDs and PV shading systems such as venetian blinds was performed in Switzerland and in the Republic of Korea; these countries are ranked 1st and 5th, respectively, by the global innovation index [88]. The innovation products presented were (i) multi-oriented PVSDs and (ii) PV venetian blinds. In the next paragraphs, a presentation is given of the status of the research.

(i) Multi oriented PVSD: In [51], the results on a new sun-tracking method to optimise the performances of special PVSDs are shown. The simulations conducted in nine cities in Europe, North America, and Asia showed that the annual energy generation and module efficiency were improved up to about 30% with a three-degrees-of-freedom sun-tracking system compared to conventional perpendicular sun tracking. The problem of mutual shading between PV modules (slats) of PVSDs is analysed in [25]. A new method is presented to predict the shading pattern for individual PV modules. The method is important for defining the electric system design and validating PV louvres and is an innovative PV diamond pattern with dual-axis solar tracking. On the same dynamic PVSD configuration was simulated the most energy-efficient system configuration for control by minimising the heating, cooling, and lighting load, while simultaneously maximising the PV electricity generation [41]. The novel configuration achieved a 20–80% net energy savings compared to an equivalent static PVSD.

(ii) PV venetian blind: A hardware and software prototype of a multifunctional PV window blind embedded into the double-glazing unit and combined with a ventilation system is presented in [57]. In terms of electricity production and economic performance, the ventilation system brought more overall benefits if installed to only the upper or lower part of the smart window (analysis performed in South Korea). The use of a mono-Si PV cell (first-generation PV cell) or the a-Si PV cell (second-generation PV cell) in the

PV blind showed better cost-effectiveness and generated a better amount of electricity. The study in [49] on responsive PV solutions integrated into an office building in Erbil (Turkey) shows that such a dynamic shading system can maximise PV cells' efficiency by about 40% compared with fixed installations. The study in [59] is based on a PV window blind, including a real-time monitoring and evaluation system and a real-time automatic control system. The system's performance was assessed in Seoul (Republic of Korea). It demonstrated that a direct solar tracking method, which directly tracked the maximum electricity generation, performed better (30%) than the indirect solar tracking method, which tracked the sun based on calculated values. In addition, the use of mono-Si modules generated higher economic benefits than a-Si modules. In [71], a similar PV window blind prototype was developed and analysed. This was a venetian blind installed between the double-glazing unit composed of slats covered by PV on the front side and a passive cooling coating on the backside. The tests showed that the efficiency of the c-Si cells was 2% due to the overlap of the window blinds and other physical parameters. The cooling coating allowed a decrease in the temperature of the PV cells of up to 9%. According to the study presented in [19], based on the analysis of a PV window blind embedded in the double-glazing unit, the azimuth, tilt angle, area of PV module, and distance of the blind frame from the outer window represented the variables for estimating the harvested electric energy from a PVSD. The maximum PV module temperature measured in a non-ventilated double-glazing unit in Seoul, Republic of Korea, was almost 78 °C. In contrast, the maximum PV module temperature measured in a ventilated system was 58.4 °C. The harvested electricity was about 8% higher than in the case without ventilation. In [77], a multifunctional PV-OLED venetian blind system was presented, and preliminary studies for a comprehensive control of the shading apparatus were performed. The venetian blind, installed internally, was equipped on the rear side of each slat with an organic light-emitting diode (OLED) lighting panel. The goal of the analysis was to assess the indoor illuminance distribution based on the control angle of the slats. Based on the preliminary results of the analysis, further studies on the optimization of the energy consumption, PV power generation, and visual comfort are expected.

4. Conclusions

The presented study is a literature review intended for both the industry and the academic sectors. This systematic assessment aimed to present an exhaustive overview of the current literature on state-of-the-art external integrated systems such as PVSDs, first by analysing the scientific framework in terms of existing technologies, the status of the research, and the hot spots in terms of institutions involved. Seventy-five articles and about 250 keywords were identified and analysed. After the publication of the PVSD review of [4], about 30 articles strongly focused on PVSDs have been published. From the analysis it, emerged that China is the most active country in terms of the conducting of academic research on PVSDs, with 15 institutions, including universities and state laboratories. The spots in which the studies are performed are more frequent in the Republic of Korea (18), Europe (including Norway, Switzerland, and the UK) (13), and China (11), probably because of their high global innovation index.

This research differs from the previous analysis on PVSDs by offering a performance-based approach focused on innovative products, design strategies, and energetic performance in distinct climate conditions and configurations. The study revealed that PVSDs require a customised design in each climate and environmental condition between the tilt angle, the blind spacing, and the width to maximise the benefits between energy production and energy savings. Indeed, the tilt angle that maximises the energy production of a PVSD does not always guarantee the overall electricity benefits. In most of the research analysed, which was located in the northern hemisphere, horizontal slats were recommended for surfaces oriented towards the south, east, and west. Even though PV fins were also recommended for east and west facades, vertical slats represented the optimal solution for facades oriented towards the north. The mutual shading effect between slats, in the case of louvres, window blinds, and multiple repeated PVSDs, increased by increasing the width of the slat. This influenced the decrease in energy production. Significant shading effects were also registered by decreasing the tilt angle of the PVSDs. However, PVSDs were less sensitive to PV blind angle than PV blind spacing. The highest energy demand reduction of 80% was achieved with PVSDs in specific case studies. The best-performing energy saving and energy generation systems were often PV eggcrates and PV panels. However, some study revealed that eggcrate solutions performed worse than PV louvres in cooling energy consumption. The implementation of optimal control methods for PVSDs increased the PV efficiency, maintaining user comfort. Indeed, movable shading systems performed better than fixed PVSDs in energy demand and production. Multi-oriented PV systems allowed savings of up to 80% in net energy compared to equivalent static PVSDs. In conclusion, some PVSDs are presented in detail and are defined as innovative because of their stage of development and distinctiveness within the BIPV framework: a multi-oriented PVSDs and PV venetian blinds. The intense research activities on innovative PVSDs, performed mainly by universities and institutions, reveal an interest in the market for innovative shading systems and the significant potential of development for the stakeholders in the value chain of shading systems for buildings in the coming years.

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