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Embedding passive intelligence into building envelopes: a review of the state-of-the-art in integrated photovoltaic shading devices

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Abstract

Façades represent both a physical barrier between inside and out, and a phenomenological medium to manifest architecture in terms of style, impression, school of thought or personal statement of their designers. With recent advancement in technology, facades are presenting themselves more and more as a canvas to put the idea of integrated design into practice and that is where the idea of Integrated Façade System (IFS), in general, and photovoltaic (PV) integrated shading devices, in particular, are probably born. This paper sets out to review the-state-of-the-art literature on integrated PV shading devices and their application to highly and fully glazed façades with an aim to investigate the influential factors, parameters and strategies as well as assessment methods and indicators for measuring energy performance of buildings where such technologies are used, by means of systems theory approach. 49 papers were found and reviewed for this study and some unexpected outcomes were revealed. The results indicate that most of the research is about how calibration of the parameters influences the performance of the system. It also reveals that there are very few studies on the PV integrated shading devices where a holistic approach has been used for system evaluation which take comprehensive account of all influential factors. Based on the findings of this paper, it is advisable that there is a need for more in-depth study of system configurations under the specific circumstances which are highlighted in this paper.

Keywords: Fully-galzed façades; Highly-glazed façades; Integrated façade systems; Intelligent façades; Photovoltaic integrated shading devices;

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1. Introduction

Intelligent buildings date back to as early as 1980s [1] if not earlier, but still denote such a broad and vibrant scope which makes it very difficult to find a general consent on the terminology attributed to the term. The fact that a big portion of literature is still concerned with definition of the term [2,3], confirms that there still is and probably will be disagreement on the definition of the terms and jargon associated with this research area. Probably one of the most comprehensive definitions of intelligence in building can be that of Clements-Croome's [4] where he suggests:

> *'An intelligent building is a dynamic and responsive architecture that provides every occupant with productive, cost-effective and environmentally approved conditions through a continuous interaction among its basic elements: places (fabric; structure; facilities); process (automation; control; systems); people (services; users) and management (maintenance; performance) and the interrelation between them'.*

The concept of intelligence (or smartness) can be chartered, in many ways, based on the focus and scope of the research. While still deeply focused on the semantics of/on the topic(s) [5], some researches have taken a little bit in-depth approach and attempted to review the matter from a theoretical – be it epistemological or ontological, direct or indirect, positivistic or constructivist, etc. – point of view, e.g. [6,7]. Others have taken socio-cultural approaches [8, 9] with people/users in general in their centre of attention [10,11] or from a pure or pragmatic psychological or sociological stand point [12,13]. On the other hand many research papers have hardly managed to get passed sustainability as in its broadest concept where links with environment, have been sought through, but not limited to, concept of intelligence/smartness [14,15]. Next group , by contrast, have chosen to take a pragmatic/empirical approach whether their main focus have been on design [4,16], management [17,18], cost [8,19], performance [20,21], impact assessment [22] or simply environment, which would probably not be mutually exclusive from some of those trying to frame the topic from a sustainability perspective. There are some researchers who have simply chosen to scale up or to attribute the concept of intelligence to community/city level as a super system or down to micro- or Nano-engineering as a sub-system for buildings where these technologies can be applied or utilized. The last group is probably those who are particularly concerned with pedagogy of the concept on its own or associated with other aspects or areas [23].

On the other hand integrated design has been gaining momentum in built environment, architecture and design disciplines over the past two decades or so, has become a part of teaching curriculum in many universities or has formed the bases for independent teaching programmes in or related to design disciplines. The concept of integration in design spans well over a multitude of different areas and disciplines, and has, from time to time, some commonalities with smart and intelligent buildings [24]. One of the areas integration in design attempts to address is the physical integration: fusing new technologies into conventional or established building systems, components, materials or detailing.

Façades on the other hand represent both a physical barrier between inside and out, and a phenomenological medium to manifest architecture in terms of style, impression, school of thought or personal statement/signature of their designers. With recent advancements in technology, facades are presenting themselves more and more as a canvas to put the idea of integration into practice and that is where the idea of Integrated Façade System (IFS)[†], in general, and PV integrated shading devices (PVSD), in particular, are probably born.

Current paper attempts to provide a critical comparative review of state-of-the-art in integration of Photovoltaics into shading devices and is aimed at with a research prospect to offer a rather systematic passive approach to enhance intelligence embedded in the built environment in developing economies.

2. Methodology

This review paper utilizes a methodology where the topic is looked into through the lens of systems theory. The new notion of 'Systems' was developed through different branches of science mostly in the six decades post WWII.

[†] Integrated Façade Systems (IFS) are systems where different technological solutions are integrated into the course of the building façade to improve performance and to lower the impact of the building. These technological solutions can broadly be classified under three categories i.e. High-performance Glazing (HPG), Shading Devices (SD) and Photovoltaics (PV).

Five names were remarkably influential in this field. Karl Ludwig Von Bertalanffy (General Systems Theory), Claude Elwood Shannon (Information Theory), Norbert Wiener (Cybernetics), Warren Sturgis McCulloch (Neurophysiology, AI), and Jay Wright Forrester (System Dynamics Theory) are the main figures in forming and improving the Systems Theory.

The idea of the building as a system was derived from modern systems theory and the application of building science to building performance [25]. Piroozfar [26] investigates the building envelope as ‘the system’, the building as ‘the super-system’ and the façade components as ‘the sub-system’ to investigate the trade-offs in mass customization of envelope systems using off-site production methods; what has then been further developed to investigate the application of BIM for a fully customisable façade system [27]. A slightly different approach has been used for this study to also include the contextual determinants to facilitate a global systematic approach to the concept of intelligence in building façades. This study takes the building level as ‘the system’. The upper level, ‘the super-system’, includes the context where the building is located (e.g. site, geographical location, climate, etc.) and the lower level, ‘the sub-system’, involves the façade as shown in Fig. 1. This triad systemic classification can and may be expanded further into next lower level which includes the façade components if and when a closer, more detailed investigation would be needed.

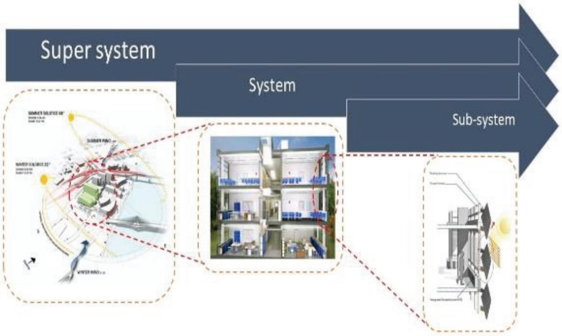


Fig. 1. Systemic approach developed and deployed for this study

This methodological approach has twofold benefits both at theory and practice level. It can facilitate not only the study of the literature on the topics related to that of this research, but can also help classify their impacts and further enables the decision support for the course of intervention/action when it comes to proposition of solutions for practical applications of building façades design. Fig. 2 further indicates this approach with specific areas indicated in this study.

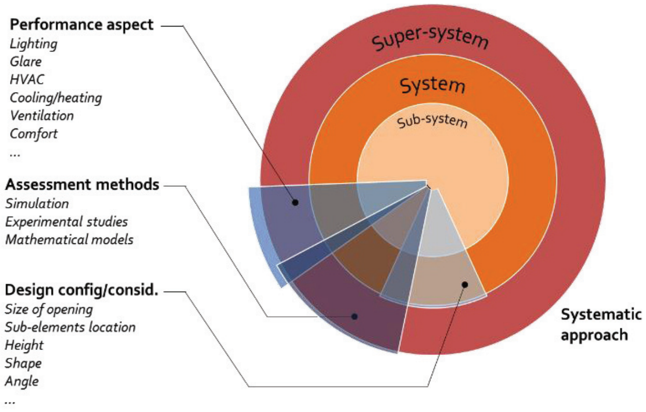


Fig. 2. Identified scopes of literature superimposed on the systemic approach

3. Critical Review of Literature

Building facades impact the energy consumption and the quality of the indoor environment hence require careful design optimization [28]. As a part of the façade components, shading devices play a significant role in reducing the heat gain into the building and providing acceptable indoor conditions [29]. Photovoltaic (PV) cells utilize sunlight to create an electric current and generate electricity [30]. Although the application of PV in buildings was introduced in late 1970s, it was first characterized as a building integrated component in late 1990s [31] and it was not until 1998 that Yoo and Lee [61] proposed, most probably, for the first time, integrated photovoltaics as shading devices. Combining external solar shading devices and photovoltaic panels has many advantages [32], such as generating clean energy which reduces reliance on fossil fuels as well as adding architectural features specific to the design of shading devices when combined with photovoltaic panels either traditional or more recent transparent see-through panels. Transparent shades that incorporate Solar PV cells convert the sunlight into electricity in addition to its function as a shading device [33]. However, the application of photovoltaic shading devices has significant challenges due to the complexity of the system and the adaptability of these systems to different contextual conditions [28]. It is, however, important to note that integration of PV panels, what is commonly known as 'Building Integrated Photovoltaic' or BIPV, is not limited to shading devices only. They can be integrated to any part of the building that can potentially receive a considerable amount of solar radiation like windows, claddings, skylight as well as external shading devices [34].

Photovoltaics as shading devices are usually an external building skin layer that can be applied independently in both new and existing buildings. This technology has dual advantage of generating electricity directly from the incident sun light and the normal function of external blinds in protecting the building from overheating, providing visually comfortable interior space and save energy [35,36]. They have proven technical advantages over other types of PV installations like roof stand-alone PV systems [37] which can include ease of inspection, ease of maintenance, freeing the roof space for other uses and higher possibilities to integrate kinetic technologies to track the sun, while acting as an interactive solution for optimizing solar gain throughout the year. In order to appropriately apply this technology into a building, it is essential to highlight the main influential parameters that affect the performance of buildings with PV shading devices such as providing optimal tilt angle of the devices with the right size and correct distance from the glazing so that they can eliminate excessive sunlight during summer while allowing it in during winter and letting diffuse solar radiation penetrate into the building [32].

4. Design considerations/configurations

Studies concerned with design consist of two different sub-categories i.e. design considerations and design configurations. Design considerations are the considerations which need to be taken into account when the design process of the building or the course of the façade (depending on the type of the project) is being carried out. These can include, climate, site, topography, neighboring buildings, etc. Most often design considerations are those factors over which there would be no direct control, and where they cannot directly be changed or modified. Design configurations by contrast are those elements which can be adjusted, changed or manipulated by the designer and are accounted for as a part of the project that can be shaped by the design process and/or impacted by it. Such variables include building orientation, building geometry, size and geometry of opening and their sub-elements, e.g. their location, height, shape, form, angle, etc.

At 'super-system' level or the building context level, building latitude determines several essential inputs like the amount of solar radiation, temperature, sky conditions and other climatic parameters. Through considering latitude, besides other variables, the type and shading dimensions can be determined [38] and the optimal design option for each location can be proposed [39]. Other studies have focused on the effect of different surroundings of building on the performance of PV shading devices. This varies from the layout of the roads to the building shape [40]. Diffuse radiation may not be considered to have a positive impact from pure urban design point of view but can be reduced by 82% where PVSDs are installed which in return reduces the building reliability on the grid [41]. Karteris et al. [42], use GIS to investigate the effect of architectural and technical aspects of the PVSD to predict their performance at urban scale. As such their work overarches all three system levels.

At ‘system’ or building level, building orientation is considered as one of the key determinants to optimize PV shading devices [38] for different latitudes, that is found to expectedly be south and south-eastern [39]. These findings were assessed according to the reduction in cooling loads, solar insulation and average daylight factor. The results were also confirmed by other researchers [see for instance 36, among others]. Interestingly enough some others have suggested slightly different orientations to maximize solar power generation by PV panels. Suggested alternatives include south-eastern or south-western [43]. Vassiliades et al. [60] suggest that architectural functions that can be affected by the application of PVs include: weather proofing, noise reduction, shading, flexibility, transparency, color and texture. In order to determine the appropriate type of shading devices that are suitable for the integration, dimensions, location and orientation have to be considered as well as the shading coefficient and daylight factor [38,54]. The potential architecturally suitable area of a façade needs to be considered according to the building type and the proposed PV solutions [42]. This area can possibly be boosted when using 3D designs at the early stages [44].

At ‘sub-system’ level or building façade envelope variations were studied by Youssef et al. [45]. One of the most influential parameters determining the PVSD’s performance is the angle of inclination, which helps ensure an optimum value for both internal solar gain control and electric generation [36,39,46,47]. Probably one of the most researched, yet still one of the least agreed upon areas at sub-system level, is the tilt angle of the PV panels either as independent installation or as integrated units. This is because it is highly and completely dependable on the building geographical location as a super-system parameter, the orientation of the building as a system level parameter and even the type of shading device as a sub-system parameter. While a context-dependent solution by some researchers have suggested that horizontal installation (0◦ tilt angle) reduces the blinds self-shading, and a tilt angle equal to the location latitude maximizes the harvested solar energy especially for horizontal louvers [38, 48], some others have proposed more prescriptive blanket solutions asserting that a horizontal inclination angle of 60° and a vertically inclination angle that is smaller than 15° will work as the best, almost totally regardless of the orientation of the building [46]. Another aspect of the various effects of changing the tilt angle of shading devices is providing a desirable indoor environment in relation to the sky conditions [49]. While Jung [50] also suggested that controlling the tilt angle was efficient regarding visual comfort and reduction in cooling loads, interestingly enough they found that tilt angle made no difference in glare. Experiments of motorized louvers to optimize control methods of inclination angle to track the sun have been conducted for two different climates by Kim et al. [51] and Kim et al. [47]. Various types were compared and evaluated for different tilt angles and orientations of PV shading devices installation by Tongtuam et al. [41]. They found that the maximum energy production can be achieved when the tilt angle is nearly 120° on South, Southeast or Southwest direction. These results were inclusive to the investigated modules that are installed on the exterior wall and have the diffuse reflectance value of approximately 30% like a rough semi-glossy surface.

The dimension of the PV panels is one of the effective parameters that have been the focus of several studies [36,52,53]. They differ from one product to another according to the overall outlines of the devices selected. Regardless of the area of the surface, different dimensions showed different responses [36]. They concluded that the length of the module was found less effective than the width regarding electricity generation. Mandalaki et al. [54] agree that performance of different PV shading devices differ according to their configurations and subsequently, their dimensions. The relationship between the depth of overhangs and the height of the opening is important. It has been proven that the ratio of the distance between the shading device slats and the depth of the slats has a significant effect on the performance of such systems [38,48,46]. This ratio has been used as an installation method to estimate the proportion of electricity generation as it determines the effect of shading on the panels [46]. Regardless of the sizes and dimensions it is recommended that PV shading devices should be applied in such a way that it is not shaded by the panel above [55]. This means the area is not the only effective parameter in electricity generation, and other parameters such as spaces between shading elements or tilt angle [36,46] should be considered to minimize the shading effects.

5. Performance aspect

Performance evaluation of PV shading devices could be a decisive factor because any decision is made based on a set target which is supposed to be met. For instance, when designing for renewable energy application, some PV shading devices can prove to be efficient for this particular purpose but less effective with regards to thermal comfort needs [54]. Therefore it is of paramount importance to set, quite clearly, from the beginning, the purpose, target and deliverables intended for the study to avoid any further confusion. Another very important point which was identified during the course of this review was that performance aspects are not mutually exclusive from design configuration and design considerations. This means that although they often are the main focus of the studies where reviewed and classified under this category, their context needed to have been set with a series of pre-set values in design areas. Sometime variations of design configurations and considerations were introduced to investigate the performance. However, the main purpose and focus of these studies were still performance rather than an investigation of the possible alternatives that the design can potentially take.

Various criteria for performance evaluation of PV shading devices have been developed by several researchers. For energy efficiency and visual comfort, an optimal design parameters of PV shading devices would be the annual total solar insolation on the panels per meter squared of the panel area (Wh/m²), the reduction of the cooling load during summer per meter squared of floor area (Wh/m²), the average daylight factor inside the office space (%) and the geometric shading coefficient on the glass façade (%) [39]. Other researchers suggest that electricity saving can be calculated by assessing the electricity production and the cooling load reduction per unit of PV to achieve optimum design for PV shading devices [33,53].

For cost-benefit analysis, different design options can be assessed based on electricity production per year in correlation with electricity saving for cooling, additional electricity consumption for artificial lighting and maintenance and cleaning cost of PV panels [48]. Electricity production of PV shading devices has been investigated by Hwang et al. [46], Kang et al. [36] and Di Vincenzo et al. [40]. Electricity production (PV output) has been a reliable indicator especially when combined with other criteria such as visual comfort [37]. In some specific cases, all the electricity production by PV can cover the artificial lighting energy [52]. It is even more useful when using multi-criteria assessment criteria such as cooling and heating loads of inner space, electricity needed to ensure visual comfort, electricity production of PV panels and the factor of visual comfort i.e. the ratio of electricity produced by PV to the electricity needed for visual comfort [54]. Karteris et al. [42] evaluated the building energy consumption represented by the energy potential prediction, domestic hot water, electrical appliances, and lighting systems, heating and cooling. The energy behavior of the studied buildings, with applied PV installations, was assessed without taking into account the electricity production to allow for emphasizing the effect of PV’s on heating and cooling loads.

The influence of solar irradiance has been studied by Yoo [43], Yoo and Lee [55], Yoo and Manz [56]. This was an indicator of the insulation ability of the systems studied but in most of the cases, other criteria should also be studied to be able to achieve an informed decision about the system design.

The annual energy yield per square meter of PVs were also evaluated by Tongtuam et al. [41]. It is a valid indicator of the system’s efficiency but cannot be referred to as the only criterion that help deciding the optimum design of the system.

6. Assessment methods

Assessment methods vary based on the available tools or the type of the study and the variables investigated, all of which have proven their reliability within their contexts. In the literature that has been reviewed here, three main methods were found; computer simulation tool, mathematical models and experimental models (test beds either in real buildings or in lab controlled conditions). These three methods were used by a number of researchers as below:

Research in different contexts is governed by many factors which will lead to the choice of the simulation tool. Different tools such as Ecotect [37-39,48], Energy plus [37,52,54], SolCel as a simulating tool for PV systems [43,55,56] have been used as direct energy simulation tools and GIS [42] has been used as an information tool to assist a methodological approach to optimization of energy use as a result of different building component configurations in different geographical locations.

Experimental studies include both scale models either in lab or real-life conditions and real building set-ups. When optimizing, operation and control methods of motorized devices, a physical scale model can be constructed to investigate the performance of these devices, such as PV integrated shading devices, under real-life conditions [49,51]. This is because these motorized devices are responsive to light sensors, therefore their efficiencies and response need to be validated to approve the design. In some cases, real set-up is used to investigate integrated PV blind system with a daylight responsive dimming system [47].

Studies using mathematical models are the ones which have used single formula or a multitude of formulae depending on the purpose, application, breadth and depth of the study. This approach can be adopted to carry out theoretical analysis of integrated photovoltaic modules [36]. A variation of parameters have been investigated to find out the optimum values such as azimuth or tilt angle of PV cladding at different orientations [33] or to describe the impacts of integrated photovoltaic modules on electricity generation and cooling load [53]. Some other studies have used mathematical models to study the dynamic performance of these modules [57].

7. Discussion of findings

Integration of photovoltaics into buildings has different methods and has been studied from different perspectives, of which PV integrated shading devices are a significant category. This study identified three main categories – design configurations/considerations, performance aspects and assessment methods – under which it clustered existing literature on PV integrated shading devices at three different systemic levels, i.e. super-system: context level, system: building level and sub-system: façade level (See table 1).

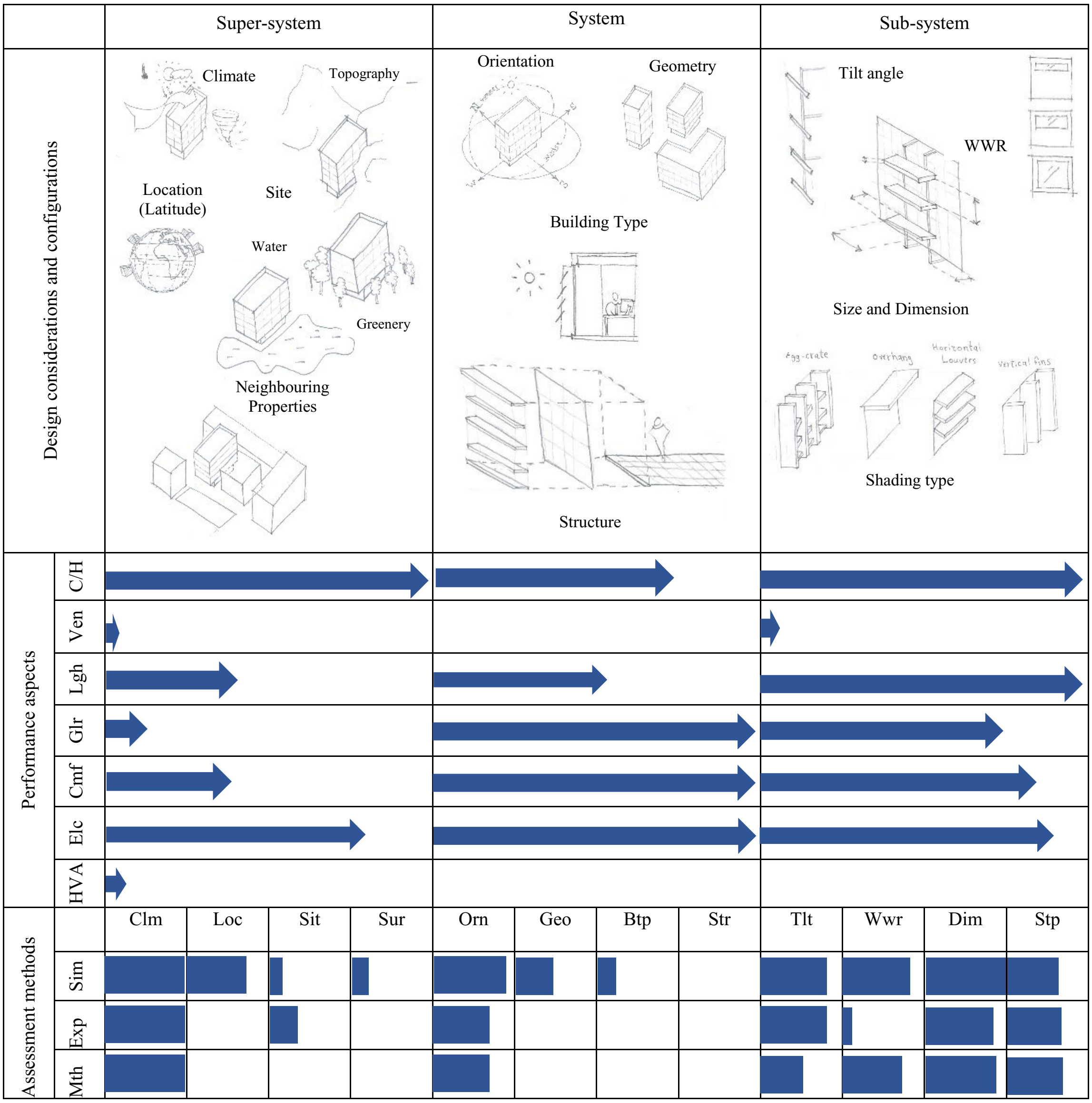
PV integrated shading devices have been proven to have several advantages, but have not been investigated systematically so far. Most of the studies have concentrated on variation of façade components; the sub-system level. A significant progress has been noticed in simulation software as a practical and precise tool that considerably helped developed methods of evaluation and optimization. Configurations and installations in different locations and climates showed dissimilarities in performance. It can be concluded that the application of PV shading devices is far complex and still very much in infancy. As this system essentially comprises PV technology, a handful of studies have been done in different climates to assess the energy production of PV panels. The typical dual function of shading devices, which is providing daylight on the one hand and controlling solar heat gain on the other hand, has now a third function which is producing electricity. The trade-offs now are not only between two functions but also the third function as the demand buildings with lower impacts on environment is growing at more an unprecedented rate than ever before. This has been the focus of many researches to enhance the performance of the buildings with PV shading devices and optimize the energy consumption, human comfort and internal environment. There is still a need of a holistic and comprehensive methodology that helps architects and designers in evaluating and optimizing the performance of buildings with this technology taking into account the weather patterns and the context-specific parameters.

The review showed that most of the research has been done in cold and mild climates. Little has been done in hot and hot-arid climates. Research showed that some such regions can potentially be leading solar energy production for the amount of solar energy available [58] but it still remains a challenge to eliminate the dust effect on PV panels [59].

8.Conclusion and future research

This paper set out to review the-state-of-the-art literature on Integrated Photovoltaic Shading Devices (PVSD) and their application in different buildings and climates with an aim to investigate the influential factors, parameters and strategies as well as assessment methods and indicators for measuring energy performance of buildings where such technologies are used, with an emphasis on systemic approach to configurations. A critical comparative analysis method has been used and literatures related to this topic have been reviewed. In doing so a systemic approach was adopted so that the study can be used as a point of reference for future research where interventions at different systemic level can be justified and recommended. This approach can also form a methodological basis for a decision support system when design decisions are to be made in practice. The results indicate that most of the research is about how calibration of the parameters influences the performance of the system. It also reveals that there are very few studies on the system where a holistic approach has been used for system evaluation; where comprehensive account of all influential factors is taken. For buildings with PV shading devices, there is still a need for further investigation to provide a methodology that takes into account all these variables in a systematic way to improve the energy performance of buildings. Thus, a comprehensive investigation of the system application is needed to further the understanding of performance of such systems.

Table 1. Mapping the literature based on three identified clusters in three systemic levels



Clm: Climate Loc: Location Sit: Site Sur: Surroundings Orn: Orientation Geo: Geometry Btp: Building type Str: Structure Tlt: Tilt angle Wwr: window-to-wall ratio Dim: Size and dimensions Stp: Shading type Sim: Simulation tool Exp: Experimental study Mth: Mathematical model C/H: Cooling/heating loads Ven: Ventilation Lgh: Lighting Glr: Glare Cmf: Visual/thermal comfort Elc: Electricity generation HVA: HVAC systems

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