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# Intelligent Facades in Low-Energy Buildings

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***Authors' contributions***

*This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

Growing interest in development of innovative solutions for enhancement of sustainability in the built environments has been observed in recent years. According to the main constituents of buildings particularly in building envelopes, facades are expected to play a significant role towards the promotion of sustainable design in low energy buildings. This study presents a holistic review towards the analysis of 'intelligent facades' according to their types, current implementations, challenges, and ultimate impacts. Intelligent facades need to be responsive and conscious to the local climate, outdoor environment, and indoor spaces with view to parameters such as energy performance, thermal comfort, indoor air quality, visual comfort, etc. The findings demonstrate that energy modeling and simulations should be performed during the early stage of design process of buildings to ensure the practicality and effectiveness of any green implementations in buildings. In conclusion, the study recommends the intelligent facades to become an inherent constituent of green buildings for future development of low energy buildings.

*Keywords: Intelligent facades; low energy buildings; sustainable developments; green implementations.*

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## 1. INTRODUCTION

Considerable attempts and endeavors based on comprehensive research efforts were observed for enhancement of energy efficiency in buildings in order to develop low energy, ultra low energy and zero energy buildings [1,2,3,4,5,6,7]. To expand this goal, researcher efforts are required to focus on all constituents of the built environments and mainly the building envelope. It is clearly stated that innovating energy efficient design could highly reduce the overall energy consumption of buildings [8]. According to Thormark [9], the 'operation' encompasses the highest rate of energy consumption in buildings; hence, the building envelope is proposed to be significantly reinforced based on enhanced building operations as an indicator of environmental responsiveness in order to contribute to the energy saving concept. In order to improve planning efficiency, Building Information Modeling (BIM) incorporates various information regarding building conditions such as thermographic databases based on laser scanning and infrared thermography in real world [10]. Respectively, BIM-based simulations, specifically with view to building envelopes, can largely contribute towards the prediction of building energy consumptions; hence, resulting in corresponding consequential energy savings.

Various energy modeling and simulation software have been developed for the analysis of building energy performances, and in particular the effects of building facades, including *ASHRAE 90, DOE-2, MIT Design Advisor, Energy Plus*, Etc. According to Maile et al. [11], two fundamental type of software are utilized today including the “design tools” and “simulation tools”. Design tools are predominantly used with focus on HVAC systems while simulation tools are used for the prediction of energy performances. This study highlights that the use of intelligent facades could considerably contribute to the enhanced energy performance of buildings, hence, the effectiveness of such systems is recommended to be verified and confirmed not only during the design stage but throughout the entire building lifecycle through the appropriate energy modeling and simulation software. In this regard, Maile et al. [11] states: “*Energy performance simulation tools are mostly used during design, but the use of such tools during the commissioning and operations phase has additional value. To leverage this value, data exchange must become more applicable and usable in other phases of a building’s life-cycle, not only in the design phase. Thus a closer integration of energy performance simulation with the actual performance of buildings during operation will not only improve existing simulation tools, but will also enable a more efficient operation of buildings.”*

Meanwhile, the study by GhaffarianHoseini et al. [12] represents the effectiveness of intelligent buildings with view to their environmentally responsive attributes. Intelligent facades as the innovative integrated constituent of building envelope were developed to rectify all the disadvantages of current facades as stated by Cetiner and Ozkan [13] in which the intelligent facades were designed and developed based upon versatile types and classifications. Moving forward for creating environmentally benign buildings based upon energy efficiency of design, there is an acute need to provide a holistic review of the significant role of facades in terms of energy saving and energy efficiency in the environmentally benign built environments. Given that the application of green facades was considered a major phase in the design process of green buildings [14,15], intelligent and green facades were accordingly summarized and discussed in this study based on the concept of sustainable facades with respect to the environmental criteria and local climate conditions.

In essence, the energy performance of buildings could be significantly improved once the intelligent facades can be successfully adopted. These facades are not only influential for enhancement of the building energy performance, but also for optimized daylighting, as well as visual and thermal comfort besides the reduction of heat gains, noises and strong winds. According to the studies by Pérez et al. [16,17], green facades are fundamentally contributive to the energy savings in buildings. In their study, samples of green facades are tested to assess its effectiveness while their findings explain that green facades embody great potentials for producing shades and reducing heat gains. Use of climbing plantations is proposed by Pérez et al. [16] for such green implementations. In general, according to Kohler [18], application of green vertical systems could be beneficial for the sustainable built environments. Similarly, Perini et al. [19] ascertained the energy saving impact of green facades based on the integration of vertical greening design strategies. These green vertical systems are categorized with view to their development structure, types of plantations and maintenance systems according to the Table 1 [16,17]. Likewise, Pérez et al. [16] highlighted that there are basically four main key factors, which affect the green vertical systems towards the concept of energy saving as represented in Table 2.

**Table 1. Categorization of green vertical constituents of buildings [16,17]**

| | **Extensive Systems** | | **Intensive Systems** |
|---|---|---|---|
| Green Facades | Traditional Green Facades<br>Double-Skin Green Façade or Green Curtain | Modular<br>Trellis<br>Wired<br>Mesh | |
| Living Walls | | | Perimeter<br>Flowerpots<br>Panels<br>Geotextile Felt |

**Table 2. Key factors affecting green vertical constituents of buildings [16]**

| **Interception of solar radiation. shadow** | **Thermal insulation and storage** | **Evaporative cooling** | **Variation of the effect of the wind** |
|---|---|---|---|
| Density of the foliage (number of layers) | Density of the foliage (number of layers)<br>Changes in the air in the intermediate space<br>Barrier effect of wind<br>Substrate: thickness, bulk density and moisture content[a] | Type of plant<br>Exhibition<br>Climate (dry/wet)<br>Wind speed<br>Subtrate moisture[a] | Density of the foliage (number of layers)<br>Orientation of the façade<br>Direction and wind speed |

[a] *Only in certain types of green verticals systems, such as living walls.*

In view of the future sustainable developments, with focus on ecologically sustainable design, utilization of green facades are primarily operative and effective, nevertheless, for the optimization of building envelopes, facades are expected to be intelligent, ventilated, and environmentally benign [20]. In this regard, for the technical assessment of building envelopes, the parameters in Table 3 were introduced by Zheng et al. [21] in order to be highly taken into account.

**Table 3. Fundamental parameters for assessment of building envelopes [21]**

| Factor | Sub-Factor |
|---|---|
| Thermal Performance | Heat Transfer Coefficient of Roof |
| | Heat Transfer Coefficient of Ground |
| | Heat Transfer Coefficient of External Wall |
| | Heat Transfer Coefficient of Window |
| | Heat Transfer Coefficient of Door |
| Building Form | Maximum Form Coefficient |
| | Perfect Form Coefficient |
| | Orientation |
| | Floor to Ceiling Height |
| | Window-to-Wall Ratio |
| | Shading Coefficient of Window Glass |
| Economy | Initial Construction Costs |
| | Maintenance Costs |
| Innovation | New Technology |
| | New Material and Product |
| Reliability | Safety |
| | Comfort |
| | Durability |
| Environmental Protection | Environmental Protection |

This study is aimed to review the current scholarly studies regarding the applications of intelligent facades as advanced energy efficient systems for enhancing the energy performance of green buildings. In particular, this study introduces the kinetic, open joint ventilated, double skin, double glazed and solar facades. Therefore, it is also important to present a clear definition of the retrospective terms before the analysis and discussion phases. According to United Nations Environmental Program (UNEP), United States Environmental Protection Agency (EPA) [22], energy efficiency is delineated as "*using less energy without compromising the performance of the building*". Meanwhile, according to IEA ECBCS Annex 53 [23], *"building energy performance is mainly determined by six factors: (1) climate, (2) building envelope, (3) building services and energy systems, (4) building operation and maintenance, (5) occupants' activities and behavior and (6) indoor environmental quality provided.*" The following discussion follows the definition logically.

## 2. SUSTAINABLE DEVELOPMENTS: LOW ENERGY BUILDINGS

Today, an accelerated rate of interest in academic research and practical implementation about the circumstances of creating the sustainable built environments is observed. According to the worldwide policies, buildings encompass significant potentials for decreasing the greenhouse gas emission [24]. It is continuously discussed and highlighted that buildings consume approximately 30 to 40 percent of overall energy consumption in developed countries [25]. With regards to the circumstances of sustainable developments, the study by Berardi [26] demonstrates the widespread interest in use of sustainability rating systems. These rating systems embrace spectrum of factors ranging from the level of energy consumptions to the lifecycle analysis and overall building performances. As a result of the sustainability rating systems, Low energy buildings, ultra low energy buildings and zero energy buildings is accordingly the ideal focused target of current endeavors. This study highlights that all these buildings share the common concept of 'significant building energy reduction' while targeting to obtain enhanced performance and operation based on the consideration of the lifecycle analysis of buildings. This fact overstresses the substantial necessity to move forward for the development of low/zero energy buildings as standardized basis for national and international building policies. Zero energy consumption and zero carbon emission is an ideal target for the development of future green buildings.

From another perspective, Berardi [27] draws attention to the actual meaning of sustainability in built environments as it is claimed that the recent studies are still arguing about the definitive meaning of sustainability and circumstances of measuring its level. Thus, this study targets to elucidate the essence of sustainability through an explicit understanding of the interrelations between the building envelopes (particularly facades) and the environment. It is inferred that the building envelopes including the building facades, as the protecting cover of the indoor spaces, are effectively influential for future sustainable developments [28]. Moreover, it is highlighted that there is a high level of congruency between the characteristics of building envelopes and the visual, acoustical and thermal comfort of indoor spaces [29]. Thereby, this study aims to generally review and analyze the current theories and scholarly researches about the concept of low energy buildings with a strong focus on the sustainable design of intelligent facades. In this regard, low energy buildings are defined as innovative buildings that are integrated with environmentally efficient and responsive features as well as the integrated renewable energy supplies. Thus, through the reinforcement of the building envelope, the level of heating and cooling demand in low energy buildings will be decreased leading to the low level of energy consumption [30].

Sustainable development is highly correlated with the interrelationship between building, environment and energy [31]. In view of the energy performance of buildings, particularly low energy buildings, it is also essential to consider the feedbacks and viewpoints of users as the indicator of their level of satisfaction [32,33]. According to Zalejska-Jonsson [34], tenants are highly satisfied with their living environments in low energy buildings while there is limited dissatisfaction about the thermal comfort and air ventilation for further improvement. Likewise, the findings of another study confirm the high satisfaction rate of users in 12 solar low energy buildings while few problems including overheating, extra noises and ventilation were highlighted by the minority of occupants [35]. In Germany, one study presented similar level of satisfaction among the occupants [36]. In Vienna, it was alsodemonstrated that the occupants are predominantly satisfied with the low energy buildings [37]. It is certain that the building envelopes, particularly the integrated facades as a substantial constituent of building incorporated with advance technologies, can be greatly contributed to the enhancement of comfort levels of occupants beside the enhanced energy performance of buildings. Among various types of comfort influenced by building facades, thermal comfort is deduced to be one of the most fundamental aspects with considerable correlations to the well-being of users.

## 3. RELATIONSHIP BETWEEN INDOOR THERMAL COMFORT AND BUILDING FACADE

Nowadays, in industrialized countries, people mostly spend their time in enclosed spaces such as homes, offices, schools, factories, libraries and indoor public spaces like shopping centers [38]. Since a wide range of environmental parameters can affect the quality of indoor spaces and user's satisfaction, numerous studies have been conducted by researchers and architects in order to establish design strategies to create acceptable indoor environments in accordance with the behavior of users and locality of the buildings. Hence, in view of the indoor environmental quality, most of the researches concentrate on the thermal aspects of environments and the condition of human thermal comfort inside the buildings [38,39].

Facade as the main constitute of building envelope and a boundary between external and internal environments, considerably impacts the environmental conditions of indoor spaces, the thermal performance of buildings and subsequently the user's satisfaction [39,40]. It is stated that a successful building is the one which can provide a thermally comfortable indoor environment while controlling the energy consumption of the building [41]. Essentially, thermal comfort conditions depend not only on the external environmental factors (i.e., air temperature, air movement, solar radiation) but also mainly on the architectural parameters and design elements such as the position and orientation of building, facade materials, shading devices, type and location of windows and roof shapes [41,42]. For this reason, during the design process of building, design and selection of facades must be considered as one of the major tasks in order to reinforce the quality of visual and thermal sensations in indoor environments.

Thermal comfort is not a recent subject and it has always been considered as a primary issue for people to express their sensation of thermal environments [43]. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) defines the psychological and subjective aspects of the thermal comfort by describing it as a condition of mind which expresses satisfaction with the thermal environment. Hence, the lack of thermal comfort or neutral thermal sensation causes one to feel warm or cold [44]. There are varieties of thermal comfort indices developed by researchers which quantitatively describe the effect of the thermal environment on the human body. In order to assess the thermal influence of the environment on the human body, the integrated effects of all factors including outdoor climate and relevant meteorological parameters (air temperature, humidity, wind velocity, thermal radiation), personal characteristics (e.g. clothing, activity) as well as building-related factors have to be taken into consideration [38,41,45]. The basis for all of the models is the energy exchanges between a human body and the surrounding environments. Therefore, with regard to the current trend in developing sustainable and green buildings, it is vital to highlight the importance of facade design decisions for creating thermally comfortable environments and optimization of the energy consumption in buildings. According to the highlighted contemplations, it is fundamentally important to introduce the circumstances of developing intelligent facades as the innovative approach for future green implementations in building industry.

## 4. ANALYTICAL REVIEW OF INTELLIGENT FACADES

### 4.1 Background

Unlike the conventional facades of typical buildings, which are inextricably bound up with versatile problems including high rate of energy consumption and poor thermal comfort [46], intelligent facades should improve the interrelations between the indoor and outdoor environments. Besides the aesthetical strengths, intelligent facades are deemed to be fundamentally important for reinforcement of the building's environmental and energy performance [47,50].

## 4.2 Intelligent Facades

With reference to the negative impacts of climate change and global warming, it has been continuously recommended to innovate, develop and utilize new solutions for the sustainable development of built environments. To achieve this goal, there is a vital task to analyze and assess the thermal performance of buildings as stated by Ochoa and Capeluto [40]. In this regard, versatile attempts are observed toward the design and creation of buildings which are responsive to the climate and environment [48,49]. When analyzing the building physics, it is noted that the buildings façade plays an important role for the overall energy performance of buildings besides its aesthetic and visual impacts [40]. Past studies confirmed this importance through presenting the contribution of building facades in approximately 36 percent of total energy costs in hot and humid climate environments [47,50]. The study by Tzempelikos et al. [51] also highlighted that the design of facades is highly related to the energy and daylighting performances. In this regard, intelligent facades are proposed as an innovative solution to the enhancement of sustainability in built environments.

Elaborations from the study of Inkarojrit [52] indicated that the utilization of intelligent facades embraces two noteworthy results as the enhancement of the user's comfort and the reduction of energy consumption rate. Expanding the intelligent façade's description by Ochoa [40], these facades are meant to be responsive and conscious to the local climate, outdoor environment, and indoor spaces with view to versatile parameters such as energy performance, thermal comfort, indoor air quality, visual comfort, etc. Supporting the elaborated points, the findings of the study by Skelly [53] were based on scrutinizing the essence of intelligent facades, articulate particular parameters associated with the effectiveness of intelligent facades. The findings explicitly denote that an intelligent façade must be responsive to three main parameters including weather, context and occupants. As stated that the interrelations between the intelligent façade and the aforementioned parameters must be dynamic, non-linear, stochastic, multi-dimensional and immeasurable as explained in Table 4.

**Table 4. The main characteristics of intelligent facades for being responsive and adaptive [53]**

| Characteristics | Explanation |
|---|---|
| Dynamic | Many parameters change over time and at different rates |
| Non-Linear | Some parameters exhibit different types of behavior in different regions |
| Stochastic | Some parameters are subject to large unpredictable/chaotic environmental disturbances |
| Multi-dimensional | Many different mechanisms interact in a complex manner |
| Unmeasurable | Some variables are difficult to measure, have unknown relationships, or are expensive to evaluate in real time, such as occupant satisfaction, psychological factors and future cloud cover |

## 4.3 Kinetic Facades

It is ideally significant to design and develop facades that are interactive and responsive to the environmental attributes. These facades, as part of the so-called intelligent facades, are capable of adjusting their shape, form, orientation or openings to automatically respond to the environmental parameters including the temperature, humidity, wind, etc. To support this contemplation, Kensek and Hansanuwat [54] strongly claims that kinetic facades are dynamic and adaptable for responding to the environment. Indeed, it is depicted that kinetic facades are considerably influential for creating low energy and ultimately zero energy buildings as an approach in the direction of sustainable development of built environments. In this regard, movable and interactive shading devices could also be highly inflectional for better performance of kinetic facades. Within the study by Tzempelikos et al. [51], shading devices are highly influential for the optimized energy performance of buildings. These shading devices, once integrated into the design of facades, could reduce the level of solar heat gains, block direct sunlight while mitigating the glare and undesirable contrasts. Accordingly, it is theorized that the automated shading devices could lead to the reduction of energy consumptions used for lighting, cooling, heating. Application of automated features into the design of building facades in the form of kinetic facades could lead to the development of comfortable indoor environments [51]. The concept of automation versus sustainable development is also expected to be achieved based on essential considerations during the early design stages. GhaffarianHoseini et al. [55] expresses the importance of considering corresponding thoughtfulness with regards to 'automation' during the early stages of architectural design process, hence, extending the theory towards utilization within intelligent facade design and further respective progressions.

Fig. 1 represents a conceptual paper model of a shading system as part of a kinetic facade inclusive of four adjustable segments and a centralized joint as developed by Suralkar [56]. The conceptual models of kinetic facades are developed to confirm the applicability and effectiveness of the automatic responses of facades to the context including the environment and people.

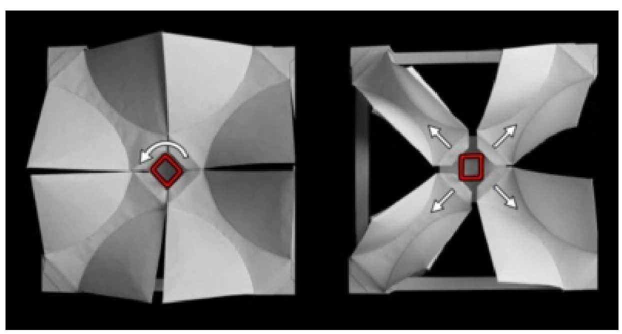

**Fig. 1. Conceptual model as part of a kinetic facade [56]**

## 4.4 Open Joint Ventilated Facades

Open joint ventilated facades (OJVFs) are currently proposed as an efficient replacement of conventional facades. OJVFs are categorized under the advanced integrated facades with great potentials as intelligent design features [57]. According to Sanjuan et al. [58] the basis of OJCFs is described as follows:

*"The main particularity of Open Joint Ventilated Facades (OJVF) is that they have an exterior opaque coating separated from the mass wall by a ventilated air cavity. The exterior coating material is arranged in slabs separated by open joints that enable exterior air to enter and leave the cavity all along the wall."*

Referring to the study by Giancola et al. [59], a sample of OJVFs is presented based on a case study in Spain (Fig 2). Meanwhile, reviewing recent studies, the main significant attribute of these facades demonstrates the flexibility and adaptability of OJVFs for being customized to any preferred shape and color. Moreover, these ventilated facades are claimed to be highly energy efficient while embodying the potentials for resolving the moisture problems. Likewise, OJVFs are also claimed to have optimized performance in confrontation with the solar radiations [57]. The heat transfer of OJVFs in comparison with a conventional sealed cavity façade is accordingly represented according to Fig. 3.

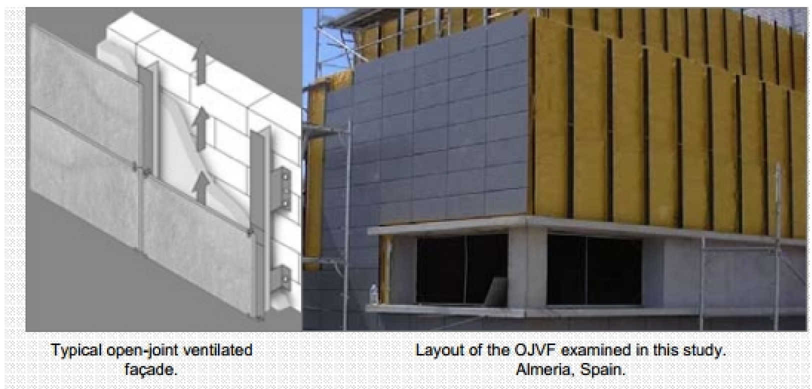


**Fig. 2. Sample of OJVFs [59]**

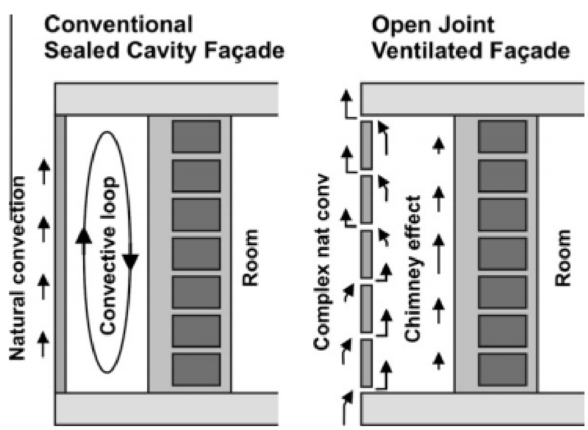


**Fig. 3. Comparison of heat transfer [57]**

Based on CFD analysis, it is concluded that ventilated facades could improve the concept of energy saving as a promising approach towards the development of low energy buildings [60]. Future research based on rigorous analysis and simulation of the energy performance of these systems is still expected to be carried out.

### 4.5 Double-Skin Facades

Double-skin facades technology is another design solution for energy conservation purposes to be implemented for creating low energy buildings [61]. It is principally expressed that these facades are significantly influential in decreasing the solar heat gains as described by [62]. Utilization of double-skin facades has become considerably widespread and common in many countries, particularly in Europe [62,63], and accordingly, this has led to the development of many studies for application of double-skin facades in buildings [64]. Furthermore, Hamza [65] highlights that double-skin facades (DSFs) are receiving more interests and approvals in Europe, North America and Japan. Nevertheless, double-skin façade is not a newly developed idea as the first attempt for creating a double-skin wall goes back to 1903 in Germany [66]. Meanwhile, according to the research by Xu and Ojima [67], DSFs are very similar to the corridor spaces in traditional Japanese houses as shown in Fig. 4.

**Fig. 4. DSFs versus corridor spaces of traditional Japanese houses [67]**

According to Saelens [68], a concise definition of double-skin facades represents DSFs as:

*“Envelope constructions, which consist of two transparent surfaces separated by a cavity, which is used as an air channel”*

Based on a research by Chan et al. [69], double-skin facades are defined as follows:

*“Double skin facade refers to a building facade covering one or several stories with multiple glazed skins. The skins can be air tight or naturally/mechanically ventilated. The outer skin is usually a hardened single glazing and can be fully glazed. Inner skin can be insulating double glazing and is not completely glazed in most applications. The width of the air cavity between the two skins can range from 200 mm to more than 2 m. An air-tightened double skin facade can provide increased thermal insulation for the building so as to reduce the heat loss in winter season. On the other hand, moving cavity air inside a ventilated double skin facade can absorb heat energy from the sun-lit glazing and reduce the heat gain as well as the cooling demand of a building”.*

Despite the weaknesses of glass facades, specifically for high-rise buildings, utilization of double-skin façade (DSF) is proposed as a proper replacement due to its potential strengths for receiving optimized daylighting, reducing the heat gain and ensuring natural ventilation [13]. DSFs are substantially effective for creating low energy buildings as highlighted by Gratia and Herde [70,71]. Likewise, it is depicted that in summer, DSFs considerably decrease the solar heat gains while in winter, they act as thermal insulation. Supporting this theory, according to Balocco and Colombari [72], Balocco [83], the application of these advanced technologies as an intelligent facade could be greatly contributive to energy conservation.

The study by Lou et al. [73] introduces three design strategies for DSFs including continuous, box and corridor DSFs as shown in Fig. 5. On the other hand, a similar study by Heusler and Compagno [74] categorizes the DSFs into three types of window, storey and multiple storeys' as represented in Fig. 6.

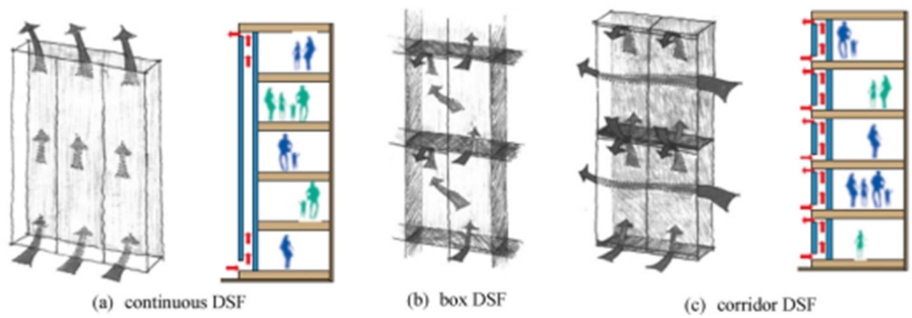


**Fig. 5. Main design strategies of DSFs [73]**

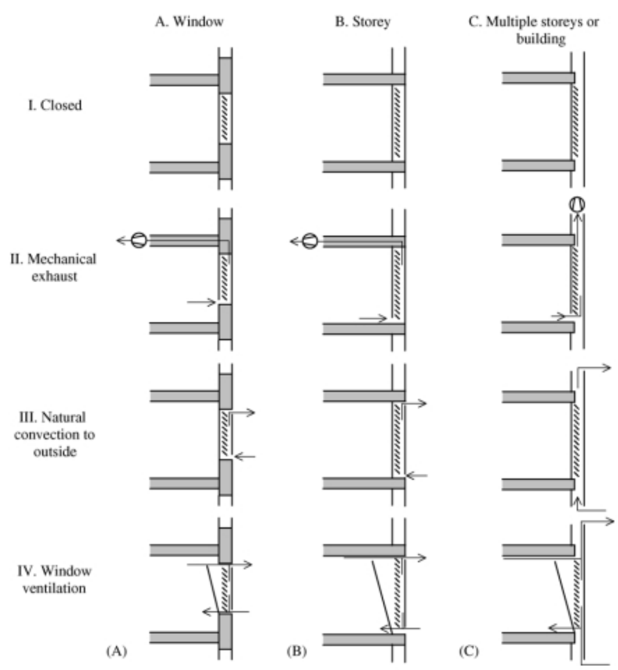


**Fig. 6. Categorization of DSFs [74,76]**

Similarly, other studies including Parkin [75] and Haase et al. [49] discuss and confirm various types of DSFs used in building envelopes, therefore, according to the findings derived from the study by Haase et al. [49], the following features are represented (Fig. 7).

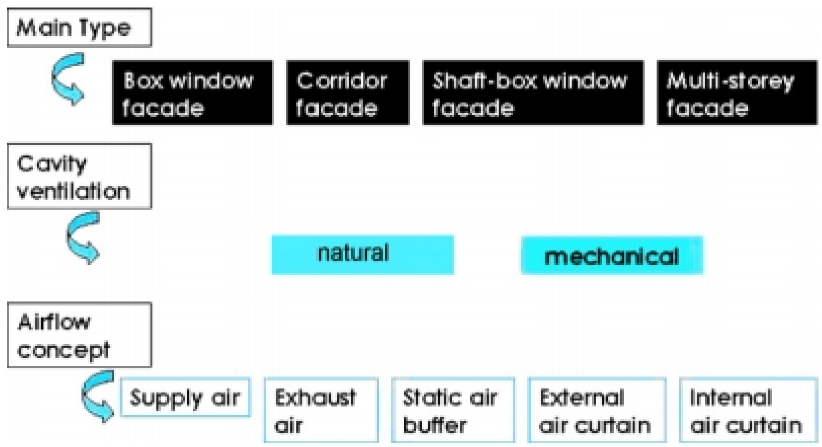


**Fig. 7. Main features of DSFs [49]**

Many studies recommend the application of double-skin facades for reducing the heat gains as an energy efficient feature for development of low energy buildings [62,77,78,79,80,81]. Shameri et al. [46] explicitly introduces the adoption of double-skin facades as an effective solution for the goal of energy saving in buildings. In principal, the combination of two façade layers with an empty space inside (air gap - cavity) develops the idea of DSFs [65]. Gratia [82] explains that double-skin facades are derived progressively from the concept of a façade deigned entirely by glass. On the other hand, referring to the study by Mingotti et al. [15], the external and internal layers of DSFs must have versatile openings in order to ensure air ventilation within the cavity as well as the interior atmosphere of the adjacent interior spaces. In view of that, it is reflected that the temperature and air ventilation are inherently related to the size of cavity, hence, the studies by Balocco and Colombari [72], Balocco [83] confirm that once the widths of cavity gets decreased, there is a high risk of being confronted with an overheating façade layer particularly, in summer. Nonetheless, in general, in double-skin facades, there is an opportunity of adding an extra glaze skin to the building which could provide enhanced visual comfort, improved daylighting and progressive energy performance. The incorporation of the external and internal façade layers in DSFs also has impact on greenhouse effect as visualized by Gratia and Herde [82] in Fig. 8.

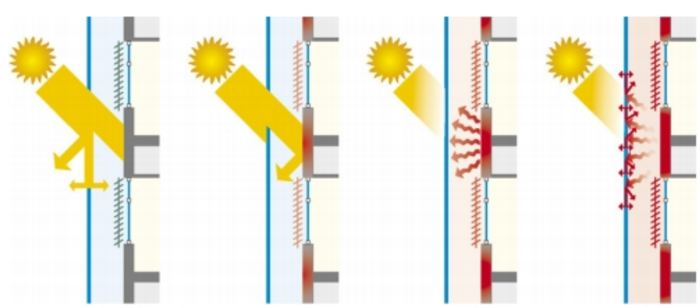

**Fig. 8. The incorporation of the external and internal façade layers [82]**

Meanwhile, with view to the sustainable energy performance of DSFs, according to the study by Chan et al. [69], the heat transfer and air movement within a section of DSF is represented (See Fig. 9).

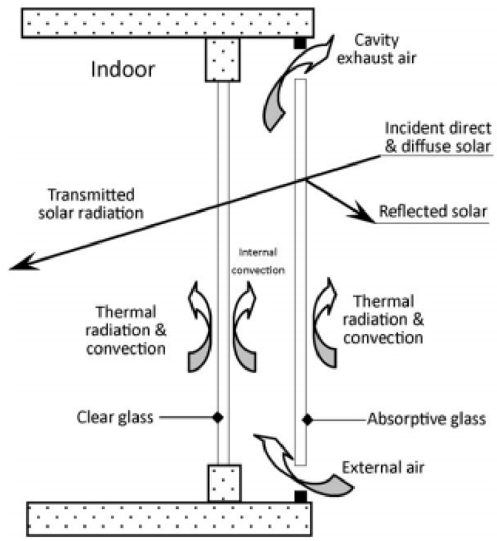


**Fig. 9. The heart transfer and air movement in DSFs [69]**

It is important to consider that the air movement in DSFs varies to suite the environmental requirements; hence, Haase et al. [49] identifies five types of air movement for application in DSFs which are visually represented in Fig. 10.

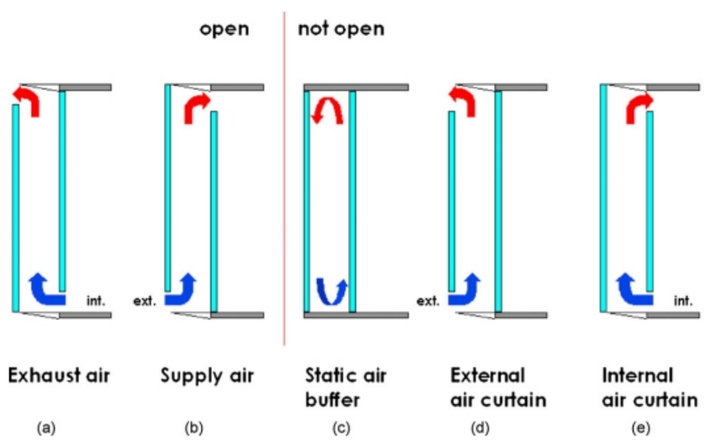


**Fig. 10. Main types of air movement in DSFs [49]**

Adding to the strengths of double-skin facades, Yılmaz and Cetintas [84] highlights other positive effects including the sound insulation and enhanced aesthetic features besides sustainable energy performances. Similarly, Byrd and Leardini [85] draws attention to the role of DSFs as the preventing system for decreasing the noises while arguing that despite the repeatedly discussed benefits of DSFs as energy efficient systems, it is difficult to

measure this effectiveness based on the statement by Lawrence Berkeley National Laboratories [86].
On the contrary, other studies have explicitly ascertained the effective result of DSFs for reducing the energy consumptions, particularly with respect to the cooling demands. Thereby, it is inferred that there is still a need for future research towards the further analysis, verification and potential reinforcement of these facades to ensure enhanced building energy performances.

Looking retrospectively, these facades could also be classified based on their construction types and the circumstances of ventilations. Thereby, in view of the construction types, there are continuous and interrupted double-skin facades while with regards to the ventilation, facades are divided into natural ventilated, mechanical ventilated as well as natural and mechanical ventilated [84]. According to the studies by Yılmaz and Cetintas [84] and Chou et al. [62], it is inferred that in summer, the reduction of solar heat gain is the main effect of double-skin facades while in winter; double-skin facades help to minimize the heat loss and improve the u-values. According to the study by Høseggen et al. [14], comparing the single and double-skin facades, the simulations confirm that the application DSFs reduces the heating energy demand in buildings.

To improve the effectiveness of DSFs, unlike the conventional DSFs, Ding et al. [87] proposes to add a thermal storage as *solar chimney* above the double-skin layers in order to improve the ventilations (Fig. 11). The analysis confirms the effectiveness of the proposed concept in order to be utilized for intelligent façade design developments.

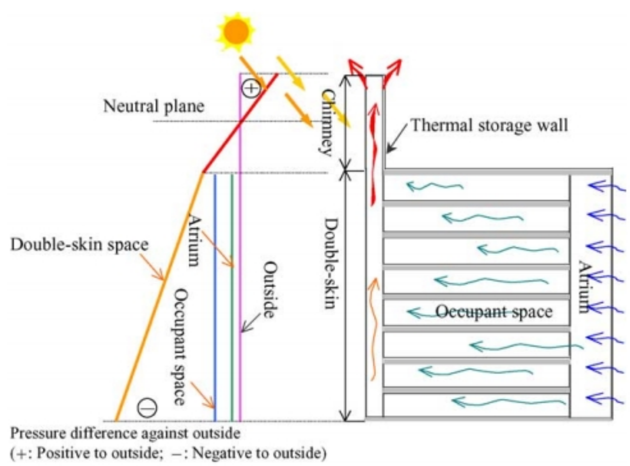


**Fig. 11. Application of solar chimney as the thermal storage in DSFs [87]**

Similarly, moving towards the enhancement of energy performance of multiple-skin facades (MSFs), the study by Saelens et al. [88] proposes the application of five systems including airflow window, double-skin facade, supply window, exterior shading device and interior shading device (Fig. 12). Accordingly, the analysis of the proposed optimizations represents a comparison of the heating and cooling energy demands between the proposed integrated systems and the non-enhanced ones as explicitly shown in Fig. 13.

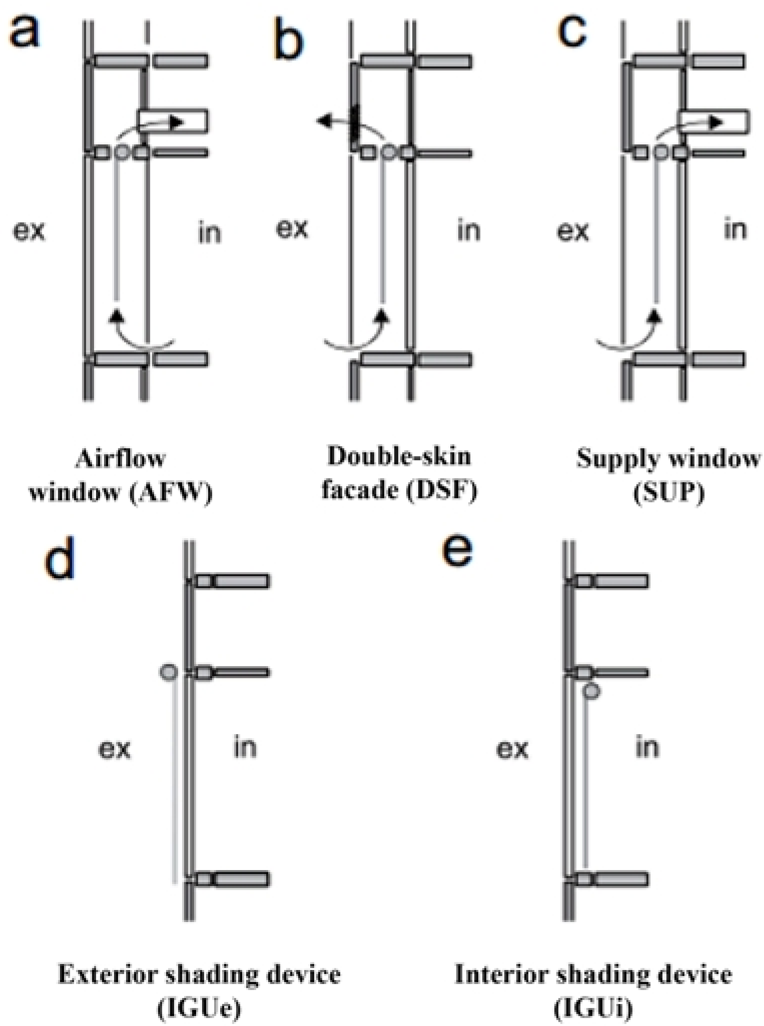


**Fig. 12. Main systems in MSFs [88]**

Analyzing the essence of double-skin facades, Shameri et al. [46] concludes that DSFs are essentially influential for enhancement of building energy performance. One of the few challenges for the application of DSFs is their cost compared to the conventional facades. Andresen [103] also highlights the required cost for development of DSFs is approximately 60-80% more than the conventional types. Nevertheless, it is also elaborated that DSFs embody the concept of cost efficiency in long-time duration. Meanwhile, Shameri et al. [46] expresses the *'fire hazard risks'* as another challenge of DSF application which requires further research and investigation.

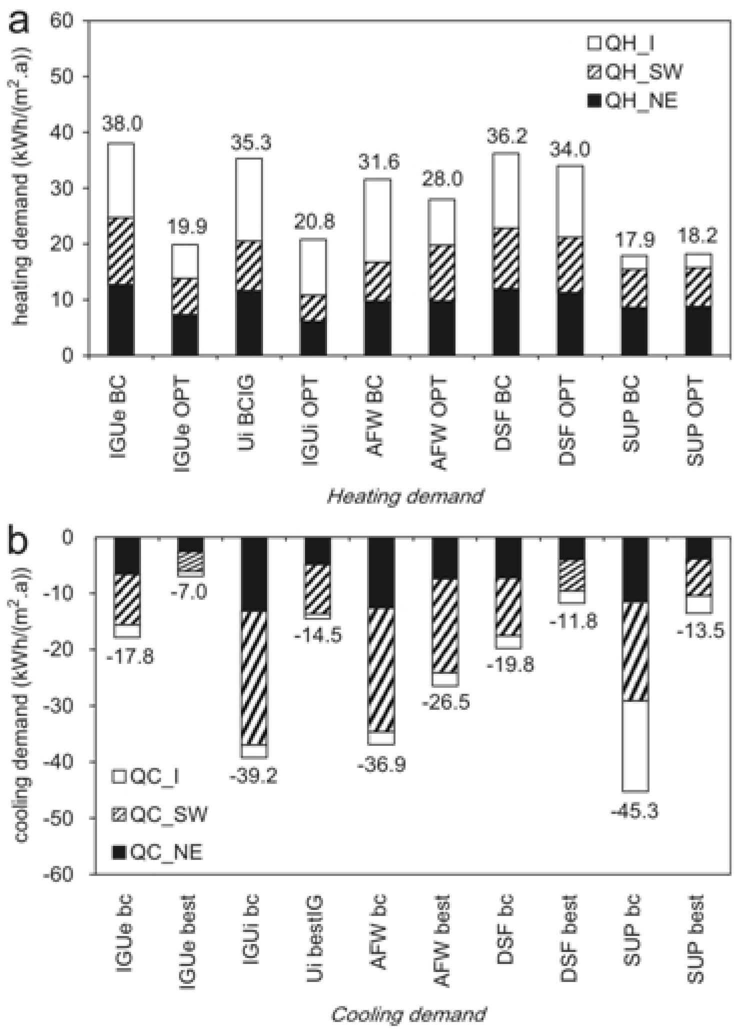


**Fig. 13. Comparison of cooling and heating energy demands [88]**

## 4.6 Double-Glazed Facades

Few decades ago, architects and designers initiated the integration of glazing windows in buildings. Nevertheless, it is critically argued that simple glazing windows do not support the energy performance of buildings [89]. With view to the energy performance of buildings, it is depicted that the windows have poor performance towards the concept of energy efficiency [90]. To rectify the mentioned disadvantages, Selkowitz [94] proposes the use of sealed glazing windows for building integrations. The insulated glazings are comprised of several glass sheets divided by air cavities which substantially decrease the level of heat transfers [92].

In this regard, Dussault et al. [89] discussed about a double-glazed smart window as shown in Fig. 14 (The opacity represents the level of solar absorption by the integrated filter). Meanwhile, for cold climates, it is proposed by Carlos et al. [90] to add a single glazed-window in order to develop a ventilated double window as part of the façade (Fig. 15). Through utilization of a shutter within the air-gap of the ventilated double window, three air movement possibilities are provided once the shutter is closed at nights. Use of such system is claimed to improve the thermal resistance of this technology (Fig. 16).

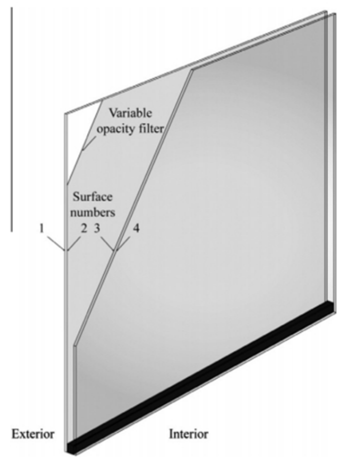


**Fig. 14. Sample of a double-glazed smart window [89]**

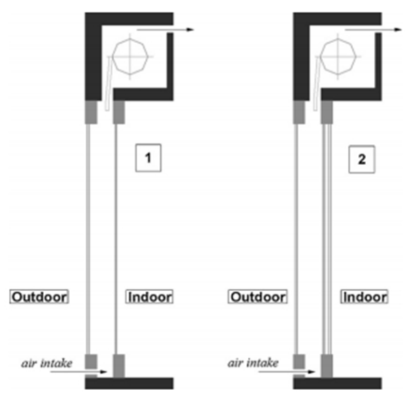


**Fig. 15. Ventilated double window [90]**

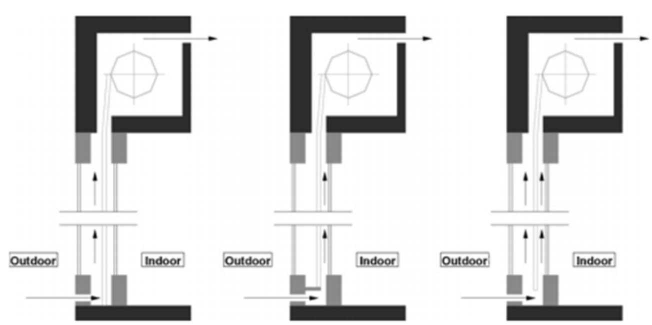


**Fig. 16. Utilization of a shutter within the air-gap of the ventilated double window [90]**

In general, according to Hien et al. [91], recent studies argued that due to the potential of fully glazed facades for receiving a high level of solar gain, the rate of energy consumption in the respective buildings is relatively high resulting in the increasing use of glazed facades in buildings. Furthermore, fully glazed facades do not provide thermally comfortable indoor spaces. Hence, to prevent the aforesaid disadvantages, application of double-glazed facades (DGFs) integrated with ventilation systems is proposed. The research by Hien et al. [91] confirms the effectiveness of double-glazed facades for enhancing the thermal comfort and reducing the energy consumption of buildings. According to Coussirat et al. [93], DGFs are widely used in many countries particularly for commercial buildings. Despite the undeniable advantages of DGFs, it is argued that an efficient design of DGF is expected for ensuring the effectiveness of this technology. Based on Guardo et al. [95], the incorporation of external glazing layer, air cavity, internal double glazing layer and the internal wall represents the detailed structure of DGFs as represented in Figs. 17 and 18.

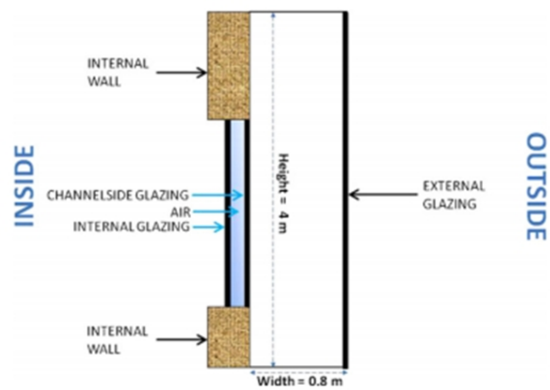


**Fig. 17. Detailed structure of DGFs [95]**

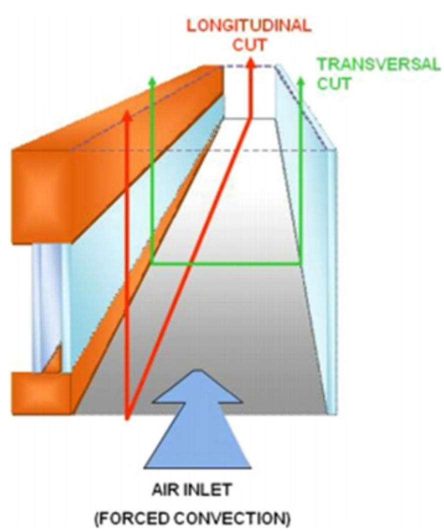


**Fig. 18. Detailed structure of DGFs [95]**

## 4.7 Solar Facades

In essence, the undeniable contribution of solar energy as a renewable energy source for reducing the level of energy consumption is discussed and represented with particular attention to the use of electricity [96]. Meanwhile, the significant importance of photovoltaic technology is repeatedly discussed and confirmed for reducing the negative environmental impacts of buildings [97]. This technology has been utilized for moving towards the development of green buildings since many years ago. Thus, the concept of solar façade based on the application of photovoltaic generators in facades is not an emerging phenomenon; however, its undeniable benefits could still stimulate the mind of architects to consider it during the design process of low energy buildings. Referring to previous studies, the integration of photovoltaic into the facades of green buildings is not only a considerable source of renewable energy for electricity, but it is also a source of heat for heating and cooling purposes.

Back to 1997, Brinkworth et al. [98] proposes to dedicate a ventilated air gap behind the PV layers in order to prevent the high temperature of PV module for increasing the ultimately gained electricity. Meanwhile, Pearsall [99] discusses about the advantages of utilizing solar facades for better energy performance of buildings. Likewise, their study overstresses the visibility as another significant advantage of PV facades. Reviewing the past scholarly studies, according to Krauter et al. [100], it is inferred that PV facades are predominantly curtain façade layers in front of insulated internal walls with an air duct in between as shown in Fig. 19.

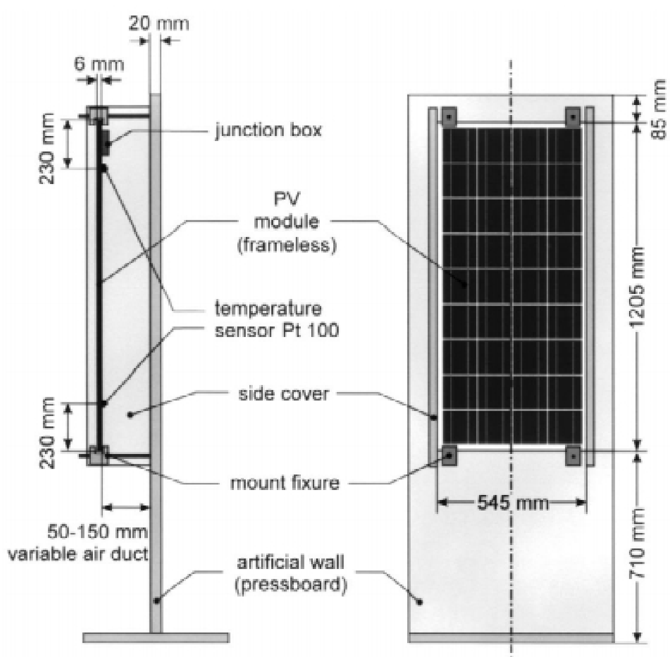


**Fig. 19. PV facades [100]**

Looking retrospectively, Quesada et al. [101] elaborates about the building-integrated solar thermal (BIST) as an integrated system for buildings. This system is generally developed to incorporate the solar collection technology with the building to act as the building envelope while collecting the solar energy for heating purposes as visualized in Fig. 20. With view to the energy balance of PV facades, there are certain environmental factors for analyzing the effectiveness of these systems including the electricity, heat, daylight, ventilation and pre-heating ventilation (Fig. 21).

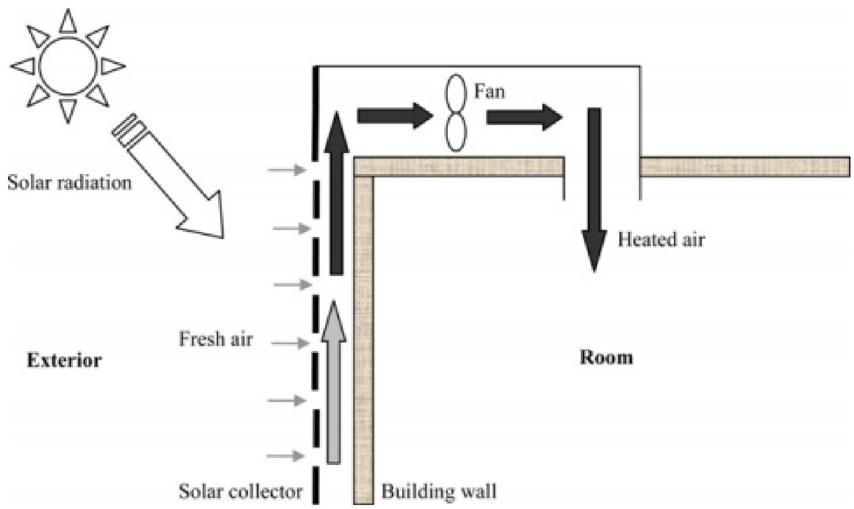


**Fig. 20. The building-integrated solar thermal [101]**

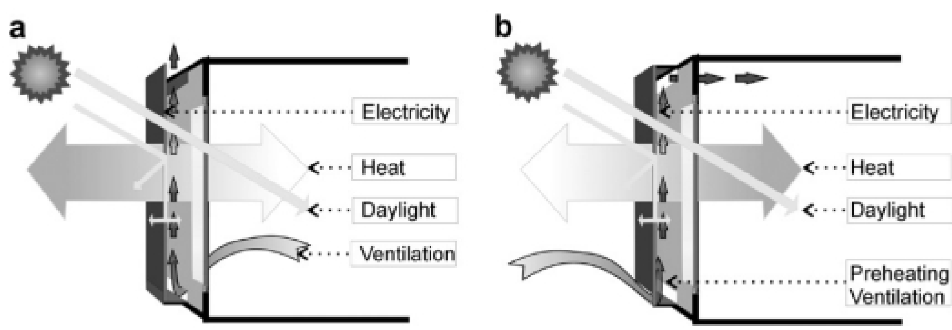


**Fig. 21. Environmental factors associated with the effectiveness of PV facades [97]**

More recently, according to the study by Quesada et al. [102], transparent and translucent solar facades are introduced. It is stated that besides the capability of transparent and translucent solar facades for receiving and transferring the solar radiations, solar heat gain could also gets transferred into the building. Accordingly, the mechanically ventilated facades are described based on the integration of mechanical system for air ventilation within the two transparent or translucent layers of façade as shown in Fig. 22.

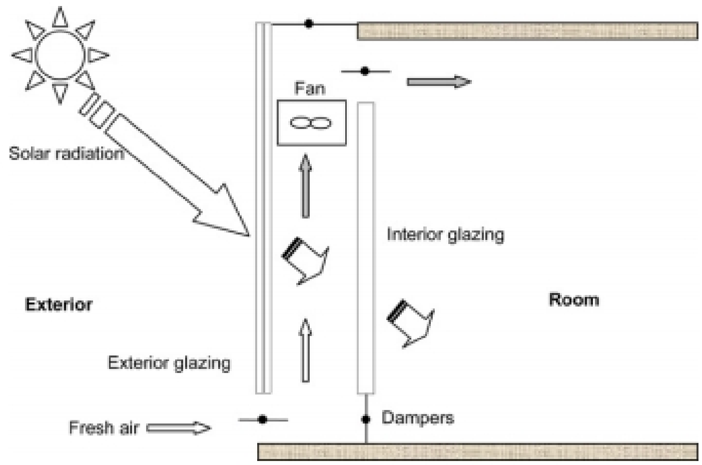


**Fig. 22. The mechanically ventilated facades [102]**

## 5. CONCLUSIONS

Development of green buildings is a fundamental agenda for sustainable development of future eco-cities. To create green buildings which are entirely responsive to the local environment and climate, versatile aspects must be taken into consideration. Focusing on the building envelopes, the role of facades in green implementations becomes significantly vital for the optimized energy performance of buildings. This study analytically reviewed the current theories and implementations for the application of intelligent facades for creating low energy buildings. Reviewing the current attempts and theoretical viewpoints regarding the newly innovated facades, the study recommends the intelligent facades to become an inherent constituent of green buildings for future development of low energy, ultra low energy and zero energy buildings. Accordingly, findings indicate that it is essential to fully consider the application of intelligent facades, as well as the required technical analysis and simulation strategies, during the early design stages of buildings. Intelligent facades are claimed to be energy efficient and responsive to the interrelation of indoor and outdoor environments. Overall, moving towards the proliferation of intelligent façade design development, it is demonstrated that the integration of double-skin facades, double-glazed and ventilated facades as well as the kinetic and solar facades could be significantly contributive towards the reduction of energy consumptions, enhancement of the building energy and environmental performance, enrichment of user's visual and thermal comfort while ultimately, mitigating the environmental hazards (Table 5).

The study concludes that the utilization of intelligent facades is a crucial criterion for development of environmentally benign built environments. Future research is expected for further analysis of the currently developed façade technologies besides innovating new design solutions to create building facades that are more interactive, adaptable and responsive through multidisciplinary studies.

**Table 5. Sustainable Potentials Embodied in Various Types of Intelligent Facades**

| Type of Intelligent Facades | Main Potentials Towards the Sustainable Design of Low Energy Buildings |
|---|---|
| Double-Skin Facade | - Energy efficient (Decreasing solar heat gains)<br>- Energy efficient (Receiving optimized daylight)<br>- Energy efficient (Ensuring proper air ventilation)<br>- Sound insulation<br>- Enhanced aesthetic feature<br>- Improved thermal comfort |
| Double-Glazed Facade | - Energy efficient (Decreasing the level of heat transfer)<br>- Improved thermal comfort |
| Ventilated Facade | - Flexibility<br>- Adaptability<br>- Customizability (Shape & Color)<br>- Energy efficient (Resolving moisture problems – air ventilation)<br>- Improved thermal comfort |
| Kinetic Facade | - Energy efficient (Interactive and responsive to the environmental attributes)<br>- Adjustable<br>- Adaptable<br>- Automatically responsive<br>- Improved thermal comfort |
| Solar Facade | - Energy efficient (Source of renewable energy)<br>- Contributive to cooling and heating purposes<br>- Visibility |

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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