A smart building material for low/zero carbon applications: heat insulation solar glass—characteristic results from laboratory and *in situ* tests

Erdem Cuce[1,2*] and Saffa B. Riffat[1]

[1]Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, NG7 2RD Nottingham, UK; [2]Department of Mechanical Engineering, Faculty of Engineering, University of Bayburt, 69000 Bayburt, Turkey

Abstract

Heat insulation solar glass (HISG) is a recently developed smart building material to minimize energy consumption of building sector. HISG might be presumed to be a conventional photovoltaic glazing product; however, it is completely unique by having some characteristic features such as superior thermal insulation, which is competitive with triple-glazed windows using argon as inert gas, acoustic and thermal comfort, self-cleaning ability owing to TiO_2 nano-coating on module surface and extraordinary energy saving potential in both summer and winter. In our previous works, comprehensive experimental and numerical works have been carried out for power generation and thermal insulation performance of HISG under various climatic conditions. Within the scope of this research, optical- and lighting-related performance parameters of this smart building material are evaluated through extensive laboratory and *in situ* tests. Shading coefficient, visible light intensity, and UV and IR penetration are investigated via the tests conducted in real operating conditions. It is achieved from the results that the shading coefficient of HISG is only 0.136, which yields almost 80% reduction in solar heat gain compared with ordinary glazing. It is also observed from the *in situ* tests that HISG has a %100 UV and 99% IR blocking rate, which is of vital importance in terms of human health and thermal comfort conditions. Glaring effects are totally resolved via HISG, which is still a challenge for the buildings with conventional glazing products, especially in summer.

*Corresponding author: erdem.cuce@nottingham.ac.uk; erdemcuce@bayburt.edu.tr

Keywords: heat insulation solar glass; indoor lighting; optical performance; thermal comfort

Received 26 January 2016; revised 26 February 2016; accepted 21 March 2016

1 INTRODUCTION

Life is greatly affected by energy and its consumption as people depend energy for almost everything in their lives. Energy-related problems are so sensitive for the world, which need drastic measures to be resolved urgently. Due to limited reserves of energy resources [1], remarkably soaring energy prices [2] and growing significance of environmental issues such as global warming, ozone layer depletion and climate change [3], the terms like energy conservation and energy saving have been the centre of interest as reported by Buratti and Moretti [4]. The importance of clean energy generation as well as energy saving has stimulated the developed countries into renewable energy technologies [5–18] over the last four decades. However, latest research reveals that renewables can supply only ~14% of total world energy demand [19, 20]. In this respect, additional decisive measures need to be taken for urgent reduction of global energy consumption and effective stabilization of greenhouse gas emissions [21, 22]. Determining sectoral energy consumption of the world in an accurate and reliable way is therefore significant to be able to achieve key solutions to mitigate global energy demand, and International Energy Agency conducts several comprehensive researches for this purpose as it is well-documented in literature [23]. It is clear from the latest works that building sector plays an important role in final energy use, thus in greenhouse gas emissions [24]. Almost 40% of total world energy consumption in 2014 is attributed to

International Journal of Low-Carbon Technologies 2017, 12, 126–135

doi:10.1093/ijlct/ctw009 Advance Access Publication 13 May 2016

buildings. In terms of environmental issues, it is emphasized by Baetens *et al.* [25] that building-related carbon emissions constitute >30% of total emissions in many developed countries. This circumstance is a consequence of poor thermal insulation performance characteristics of conventional building elements essentially windows [26]. Windows in general are responsible for a noteworthy amount of energy loss from building envelope. Traditional window technologies in market typically have high overall heat transfer coefficients (*U*-value); therefore, they differ from other building elements in terms of their impact on heating and cooling demand as reported by Grynning *et al.* [27].

The role of windows in total energy loss from building envelope becomes much more considerable when window area is large like in highly glazed buildings. It is clearly reported by Jelle *et al.* [28] that ~60% of heat loss from building fabric is attributed to the existing conventional windows. This scenario can be explained by the insufficient thermal insulation performance of conventional glazing products. Air- or argon-filled double-glazed windows are the most prevalent fenestration products in market owing to their well-known fabrication process and significantly better thermal insulation feature compared with ordinary single glazing [29]. However, existing *U*-value range of air- or argon-filled ouble-glazed windows is not sufficient enough as shown in Table 1 [31, 32] to meet the latest low/zero carbon building standards. This output from Cuce and Cuce [32] is also verified by Pilkington [30] through their recent report on the *U*-values of different glazing types. In this respect, highly thermally resistive and cost-effective glazing technologies are definitely required towards low/zero carbon targets adopted by developed countries.

In recent years, considerable attention is given to novel glazing technologies to enhance thermal insulation feature of windows, thus to mitigate window-related energy losses in buildings. It can be easily asserted that a definite solution is very difficult to achieve in most cases due to some issues such as cost, thermal comfort, performance and aesthetic aspects [33]. For instance, multilayer glazing is capable of providing highly thermally resistive structures, especially when supported by low-e coatings and suspended films. However in most cases, notably thicker and heavier constructions are required for an optimum retrofit, which is not preferred by most residents. Another option is vacuum glazing, which enables highly resistive structures at very slim designs to minimize energy loss from glazed areas [34]. However, it needs to be noted that commercialization is still a challenge for vacuum glazing due to significantly higher fabrication cost in comparison with conventional glazing types [35, 36]. Aerogel glazing [20, 37, 38], PCM glazing [39] and TIM glazing are other novel glazing solutions for efficient thermal regulation of building envelope, but they remarkably deteriorate the vision, and therefore the thermal comfort of the residents. Adaptive glazing technologies are also attractive in terms of multi-functional use, but their current overall cost is not at desired level [40]. Photovoltaic (PV) glazing is another technology, which is highly preferred in modern architecture [41]. However, despite the intensive efforts, their current *U*-values are still very high causing significant heat loss and gain in winter and summer, respectively. Overall, it can be easily concluded from the literature survey that each novel glazing technology has some characteristic advantages with particular drawbacks, and no attempt has been made so far in literature to combine specific benefits of different glazing technologies into a single unique window. Therefore, a novel glazing technology called heat insulation solar glass (HISG) has been recently introduced by Cuce *et al.* [42], and its thermal insulation, power generation and energy saving performance have been analysed in detail. Within the scope of this work, previous research is extended to investigate lighting-related thermal comfort and optical performance of HISG through extensive laboratory and *in situ* tests. One of the creative energy homes in the University Park Campus is utilized for the *in situ* tests for a realistic approach.

Table 1. U-*values of commercial glazing products.*

U-value (W/m^2 K)	Pilkington [30]	Cuce and Riffat [31] and Cuce and Cuce [32]
Air-filled double-glazed window	2.70	2.53
Air-filled double-glazed window with low-e	2.00	2.10
Argon-filled double-glazed window with low-e	1.80	1.90

PV glazing is commonly utilized in modern architecture because of aesthetic features as well as being able to generate electricity. However, thermal insulation performance of conventional PV glazing products is very poor, which is even worse than conventional single glazing as reported by Peng *et al.* [43] in their recent experimental research. On the other hand, the concept of PV glazing is very dynamic and numerous works are in progress to improve their current power generation, thermal insulation and optical performance.

Conventional PV glazing systems are fabricated from crystalline silicon solar cells (c-Si PVs). There are several researches in literature where semi-transparent c-Si PVs are used to replace conventional glazing at residential and commercial buildings as given by Skandalos and Karamanis [44]. Typical c-Si PVs are encapsulated between highly transparent glass panes to form a standard PV glazing. Ethylene vinyl acetate film is mostly used for encapsulation. The orientation of PV cells is adjusted properly to be able to achieve the required level of transparency. Current electrical efficiency of conventional c-Si PV glazing products varies from 16 to 22%. However, the technology is expensive because of the high costs of silicon wafers. Another disadvantage of these products is the limited external view as c-Si PVs are typically opaque. Semi-transparent c-Si PVs enable better lighting performance, and increasing the area covered by the cells in a semi-transparent PV glazing leads to more electricity generation. But, this causes excessive solar heat gain in summer resulting to considerable rise in cooling demand of buildings. Therefore, a balanced solution between daylighting, solar heat gain and electricity generation is usually required in conventional c-Si PV glazing products [45].

Table 2. *Evaluation of advanced PV glazing systems in terms of several performance parameters.*

Ref.	Structure	Efficiency (%)	Transparency (%)	Benefits/issues	Year
[56]	Nine PV cells in series	–	60 (visible)	The method for electrical contacts can suppress the IR drop	2003
[57]	Glass frit sealing technology	3.5	Semi-transparent	Successful in a large-scale application	2008
[58]	Twenty-nine PV cells in series	7.0	Semi-transparent	Cost-effective	2006
[59]	Flexible dye-sensitized PV cell	7.6	–	High efficiency and low-cost	2010
[60]	Silver grid-embedded transparent conducting glass	4.2	Semi-transparent	Similar performance with platinum	2008
[61]	Stainless steel substrate, flexible dye-sensitized PV cell	4.2	–	High temperature sinter ability Small loss in efficiency	2006
[62]	Screen-printing technology	5.5	–	Stable performance	2007
[33]	Heat insulation solar glass, thin-film amorphous silicon	12.0	Semi-transparent	Cost-effective and energy-efficient Suitable for retrofitting purposes	2007 2016

As the cost is still challenging for c-Si PV glazing products, the development of low-cost PV cells to form cost-effective and energy-efficient glazing systems is the centre of interest in recent years. Numerous attempts are made at global scale on dye-sensitized and organic PV cells as a consequence of their special properties and low-cost [46], easy scalability, simple manufacturing process [47, 48], low material consumption, sensitivity to low light levels and ease of use for large area applications [49–53], which make them potential candidates for use as energy windows [54, 55]. The dye-sensitized PV glazing products are promising because of their attractive cost range; however, their energy conversion efficiencies are very poor compared with conventional PV glazing systems. A comprehensive illustration of advanced PV glazing systems in terms of structure, electrical efficiency, cost, transparency and time [56–62] is presented in Table 2.

The comprehensive literature survey clearly indicates that each novel glazing technology has some characteristic advantages with particular drawbacks, and that would be a point of interest to combine beneficial features of different glazing technologies into a single window. Therefore in this research, a unique multi-functional glazing technology called HISG is introduced and investigated in terms of optical- and lighting-related performances. In our previous works, thermal insulation and power generation features of HISG have been evaluated in detail. The goal of this research is to extend the previous attempts to optical and lighting performance through several experimental works. Optical- and lighting-related thermal comfort performance investigation of glazing systems is of prime interest as they might play an important role in total heating and cooling demand of buildings.

2 HEAT INSULATION SOLAR GLASS

HISG is a multi-functional novel PV glazing technology, which provides superior thermal insulation, remarkable power generation, efficient self-cleaning, noteworthy energy saving, and attractive aesthetic and acoustic features in a single window design. HISG can be described as a unique application of PV glazing, in which a transparent amorphous silicon (a-Si) PV module is supported by special coatings and structures as illustrated in Figure 1.

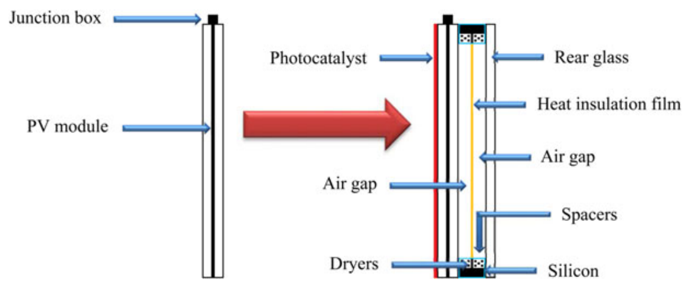

Figure 1. *Cross-sectional view of HISG with structural details.*

HISG has a great potential to mitigate energy consumption of buildings while providing preferable thermal comfort conditions to residents owing to its superior structure enabling clean energy generation as well as extraordinary thermal insulation.

2.1 Structural details of HISG

HISG is basically a multiple-layered glazing technology with superior structural details and thermophysical properties [63]. Power generation in HISG is provided by a transparent a-Si PV module, which is integrated with a TiO_2 nano-coating for high transmittance and low reflection. The accumulation of pollutants on PV module is prevented by the nano-TiO_2 photocatalyst coating. The coating also plays a significant role in power generation efficiency as given in Figure 2 by notably reducing the light reflection from the PV module surface. The independent tests conducted on several HISG samples reveal that nano-coated modules generate almost 7% more electrical power in comparison with ordinary modules. HISG also includes a nano-layer insulation film with high reflectivity at the back of a-Si PV module located between two layers of spacers. The nano-film reflects the transmitted light back on the PV module and provides secondary power generation. The power generation is enhanced while the a-Si PV module captures the reflected light. An air gap is provided on each side of the nano-layer insulation film by placing a sheet of layer glass behind the second spacer layer. The said air gaps remarkably improve the thermal insulation ability of HISG, while overall heat transfer coefficients are incomparably high for conventional PV glazing products. In order to maintain absolute dry conditions inside HISG, suitable

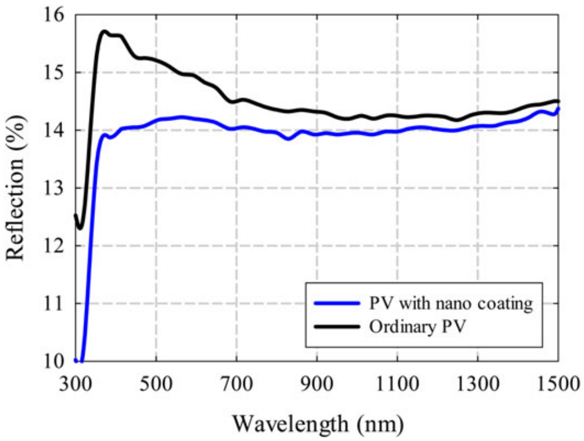

Figure 2. *The role of nano-TiO_2 photocatalyst coating on the reflection from PV module surface.*

Figure 3. In situ *testing of HISG through creative energy homes at the University of Nottingham.*

driers are utilized between the layers of spacers. Hot-melt adhesive and silicone are used for fixing and sealing materials. The fabrication process is finalized by heating the materials in an oven at 120°C during 4 h. At the end of the solidification mechanism, a-Si PV module is coated by a layer of photocatalyst. This entire fabrication process can be performed to any transparent PV module, and different types of inert gases can be utilized instead of air depending on the requirements.

2.2 Multi-functional features of HISG

It is unequivocal that HISG is an efficient application of PV glazing, and hence HISG has similar electrical characteristics with conventional transparent PV modules. When sunlight falls on the nano-coating of HISG, some of incoming solar energy is directly converted into electrical power as a consequence of photoelectric effect. The rest of the sunlight transmits and arrives at the nano-layer insulation film. Then secondary power generation occurs as a consequence of reabsorption of reflected sunlight. The remaining sunlight coming to the insulation film is greatly blocked, which yields remarkably low shading coefficient range for HISG. Moreover, multilayer structure of HISG results in attractive thermal insulation ability. Air gaps play an important role in thermal behaviour of HISG. Heat penetration is notably mitigated through the optimized double air gaps of HISG. Owing to the considerably low shading coefficient of HISG, insignificant amount of solar radiation penetrates into the living spaces in summer resulting in notable reductions in cooling demand. Similarly in winter, heating demand can be greatly reduced as a consequence of very promising *U*-value range of HISG. Photocatalyst coating provides self-cleaning ability by rendering the external surface hydrophilic. The pollutants accumulated on the PV module surface are decomposed by the nano-coating, and they are removed when rain falls. This self-cleaning ability provides a significant energy saving and noteworthy enhancements in overall energy efficiency. It can be easily asserted that the issue of window cleaning in tall buildings can easily be resolved through appropriate retrofitting of such buildings with HISG.

3 EXPERIMENTAL ANALYSIS OF HISG

In our previous works, thermal insulation, power generation and energy-saving performances of HISG have been evaluated in detail through comprehensive laboratory and *in situ* tests. Previous works clearly reveal that HISG is not only a power generator but also a promising thermal insulator. However, optical, lighting and thermal comfort performances of HISG have not been evaluated previously, which are of vital importance for an overall performance assessment of a building element. Within the scope of this research, optical- and lighting-related performance parameters of this smart building material are experimentally investigated through a retrofit application. The research methodology is totally based on an experimental approach. The tests are conducted in real operating conditions for a reliable and realistic assessment. In this respect, one of the creative energy homes in the University Park Campus of University of Nottingham is utilized for the real-time testing as shown in Figure 3. Power generation efficiency, UV and IR absorption and lighting-related thermal comfort performance of HISG are evaluated through *in situ* tests. Temperature differences across the HISG samples are measured, and the results are compared with those of conventional double-glazed window to evaluate the thermal insulation and thermal regulation feature of HISG. Light intensity measurements are conducted internally to assess the influence on HISG on indoor thermal comfort. These tests enable to show that how efficiently glaring effects are resolved via HISG. Solar intensity-dependent electrical power output is also specified for each HISG sample to characterize the power generation potential of HISG under different climatic conditions. UV and IR blocking rate of HISG is justified through the said *in situ* tests. UV blocking rate is determined through calibrated UV meters as measuring the UV part of incoming sunlight in the front and at the back of HISG. These tests are repeated at different times of the day for an estimated performance of HISG in UV and IR blocking. For the power output measurements, a well-known commercial PV analyser HT IV-400 is utilized. Standard K-type thermocouples and Omega HFS-4 thin film heat flux sensors are used for temperature and heat flux measurements, respectively. DT85 Data Acquisition System is utilized for time-dependent data triggering. The sensors utilized in the measurements have very low response time and high sensitivity. The total uncertainty is calculated to be below 2%, which is acceptable for such a research. The *in situ* tests of HISG are also supported by comprehensive laboratory and outdoor tests. In this respect, two separate glass houses are built with identical external dimensions as illustrated in Figure 4. First glass house is constructed by 12 mm thick ordinary glass to represent the conventional case while the second house is built by HISG for comparison. External dimensions of the glass houses are given in Table 3. Aluminium frames are preferred in the said designs in order to have a lightweight construction. For a reliable and realistic experimental research, glass houses are tested simultaneously under the same environmental conditions. Various thermal insulation-, thermal comfort-, optical- and lighting-related

Figure 4. *Photograph of the test houses constructed for outdoor testing.*

parameters are investigated in those test houses for a better understanding and tracking the difference in performance.

4 RESULTS AND DISCUSSION

Optical- and lighting-related performance parameters of HISG are investigated via one of the creative energy homes in the Department of Architecture and Built Environment at the University of Nottingham. Two different HISG samples are evaluated in the retrofit work, in which nano-layer Al and TCO reflective films are utilized for secondary power generation.

4.1 Power generation tests

As a first attempt, power generation efficiency of those HISG samples is determined. It is clear from power generation characteristics that the samples have a similar electrical power output as shown in Figure 5. For a solar intensity of 900 W/m^2, 118 W electrical power is obtained from the HISG sample equipped with nano-layer Al reflective film from a glazing area of 1.54 m^2, while the power output is 116 W for the other sample. In the previous work [42], standard HISG samples have found to be producing ~71 W/m^2 electrical power under a solar intensity of 1000 W/m^2. Through nano-layer Al and TCO reflective films, power generation ability of HISG is enhanced to 85 W/m^2 as can be understood from the results.

Table 3. *External dimensions of the test houses.*

	Ordinary glass	HISG
Thickness (mm)	12.00	28.00
Length of the house (m)	3.04	3.04
Width of the house (m)	2.51	2.51
Height of the house (m)	3.17	3.17
Vertical glazing area (m^2)	24.64	24.64
Roof glazing area (m^2)	6.16	6.16

4.2 Thermal insulation tests

Thermal resistance feature of HISG samples is evaluated in comparison with conventional double glazing as a second goal of this research. Determination of the temperature difference across the building element can be presumed to be one of the easiest ways of assessing the thermal insulation feature of the said material. In this respect, temperature measurements are conducted for a particular period of time for each sample. For the indoor air temperature of 18°C and outdoor temperature of 10.6°C, internal glazing temperatures of conventional double glazing, Al-based HISG and TCO-based HISG are measured to be 14, 15.2 and 16°C, respectively. Each HISG sample is found to be providing comfort lighting level, whereas the glaring effects are unequivocal in case of conventional double glazing as illustrated in Figure 6. It can be concluded from the results that HISG is very promising for energy-efficient thermal regulation of indoor environments [22].

4.3 Lighting tests

Lighting performance assessment of HISG samples is done through instantaneous tests at different locations of the indoor

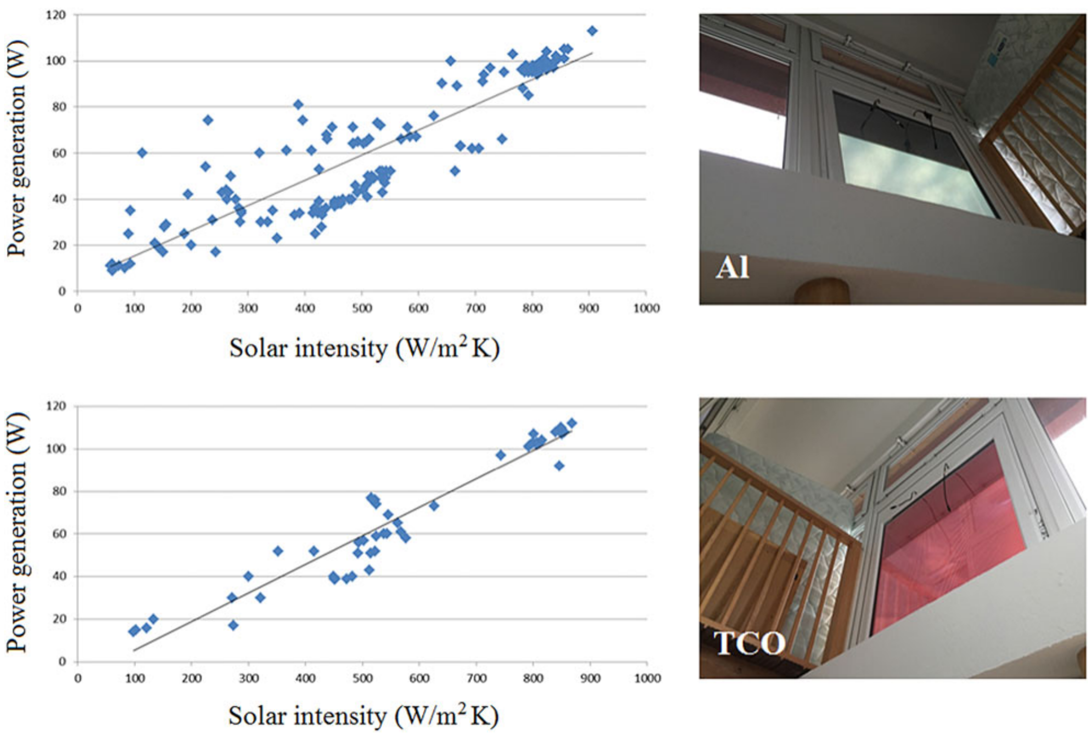

Figure 5. In situ *testing of different HISG samples.*

Figure 6. *Indoor lighting levels of HISG samples and conventional double glazing.*

environment. It is well-documented in literature that glaring effects are very dominant in buildings having traditional glazing systems [21]. Indoor light intensity for Al- and TCO-based HISG is measured to be 1125 and 904 Lux, respectively, whereas it is 21 470 Lux for conventional double glazing. Through the *in situ* tests conducted, it is clearly justified that HISG is not only a promising power generator but also a very good thermal insulator both in summer and winter time, which can remarkably mitigate energy demand of buildings. Efficient control of penetrated light via HISG samples can provide attractive indoor environments to the occupants without requiring additional materials or devices such as window blinds and sunshades.

4.4 Optical performance tests

Optical performance of building elements needs to be in a satisfactory level. In this respect, several independent tests are carried out in order to evaluate the UV and IR penetration rates of HISG samples in comparison with conventional glazing products. The UV and IR penetration through the HISG samples is determined via highly sensitive sensors. For a typical time of the day, it is observed that each HISG sample blocks 100% of incoming UV as shown in Figure 7. On the other hand, conventional double glazing is found to be very poor in terms of UV blocking rate. Internal UV is measured to be 108 $\mu W/cm^2$ in the test time, whereas it is 340 $\mu W/cm^2$ for the outside. Comprehensive laboratory tests are conducted to determine other thermal and optical properties of HISG as presented in Table 4. Further tests reveal that 99% of incoming IR light is absorbed by HISG and utilized in power generation, which is very attractive.

4.5 Thermal comfort tests

Thermal regulation feature of HISG in any type of climate is also demonstrated within the scope of this research. In this respect, indoor and outdoor air temperatures are measured for different ambient and sky conditions as shown in Figure 8. It is clearly observed from the tests done in sunny days that HISG can greatly resolve the overheating problem, which is currently a challenge for

Figure 7. *Indoor lighting levels of HISG samples and conventional double glazing.*

Table 4. *Thermal and optical properties of glazing materials utilized in the test houses.*

	Ordinary glass	HISG
Visible light transmittance (%)	87.00	7.15
Solar thermal transmittance (%)	60.00	2.60
Absorption rate (%)	5.75	79.35
Thermal conductivity (W/m K)	1.05	0.032
Overall heat transfer coefficient (W/m^2 K)	5.97	1.10
Shading coefficient	0.87	0.136

highly glazed buildings as also emphasized by Larsen *et al.* [64]. It is also achieved from the tests conducted in rainy days that much more comfortable indoor conditions is provided by HISG although the differences in air temperatures are insignificant except the noon times. Overall, it can be easily concluded from the results that HISG provides superior optical-, thermal comfort- and lighting-related performances as well as having additional multi-functional features such as thermal insulation and power generation. Hence, HISG can be effectively considered in buildings not only for retrofitting purposes but also for new built applications.

5 CONCLUSIONS

In this research, optical- and lighting-related performance parameters of a smart building material called HISG are evaluated

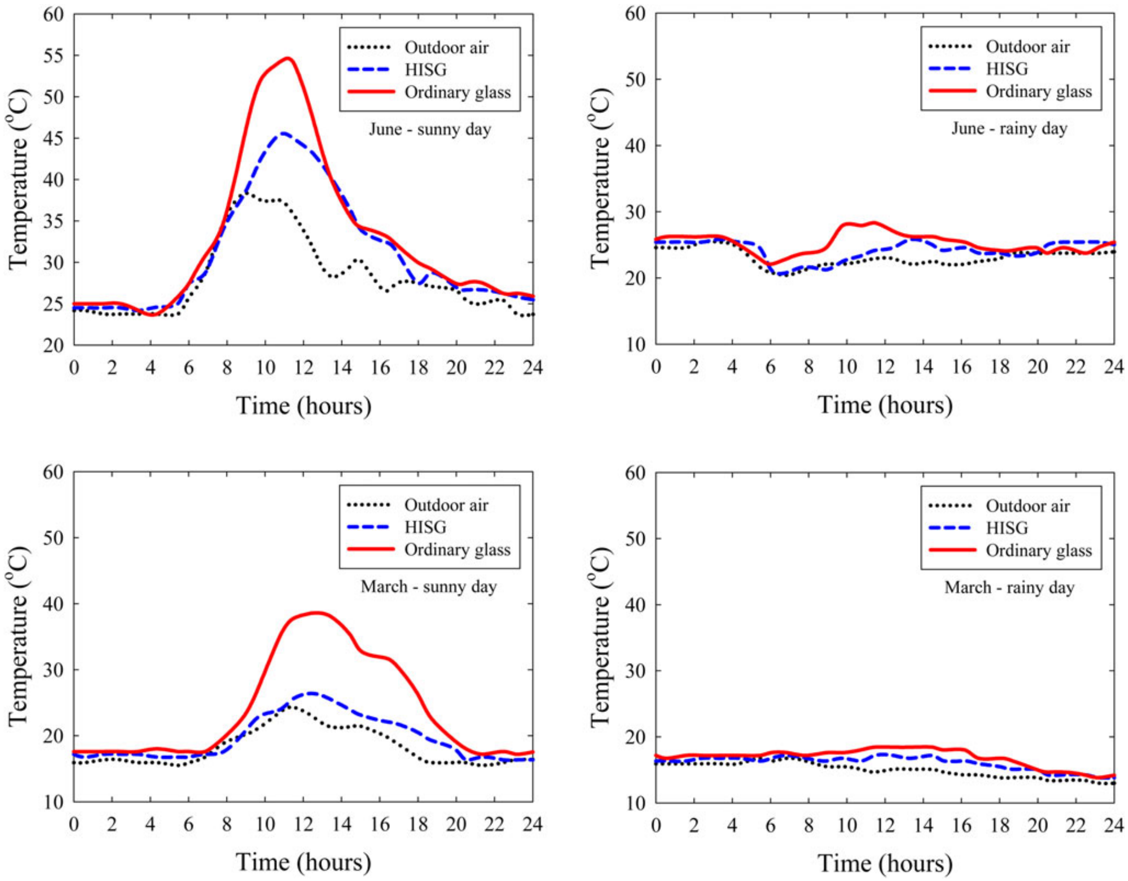

Figure 8. *Indoor and outdoor air temperatures in the test houses for different sky conditions.*

through comprehensive laboratory and *in situ* tests. Important optical-, lighting- and thermal comfort-related performance parameters such as shading coefficient, visible light intensity, and UV and IR penetration are analysed via the tests conducted in real operating conditions. The results reveal that the shading coefficient of HISG is only 0.136, resulting to 80% reduction in solar heat gain in comparison with ordinary glazing. It is also achieved from the *in situ* tests that HISG has a %100 UV and 99% IR blocking rate, which is of vital importance in terms of human health and thermal comfort conditions. Glaring effects are completely resolved in case of HISG, which is still a significant issue, especially in summer for the buildings having conventional glazing products. Indoor light intensity for Al- and TCO-based HISG is found to be 1125 and 904 Lux, respectively, while it is 21 470 Lux for conventional double glazing. Overall, HISG is found to be an attractive smart material to be utilized in existing buildings and new built applications.

ACKNOWLEDGEMENTS

E.C. gratefully acknowledges the financial support of TÜBITAK (Scientific and Technological Research Council of Turkey) through Grant BIDEB 2219 2015/1. Authors also notify the funding to the research by Innovate UK through the research project entitled 'Innovative energy saving and climate control system for greenhouses'.

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