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Energy performance analytical review of semi-transparent photovoltaics glazing in the United Kingdom

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ABSTRACT

This work reviews the recent achieved advancement in semi-transparent photovoltaics (STPV) glazing systems, which are considered as a possible solution to improve the thermal performance of buildings. A numerical model was developed utilising EnergyPlus to investigate the impact of integrating STPV glazing systems in the United Kingdom. The simulation investigated the overall energy consumption under different Window-to-Wall ratio (WWR) for south-oriented STPV glazing systems with different transparencies and materials. The results indicated that employing clear double-glazing in small glazing situation at WWR = 30% would reduce the overall energy consumption by (7.5–26) % depending on the implemented STPV glazing systems. Furthermore, applying STPV glazing system in large glazing (WWR ≥70%) would lead to a decrease in the overall energy performance by 40% compared with the conventional clear double-glazing systems. However, utilising STPV glazing systems in medium-sized glazing is dependent on the solar material that is used. The results indicated that employing a-Si STPV glazing system is inefficient when the glazing cover (30% < WWR <70%) comparing to the clear double-glazing system. This result is a consequence of to the thermal and optical characteristics of a-Si solar cells. These characteristics would eventually lead to a higher heating and lighting requirements.

1. Introduction

As the population of humankind increases, the demand of the energy sources in general and the electrical ones in specific increase, where most of this demand is diverted towards the buildings sector. The buildings sector represents a major contributor to the globe economy with estimation of around 20% of the total worldwide Gross Domestic Product (GDP). On the contrary, this sector brings several challenges related to the energy supply and resources, the environment and climate crisis [1]. As a result, the movement to understand how to reduce the energy consumption levels and utilising the renewable energy resources has gained momentum. The building sector consumes around 40% of the overall generated electricity globally, most of the consumption is concentrated on satisfying the heating and cooling demands of the buildings, and most of this consumption is caused by the glazing systems, that is, 61% in the United States [2–5].

Establishing an effective roadmap to tackle these problems could not occur without analysing the building energy causes and sources. Many researchers have identified the glazing systems as an area that could be improved. This interest was evidently based on the prominent role that the glazing systems play at the heat transfer process that goes through the building structure and their key

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impact on their thermal performance [5,6]. An interest in the photovoltaic technologies has been growing driven by the flexibility that this technology provides shown in the ability to be utilised inside the cities and the urban areas. As well as the method of installation, whether that was as an added feature on the roofs of the buildings or as a part of the building structure, enabled by the variety of developed materials for these technologies, like thin film [7–10]. The conventional glazing systems tend to be poor insulators and the integration of the solar cells into the glazing might be a possible solution to improve the overall energy consumption of the whole building. One solution is using semi-transparent photovoltaic (STPV) that extends beyond the ability of generating electricity, and improves the thermal performance of the building [11–13]. Multiple factors need to be taken into considerations before utilising this technology, such as the weather profile of the building location, orientation, space ratio and efficiency [14–16]. Implementing STPV glazing systems require deep analysis to conclude the optimal design to be embedded into buildings. This optimal design is achieved by finding the most balanced trade-off between useful solar radiation, transparency, reduction in the natural daylight and obstruction of the outdoor view [17,18].

Several review studies have been caried out to identify the gaps, challenges, and emphasis the protentional of this technology to meet the net zero plans. Shukla et al. [7] reviewed the existing Building Integrated Photovoltaics (BIPV) and STPV technologies that are circulating in the market. This work has shown the contrast between each existing technology and their life cycle. The review concluded that more work is still needed on few aspects toward lowering the cost of the BIPV technologies and utilising BIPV technologies that are more efficient in converting solar radiation into electrical power, regardless of whether these technologies were based on organic materials or thin film technology. Similarly, Husain et al. [19] has highlighted the role of STPV system and retrofitted glazing to address the energy challenges for the building sector. These challenges include the materials that are used to construct the STPV glazing systems, the procedure to manufacture the STPV glazing systems alongside the integration process and the cost of the STPV into the building fabric. In Refs. [20,21], work has identified and classified the challenges that face BIPV technologies as lack of a specialised database, lack of technical expertise and feasibility.

Bizzarri et al. [22] has presented a review of implementing the STPV technologies alongside a case-study to present the overall implications of utilising an optimised STPV glazing system in the building structure. The results have represented an improvement on the thermal performance and as consequence a reduction on the energy consumption. However, when looking at the feasibility much work needed to be implemented. Most researchers have opted toward investigating the effects that utilising STPV glazing systems have on the buildings. These effects were studied by implementing experimental measures, which led to constructing testbeds and developing numerical models. Depending on the solar cells that have been employed in the STPV glazing systems, the review of these research can be broken down accordingly. Most of the conducted research were based on integrating Cadmium Telluride (CdTe) solar cells or silicon solar cells, whether these cells were Crystalline Silicon (c-Si) or Amorphous Silicon (a-Si). It is worth mentioning that there are huge efforts to make a breakthrough in utilising synthesis materials as well as organic solar cells in the solar cell's technology [23,24]. Selvaraj et al. [23] work was based on developing dye-sensitized solar cells (DSSC) glazing system in the laboratory, and then conducting several tests to identify the thermal, electrical, and optical characteristics of the DSSC glazing system. Whereas the work of Tak et al. [24] was on organic solar cells. This work was established on the results of a numerical model that simulates the effect of installing a changeable organic semi-transparent glazing system into the building. Comparing the results with a conventional double-glazing system, the outcomes indicated that the novel glazing system represent an improvement on the electrical and thermal performance of the building where a reduction on the overall energy consumption around 15 kW/m^2 have been achieved. However, this work will focus on the inorganic technologies, which at the moment tend to have a higher potential and is sought after to be utilised in the building sector.

In this paper, an in-depth review for the existing literature has been carried out. The outcomes of the literature review have indicated that more research is needed to investigate the implication of installing STPV glazing system, especially in locations where the heat load is the dominant load. Therefore, this work has highlighted the influential role that the STPV glazing systems would have on the overall energy consumption of the buildings. Furthermore, a numerical model to study the effects of integrating STPV glazing system to the building structure in the United Kingdom has been developed. The United Kingdom climate profile tends to be moderate, and the heating load is the dominant load. This climate profile helps investigating the implication of installing STPV glazing system in locations where the heat load is the dominant load.

2. Methods

For this review, a through investigation in relevant databases, including Google Scholar, Science Direct, Web of Science, was conducted to identify published literature in the past few decades. As indicated by the title, this paper focuses on the research and development of Semi-Transparent Photovoltaics glazing systems. The work is twofold: (a) reviewing the recent work on each technology, Silicon and Thin film, in the BIPV. This paper will not discuss the structure of each technology as it is well-established in the literature (b) establishing a unified case study for the thin film technologies that are commercially available under the conditions of the United Kingdom household and weather to quantify the feasibility and provide real figures of energy savings while tailoring factors like transparency and Window-to-Wall ratio (WWR). This includes modelling and simulation using EnergyPlus. The methodology of the case study establishment will be discussed later.

3. Literature review

3.1. Silicon solar cells

3.1.1. Crystalline Silicon solar cells (c-si)

This work in Ref. [2] was based on constructing a testbed to investigate the effects of employing c-Si STPV glazing system. The investigated effects were focused on the electrical, thermal and the daylight performance of the glazing systems. The results indicated that, the generated energy would reach the peak levels when the glazing system is facing the south and southwest orientations with a daily average electrical production in range of (1.9–1.94) kWh. Furthermore, the daylight performance of the sample has delivered a sufficient daylight for around 80% during the span of the experiments. Whereas the results on the thermal performance have indicated that utilising a conventional Low-E double-glazing system would be more efficient. The effect of the surrounding shading has been recorded and would result a decrement in the overall generated energy. This decrement is dependent on the shape of the shading whether it is a horizontal or vertical shading. In addition to that, the solar cells temperature is another factor that effect the generated energy.

Bambara and Athienitis [25] work was based on simulating the effects of integrating c-Si STPV glazing system in an agricultural building. The study established a link between the economic return of implementing such a system and the life cycle, thermal, electrical and daylight parameters. The results indicated that the implementation of the STPV glazing system would increase the lighting load by at least 80%, save around 40% of this load energy furthermore the system would lead to a decrease in the heating load by more than 10%. However, considering the life cycle, a 30% deteriorating in the performance would make it less feasible to implement.

Lu and Law [26] showcased the effects of implementing c-Si STPV glazing system over the energy overall consumption for the whole building. The experiments were conducted in Hong Kong where the cooling load is the dominating load. The cooling load whether it was for cooling the water or as a part of HVAC system has decreased by more than 60% as it mitigated the solar heat gain. The optimal orientation was investigated, and the south-east has provided the most efficient overall energy consumption.

Xu et al. [18] research was based on developing a numerical model to be validated using experimental measures for the c-Si STPV glazing system. The aim was, to find the optimal coverage ratio levels (transparency levels, low coverage levels high transparency but it depends on the way the solar cells are installed not the materials structure) for the STPV taken into consideration (WWR), STPV samples orientation and simulated zone area (room depth). The results indicated that, as the coverage ratio of c-Si solar cells into the glazing system increases the electrical conversion ability of the glazing system decreases because of the increment of c-Si solar cells temperature (although the increase in the coverage ratio means more active solar cells and as a result more electricity). Furthermore, the lighting load increases with the decrement of the glazing transparency capabilities, more to that, the daylight performance was affected more by the area depth than the WWR the glazing system occupy. The heating and cooling load have an opposite trend when compared with lighting load which is driven by the geometrical profile of central China.

Yun et al. [27] research has focused on investigating the effects that installing a passive ventilated double-glazing c-Si STPV glazing system would have on various aspect of the building in quest to find the optimal glazing system that contains solar cells. The work was based on the Environmental System Performance for research (ESP-r) software to compare the results in three different locations in the continent, Madrid (Mediterranean climate), London (moderate climate), and Stockholm (cold climate). The results indicated that the WWR in London is the biggest to achieve the maximum efficiency, whereas, in Madrid, the WWR tend to be lower to reduce the passive heating element and reduce the cooling demand. However, in Stockholm the integration of such a system does not provide a sufficient improvement in the overall energy consumption. Integrating the system in small rooms tend to have a better energy consumption due to the lighting demands. To reach an optimal design regarding this system an addition of insulation materials is crucial as is indicated in the results.

3.1.2. Poly-crystallin silicon solar cells (p-si)

Ploy-crystallin silicon solar cells materials are similar to c-Si solar cells, but the structure process of the solar cells is different [28]. The developed works that used p-Si STPV include the following.

Wong et al. [15] research has introduced a novel way to integrate the STPV solar cells materials into the residential building roofs and developing a numerical model. A correlation between the effectiveness of the glazing system and the location geometrical profile has prevailed. The proposed system achieved an overall annual heating saving but will result to increase the cooling one. Efforts are spent to develop an optimised model. With various weather conditions, their proposal revealed energy saving potential for moderate and temperate climates. Fung and Yang [29] investigated the thermal performance and in specific the heat gain aspect of the building model deploying p-Si STPV glazing system. The considered factors are the orientation of the glazing, the transparency (solar cells coverage area), the electrical efficiency the glazing system as well as the structure of the system. The p-Si STPV glazing system has the highest heat gain when the glazing is southwest orienting the heat gain to about 230 kWh/m^2. The heat gain reduces when the transparency reduces with a difference of 70% drop between the highest and lowest transparency, the drop is caused by the absorbance of the solar radiation by the solar cells. Whereas the solar cells efficiency tends to have a minor effect on the heat gain due to the structure of the glazing system. Also, the results indicated that the difference between the thinnest and thickest glazing gives around 15% drop in the heat gain. With that been said, the effect of the structure is marginal due to the fact that increasing the thickness of the glazing system will lead to an increase to the thermal resistance.

Park et al. [30] work has investigated the electrical performance for a STPV glazing system taking into consideration the following aspects: the solar radiation, the climate profile of the location and the glazing structure. The results revealed minor differences between transparent and coloured glazing. A transparent outdoor surface and a bronze one, are tested. It was expected that the indoor temperature during the summer is higher than winter, however, the STPV glazing tends to have the opposite results, reasoned by the models tend to have variable amount of solar radiation depending on the climate profile of the location and the location tend to have seasonal rains during the summer which will reduce the solar radiation gain at its peak, furthermore, the generated electricity in the cold seasons tend to be greater than the generated amount in the hot seasons which is driven by the temperature of the solar cells and as the temperature of the solar cells increases the generated energy decreases by (0.4–0.6)% for each 1 °C surge.

3.1.3. Amorphous Silicon solar cells (a-Si)

Cheng et al. [3] investigated the effects of installing a-Si STPV glazing system on the daylight performance and the overall energy consumption. The results have been interpreted considering the WWR, the transparency levels of the glazing system and the orientation of the glazing. The results indicated that the daylight performance tends to improve as the transparency levels increases to a certain level and peaked when the transparency was 60% which is driven by the fact that the useful daylight illuminances that meet the threshold has increased across the whole simulation setting. Also, the increase in transparency levels increased the heat gain which would have a positive impact on the heating demand, however, the cooling load would increase which is not an issue for cold-climate location. The outcomes indicated that the increase in the transparency levels tend to increase the overall energy consumption by 23%. Achieving optimal design required transparency in range of (40–50) %, south oriented and the WWR would be in range of (40–50) %.

Peng et al. [5,16,31] used a-Si STPV double-glazing system aiming to optimize air gap width to maximize energy savings. The results have stated that utilising an optimised model would generate around 65 kWh/m^2 annually and reduces the overall energy consumption by 50%. It has been identified that a 400 mm air gap would lead to an overall energy consumption of 290 kWh annually which is a reduction of 58% compared with a conventional clear double-glazing system [5]. The other part of the research has focused on the effects that a suitable ventilation system installation would have on the overall energy performance [16,31]. The results indicated that utilising a ventilation system would lead to enhance the temperature distribution across the whole a-Si STPV glazing system, achieving a reduction of the solar heat gain by 20% while the energy generation changed marginally by 3%. The reason behind this enhancement is the fact that utilising a ventilation system would reduce the solar heat gain and as a result the cooling demand; however, the surface temperature of a-Si solar cells is not affected significantly. Miyazaki et al. [6] found that the daylight control mechanism has a catalyst effect on the overall performance. Without daylight control, a compensation in the transparency levels is needed. To increase the generation aspect of the glazing system, the transparency levels would decline and as a result, the heating and lighting demand would increase due to the lack of the passive heating element against natural light that indoor environment receives. However, if a daylight control algorithm were implemented, the optimal design would deliver an overall energy saving of 55%. The delivered optimal model covered 50% of the wall area and the transparency was 40%.

Weng et al. [8] work was also based on developing a validated numerical model that utilises a-Si STPV glazing system. The purpose was identifying the optimal structure that contains the a-Si STPV as part of the insulation materials of the glazing system. The results have indicated that, the air gap depth tends to have a marginal effect due to the climate profile of the location that the experiments have took place in. It is found that Low-E glass layer is required to realize optimal structure that would achieve an overall energy saving by 25% compared to a single glazing system and 11% in comparison with Lowe-E glazing.

Weng et al. [9] work was to determine the difference between the double skin façade (DSF) STPV (with large air gap 400 mm) and Insulation Glazing Unit (IGU) STPV (no big air gap). The results of the thermal analysis of the models have shown that DSF-STPV will reduce the heat gain which leads to reducing the cooling load, while the STPV-IGU will increase the heating gain element which consequently will reduce the heat load. Whereas, comparing both models with conventional glazing system would result a reduction of around 30% for STPV-DSF and STPV-IGU. The research has examined the effect of ventilation system with STPV-DSF and compared with STPV-IGU. The results indicated that STPV-IGU is slightly better specially when the louvres are open. Olivieri et al. [13] work has been based on developing multiple numerical models utilising different a-Si STPV glazing systems. This work aimed at exploring the outcomes of applying different STPV glazing systems at different WWR, to present the optimal model from the energy saving potential point of view. The results have indicated that, a-Si STPV glazing systems tend to have an identical performance to the conventional clear double-glazing system or at best case scenario would result a decrement around 6% in the energy consumption levels, when the glazing systems cover small area of the wall (WWR $\leq$30%). However, when the STPV glazing system covers an intermediate area of the wall or covers most of the wall (WWR >30%), the energy saving potential increases and ranges between (15–60) % compared with a conventional clear double-glazing system. Regarding the indoor comfort levels, the glare phenomena has only occurred when the weather profile was examining the indoor comfort levels at midday, with winter condition, and under clear skies situation.

Song et al. [10] research has investigated the effects of the utilising a-Si PV glazing system that is installed on the roof of the building and comparing it with a conventional double-glazing system, while monitoring the different incident angles. The results have indicated that installing the a-Si PV glazing system with a 30° tilt angle south oriented would represent the optimal states for the location of experiments. Furthermore, the azimuth angle played a focal point regarding the output energy generated which could be around 22% improvement when it is 0° if compared with 90°.

Yoon et al. [32] research has investigated the effects of the surface thermal profile using a practical testbed including evaluation of conventional double-glazing system and a-Si STPV glazing system at different tilt angles. The results indicated that the a-Si STPV glazing systems that are installed flat (0° tilt angle) tend to have higher external surface temperatures when compared with similar glazing systems but installed at different tilt angles (30° and 90°) during the cold weather conditions (winter), whereas this trend is reversed in the hot weather conditions (summer). As for the internal comfort levels, the results indicated that utilising a-Si STPV glazing system would lead to a lower ambient temperature during the day and a higher one during the night. These results are driven by the fact that a-Si STPV glazing systems tend to have a lower heat gain coefficients and higher ability to execute thermal insulation when compared with the conventional double-glazing systems.

He et al. [33] research has analysed the electrical and thermal performances of a-Si STPV double-glazing system and single glazing system. This research was achieved through a heat balance analysis that have been validated through a practical testbed. The results indicated that a-Si STPV double-glazing system reduces the solar heat gain and as subsequent reduces the heat demand driven by the fact that the air gap decreases the solar cells surface temperature when compared with a single glazing system.

The results in Ref. [34] indicated that implementing a STPV double-glazing system would at least reduce the overall consumption by 23% without any ventilation elements, extra 5% with it. The ventilation element tends to reduce the solar heat gain of the indoor environment leading to reduce the cooling load, but minimal impact on the efficiency of the solar cells.

Peng et al. [35] developed a numerical model that utilise a-Si STPV double-glazing ventilated system and validate this model through a comparison with a practical testbed setup. The results indicated that the numerical model has predicted that the model m would generate electrical energy of 11.19 kWh in October 2012 and 13.96 kWh in January 2013, whereas the actual results were 11.46 kWh and 13.56 kWh. These results indicate that the numerical model is accurate and can be used as a steppingstone in the optimisation stage of the future works.

Didoné and Wagner [36] used a-Si and organic STPV glazing system in south America (Brazil). The research has compared between the STPV glazing systems and traditional systems (single-glazing, double-glazing and Low-E). The results indicated a reduction in the overall energy consumption ranging between (39–43)% depending on the geographical location. Also, authors concluded that utilising Low-E glazing systems for the glazing that are orientated towards least solar radiation while implementing STPV glazing systems on the other glazing would present the optimal model regarding the energy performance.

Zhang et al. [37] research has focused on establishing the difference between utilising the STPV glazing systems and the evolved glazing systems. These glazing systems (Double-glazing and Low-E) tend to be more efficient in the point view of the overall energy performance. The comparison was established with a numerical model that have shown the effects of utilising a-Si STPV glazing system, double-glazing and Low-E glazing systems. The results indicated that the STPV glazing system achieved a decrease of 48% and 38% in the solar heat gain respectively. But on the downside, the heating load and the daylight demand tend to increase because STPV restrict the amount of the natural light and solar radiation that passively reduces the lighting load as well as the heating load.

Chen et al. [38] research investigated the Solar Heat Gain Coefficient (SHGC) with different tilt angles while a-Si STPV glazing system is connected to an electrical load. The results indicated that the SHGC of the STPV double-glazing is lower than the STPV glazing system due to the existence of Low-E materials in the STPV double-glazing system. It is found that if the tilt angle is less than 45° then the decrease in the SHGC is marginal, which is around 5%. However, if the angle is between 45° and 70° then the decrement in the SHGC is around 20%. Furthermore, the electrical loads tend to have minimal effect on the SHGC of (3–6) %.

Cuce et al. [39] work aimed toward identifying the thermal characteristics of the heat insulation solar glass (HISG) which is a type of the a-Si STPV glazing system. The results indicated that the U-value of HISG is 1.1 W/(m^2. K). Comparing the HISG with a conventional clear double-glazing system, the HISG tends to represent a much better insulation tool.

3.1.4. Comparing the c-Si and a-Si solar cells

Few researchers have opted toward establishing a comparison between integrating c-Si and a-Si solar cells into the glazing system. This section will go through a limited number of works in this field.

In the research of Skandalos et al. [4,40] an in-depth analysis in relation to the thermal characteristics, alongside the optical performance have been conducted. As for the electrical performance, the analysis was dependent on tracking the cooling and heating demands. The results were generated from multiple validated numerical models, these models were developed using multiple software packages that have identified the thermal, optical, and electrical characteristics then imported to TRNsys software tool to do the heat balance analysis. The results have indicated that utilising STPV glazing systems would lead to reducing the solar heat gain by around 30%, which would lead to a decline in the cooling load. However, the lighting load as well as the heating demand would increase. As for the optical aspect applying STPV reduces the glare by around 22% for the c-Si solar cells and, 27% for the a-Si solar cells. Finally, a-Si solar cells operate efficiently in low solar radiant situations, while c-Si then to be more effective in converting the solar radiation into electrical energy. Saber et al. [17] work has reviewed the different types of the PV technologies, and in-depth analysis was conducted to evaluate their effects when these technologies are implemented. The results have shown that p-Si solar cells tend to have a better electrical performance compared with c-Si and a-Si solar cells. (This research has investigated PV unites on the roof).

The research of Kapsis and Athienitis [41] has studied the outcomes of utilising different solar cells (p-Si & a-Si) integrated into the glazing system, and their effect on the overall energy performance. The results have revealed that the orientation of the glazing system alongside the WWR and the artificial light controlling mechanism are major factors on the overall energy performance. The optimal design has been able to present a low consumption ratio. The annual consumption ratio is as low as 5 kWh/m^2. It should be noted that the research geographical location tends to have a dominant cooling load, hence the transparency levels were as low as 10%.

3.2. CdTe solar cells

Many researchers have focused on using CdTe solar cells because of their higher electrical efficiency, and unique thermal characteristics. Barman et al. [11] work was based on developing multiple validated numerical models to employ different CdTe STPV glazing systems. The outcomes were tested against transparency, orientation, and WWR. The results have indicated that the south orientation leads to highest energy generation, particularly with low transparencies. The cooling and heating demands tend to be affected in a contrary manner, when comparing the effect of the WWR and the transparency levels. A reduction of 60% in the overall energy consumption levels when compared with a conventional glazing system is achieved.

The results in Ref. [12] indicated that the STPV glazing system should cover more than 30% of the wall area to influence the overall energy performance. Furthermore, when the STPV glazing system cover 45% of the wall area or more, the amount of the energy that is

Table 1
Literature review.

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
[47]	Developing an accurate numerical model through a direct testing methodology to identify the required coefficients.	Inhouse and outdoor testing procedures were applied to obtain the needed parameters.	SAPM	Hong Kong, China	Warm and Temperate.	a-Si	Different coefficients calculations and fitting.	• Calculating the required 26 coefficients for the SAPM model. • The model was accurate when compared with energy output of the testbed, with a margin of error around 3% under clear sky conditions. • The model cannot be utilised to estimate the energy output under overcast sky conditions, where the margin of error is around 14%.
[48]	Establishing the point that utilising solar cells technologies within the building structure benefits are not limited to the saving the energy consumption, but it is extend more toward the indoor comfort levels.	Introducing two novel parameters to assess and comprehend the advantages of integrating the solar cells. These parameters are the design space parameter and the evaluation space parameter.	TRSYS, CFS, and RADIANCE (Mentioned but not used)	Freiburg, Germany.	Warm and Temperate.	General mentioning of the existing photovoltaic technologies	No simulations were conducted.	• Provide a deliberate review that discuss the design aspect and the evaluation aspect of integrating solar cells into the building structure. • The work has recommended improving the software tools, so they are able to conduct more complex simulation that reflects he day-to-day activities in buildings. • Further research was recommended to improve the measurement methodology used when implementing bi-directional scattering distribution function tool.
[49]	Exploring the impacts on the electrical and thermal characteristics of the whole building when	Develop three numerical models with different solar cells structure. Track the overall energy consumption, the heating	EnergyPlus	Six different locations in the United State. (Miami, Phoenix, Los Angeles,	Miami: Tropical monsoon climate. Phoenix: tropical and subtropical	a-Si:H (Hydrogenated amorphous silicon)	Lighting power density: 10.76 W/m^2 Heating: 21 °C Cooling: 24 °C	• The location and the climate profile of that location represent a key factor on the overall energy performance.

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
	integrating solar cells into the glazing systems.	and cooling demand and the amount of the emission is reduced.		Baltimore, Chicago, and Duluth)	climate. Los Angeles: hot-summer Mediterranean climate. Baltimore: Mild, warm, and temperate. Chicago: hot-summer humid continental. Duluth: humid continental with warm summer.			• STPV glazing systems in Los Angeles were able to reduce around 30% in the energy consumption that is dedicated toward satisfying the heating and cooling demand. • STPV glazing systems were able to generate the most energy in Phoenix, which was around 62 kWh/m^2 annually. • STPV glazing systems in Chicago has the highest effect on reducing the emissions. Applying such a technology would cut the carbon print of the building by 68 tons.
[50]	Investigate the optimal tilt angel and the best orientation to integrate photovoltaics into buildings from the electrical generation point of view	Developing an accurate numerical model that would enable an educated decision to select the most BIPV technology to integrate into the building to offset the electrical consumption.	eQUEST and PV-DesignPro	Seoul, South Korea	Humid continental with dry winter	c-Si and a-Si	The simulations were based on replacing the façade with BIPV glazing systems at different orientation and tilt angles.	• The highest amount of solar irradiation was achieved on the south orientation with tilt angles between (40°–60°). The solar irradiation was 1100 kWh/m^2 annually under the assumption that no shading is applied. • The results have indicated that adding a c-Si solar panels above the conventional glazing systems without any gap would generate 6% of the needed energy. This percentage represent the highest that can be generated. • The work has concluded that installing BIPV technology would not achieve a reduction higher than 5% on the

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
								overall energy consumption,
[51]	Introducing a systematic method to classify the most effective model to be utilised for STPV glazing systems. This approach aims to improve the electrical efficiency of the STPV glazing systems when integrated into the national grid.	Developing a sequential method to assess the overall performance. Mapping out the electrical efficiency of the solar cells, followed by identifying the thermal characteristics and finishing of by studying the indoor comfort levels.	N/A	Review paper, the location was not specified.	N/A	Reviewed c-Si, a-Si, CdTe and CIGS while mentioning the organic and sensitized solar cells.	No simulations were carried out.	• Provided a detailed review for the electrical, thermal, and optical outcomes for different works. • Investigated the climate impact on the electrical performance of different STPV glazing systems.
[52]	Investigate the overall energy performance practically of DSF-STPV glazing system.	To achieve the research target, two testbeds have been developed to collect the required data.	N/A	Chengdu, China	Temperate, hot summer and dry winter	a-SiGe	N/A	• The electrical efficiency the a-SiGe STPV glazing system would be around 5.8% regardless the amount of solar radiation. • The amount of generated energy is not adequate to satisfy the electrical needs of the testbed. • The thermal characteristics indicate that a-SiGe STPV glazing system is a better insulation tool compared with the conventional clear double-glazing system. • The comfort levels of the testbed that utilise a-SiGe STPV glazing system tend to reduce the useful daylight illumines (UDI) by 50% compared with the conventional clear double-glazing system. • The implementation of the a-SiGe STPV glazing system would be able to prevent the glare phenomena and as a

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
								consequent improve the indoor comfort levels.
[53]	This works investigated the overall energy performance oof the building when integrating DSSC STPV glazing system. Furthermore, this work aimed toward establishing a database that could be used in the future.	Develop two numerical models that represent DSSC STPV glazing coloured systems (Red, Green) through collecting the essential (optical, thermal, and electrical) data to compute them. The results of the numerical model have been compared to different iterations of Low-e glazing system to establish the feasibility and the performance aspects of a DSSC STPV glazing system.	DesignBuilder which is based on EnergyPlus.	Seoul, South Korea	Humid continental with dry winter	DSSC	Heating setpoint, setback temperature: 20 °C/ 15.5 °C. Cooling setpoint setback temperature: 26 °C/ 29.4 °C. Lighting power density: 10.2 W/m^2.	• Employing DSSC STPV glazing systems would restrict the amount of natural light that the indoor environment receives. The two DSSC modules has allowed 84 lux (Red) and 47 lux (Green), which is below the minimum natural light requirement of (300–500) lux. • The ambient temperature of the indoor environment tends to be lower when utilising Low-e glazing systems compared with DSSC STPV glazing system. • Integrating DSSC STPV glazing systems (Red and Green) would increase the overall energy consumption by average of 86%. These outcomes were reached by the increase in the artificial demand as well as the cooling one. • The DSSC STPV glazing systems were not able to generate more than 10% of the overall needed energy.
[54]	Reviewing the existing literature regarding the energy storage technologies that are being used within the BIPV technologies. this review is going to be conducted from the point view of the	Highlighting the existing literature that investigate the combination of the BIPV technologies and the energy storage systems that has be used while discussing the potential health and environmental	SimaPro	N/A	N/A	Multiple types of solar cells were mentioned in the review most of it were silicon based (a-Si, c-Si, p-Si)	N/A	• The review has highlighted the research that has been carried for the work that investigate the BIPV technologies and the use storge systems that have been used along.

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
	environmental cost that these technologies bare.	hazards that these technologies can cause.						• This work has highlighted the potential health hazards and the environment effect each technology could represent (BIPV and energy storage system).
[55]	Examining the effects of integrating energy-saving insulation windows (ESIWs) on the overall energy performance. Furthermore, investigating the correlation between the ESIW and multiple factors such as (WWR, the orientation of the building)	A numerical model has been developed using DeST and Airpak software tools based on practical set-up to validated. The results of the simulations were used to establish the optimal process to embed the ESIWs into the building structure.	DeST, Airpak and FLUENT	Taiyuan, China	Cold semi-arid	No solar conversion element was used	Heating setpoint, setback temperature: 26 °C/ 18 °C. No controlling means were implemented for the daylight and cooling demands.	• Utilising ESIW technology would reduce the ambient temperature of the indoor compared to several conventional glazing systems. • Utilising the ESIW technology would reduce the overall energy consumption due to the reduction in the heating and cooling load. • The optimal design to integrate ESIW technology would have a U-Value = 1.02 W/m^2. K, at WWR% = 26%.
[56]	Investigated the thermal characteristics and the indoor environment comforts levels when replacing the integrating (DSF/IGU) a-Si STPV glazing systems. These results were compared to reference values that are taken from a conventional clear double-glazing system.	Building two highly equipped testbed, one has integrated a-Si STPV glazing system while the other has utilised conventional clear double glazing. The results were based on analysing the measured varies thermal parameters such as the ambient indoor temperature, the surface temperature of the glazing system and the air flow in the indoor environment.	N/A	Chengdu, China.	Monsoon-influenced humid subtropical	a-Si (DFS/IGU)	No controlling measures were implemented.	• The results indicated that the electrical conversion capabilities of a-Si STPV glazing systems were around 5.5 regardless of the sky conditions. • The IGU a-Si STPV glazing system surfaces temperature is higher than the DSF a-Si by 4 °C in-average. • The ambient temperature of the indoor environment in lower by 5 °C when employing the a-Si STPV glazing systems compared with the conventional clear double-glazing.
[57]						c-Si, a-Si		

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
	Highlighting the impacts that the integration of STPV glazing systems will yield on the overall energy consumption and the comforts levels for an office setting.	*Numerical model has been developed to investigate the overall energy performance and the indoor comfort levels for five different settings. The first two setting PV models were installed around the frame of the glazing. Whereas the third and fourth tests the PV models were installed horizontally across the conventional glazing. In the fifth situation the conventional glazing system was replaced with STPV glazing system.*	EnergyPlus and DIVA-for-Rhino.	Ha'il, Saudi Arabia.	Tropical and subtropical Desert.		Glazing southernly oriented with WWR% = 30%, Transparency of STPV = 20%, Transparency Of conventional glazing system = 79%, Cooling system Setpoint: 20 °C, Heating system Setpoint: 26 °C, Daylight minimum threshold: 300 lux.	• Implementing STPV glazing systems would lower the cooling demand by 75% compared to the conventional clear double-glazing systems. • The lighting demand would increase when the STPV glazing systems are in place by 20% compared with the clear double-glazing system. • The utilisation of a STPV glazing system would cut the overall energy consumption by 58% or 470 kWh/yr. compared with the clear double-glazing system.
[58]	Quantifying the saving potential in the overall energy consumption while utilising a-Si STPV glazing in Chengdu, China.	Building two highly equipped testbed, one has integrated a-Si STPV glazing system while the other has utilised conventional clear double glazing. The output data were used to compare the overall energy performance between the two models.	N/A	Chengdu, China.	Monsoon-influenced humid subtropical	a-SiGe	Transparency of the STPV = 20%, Electrical efficiency = 6.7%, Daylight minimum threshold: 300 lux.	• The a-Si STPV glazing system would consume around 70 W a day in-average under clear sky condition which is an increase of 43% when compared with the conventional glazing. • Under overcast skies conditions, the heating demand for both models are the similar. however, the lighting load would increase by 21.1 W a day in-average for the STPV model. • Utilising STPV glazing systems under clear skies situations would result an electrical generation pf 50 W a day in-average. Furthermore, utilising such a system would under clear skies would reduce the overall energy

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
								consumption by 30% compared with a conventional glazing.
[59]	Examine the electrical and thermal outcomes of a modified PV-thermoelectric (PV-TEC) glazing system by replacing the PV with STPV model. in addition to that, this work aims to establish an understanding for how to integrate such a model into the building structure.	Developing a mathematical model aimed towered establishing a balanced heat exchange model for the STPV-TEC model. following that validation process through practical tests have taken place to determine the accuracy of such model.	MATLAB	Nanjing, China.	Humid subtropical climate.	p-Si	The ambient indoor temperature: 26 °C. The ambient outdoor temperature: 34.8 °C.	• The generated energy of the STPV-TEC is 45.4 kWh whereas, the PV-TEC has generated 83.9 kWh. • The overall energy consumption for the PV/STPV-TEC is almost the same, which is around 71.8 kWh. • The cooling load was the prevalent energy consumer with almost 51 kWh for both systems (PV/STPV-TEC).
[60]	Investigate the possible role that silicon based STPV glazing systems would play in facilitating the building transition to energy net zero.	A mathematical model was developed depending on a thermodynamic model. afterword, a numerical model was developed using different software to investigate the thermal characteristics as well as the overall energy performance of the building.	SketchUp, OpenStudio, EnergyPlus and SAPM.	Dhaka, Bangladesh. Abu Dhabi, UAE. Chicago, USA. Oslo, Norway.	Dhaka: Tropical. Abu Dhabi: Desert. Chicago: Hot summer humid continental. Oslo: Cold and temperate.	Silicon based solar cells.	Heating system setpoint temperature: 18 °C. Cooling system setpoint temperature: 24 °C Daylight minimum threshold: 500 Lux. Daylight load density: 10 W/m^2. WWR% at reference building is 20%.	• The results have indicated that utilising STPV glazing systems with clear glazing being the inner surface material at WWR% = 60% or more would lead to an increase in the overall energy consumption regardless of the location. • Utilising such a system at WWR% = 10% would reduce the overall energy performance between (20–50) % depending on the location. • Replacing the clear glazing with Low-e material for the inner surface of the STPV glazing systems would lead to a reduction of the overall energy performance by (45–70) % depending on the location.
[61]			EnergyPlus			a-SiGe		

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
	Quantifying the saving potential in the overall energy consumption when implementing a-Si STPV glazing system as the glazing unit in the building.	A numerical model was developed to investigate the effects of employing a-Si STPV glazing systems on the overall energy performance in different location in the southwest region in China.		Four different locations in China (Chengdu, Guiyang, Lhasa, Kunming).	Chengdu & Guiyang: Monsoon-influenced humid subtropical. Lhasa: Monsoon-influenced subarctic. Kunming: Monsoon-influenced temperate.		Electrical efficiency = 6.7%, Daylight minimum threshold: 300 lux, the indoor setpoint temperature in winter/summer: 18 °C/26 °C.	• Due to the existence of solar cells into the STPV glazing system, the cooling load would decrease in summer periods leading to a reduction in the overall energy consumption by 29%. • Utilising the STPV glazing systems would reduce the overall energy consumption on all regions with (24–54) % decrease depending on the climate of the location.
[62]	Investigate the overall energy performance of a p-Si STPV glazing system that is being installed within the roof structure of a residential building in India.	A mathematical model was developed to examine the data that have been collected for the rig test. The rig test simulates a scaled down residential area. The collected data were used to investigate the electrical and thermal performance of integrating a p-Si STPV glazing system within the roof structure.	MATLAB	Kovilpatti, Tamil Nadu, India.	Tropical savanna, wet	p-Si	No control measurements were used inside the tests rig. However, four p-Si STPV glazing systems were used that differ with their structure. Model-1: three layers, 2 clear glazing (inner/outer) surface, 62% p-Si solar cells in the gap. Model-2: three layers, 2 clear glazing (inner/outer) surface, 72% p-Si solar cells in the gap. Model-3: three layers, 2 clear glazing (inner/outer) surface, 85% p-Si solar cells in the gap. Model-4: similar to Model-3 but the outer surface is tinted glazing.	• The model with most solar cells (Model-3) has been able to generate 131 kWh annually which is the highest between all models. • Utilising p-Si STPV as a part of the roof would reduce the lighting load between (87–131) kWh annually depending on the model that has been used. • Utilising Model-4 would reduce the cooling demand by 255 kWh yearly which is the most between the four models.
[63]	Investigating the overall energy performance of STPV-DSF glazing systems under different ventilation models	Utilising the MATLAB, a numerical model was developed to investigate the optimisation attempt of installing a mechanical ventilation mechanism in the STPV-DSF glazing system. The results of that model were validated	MATLAB	Jaipur, India.	Monsoon-influenced, hot, semi-arid	CdTe	WWR% of the glazing: 28%, while the glazing being southernly oriented. The indoor ambient temperature: 28 °C.	• Utilising mechanical ventilation mechanism in the STPV-DSF glazing systems would reduce the overall energy consumption by 4% in June, 10% in October and 14% in December.

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
		through the collected data of practical tests that have been conducted on a testbed.						• The mechanical ventilation method has proven the ability to reduce the temperature of the gap that the solar cells that are stated in-average of 1.83 °C.
[64]	Investigate the overall energy consumption and the daylight performance of an office setup while integrating the a-Si STPV-DSF.	A numerical model was developed to quantify the daylight performance as well as the energy consumption level. A daylight measuring metric was developed as well to simplify the process of examining the daylight performance, which is N-Daylit ratio.	Daylighting, EnergyPlus and DAYSIM	Taiyuan, China	Cold semi-arid	a-Si	The ambient temperature of the indoor environment in summer/winter: 20 °C/ 26 °C. Daylight minimum threshold: 450 lux.	• The results have indicated that the structure of optimal a-Si STPV-DSF glazing system would be solar cells cover (30–40) % while the glazing systems cover 30% of the WWR%. • The annual consumption rate of the optimal a-Si STPV-DSF model was 33.9 kWh/m^2, which is represent a reduction of 9.4 kWh/m^2 compared with the conventional clear double-glazing system. • The N-Daylit ratio of the optimised a-Si STPV-DSF model was around 57%.
[65]	Investigate the different characteristics of a modified p-Si STPV glazing system that is being installed within the roof structure of a residential building in India. This novel model has contained a phase changing materials (PCM) that being coated into the backside of the solar cells.	Several p-Si STPV-PCM glazing systems were constructed depending on the concentration of the added materials to the solar cells. These models were integrated into an equipped testbed to investigate the electrical and thermal characteristics of p-Si STPV-PCM glazing system.	N/A	Kovilpatti, Tamil Nadu, India.	Tropical savanna, wet	p-Si	The experiments were focused on the electrical power generated from the STPV-PCM models on the two hottest days in the year. Consequently, no control measures were implemented.	• The integration of PCMs would result a reduction in the surface temperature of the p-Si STPV glazing system by 9 °C. • The implementation of PCMs would increase the p-Si STPV glazing system power conversion ability by 9.4% and the generated energy by 12%.
[66]	Examine the daylight performance and the indoor environment comfort levels while	A numerical model was developed to follow the indoor comfort levels through the analysing the CRI, CCT and the glare	Diva-for-Rhino	Riyad, Saudi Arabia	Hot Desert	Perovskite, CdTe, DSSC	WWR% of the glazing is 100% %, while the glazing being southernly oriented. The simulations were	• The results have indicated that Perovskite STPV glazing system needs to have a 50% ≥ VLT ≥70% in winter for

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
	integrating a Perovskite STPV glazing system.	probability of different STPV glazing systems.					conducted under the assumption that the building is built in vacuum.	the model to be able to provide an acceptable indoor comfort level. • At summer the Perovskite STPV with 70% VLT has provided an acceptable comfort level for the indoor environment, however the glare phenomena needed to be addressed at midday.
[67]	A literature review has been conducted based on identifying the limiting factors that restrict overall energy performance of STPV glazing system.	Analysing the existing literature that research scope is focused on the BIPV technologies and classified the reasons that limit the BIPV technologies.	N/A	N/A	N/A	c-Si, a-Si, copper indium gallium selenide (CIGS) and CdTe	N/A	• The structure of c-Si solar cells represents the most challenging aspect of integrating them into the glazing system. • The health hazards the CdTe and CIGS solar cells represent a major obstacle that prevent from utilising them into residential buildings. • An in-depth analysis in the planning stage for the is needed to utilise the most efficient BIPV technology.
[68]	Developing a numerical model to investigate the effects of shading sources tend to have on the electrical and thermal performance of the STPV glazing system.	Mathematical models that investigate the shading impact, electrical generation and heat transfer performance have been developed. The results of these models were utilised in creating an algorithm that combine outcomes of these models. The results of the algorithm have been used as the input data for the simulation tool, which investigated the overall energy performance. The results of the simulations were validated against experimental results.	N/A	Changsha, Hunan, China	Monsoon-influenced humid subtropical.	c-Si	N/A	• The results have indicated that, when the STPV glazing systems are under different levels of shading the overall generated electricity reduces. The P–V curve tends to have multiple peaks, depending on the how many different levels of shading do exist. • The temperature of the STPV glazing system that is under shading situation tend to be higher driven by the hotspot issue.

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
								• The results have shown that the generated energy decreases as the shadow width increases. • The month of April in Changsha, Hunan, China had the highest drop in generated electricity. Which is around 15%. • Similar to the generated energy, the heat gain decreases as the shadow width increases. • The month of August had the highest drop in the heat gain. which is around 1.2%. This reduction leads to a decrement in the cooling demand in the summer.
[69]	Establishing the Inter-Building Effects on the electrical performance of the STPV glazing systems, while being under real time shading profile.	This work was based on developing different mathematical model that investigate the generation aspect of the STPV glazing systems under different shading conditions utilising MATLAB. The results of the mathematical models are going to be validated by employing Ecotect software and comparing the results with experimental data that have been collected through a series of tests.	MATLAB and Ecotect	Changsha, Hunan, China	Monsoon-influenced humid subtropical.	c-Si	The following assumption where in place during the validation process: • The STPV glazing system was southernly oriented. • The 21st of January was selected to conduct the experiments. • Three samples were selected with 1 h time step between each step.	• The results have indicated that the STPV glazing systems tend to loss around 36% of the solar radiation in December due to shading. • The generated energy of the STPV glazing system decreases by 40% in December as well. • A reduction in solar conversion ability of the STPV glazing system has been recorded, which is around 39%.
[70]	Establishing the effects of Inter-Building Effects in a populated urban area. In order to produce a more accurate estimation of the overall energy performance of the buildings.	A numerical model employing EnergyPlus software was developed. The simulations were conducted in three different locations with distinct different climate profile.	EnergyPlus	Several Locations in the United State: (Miami, Washington, Minneapolis)	Miami: Tropical monsoon climate Washington: humid subtropical climate. Minneapolis: humid continental with warm summer.	N/A	N/A	• The results of simulations have indicated that the shading tends to have a major impact on the overall energy consumption of buildings.

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Table 1 (*continued*)

Reference	Objective	Methodology	Software tool	Location	climate profile	Technology	Simulation set-up	Findings
								• The results indicated that shading tends to decrease the cooling demand in Minneapolis by 50% while increase the heating demand by 14.5%. • However, in Miami the heating load increases by 29.2% and cooling load decreases by 28.5% under shading. • Meanwhile, in Washington the heating load increases by 21% and the cooling load decreases by 42% under shading.

generated tends to increase, especially when most of the glazing system is covered by solar cells. Their optimal design would cover 75% of the wall area by glazing, with solar cells covering 80%. Regarding the indoor environment comforts levels, employing STPV glazing systems tend to eradicate the glare phenomena that usually occur when utilising conventional clear double-glazing systems.

Sabry [14] has developed a numerical model on MATLAB using Custom Neural Network (CNN). The results have provided the electrical profile of the CdTe STPV units alongside the I–V curves. The results have highlighted that the CdTe STPV glazing model would generate 22 W at irradiance of 1000 W/m^2 while the temperature is at 45 °C.

Alrashidi et al. [42] research has investigated the thermal characteristics of a CdTe STPV glazing system through practical setup. The results have indicated that the U-value of the CdTe STPV glazing system is 2.7 W/(m^2. K), which is lower than the conventional clear single glazing system by 3 W/(m^2. K). Moreover, utilising the CdTe STPV glazing system would reduce the solar heat loss by 40% when compared with conventional clear glazing system.

Sun et al. [43] analysed the daylight performance of different STPV glazing systems (CdTe and c-Si) under different levels of transparency and different WWR. The outcomes of the research have established that applying STPV glazing systems would reduce the probability of the over-illuminate phenomena to occur, as well as limiting the possibility of the glare phenomena to happen, compared with the conventional clear double-glazing systems as the transparency levels decline. In Ref. [44] they explored the overall energy performance alongside the daylight performance, which was conducted under different levels of transparency and different WWR. The results indicated that STPV glazing systems for WWR of 30% or less would not lead to any sensible lessening of the overall energy consumption even if the whole glazing system has been replaced with a CdTe PV glazing. As for the energy consumption, the optimal model would be a CdTe STPV glazing system that is 20% transparent and covering 75% of the wall area. This model decreases the overall energy performance by 73% or 1017 kWh annually compared to a clear double-glazing system.

Liu et al. [45] research has examined the effects of installing a CdTe glazing system into the fabric of the building and specifically the daylight performance. Using CdTe STPV glazing systems are going to increase the ratio of the useful and desirable illuminance, especially when the glazing is covering large area of the wall (WWR ≥70%). Furthermore, the CdTe STPV glazing system would limit the glare potential [45]. Additionally, the colour comfort analysis has been evaluated based on the Correlated Colour Temperature (CCT) and Colour Rendering Index (CRI). The results indicated that CdTe STPV glazing systems present an efficient method to control the amount of the CCT within the transmitted light to the indoor environment. As for the CRI aspect, all of the CdTe STPV samples obtained CRI of >97; however, the minimum comfort colour levels of the transmitted daylight through glazing should be 90 or more (CRI >90) [46].

3.3. Literature summery

Table 1 introduce a concise summary of a further literature that has not been reviewed above. This table will highlight the objective of each research, the methodology that has been followed and the simulation tool that has been used. Furthermore, the geographical profile of the location and the simulation set-up has been mentioned alongside the key findings of each research.

4. Case study – Parametric simulations

4.1. Rational

Based on the conducted literature review, it has been emphasised that the integration of STPV glazing systems would reduce the overall energy consumption. This reduction has been achieved through generating electrical energy and optimising the thermal performance in general. However, the amount of research that have been conducted in a geographical location where the heating demand is the dominant one has been limited. Therefore, a numerical model is developed in this paper to explore the overall energy consumption for the STPV glazing systems in the UK where heating load is the primary energy consumption load.

4.2. Methodology

A numerical model will be built in EnergyPlus targeting the overall energy consumption of a sample building. The factors that will be considered include different WWR and transparencies. The analysis of the numerical model was divided into three categories of wall ratio. The results of the different STPV glazing systems were compared with a conventional clear double-glazing system.

4.2.1. Geographical profile

The numerical model was assumed to be built in Sheffield, northeast of England in the United Kingdom. The climate in this location tends to be temperate or according to Köppen climate classification [71], the United Kingdom has an oceanic climate. This classification means that the weather tends to be cold and wet in the winter, whereas in the summer the weather tends to be warm but nevertheless wet. It is worth mentioning that is highly unlikely for extreme weather to occur, whether that would be heat or cold, wind or drought. As for the weather profile that has been used in simulations, this model has used the EnergyPlus weather data profiles.

4.2.2. Reference building

The model will simulate an office space in accordance with the European Commission Joule projects REVIS and SWIFT [72]. The dimensions of this office space are 3.5 m for width, 5.4 m for the length and 2.7 m for the hight. The orientation of the glazing system was directed towards the southern orientation since the assumed location of the reference office space is in the northern hemisphere of the plant, and as stated before, this orientation performs the best. The visual presentation of the numerical model is shown in Fig. 1.

4.2.3. Glazing systems

Eleven STPV and one conventional clear double-glazing systems were utilised in the simulations. The conventional system was used

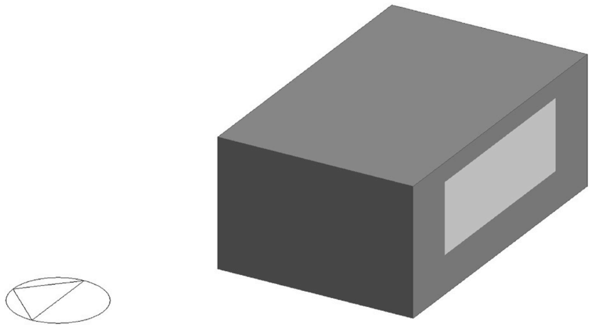

Fig. 1. Reference office space.

as reference point which is in line with the reviewed literature above. This reference point was used to understand, compare, and investigate the thermal, lighting, and electrical performances of each system. Calculation of the overall energy will be performed, and energy saving will be estimated.

Table 2 includes the used materials of the STPV, thermal characteristics (SHGC and U-value), Visible Light transmittance (VTL-transparency levels) and electrical efficiency. The model names indicate also the claimed/named transparency from the manufacturers, despite it is different relatively from VLT values. The source of the data for the a-Si STPV (A0-A4) glazing systems were taken from the work of Olivieri et al. [13]. Whereas the related data of CdTe STPV (C0–C4) glazing systems were taken from the work of Barman et al. [11]. Furthermore, the data of the c-Si STPV (CS) glazing system was taken from the work of Peng et al. [2]. As for the conventional clear double-glazing system (DG) characteristics, the stored data within the software was used.

4.2.4. Simulation thermal settings

The thermal performance simulations were carried out under the assumption that the heating and cooling demand are in accordance with the European Commission Joule projects. To achieve that a Heating, Ventilation and Air Conditioning (HVAC) scheme based on utilising a Fan-coil unit has been implemented. The conversion factor for the heating and cooling loads is 1.67. The conversion value represents the overall conversion ability of the system combined with all the possible losses, which could occur during the distribution stage, or the inefficiency that is resulted by the indoor environment control equipment [73]. Furthermore, the indoor environment control setting for heating is 20 °C as a setpoint whereas the setback point is 12 °C. On the other hand, the setpoint and the setback point for cooling are 26 °C and 28 °C, respectively.

4.2.5. Simulation lighting settings

The STPV glazing systems limit the amount of the natural light that enters the indoor environment, and as a result, the lighting demand increases. To ensure that the indoor setting has an adequate daylight, the numerical model has set 500 lux as a knee point that should be meet during the simulations. This would require a lighting power density of 8 W/m^2.

4.3. Results and discussions

4.3.1. Small glazing systems

The glazing system would be considered small, when the glazing system covers up to 30% of the wall area (WWR $\leq$30%). Fig. 2 shows the outcome results for the different glazing systems when the glazing system covers small portion (WWR $\leq$30%) of the wall area. The results were in-line with the literature that stated low WWR would achieve negative performance. Since the STPV glazing system obstruct and limit the amount of natural light, the lighting load will increase accordingly. In addition to that, the amount of the heat gain is reduced leading to eliminate huge amount of the passive heating element, and as a result an increment in the heating load. This trend was shown in the eleven STPV glazing systems results, regardless of the used solar cells materials.

Table 2
Glazing systems characteristics.

Model Name	Integrated Solar Cells	U-Value	SHGC	VLT	Efficiency	Symbol
a-Si PV 0%	a-Si	2.783	0.145	0.01	6.20%	A0
a-Si 10% STPV	a-Si	2.783	0.216	0.11	4.43%	A1
a-Si 20% STPV	a-Si	2.783	0.253	0.16	3.79%	A2
a-Si 30% STPV	a-Si	2.783	0.316	0.26	3.16%	A3
a-Si 40% STPV	a-Si	2.783	0.367	0.35	2.53%	A4
c-Si STPV 0%	c-Si	3.5	0.25	0.42	7%	CS
CdTe PV 0%	CdTe	1.812	0.129	0.06	9.91%	C0
CdTe 10% STPV	CdTe	1.812	0.158	0.102	8.80%	C1
CdTe 20% STPV	CdTe	1.812	0.186	0.145	7.73%	C2
CdTe 30% STPV	CdTe	1.812	0.228	0.21	6.64%	C3
CdTe 40% STPV	CdTe	1.812	0.271	0.275	6.04%	C4
Reference point	N/A	2.761	0.761	0.812	N/A	DG

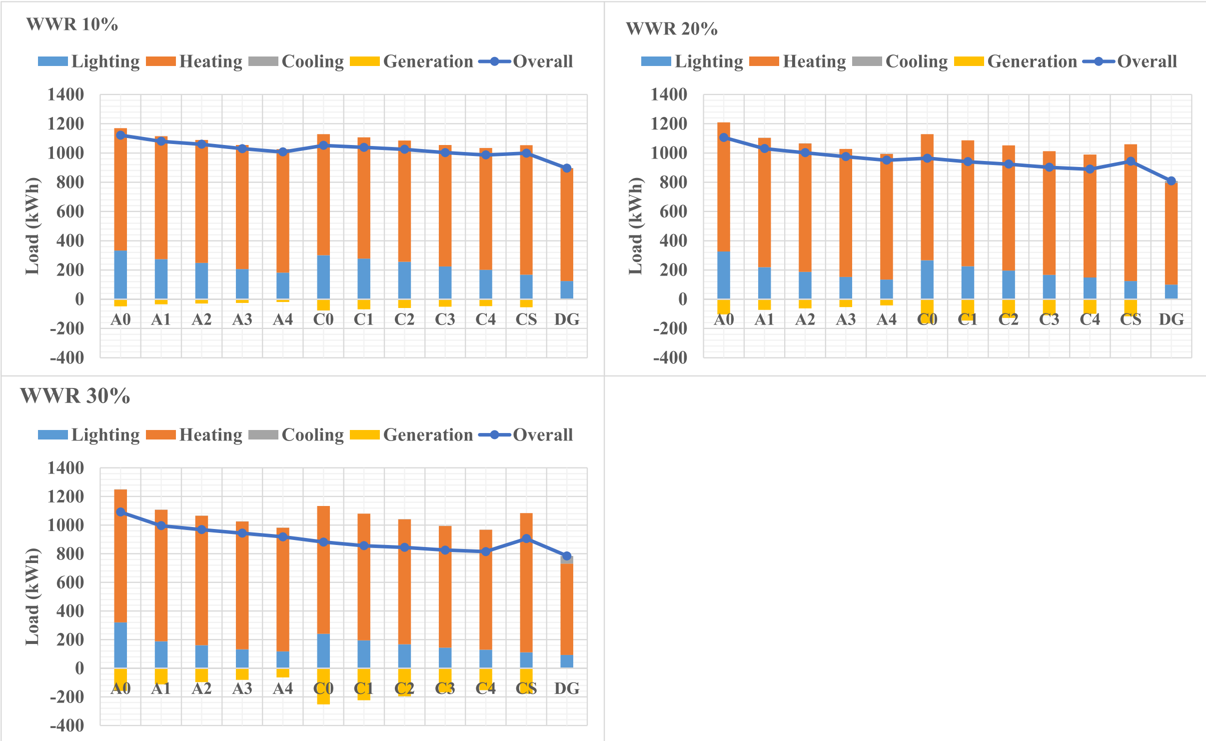

Fig. 2. Overall Energy Performance for small glazing.

Reviewing the energy generation aspect, as the transparency of the systems increases, the amount of the generated electricity decreases. This trend is detected in all STPV glazing systems, whether these systems were a-Si STPV glazing, CdTe STPV glazing or c-Si. As seen in Fig. 2 the c-Si STPV and the CdTe STPV systems generated more energy compared with a-Si STPV at the same WWR. These results are driven by the fact that the c-Si and CdTe solar cells materials tend to be more capable of converting the solar radiation into energy when compared to a-Si solar cells.

The transparency of the different systems plays a vital role regarding the heating and lighting demands, as the transparency of the system increases, the heating and lighting demand decrease. Integrating STPV in small glazing results an increase in the overall energy performance ranging from (17–39) % for the a-Si STPV case, (4–19) % for the CdTe STPV and (11–17) % for the c-Si STPV. These results are dependent on the transparency of each model, as well as the WWR that the model covers when compared with the conventional clear double-glazing system.

4.3.2. Moderate glazing systems

The glazing system would be considered a moderate one when it covers more than 30% of the wall area but less than 70% of that area (30% < WWR <70%). According to literature, integrating solar cells into the glazing systems would result a saving potential. This potential is dependent on the materials that solar cells are made of. Most of the literature have indicated that with the increase of the area that the glazing system covers, the number of the solar cells increases and as a result an increase in the generated electricity occur. Furthermore, the amount of the natural light that supplies the indoor setting increases, leading to an increase in the solar heat gain and resulting a decrease in the heating and lighting load. Alternatively, the increase in the solar heat gain leading to an increase in the passive heating element which will result an increase in the cooling load.

Fig. 3 shows the simulation results for the different glazing systems when the STPV glazing systems covers moderate area of the wall (30% < WWR <70%). As for this numerical model, the STPV glazing systems that are based on integrating CdTe solar cells simulation result are in-line with the literature. The simulation results indicate that when the glazing system covers more area of the wall, the saving in energy consumption increases. Furthermore, when the transparency of the STPV increases the overall energy performance improves. The most efficient model that utilises CdTe solar cells was the C4 model. This model has the highest transparency levels which means the lowest lighting and heating load. This model could result a saving potential of 32% on the overall energy consumption, when the C4 model is compared with the conventional double-glazing system. This saving in the energy consumption has been achieved when the glazing system covers 60% of the wall area. It is worth mentioning that other CdTe STPV glazing system models (C0, C1, C2 & C3) reduce the energy consumption in a range between 29% and 31%.

Under the same circumstances, a-Si STPV glazing systems models tend to have a limited effect when they are compared to the conventional clear double-glazing. A reduction in energy consumption is limited and could go as high as 6.06% for the A4 model. Whereas the A0 model, tends to result an increase in the overall energy consumption around 13.6%. The explanation behind these

Fig. 3. Overall Energy Performance for moderate glazing.

results attributed to the thermal and optical characteristics of the a-Si solar cells. These characteristics would eventually lead to a higher heating and lighting demands. Furthermore, the United Kingdom climate profile tends to be temperate, nevertheless the heating load is classified as the dominant load unlike many locations that have been discussed in the literature with a similar climate profile.

Similarly, c-Si STPV tends to have an identical behaviour to the a-Si STPV glazing systems when glazing is covering 40% or 50% of the wall area. That is because the high U-value which would lead to an increment in the heating demand is on the levels of the heating demand of the clear single glazing. When the glazing is covering 60% of the wall area, c-Si STPV glazing system would reduce the overall consumption level by around 16%. This reduction is driven by the two factors: the amount of the generated energy, and the lesser lighting load. The c-Si solar cells are highly efficient in converting the solar radiation into electrical power, which would lead to generate more energy. Whereas the high VLT capabilities of the used c-Si STPV glazing system, the lighting demand is much lower.

c-Si and a-Si STPV glazing systems have not produced any reduction in the overall energy performance for the office setting, when the WWR was 40% or even 50%, whereas, the CdTe STPV systems have reduced the overall energy consumption.

4.3.3. Large glazing systems

The glazing system would be considered a large one, if the glazing system covers at least 70% or more of the wall area (WWR ≥70%). At this size, almost all the literature agreed that this is the optimal situation to utilise the STPV glazing system, driven by the fact that the lighting load alongside the heating load would decrease significantly. In addition, the generated energy would reach its peak levels since the number of the active solar cells increases, but on the opposite side the cooling load will increase and reach its peak levels too, consequently the rising solar heat gain. The analysed data in the literature have drawn a conclusion that utilising the STPV glazing system at this size regardless of the solar cells that are integrated in the glazing system is the optimal way to reduce the overall energy consumption in the building.

Fig. 4 shows simulations outcome for different STPV glazing systems, when the STPV glazing systems cover most wall area (70% ≥ WWR ≥100%). As for the results for this numerical model, the results indicated that a reduction in the overall energy consumption for the simulated office space when utilising STPV glazing system, regardless of the used solar cells materials in the STPV glazing system. As stated in the moderate glazing systems analysis, the CdTe STPV glazing system are more efficient than both the c-Si and a-Si STPV glazing systems. But in this case, all STPV glazing systems are efficient when compared with the conventional clear double-glazing systems. The results indicated that a-Si STPV glazing systems reduction of the overall energy consumption increases as the transparency levels of model and the area that the glazing covers increase. So, the A4 model tends to be the optimal design when utilising the a-Si solar cells and integrate them into the glazing systems. As the area that the glazing system cover increases, the amount of reduction in the overall energy consumption increases. These results would be explained by the fact that the A4 model has the highest levels of transparency, meaning the lowest lighting and heating loads alongside a reasonable amount of generated energy. On the other hand, CdTe STPV simulations results pointed out that the deployment of these models would result a reduction in the overall energy

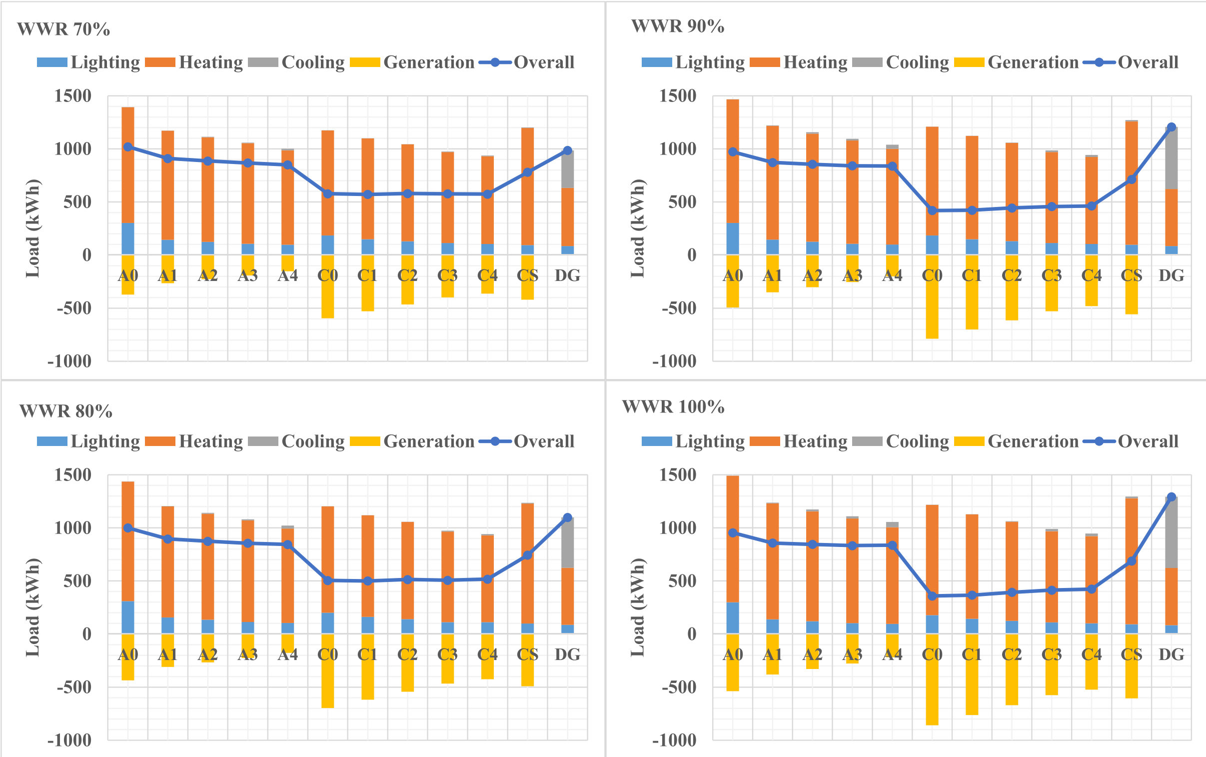

Fig. 4. Overall Energy Performance for large glazing.

performance when compared with the conventional clear double-glazing system as well as in the moderate glazing system. However, and unlike in the moderate glazing systems, the least transparent models tend to be more effective. Whereas the C1 model is the most efficient when the glazing system covers (70–80) % of the wall area. The C0 model was the optimal model to be utilised when the glazing system covers almost or whole wall area. The explanation for these results can be summarised as following. As the area that the glazing system cover increases, the number of active solar cells increases, and as a result the amount of the generated energy increases. So, the models with the highest converting abilities will create the most amount of energy which is represented in C1 and C0. Furthermore, these two models have the lowest transparency levels between the five CdTe STPV glazing systems, which as a result, would lead to the lowest cooling load consumption. With all that been said, the difference between the optimal model and the other ones is around 3% at most.

Also, the results indicate that the most efficient model between the a-Si STPV glazing systems is the A4 model. The A4 model has generated around 35% saving in the overall energy consumption, when compared with the conventional clear double-glazing system. On the other hand, the results emphasis that the most efficient model between the CdTe STPV glazing systems is the C0 model, which is also the efficient model among all glazing, achieving overall energy saving around 72%.

As for the c-Si STPV glazing system, utilising such a glazing would result a 41% reduction in the overall energy consumption against a clear double-glazing. However, it is worth mentioning that the thermal characteristics of this model needs improving as the heating demand is very similar to the clear single glazing system.

4.3.4. Results summary

The overall performance of the different glazing systems tends of the simulation is shown in Fig. 5.

Summarising the results, the cooling and heating loads consumption levels tend to increase as the transparency of STPV glazing systems models, as well as the area that these models cover expand. This increment is attributed to the growth in the amount of the nature light and the solar heat gain that penetrate the glazing systems. The increase in the solar heat gain will lead to enlargement in the passive heating element during the day, and a growth in the passive cooling element in the night. However, the rise in cooling load is relatively negligible compared to the overall energy consumption of the different STPV models. On the other hand, the heating load is going to be the prevailing consumption factor.

As for the clear double-glazing system, the cooling load tends to increase raptly as the glazing system covers larger area of the wall. This increase has made the cooling load the main consumption factor when the glazing covers larger areas. On the other hand, the heating consumption levels tend to decrease as the area that the glazing system covers increases.

The lighting load consumption tends to decrease as the area that the glazing system covers, alongside the increasement of the transparency levels of each model. This trend is attributed to the increase of the natural light that the indoor environment receives.

The generated energy of the of the different STPV glazing system increases as the WWR that each model covers increases. This

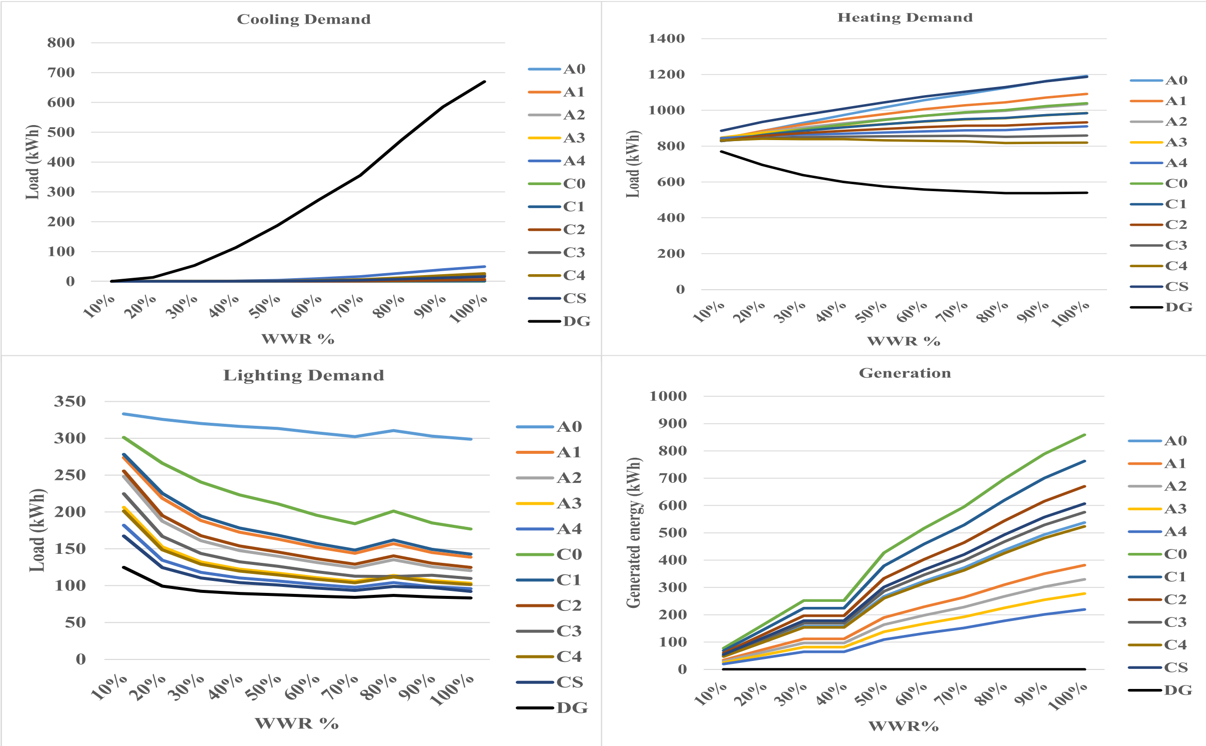

Fig. 5. The overall trends that the STPV glazing systems follows depending on the WWR that each model covers.

increase is driven by the increase of the active solar cells. However, the results indicate that CdTe models tend to be more efficient than a-Si models. This is essentially caused by the higher conversion that CdTe solar cells tends to have compared with a-Si and c-Si solar cells.

5. Conclusion

In this work an in-depth analytical review based on the solar cells materials has been conducted, followed by a case study based on a numerical model that has been developed utilising EnergyPlus software tool for the UK weather to address the knowledge gap for buildings performance in the UK The analysis has taken into consideration the effects of the transparency levels of the STPV glazing systems and different WWR have on the overall energy consumption. The highlighted conclusions are:

- ❖ Utilising STPV glazing systems in small glazing (WWR ≤30%) would represent an insignificant impact, this conclusion is driven by the fact that the clear double-glazing systems tend to consume less energy when compared with different STPV glazing systems.
- ❖ Employing a clear double-glazing in small glazing situation at WWR = 30% would reduce the overall energy consumption by 25.35%, 7.6% and 15% on average for a-Si, CdTe and c-Si STPV glazing systems respectively.
- ❖ Integrating CdTe STPV glazing systems in intermediate glazing (30% < WWR <70%) would be a more efficient solution in comparison with the conventional clear doble-glazing system. This conclusion was attributed to the energy saving potential being around 24% compared with the clear double glazing.
- ❖ Applying STPV glazing system in large glazing (WWR ≥70%) would lead to a decrement in the overall energy performance by 40% compared with the conventional clear double-glazing systems.
- ❖ Employing a-Si STPV glazing systems would be more efficient when the glazing systems cover more than 70% of the wall area, where the most efficient model is the one with the highest transparency levels.

The results of the numerical model have indicated that utilising CdTe STPV glazing systems is an efficient approach to achieve the optimal overall energy performance in buildings. Furthermore, when CdTe STPV glazing systems cover the whole wall area, a net energy savings of 67% in Façade buildings would be achieved. These results attained when WWR = 100% and the transparency of the CdTe STPV glazing system is around 40%, as in model C4 in Table 2. However, this might bring the cost of these STPV glazing into a challenge that should also be considered. The future work on manufacturing these panels might lead to cheaper solutions and this will increase the protentional of unitizing these glazing massively.

In the end, the STPV glazing systems and BIPV technologies in general have the potential to reduce the overall energy consumption and as a result pave the way to reach zero net buildings. Nevertheless, much work is needed on different fronts; these can be summarised as following:

- ❖ Further research is needed to study the effects of using organic and synthesised solar cells.
- ❖ Further research is needed to investigate the performance of hybrid integrated solar cells for different locations where the heating load is the dominant load.
- ❖ Optimisation development to select technologies, WWR, and transparency to achieve the most efficient performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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