TiO_2 nano-coated thin film PV glazing with superior thermal resistance, self-cleaning, electricity generation and adaptive optical control

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Abstract

A unique nano-coated photovoltaic (PV) glazing technology with superior multifunctional features, thermally resistive PV glazing (TRPVG), is introduced, and for three different configurations of TRPVG (TRPVG-Air12, TRPVG-Ar12, TRPVG-Ar16), UVC/UVA absorption, noise reduction, thermal insulation, electricity generation, visible light and solar radiation control are evaluated through an extensive experimental methodology. Energy production and acoustic tests are conducted in a simulation house, whereas the rest of the experiments are carried out under real operating conditions. The results reveal that each sample is capable of blocking 100% of incoming UVC and UVA light. Visible light control of TRPVG-Ar12 (Glass 1) is found to be 94.4%, whereas it is 88.9% for TRPVG-Air12 (Glass 2) and 93.6% for TRPVG-Ar16 (Glass 3). Solar radiation blockage of Glasses 1–3 is found to be 93.5%, 90.9% and 94.8%, respectively. Average temperature difference between front and rear glazing is determined to be 21.3°C, 19.9°C and 21.7°C for Glasses 1, 2 and 3, respectively. A total of 25 independent acoustic tests are performed for Glass 3, and the sample is observed to reduce 33% of outdoor noise in dBA. Solar simulator tests reveal that Glass 3 can generate 102.6 W of electricity per square metre of PV module area.

Keywords: energy-efficient retrofit; U-value; optical and acoustic performance; thermal; electricity production; TiO2 nano-coating; thin film PV glazing

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1 INTRODUCTION

Current buildings need cost-effective and eco-friendly retrofitting to mitigate their outstanding role in global energy use. Windows, among the building elements, are primarily in the centre of action plans since their overall heat transfer coefficients (U-value) are notably greater than the other parts of building envelope [1]. When the potential novel glazing technologies are considered, photovoltaic (PV) glazing draws the attention of a wide range of people as it has a remarkable potential to reduce the heating and cooling demand of buildings [2]. PV glazing systems supply electricity to the houses as well as being a novel building material of modern architecture. However, they have also some handicaps like having higher U-value range especially when they are not structured along with a thermally resistive medium. This can be ascribed to the inadequate thermophysical properties of window

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panes, PV materials and edge seals [3]. Poor thermal insulation feature of PV glazing products is an obstacle to the commercialization of this technology [4]. Therefore, there are several attempts in literature to enhance thermal, optical and acoustic performance parameters of PV glazing systems. As an example, Ghosh *et al.* [5] consider the vacuum medium to improve the U-value and solar factor of a semi-transparent amorphous silicon (a-Si) PV glazing in comparison with PV double glazing. The U-value after the vacuum medium integration is measured to be 0.80 W/m^2K, whereas the solar factor is 0.42 W/m^2K. That corresponds to 66% and 46% reductions in the U-value and solar factor compared with PV double glazing. Low-e coating and inert gas combination is reported to reduce the solar heat gain coefficient in another research [6]. Especially in harsh weather conditions, cooling demand of buildings in summer is notably high, and the works in literature underline that the efficient control of solar thermal radiation penetration across the glazed areas has a great potential to reduce cooling expenses of houses [7]. In this respect, PV glazing systems are considered on facades and roofs [8] as a novel and effective building element [9].

PV glazing systems are usually studied in terms of some performance parameters such as clean energy generation under certain solar intensities and thermal resistance against heat losses [10]. On the other hand, optical, acoustic and thermal comfort-related analyses are almost missing [11]. Very limited information is available like visible light transmittance of such systems is to be about 0.10 [12]. Visible light control is of vital importance in building integrated PV systems (BIPVs) in regions with extreme summer conditions. The case is more problematic when BIPV is structured as a transparent or translucent building envelope material such as window on facade or VELUX window on roof. Thermally and optically uncomfortable indoor conditions usually take place in such conditions due to glared effects and excessive brightness. Therefore, optical control in PV glazing is still a challenge, and it is rarely studied by researchers so far [13]. Shading coefficient (SC) of conventional transparent PV modules in market is about 0.28. Li *et al.* [14] develop some transparent conductive oxide (TCO) nano-coated sandwich structure in thin film PV glazing technology for further improvement in SC, and it is enhanced to 0.125 in summer and 0.144 in winter. Further developments are also observed in thermal resistance performance of thin film PV glazing products. a-Si thin film PV cells are integrated into thermally resistive inert gas medium in the concept of heat insulation solar glass, and the overall U-value of the product is given to be 1.10 W/m^2K for a glazing thickness of 28 mm [15]. When the latest codes released towards nearly zero energy buildings (nZEBs) are taken into consideration, it can be asserted that building envelope thermal properties for glazed areas are met by the said concept for even the most challenging countries like Finland [16]. Thermally resistive building envelope design through thin film PV glazing has an outstanding potential to reduce heating and cooling demand of residential buildings, which is critical for the nZEB requirements [17]. Naked PV glazing units usually have very high U-values; hence, they are structured with different inert gas or liquid media to increase the thermal resistance and to reduce the U-value. Air is often used behind thin film PV cells due to its notably lower thermal conductivity than silicon [18]. However, Argon is also utilized in some products in combination with low-e coating for extra thermal resistance and optical control. Transparent PV glazing systems supported with Argon medium with an optimized thickness can be proposed as an ideal solution to maximize window-related energy saving in buildings owing to lower thermal conductivity of Argon (0.016 W/mK) even than air (0.026 W/mK). Thermal bridging is a challenge for highly thermally resistive PV glazing (TRPVG) products. The U-value of glazed areas highly depends on thermal conductivity of edge seal materials [19] and dividers as well as airtightness [20]. The aforesaid challenges still take place in any type of glazing technology at a certain rate, and this adversely affects the thermal behaviour of the product. As an example, even in case of vacuum medium, experimental U-value of the glazing is only 1.40 W/m^2K as notified by Ghosh *et al.* [21]. Acoustic features and noise control are also of vital importance for general comfort level of occupants in buildings, and there are some recent attempts to evaluate BIPVs as sound barriers in building envelope as reported by Meinardi *et al.* [22]. However, there are no attempts to date in literature for noise abatement performance of thin film PV glazing systems through *in situ* tests conducted in real operating conditions.

Self-cleaning is another performance-related aspect in thin film PV glazing systems. Since these systems are also retrofitted to high-rise buildings like skyscrapers, self-cleaning is indispensable due to safety and security measures. Cleaning is a costly process for such buildings as well. Therefore, hydrophilic self-cleaning coatings are developed for thin film PV cells as reported by Nundy *et al.* [23]. For instance, ZnO hydrophilic and superhydrophilic nano-coatings are implemented on PV cells for three different morphologies called ZnO microflowers (F-ZnO), ZnO nanorods (R-ZnO) and ZnO microspheres (M-ZnO). Self-cleaning is successfully achieved via the said nano-coatings as well as up to 5% enhancement in electricity generation owing to the prevention of dust accumulation. Nanospray coatings (TiO_2 based) are tried by some researchers for self-cleaning feature in solar applications, and it is observed that the said coatings are capable of reducing transmission losses from 22% to 0.5% [24]. Self-cleaning hydrophobic nano-coatings are also evaluated in PV modules, and excellent self-cleaning behaviour is achieved [25]. On the other hand, very few works are noticed based on TiO_2 nano-coatings [26] despite their simplicity, cost-effectiveness, durability and antireflection (AR) performance.

It is unequivocal from the literature survey that PV glazing technology contains a number of shortcomings on its own such as limited electricity generation in case of dust accumulation on cell surfaces, notable reflection losses from the PV cells due to poor quality of AR coatings, somewhat considerably higher U-values than conventional double glazing because of poor thermal resistance of Si, edge seal materials, as well as thermal bridging effects, thermally and optically uncomfortable indoor environments due to somewhat high SCs, etc. Therefore, improved designs of PV glazing are required to develop towards the strict

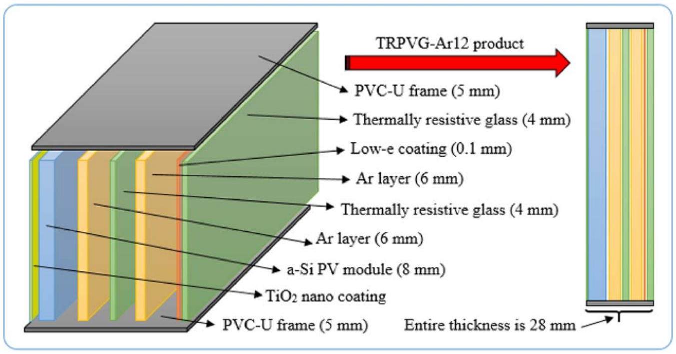

Figure 1. *TRPVG-Ar12 glazing technology.*

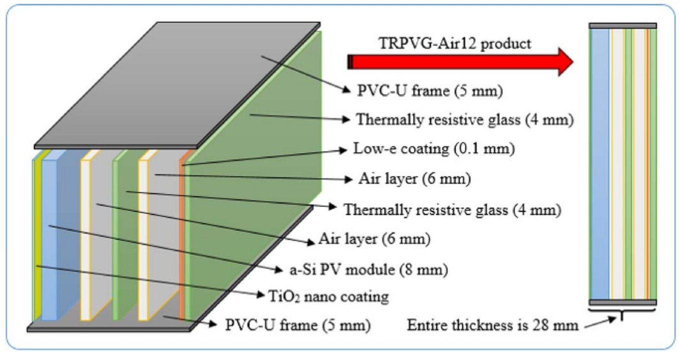

Figure 2. *TRPVG-Air12 glazing technology.*

code requirements of nZEBs. Thus, this paper aims at developing, analysing and evaluating a novel TiO_2 nano-coated thin film PV glazing technology called TRPVG with superior thermal resistance, self-cleaning, enhanced electricity generation and optical control. UVC/UVA absorption, noise reduction, thermal insulation, electricity generation, visible light and solar radiation control are experimentally analysed in the research for three different configurations of TRPVG, and the findings from indoor and outdoor tests are elaboratively discussed as a novel alternative to conventional building envelope materials.

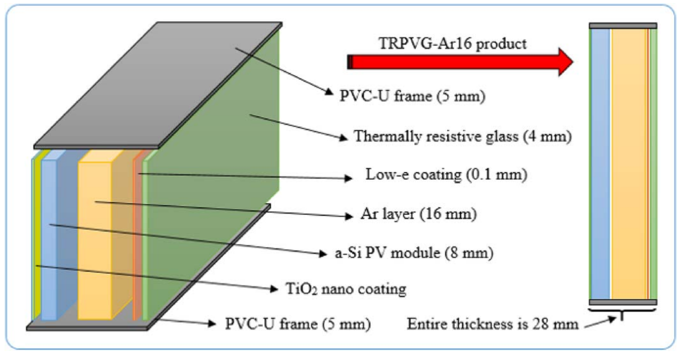

Figure 3. *TRPVG-Ar16 glazing technology.*

2 NOVEL THIN FILM TRPVG TECHNOLOGIES

The goal of this research is to devise, produce and experimentally investigate an improved design of nano-coated thin film PV glazing towards nZEBs. TRPVG is a multifunctional PV glazing technology for buildings, which can generate electricity, clean itself, provide high thermal resistance and contribute to indoor thermal comfort by controlling solar thermal radiation penetration, visible light transmittance, UVC/UVA light and noise level in dBA. Three different configurations of TRPVG as shown in Figures 1–3 are proposed in this research for optical, acoustic and thermal comfort-related performance assessment. TRPVG have different layers for thermal insulation and electricity generation purposes. Energy generation is provided by semi-transparent a-Si PV cells. The cells are covered by a TiO_2 nano-coating to mitigate reflection losses via its AR feature and supply self-cleaning ability. The highly reflective property of low-e film returns the transmitted sunlight back on the a-Si PV cells resulting in secondary energy production. Argon layers give extra thermal resistance to the structure. PVC-U material at the edges prevents thermal bridging effects. Composite configuration enables effective control of solar thermal radiation and visible light transmittance as well as noise reduction. The entire thickness of each TRPVG sample is 28 mm, which is competitive with the conventional double glazed windows in market. Thanks to the latest developments in material and manufacturing processes, the current cost of TRPVG technology is ∼180€/m^2, and the lifetime is predicted to be 20 years.

3 EXPERIMENTAL PROCEDURE

In the experimental performance analysis of TiO_2 nano-coated thin film PV glazing, three samples are fabricated with the identical entire thickness and material properties, but with different design aspects. TRPVG samples are subjected to simultaneous outdoor and indoor tests for optical, acoustic and thermal insulation related performance assessment. Electricity production performance of each sample is also evaluated through indoor and outdoor tests. Indoor tests are conducted inside a standardized environmental chamber by using a solar simulator. The accuracy of the energy performance tests are verified through the outdoor tests under real operating conditions. Acoustic tests are carried out in a small test house constructed by particleboards with XPS insulation as shown in Figure 4.

Artificial noises are produced outside the test house, and the noise reduction across the TRPVG samples is measured. BENETECH GM1352 sound level metres are preferred for the noise reduction tests with an accuracy of ±1.5 dBA. A total of 25 different tests with various noise levels in dBA are conducted for a reliable and accurate performance evaluation.

Within the scope of the optical tests, UVC/UVA light absorption of TRPVG technologies is evaluated through outdoor tests under real operating conditions. EXTECH SDL470 UVA/UVC data logger is utilized for the said experiments. Solar radiation penetration across the samples is analysed via MEGGER PVM210

Figure 4. *Test house used for acoustic tests of TRPVG.*

power metres. Visible light control of the samples is also evaluated through TT TECNIC VC1010D digital lux metres. Temperature difference between internal and external glazing surfaces of TRPVG samples is a good indicator of thermal resistance. Temperature, heat flux and incoming solar intensity measurements are also tracked via DT85 16 channel universal input data logger from DataTaker company. For temperature measurements, Teflon coated K-type thermocouples are utilized from TEKON company. For heat flux measurements, HFS-3 thin film heat flux sensors from Omega Engineering, Inc. are used. Thermal resistance tests are performed via UT300 infrared thermometer. The measurements are repeated for every 15 minutes. Total uncertainty is calculated for each measurement, and it is determined to be below 2% for the worst case, which is sufficient for such an experimental analysis.

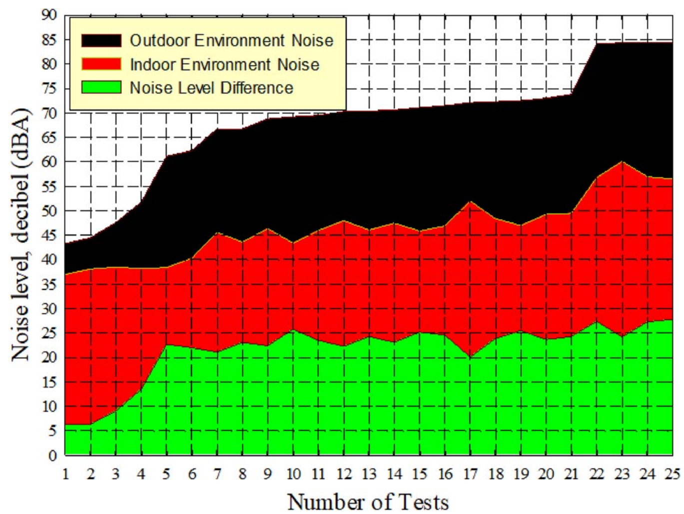

Figure 5. *Acoustic test results for Glass 3.*

4 RESULTS AND DISCUSSIONS

Demonstration of the test results start with the acoustic performance of TRPVG technology. Due to the identical material features, fabrication processes and similar multilayer sandwich structure, TRPVG samples show very similar acoustic performance. In this respect, noise reduction results are given for TRPVG-Ar16 (Glass 3) only as illustrated in Figure 5. The external noise in the tests is found to be in the range of 43.3–84.3 dBA. On the other hand, the said level for the indoor is measured to be in the range of 37.0–60.1 dBA. Noise reduction performance becomes much more sensible for the greater noise levels. For the best and the worst case, the noise absorption is found to be 37.3% and 14.4%, respectively. The average figure of 25 experiments is determined to be 30.9%, which is very promising.

The UVC light absorption, UVA light absorption, visible light control, solar radiation regulation and thermal resistance performance of Glass 1 are illustrated in Figures 6–10, respectively. It is understood from the results that Glass 1 is capable of blocking 100% of UVC and UVA light. Glass 1 is also successful in terms of visible light control. A total of 94.4% of incoming visible light is prevented to enter the living spaces. This is of vital importance especially for harsh climatic conditions to overcome the glaring effects occurring inside the buildings.

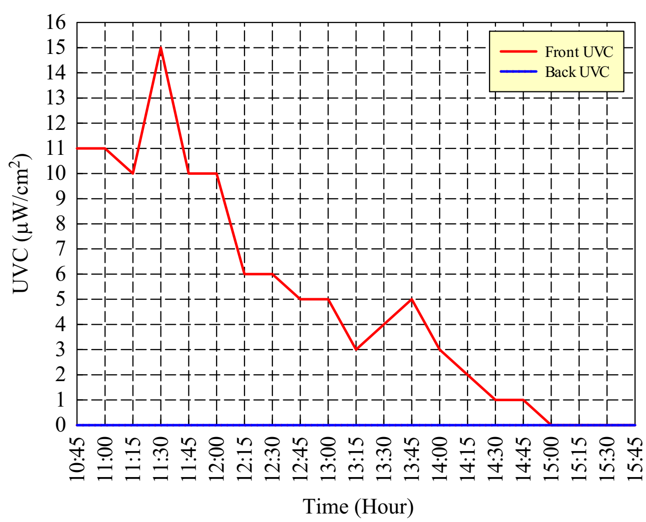

Figure 6. *UVC light absorption of Glass 1.*

Solar thermal radiation penetration through glazed areas is a handicap for cooling demands especially in hot climatic regions. The results reveal that Glass 1 is capable of blocking 93.5% of

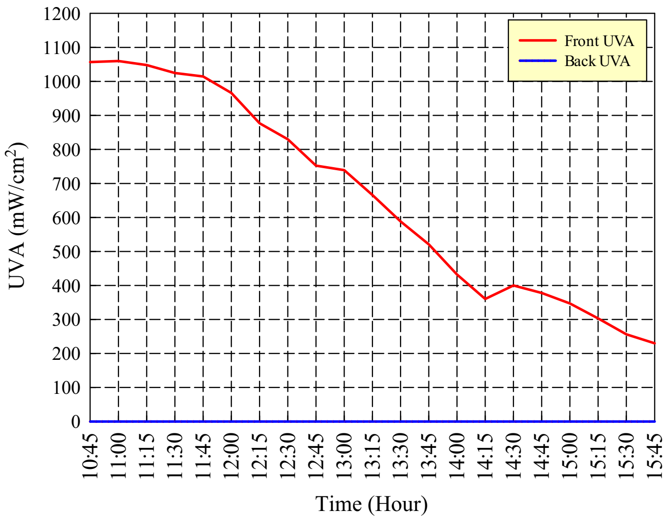

Figure 7. *UVA light absorption of Glass 1.*

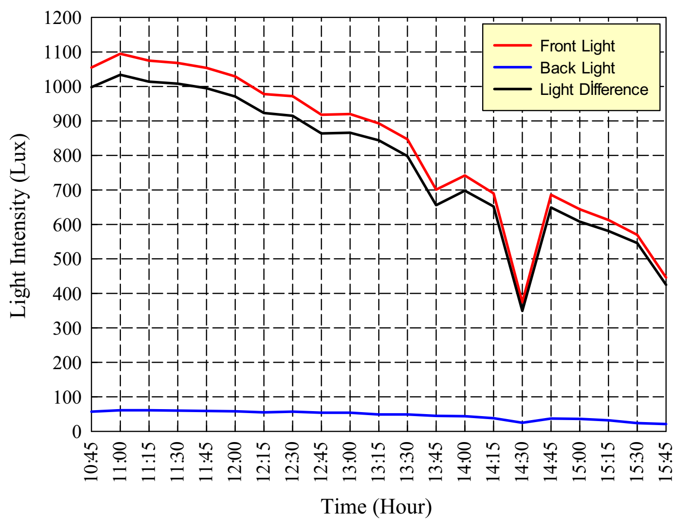

Figure 8. *Visible light control of Glass 1.*

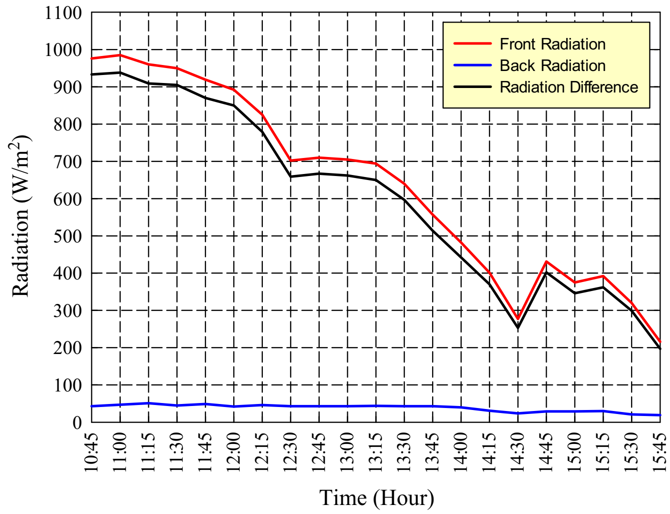

Figure 9. *Solar radiation regulation of Glass 1.*

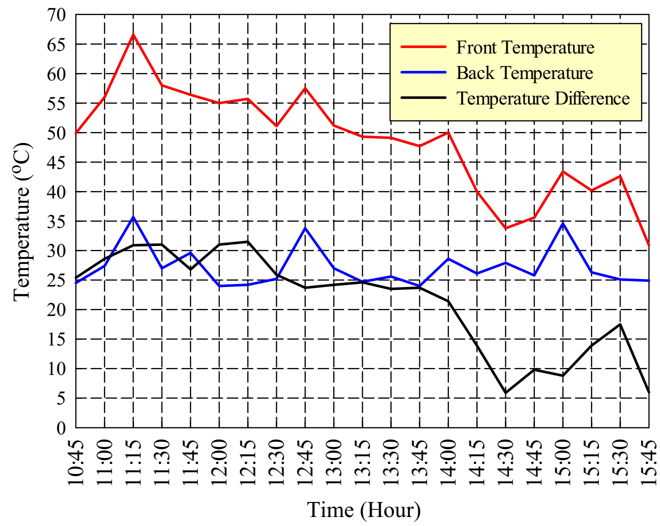

Figure 10. *Temperature difference of Glass 1.*

incoming solar radiation. Throughout the tests, the temperature difference between internal and glazing of Glass 1 is observed to be remarkable. The average temperature difference is noted to be 21.3°C, which is outstanding. The UVC light absorption, UVA light absorption, visible light control, solar radiation regulation and thermal resistance performance of Glass 2 are illustrated in Figures 11–15, respectively. It is observed that Glass 2 is also able to block 100% of UVC and UVA light. Glass 2 is also effective in terms of visible light control. A total of 88.9% of incoming visible light is prevented from reaching the indoor environment. Compared with Glass 1, slightly lower solar radiation is absorbed in Glass 2 with 90.9%. A similar case is observed for the temperature difference figures. The average temperature difference between internal and external glazing of Glass 2 is measured to be 19.9°C.

The UVC light absorption, UVA light absorption, visible light control, solar radiation regulation and thermal resistance performance of Glass 3 are illustrated in Figures 16–20, respectively. It is obtained that Glass 3 is also able to absorb 100% of UVC and UVA light. Glass 3 is also efficient in terms of visible light control. A total of 93.6% of incoming visible light is prevented through Glass 3. A total of 94.8% of solar thermal radiation is not allowed to enter the living spaces, which needs to be noted. The average temperature difference between internal and external glazing of Glass 3 is measured to be 21.7°C.

Some CFD attempts are also conducted as given in Figures 21 and 22 for Glass 1 and Glass 3, respectively. It is understood from the static contours of temperature that conductive effects are dominant in Glass 1, whereas convective effects start to take place in Glass 3 as a consequence of the increase in argon thickness. The U-value from the CFD research for Glass 1 and Glass 3 is determined to be 1.37 and 1.19 W/m^{2}K, respectively. The said figures are sufficient enough to meet the latest nZEB standards.

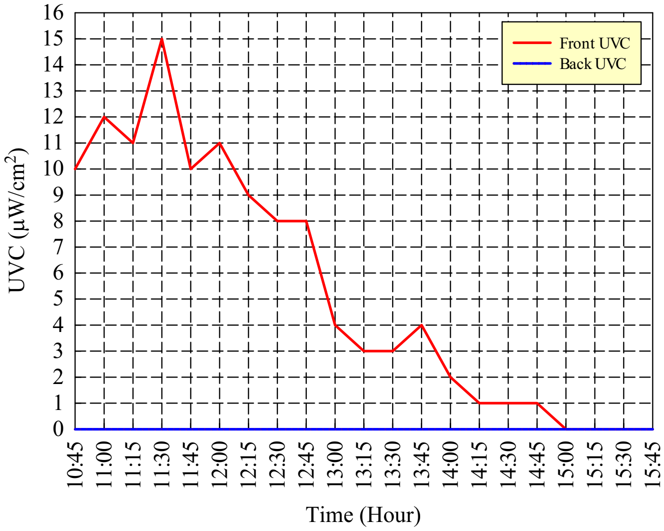

Figure 11. *UVC light absorption of Glass 2.*

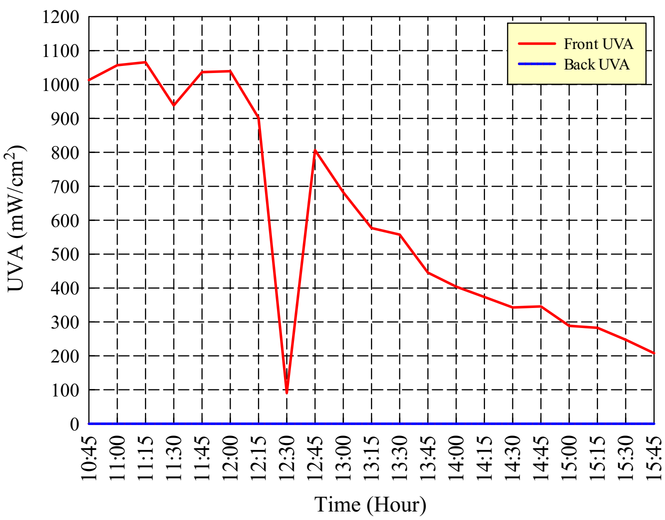

Figure 12. *UVA light absorption of Glass 2.*

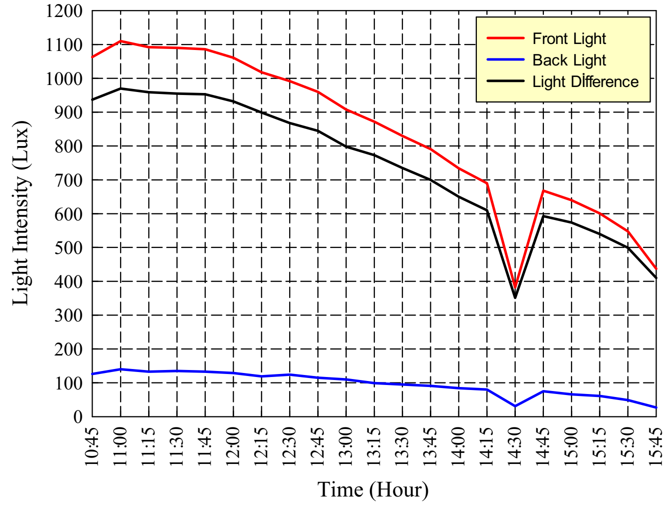

Figure 13. *Visible light control of Glass 2.*

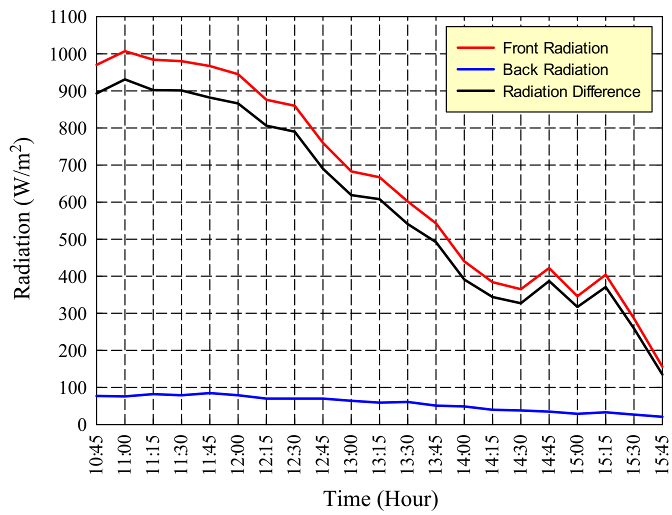

Figure 14. *Solar radiation regulation of Glass 2.*

By the way, it can be further concluded that the U-value of thin film PV glazing notably increases when the fraction of glass mass in total glazing rises, and Argon volume decreases.

It is also understood from the static contours of temperature inside the PV glazing samples that conductive effects dominate in Glass 1, which is desirable. However, U-value is still somewhat above the critical U-value. This is because of the developing thermal bridging effects by the increasing number of conductive glass panes between highly thermally resistive inert gas media. On the other hand, Glass 3 provides better thermal insulation performance compared with Glass 1, but not at predicted rate due to the enhanced buoyant effects inside the enclosure. By widening the Argon gap behind the PV cells, thermal resistance of the glazing rises up to a certain value, and then gets worse. However, the U-value of 1.19 W/m^2K is a very promising U-value for building envelopes, and it is a better performance figure than that of Argon filled triple glazed windows with an entire thickness of 36 mm. Moreover, it is a remarkably lighter building element compared with other conventional glazing technologies. Thus, it is very appropriate for the energy-efficient retrofit applications in existing buildings and for the newly built structures.

The self-cleaning feature and visual quality of thin film PV glazing samples are also evaluated within the scope of this research as shown in Figure 23. Artificial dust accumulation is provided on the sample surfaces, and then water spray test is implemented on the PV cells, as well as TGW. The results reveal that a superior self-cleaning behaviour is provided by TiO_2 nano-coated thin film PV glazing, whereas partly dirty areas are noticed on TGW with notable water clings. Conventional PV modules and PV glazing systems generate less electricity due to the aforesaid water clings since they adversely affect the solar absorption utilized in energy conversion process [27]. They also facilitate the dirt deposition and mould growth on the cell surfaces later on.

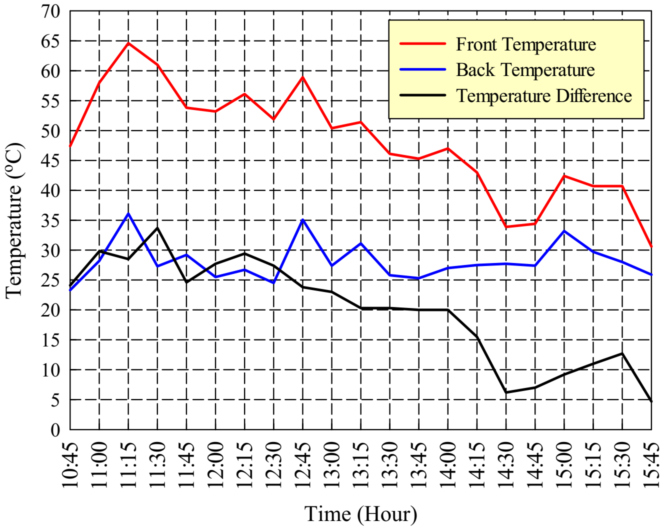

Figure 15. *Temperature difference of Glass 2.*

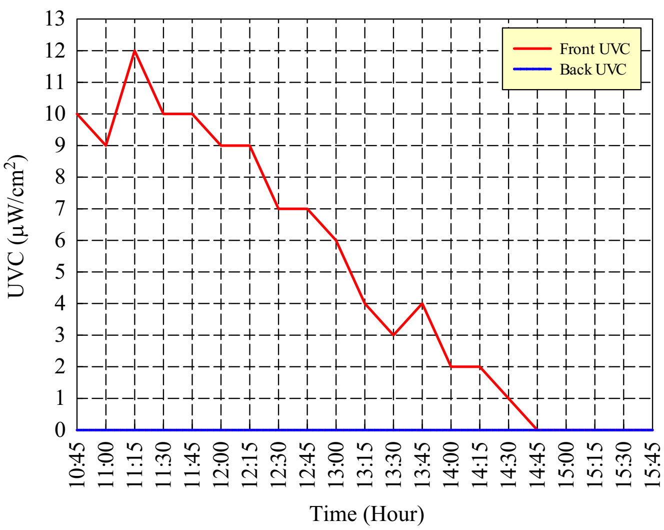

Figure 16. *UVC light absorption of Glass 3.*

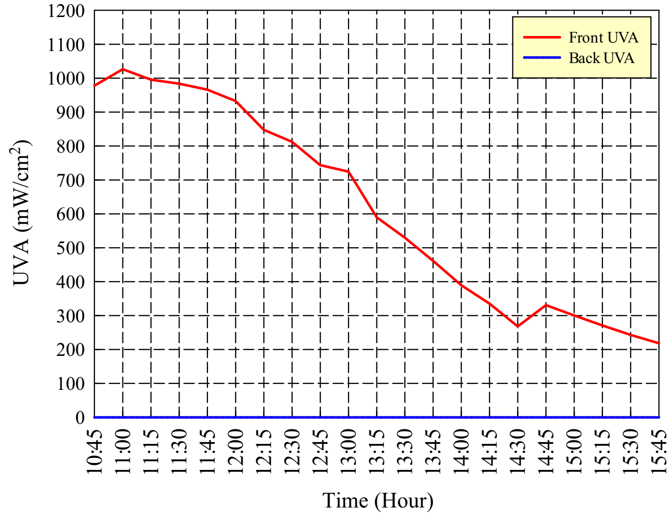

Figure 17. *UVA light absorption of Glass 3.*

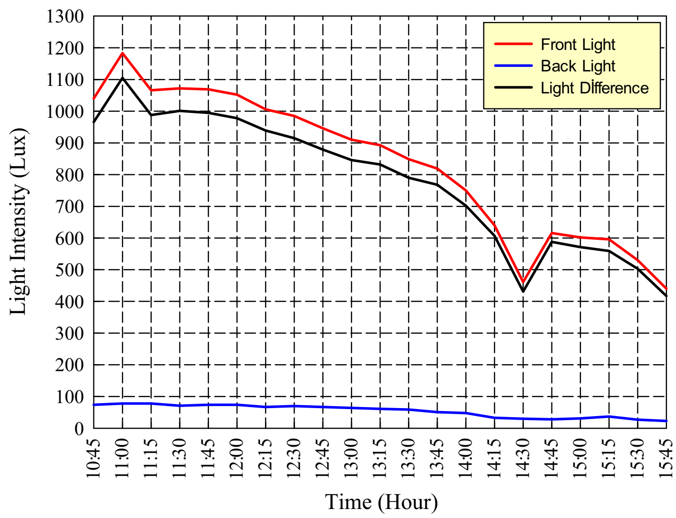

Figure 18. *Visible light control of Glass 3.*

Electricity production performance of TiO_2 nano-coated thin film PV glazing is also investigated in this study as shown in Figure 24 for the sample of Glass 3. The tests are carried out for both simulated and real time conditions as illustrated. For the standard test conditions (G = 1000 W/m² and Tc = 25°C), Glass 3 is found to produce 102.6 W electrical power (*P*) per square metre of PV module area. The solar simulator tests are also conducted for 200, 400, 600 and 800 W/m² of solar intensities, and the corresponding *P* values are observed to be 20.7, 40.1, 62.3 and 81.2 W/m², respectively. A linear regression model with a correlation coefficient (*R*) of 0.9995 is developed for the interaction between the power output and the solar intensity as follows:

$$P = -0.12 + 0.1025G. \quad (1)$$

The accuracy of the solar simulator tests are also verified by the real-time outdoor tests conducted in the winter season of 2020 in Zihni Derin Campus, Rize. It is clear from the findings that power output figures of outdoor tests are in good accordance with the simulation results. Energy conversion efficiency of a-Si PV cells is found to be 10.26%. In previous works, a-Si PV module efficiency was reported to be 8.45% [13]. The improved design of thin film PV glazing via TiO_2 nano-coating gives better AR performance, and enhanced TCO coatings yielding better secondary power generation corresponds to ~21.4% improvement in overall module efficiency. The aforesaid performance figures and thermal resistance values clearly illustrate that the novel TRPVG design is an ideal retrofit material for building envelopes, and this unique building element can provide energy to the built environment greater than that of being lost across the glazing.

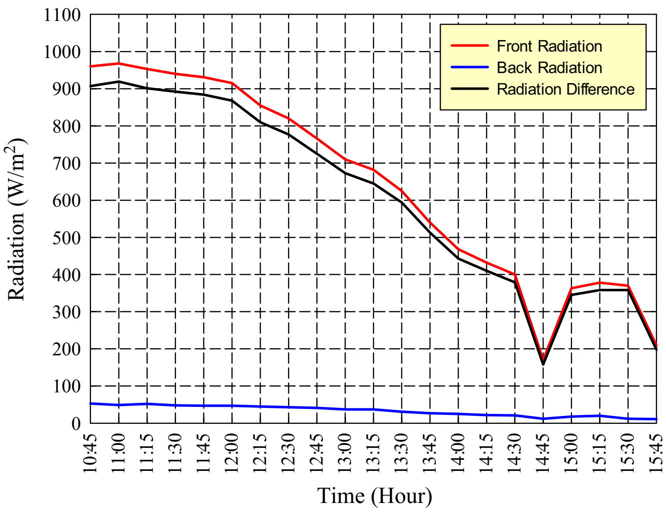

Figure 19. *Solar radiation regulation of Glass 3.*

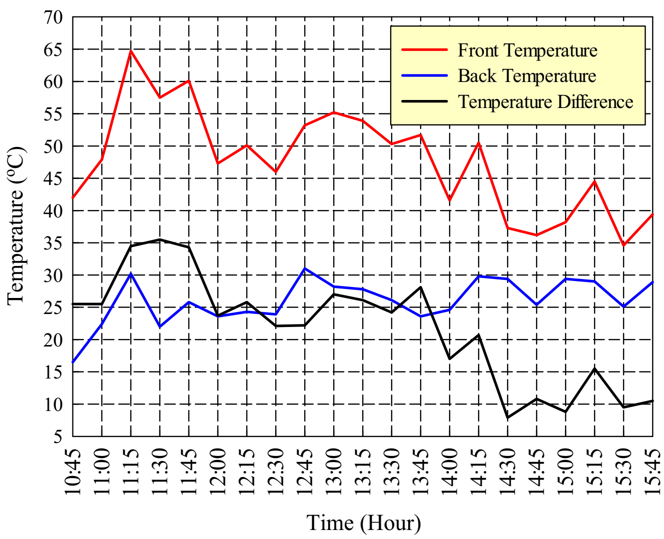

Figure 20. *Temperature difference of Glass 3.*

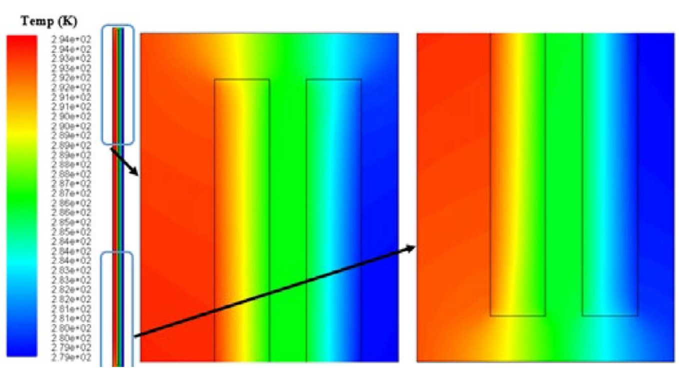

Figure 21. *CFD analysis of Glass 1.*

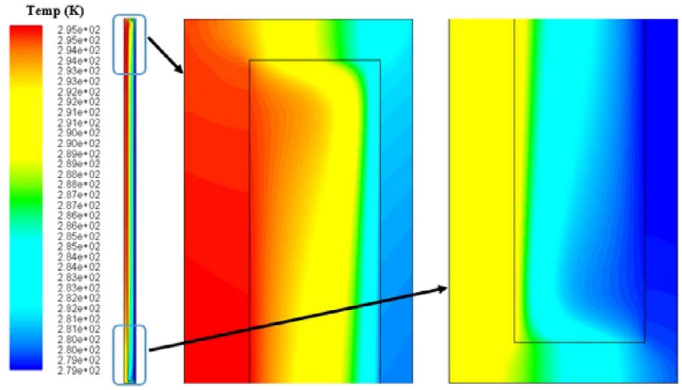

Figure 22. *CFD analysis of Glass 3.*

Figure 23. *Visual quality of Glass 1 and Glass 3 in comparison with commercial air filled triple glazed window (TGW) and self-cleaning feature of Glass 3 through water spray test.*

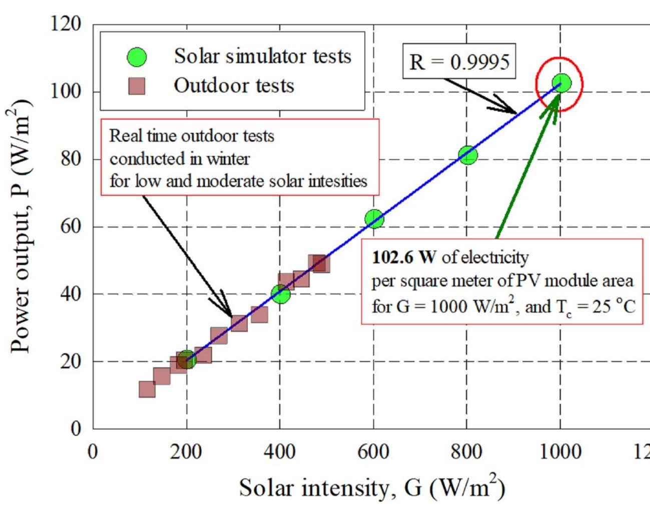

Figure 24. *Electrical power output of Glass 3 through solar simulator and outdoor tests.*

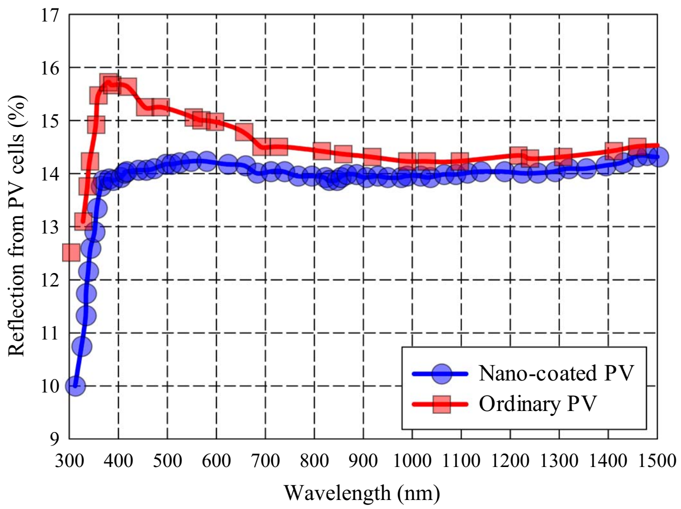

Figure 25. *Mitigation of reflection losses from PV cells via TiO_2 nano-coating [15].*

It is also useful to underline that AR performance is of vital importance for power output of PV cells. In this respect, several independent tests are carried out to evaluate the rate of enhancement with TiO_2 nano-coated thin film PV glazing. Under standard test conditions, ordinary PV yields 95.4 W electricity, whereas it is 102.6 W with nano-coated PV. In addition, reflection from ordinary and nano-coated PV is given as a function of wavelength as shown in Figure 25 [15]. In further works, TRPVG technology will be integrated into highly thermally resistive glazing systems such as aerogel [28] and vacuum glazing [29] in order to develop multifunctional fenestration products with superior thermal insulation feature and notable clean energy generation potential.

TRPVG is a slim, eco-friendly and low-cost glazing technology. The total thickness of TRPVG samples developed within the scope of this research is 28 mm, which is competitive with the well-known fenestration products in market. Thanks to the latest developments in material and manufacturing technologies, the cost of TRPVG is about 180€/m^2, and the lifetime is projected to be 20 years. The current cost figures of TRPVG are highly competitive with the air or argon filled double glazed windows in Europe. Besides its cost-effectiveness, thanks to the multifunctional features of the product such as thermal insulation, acoustic and optical control, self-cleaning, etc., TRPVG has a great potential to minimize building-oriented energy consumption at global scale [30].

5 CONCLUSIONS

Within the scope of this research, TRPVG technology is introduced, and for three different configurations, UVC/UVA absorption, noise reduction, thermal insulation, visible light and solar radiation control performance are evaluated through comprehensive experimental methodology. The results reveal that TRPVG technology is capable of blocking UVC and UVA light completely. More than 90% of visible light and solar thermal radiation is mitigated through the samples. An average temperature difference over 20°C is achieved between internal and external glazing surfaces. In previous works, thin film PV glazing efficiency had been reported to be 8.45%. Through the novel design having enhanced TiO_2 and TCO nano-coating properties, this figure is enhanced to 10.26% in this research, which is noteworthy. At STCs, Glass 3 is found to produce 102.6 W electrical power per square metre of PV module area. AR behaviour is improved, and dust accumulation, as well as water clings, is prevented in the novel TRPVG design, which yields to better power generation. Hot box tests reveal that the U-value of Glass 3 is 1.19 W/m^{2}K, which is sufficient for latest nZEB code requirements, and competitive with the Argon filled TGW. TRPVG is a slim glazing product and ideal for both energy-efficient retrofit applications and newly structured buildings.

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