



## HEAT INSULATIVE PHOTOVOLTAIC GLASS: OPTICAL, ACOUSTIC, THERMAL AND ELECTRICITY PRODUCTION PERFORMANCE

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### ABSTRACT

In this communication, a unique photovoltaic (PV) glass concept, heat insulative PV glass (TRPVG), is introduced, and its energy production, thermal, optical and acoustic performance parameters are experimentally investigated. In the previous literature works, multifunctional benefits of TRPVG as a novel building element such as high thermal resistance, self-cleaning and competitive cost are addressed. Within the scope of the present research, absorption of UVC and UVA part of incoming sunlight, control of visible light transmittance and solar thermal radiation, reduction of different noise levels, electricity production performance and temperature difference throughout the solar glass are comprehensively analysed. The tests are conducted in April 2019 for a specific sample (TRPVG-Ar16) in which argon gas fills a 16 mm thick gap at the rear of PV cells for thermal resistance, and a novel low-e coated thermally resistive glass is reinforced behind the structure. The results reveal that TRPVG-Ar16 is a very good thermal insulator at first glance. The average temperature difference between front and back surfaces is determined to be 16.59 °C, which is promising and a strong function of incoming solar radiation. The average solar radiation is measured to be 527.6 W/m<sup>2</sup> during the test period, and the aforesaid value behind the PV glazing is found to be 41.6 W/m<sup>2</sup>. A similar tendency is observed for the visible light transmittance. Average light intensity measurements from the front and back of TRPVG-Ar16 are reported to be 622.3 and 75.4 lx, respectively. UVC and UVA measurements reveal that the novel TRPVG-Ar16 technology is capable of blocking 100% of UV part of incoming sunlight, which needs to be noted. The tests carried out for various noise levels also demonstrate that TRPVG-Ar16 is a promising noise absorber. Outside the simulation environment, the noise level is measured to be 84.3 dBA while it is 56.5 dBA for the indoor, which corresponds to about 32.9% reduction in dBA value.

**Keywords:** TRPVG, PV glass, Optical and acoustic parameters, UVC and VA blocking, Light intensity

## ISI YALITIMLI FOTOVOLTAİK CAM: OPTİK, AKUSTİK, ISIL VE ELEKTRİK ÜRETİM PERFORMANSI

### ÖZET

Bu çalışmada, benzersiz bir fotovoltaik (PV) cam konsepti, ısı yalıtımlı PV cam (TRPVG), tanıtılmakta ve enerji üretimi, ısı, optik ve akustik performans parametreleri deneysel olarak incelenmektedir. Literatürde yapılan çalışmalarda, yenilikçi bir yapı elemanı olarak TRPVG'nin yüksek ısı direnç, kendi kendini temizleyebilme ve rekabetçi maliyet gibi çok fonksiyonlu faydalarına işaret edilmektedir. Mevcut araştırmanın kapsamı içerisinde, gelen güneş ışığının UVC ve UVA kısımlarının soğurulması, görünür ışık geçirgenliği ve ısı radyasyonunun kontrolü, farklı gürültü seviyelerinin azaltılması, elektrik üretim performansı ve solar cam boyunca sıcaklık farkı kapsamlı olarak analiz edilmektedir. Testler Nisan 2019'da ısı direnç için argon gazının PV hücrelerin arkasında 16 mm kalınlığındaki bir boşluğu doldurduğu ve konstrüksiyonun gerisinde düşük emisyonlu kaplamalı ısı dirençli yenilikçi bir cam ile desteklenen özellikli bir numune için (TRPVG-Ar16) yapılmıştır. Sonuçlar ilk bakışta TRPVG-Ar16'nın iyi bir ısı yalıtıcı olduğunu göstermiştir. Ön ve arka yüzeyler arasındaki ortalama sıcaklık farkı gelen güneş ışınımının güçlü bir fonksiyonu olarak 16.59 °C ve ümit verici bulunmuştur. Test süresi boyunca ortalama güneş ışınımı 527.6 W/m<sup>2</sup> olarak ölçülmüş ve PV camın arkasında ilgili değer 41.6 W/m<sup>2</sup> olarak bulunmuştur. Benzer bir eğilim görünür ışık geçirgenliği için gözlenmiştir. TRPVG-Ar16'nın ön ve arkasındaki ortalama ışık yoğunluğu sırasıyla 622.3 ve 75.4 lx olarak rapor edilmiştir. UVC ve UVA ölçümlerine göre TRPVG-Ar16, gelen güneş ışığının UV kısmının %100'ünü bloke etme kapasitesine sahip olup bu durum dikkat çekicidir. Farklı gürültü seviyelerinde yürütülen testler ayrıca göstermektedir ki TRPVG-Ar16 ümit verici bir gürültü emicidir. Simülasyon ortamının dışında gürültü seviyesi 84.3 dBA olarak ölçülürken, iç ortam için bu değer 56.5 dBA'dır ki bu durum dBA değerinde yaklaşık %32.9'lük bir azalmaya karşılık gelmektedir.

**Anahtar Kelimeler:** TRPVG, PV cam, Optik ve akustik parametreler, UVC ve UVA tutma, Işık yoğunluğu

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## 1. INTRODUCTION

Total energy consumption figures in today's world push many countries for rechecking their energy policies and carrying out precise sectoral energy consumption analyses. Recent reports clearly indicate that buildings stand as the most crucial sector for today and future since they account for about 40% of global energy use [1]. At first glance, the crucial role of building sector in total energy use can be ascribed to the insufficient thermal insulation features of current building materials [2]. Further investigations reveal that glazed areas among the aforesaid building elements are considered as the weakest ring in most cases due to deficient total heat loss coefficient (U-value) values of existing window products [3]. As an example, double glazed windows, which currently dominate the fenestration market, have a U-value varying from 1.80 to 2.70 W/m<sup>2</sup>K depending on the inert gas inside, and this range is quite far beyond the nearly zero energy building (NZEB) or low/zero carbon building (L/ZCB) targets [4]. As a consequence of this, there is an inclining towards innovative glass technologies worldwide such as aerogel glazing, vacuum glazing, transparent insulation material (TIM) glazing, phase change material (PCM) glazing and PV glazing to mitigate building oriented energy consumption figures. Among the available glazing technologies, PV glazing currently arouses too much interest because of the feature of clean energy generation [5].

PV glazing is reported to be a promising building element for cost-effective restoration of existing dwellings. Heating and cooling demand of houses can be considerably mitigated by the help of PV glass systems [6]. However, current heat loss coefficients of PV glazing units is not promising especially when they are not integrated with a thermally resistive medium. The inadequate heat insulation ability of PV glass systems can be attributed to poor material properties of PV cells, edge seals and glass panes [7]. Insufficient U-values of PV glazing products is still a challenge prior to commercialisation of this technology. Therefore, several attempts are in progress to enhance thermal resistance, optical and acoustic performance parameters of PV glazing systems. For instance, semi-transparent amorphous silicon PV glazing is integrated with vacuum medium by Ghosh et al. [8], and solar factor and U-value of the sample are experimentally evaluated in comparison with the PV double glazing. The solar factor is found to be 0.42 and the U-value 0.80 W/m<sup>2</sup>K, which corresponds to 46 and 66% reduction in solar factor and U-value, respectively compared to PV double glazing. In another research, it is noted that low-e coating and inert gas integration into PV glazing systems successfully mitigate the solar heat gain coefficient [9]. Efficient prevention of thermal radiation from entering into indoor environment is of crucial significance for reducing cooling demand notably in hot weather conditions [10]. From this point of view, PV and PV/Thermal glazing systems are structured on facades and roofs [11] as an alternative and additional envelope element [12].

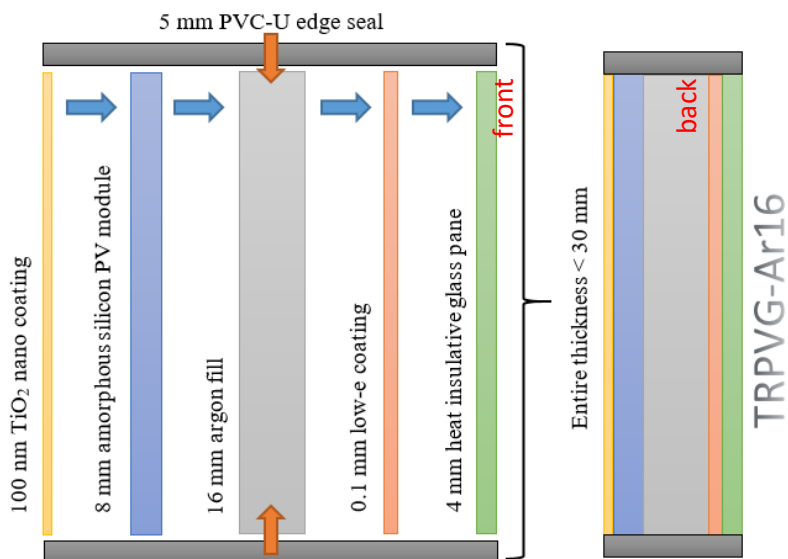
When the recent literature on PV glazing systems is gone through, it can be easily asserted that the majority of research focuses on the improvement of thermal resistance features, and optical and acoustic parameters are rarely studied. Cuce et al. [13] experimentally investigate the UV absorption, visible light and solar radiation control, self-cleaning and energy generation potential of a specific PV glazing technology. The results reveal that the product is capable of absorbing 100% of UV light. In addition, 95% of thermal radiation is prevented, which is crucial in terms of reducing cooling demand in summer. PV glazing structures are also found to be effective in terms of shading performance. Visible light transmittance of some commercial products in market is about 0.10, which proves this statement [14]. In another research, the aforesaid optical values are justified for solar facade applications [15].

It can be summarised through the findings of literature analysis that there is a consensus on the suitability of PV glass units as a cost-effective restoration option toward NZEB and L/ZCB. However, a comprehensive assessment of optical, acoustic and thermal performance of PV glass technology is already missing. This research aims at introducing a unique PV glass product named TRPVG, and then presenting the abovementioned performance parameters through an elaborative experimental research. From this point of view, UVC (ultraviolet C) and UVA (ultraviolet A) absorption of incoming sunlight, visible light and solar thermal radiation control, noise reduction, and temperature difference throughout the solar glass are investigated in detail for TRPVG technology.

## 2. HEAT INSULATIVE PV GLASS

TRPVG is a unique type of PV glass, which is designed, manufactured and experimentally investigated as part of an R&D project financially supported by TÜBİTAK. In this research, a specific sample of TRPVG technology, TRPVG-Ar16, is experimentally analysed from the standpoint of thermal, electricity production, acoustic and optical parameters. Structural details of TRPVG-Ar16 are depicted in Figure 1. TRPVG-Ar16 brings many novelties into PV glazing industry in the way of cost, heat insulation and electricity production performance, acoustic, optical and self-cleaning features and energy saving performance.

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**Figure 1.** Structural properties of novel heat insulative PV glass technology

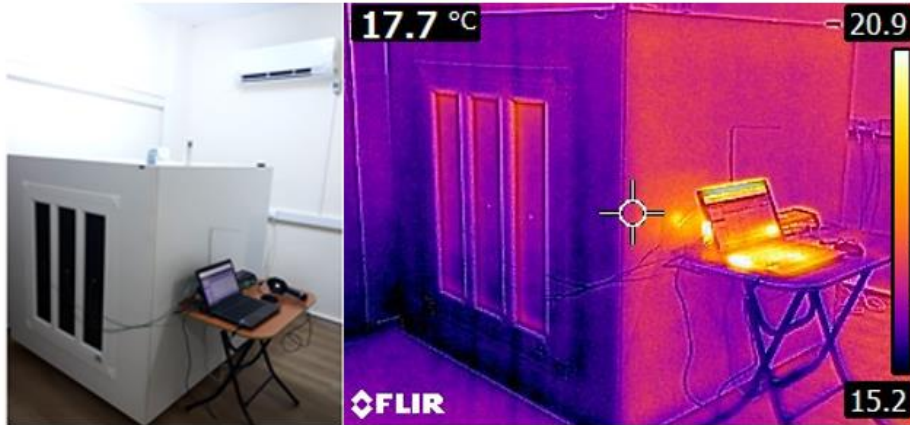
TRPVG consists of amorphous silicon solar cells and insulative layers at the rear with a basic explanation. The said amorphous silicon solar cells have a semi-transparent feature, and they are coated with a TiO<sub>2</sub> nano film, which both reduces reflection losses and enables the solar cells to clean themselves without human requirement. The dominant thermal resistance impact is supplied by 16 mm thick argon layer. This inert gas medium is supported by a low-e coated glass, which has a remarkably lower thermal conductivity than conventional window panes. The reflective nature of low-e film returns the transmitted sunlight on the PV surface again yielding to additional energy production. Thermal conductivity of a-Si PV cells, argon, low-e coating and thermally resistive window pane are given to be 1.50, 0.0158, 1.20 and 0.96 W/mK, respectively. Various edge seal materials are utilised in PV glazing products. For TRPVG-Ar16, PVC-U material is preferred owing to its low thermal conductivity (0.19 W/mK), low-cost and easy-to-implement feature. The entire thickness of novel PV glass is below 30 mm, that is accepted lightweight and slim enough for cost-effective restoration applications. The current unit cost of TRPVG-Ar16 is enhanced from 200 to about 185 €/m<sup>2</sup>, that is competitive with the conventional multilayer glazing products.

### 3. EXPERIMENTAL

Semi-transparent PV glass technology named TRPVG is designed, structured and experimentally analysed as part of an R&D project financially supported by TÜBİTAK. Several samples of TRPVG are experimentally analysed throughout the work packages, however in this specific research, a single sample is proposed and examined in the way of optical, electricity production, acoustic and thermal resistance performance. The tests are conducted for both indoor and outdoor conditions. For the indoor tests, a small building sample is constructed as shown in Figure 2, and one side of the test house is retrofitted with TRPVG products whereas the door is located on the opposite. In the construction of the test house, 10 cm thick foams from XPS (extruded polystyrene) material are fixed between two 2 cm thick particleboards. Through repetitive noise control tests, acoustic features of TRPVG-Ar16 is experimentally evaluated. BENETECH GM1352 sound level meters are utilised for the acoustic tests with an accuracy of  $\pm 1.5$  dBA. Different noise levels are artificially produced in outdoor environment, and the reduction of noise via TRPVG-Ar16 for the indoor conditions is specified through 10 independent tests.

UVC and UVA measurements are carried out under real operating conditions at Zihni Derin Campus of Recep Tayyip Erdogan University. EXTECH SDL470 UVA/UVC data logger is used for the aforesaid tests. Similarly, thermal radiation control of TRPVG-Ar16 is investigated in outdoor conditions via MEGGER PVM210 power meter. Visible light transmittance is evaluated through TT TECNIC VC1010D digital lux meter. Temperature difference achieved across the PV glazing is determined by UT300 infrared thermometer. The measurements are conducted for every 15 minutes from the front and back surfaces of TRPVG-Ar16.

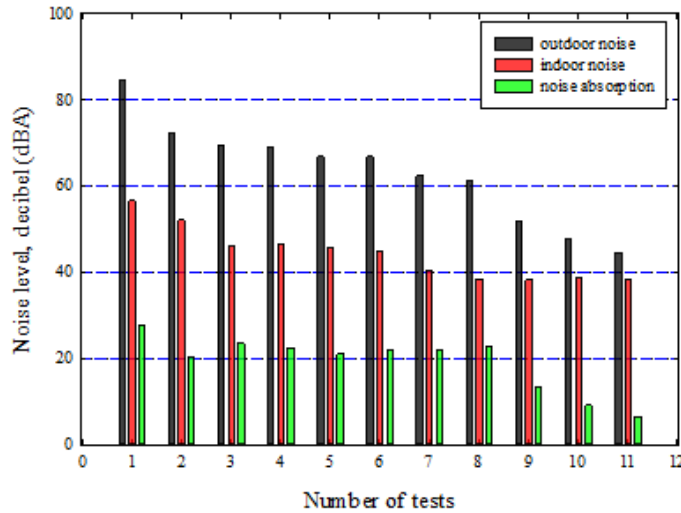
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**Figure 2.** The test house which is constructed for the indoor thermal insulation and acoustic tests of PV glass

#### 4. RESULTS AND DISCUSSIONS

The presenting of the test results begins with the noise control feature of TRPVG-Ar16 technology as shown in Figure 3 through 10 independent tests carried out for different noise levels. The sensors are positioned facing one another as depicted in Figure 4, and the noise levels are measured simultaneously for steady-state conditions. The outdoor noise level is found to vary in the range of 44.5-84.3 dBA. On the other hand, noise level for the indoor conditions is observed to be in the range of 38.1-56.5 dBA. For the greater noise levels, noise absorption feature becomes much more noticeable since the absorbed noise band notably increases. The noise reduction is found to be 14.3 and 37.1% for the worst and the best case, respectively. The average noise reduction performance of TRPVG-Ar16 is determined to be 29.5% for the said 10 independent tests. The calculations are conducted over average figures.

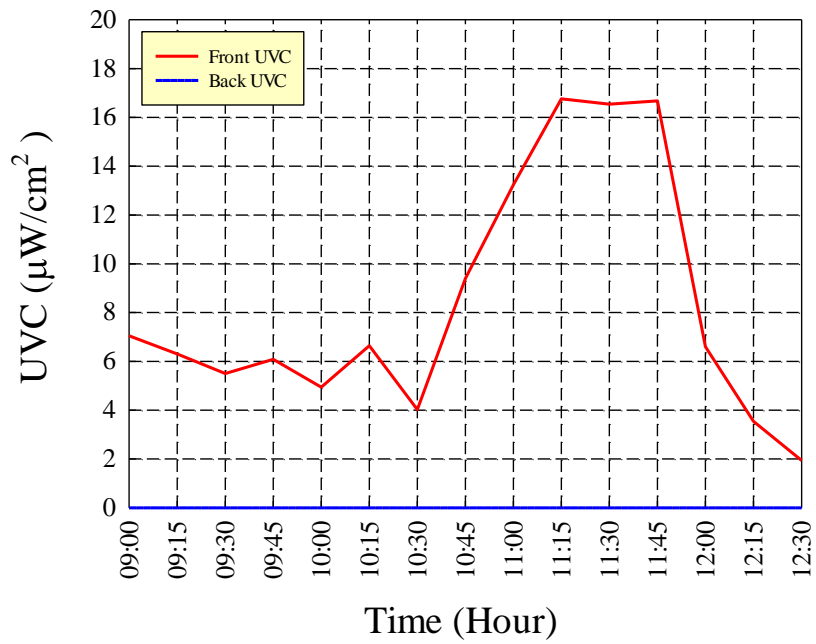


**Figure 3.** Noise absorption performance of TRPVG-Ar16 product through different tests

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**Figure 4.** Acoustic tests of TRPVG-Ar16 which are conducted simultaneously from indoor and outdoor

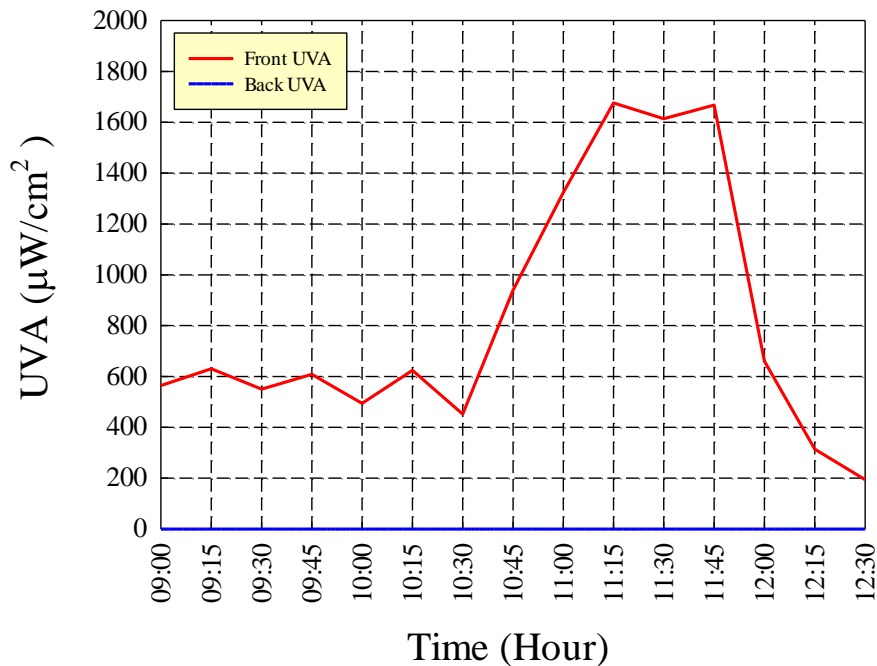


**Figure 5.** UVC absorption tests of TRPVG-Ar16 under real operating conditions

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UVC and UVA measurements performed within the scope of this research are of vital importance because of clarifying some important points as well as presenting the UV absorption performance of TRPVG-Ar16. The UVC light, which has a wavelength in the range of 100-290 nm, is the most dangerous UV light in terms of human health. This light is assumed to be absorbed completely by the ozone layer. However, it is understood from the outdoor tests that the UVC light is noticeable although the level can be considered negligible. The good point is that TRPVG-Ar16 is capable of blocking 100% of UVC light as illustrated in Figure 5.

UVA light has a wavelength range from 320 to 400 nm, and it accounts for about 95% of UV light reaching the surface by passing the atmosphere. Due to the wavelength, it is also known as black light. UVA is considered as the safest spectra of UV light. The absorption of UVA across TRPVG-Ar16 is given in Figure 6. It is observed from the results that the maximum UVA intensity is observed to be  $1676 \mu\text{W}/\text{cm}^2$ . TRPVG-Ar16 absorbs the full part of incoming UVA light as depicted.



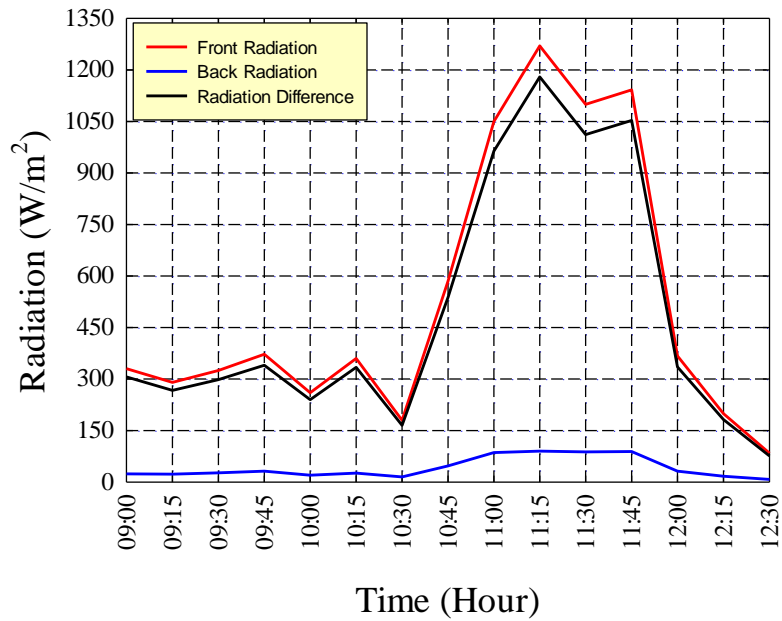
**Figure 6.** UVA absorption tests of TRPVG-Ar16 under real operating conditions

Effective control of solar thermal radiation is significant especially in extremely hot weather conditions because of its notable impact on reducing cooling demand of buildings. Penetration of thermal radiation across the PV glazing is also evaluated in this research as shown in Figure 7. It is observed that 91.9% of incoming solar radiation is prevented from transmitting through TRPVG-Ar16, which is quite significant for cooling demand and thermal comfort parameters. A similar tendency is achieved for visible light transmission figures. Light intensity values play a notable role in thermal comfort parameters especially in severe summer conditions like in the Middle East. The results from the visible light penetration tests reveal that TRPVG-Ar16 is also successful in controlling the light intensity. About 88.1% of incoming visible light is reduced via TRPVG-Ar16 sample as depicted in Figure 8. Both solar radiation and visible light control performance are conducted through the average data.

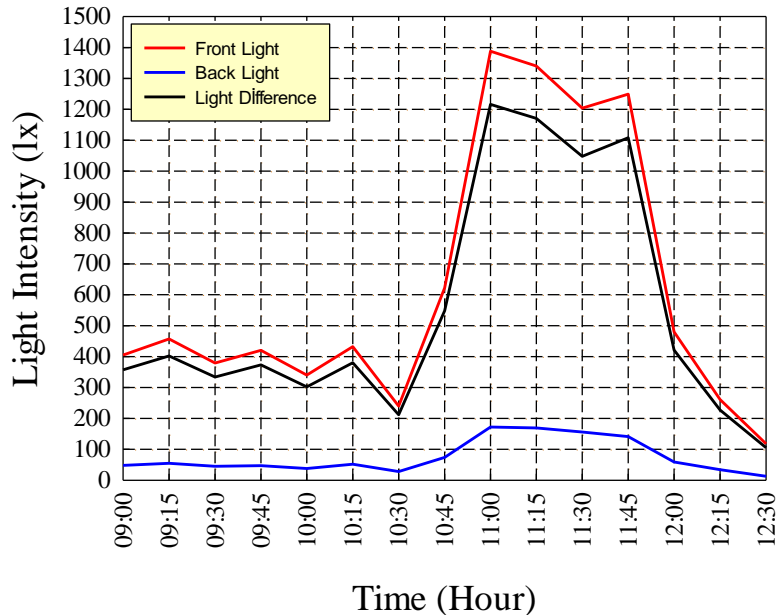
Temperature difference across a glazing material gives an idea about the thermal resistance of the said building element against heat losses. From this point of view, inner and outer glass temperatures of TRPVG-Ar16 are determined as a function of time. As it is depicted in Figure 9, TRPVG-Ar16 is an effective thermally resistive building material since sensible temperature differences across the PV glazing are achieved in the outdoor tests. Temperature difference is found to be in the range of 6.1-36.5 °C depending on time. Maximum difference in temperature between inner and outer surfaces is observed during the noon time (11:45am) as expected with 36.5 °C. Even in the earlier hours of the day, the average temperature difference is determined to be 10.7 °C, which is promising.

Through the experimental results, it can be easily asserted that TRPVG-Ar16 is an appropriate retrofit solution for existing buildings toward NZEB and L/ZCB standards. The entire width of TRPVG-Ar16 is below 30 mm, and it is slim and lightweight enough when compared to the conventional multilayer glazing systems. Current product cost of novel PV glass is about 185 €/m<sup>2</sup>, and this figure is competitive with the commercial fenestration products in market.

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**Figure 7.** Radiation absorption tests of TRPVG-Ar16 under real operating conditions



**Figure 8.** Visible light penetration tests of TRPVG-Ar16 under real operating conditions

TRPVG-Ar16 is found to be ideal for any type of buildings in terms of acoustic, optical and thermal resistance performance. Recent hot box co-heating tests indicate that the product has a heat loss coefficient of 1.135 W/m<sup>2</sup>K, which is competitive with even vacuum glazing products. The said U-value is calculated based on a standardised hot box testing method. Owing to a special TiO<sub>2</sub> nano coating on the surface of PV cells, TRPVG-Ar16 rejects excessive heat and provides an effective self-cleaning. For the standard test conditions, which is identified as 25 °C PV cell temperature and 1000 W/m<sup>2</sup> solar radiation, the product is capable of producing electricity over 100 W. Owing to the multiple benefits of this novel PV glass technology, existing buildings and new-built structures are predicted to consider TRPVG-Ar16 as a facade or roof material in the near future. TRPVG-Ar16 is

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also eco-friendly as it provides a remarkable energy saving potential to the buildings and mitigates fossil fuel based greenhouse gas emissions.

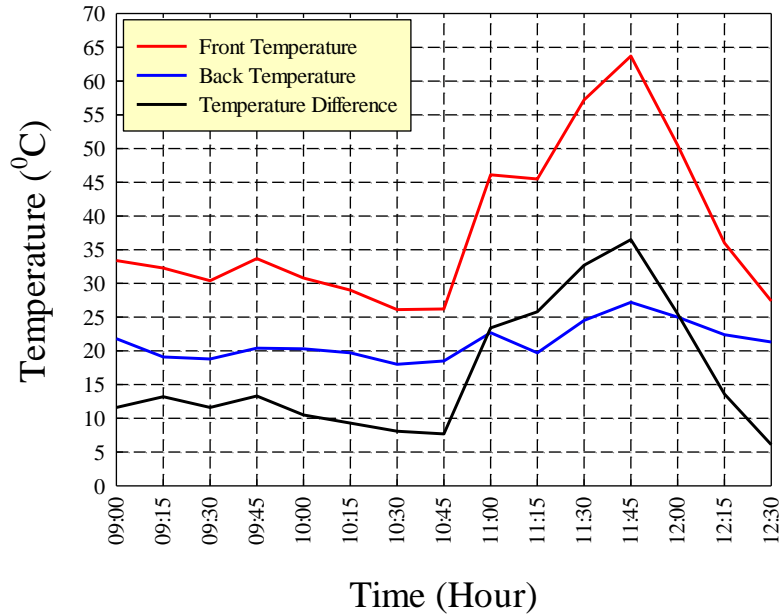


Figure 9. Thermal resistance tests of TRPVG-Ar16 under real operating conditions

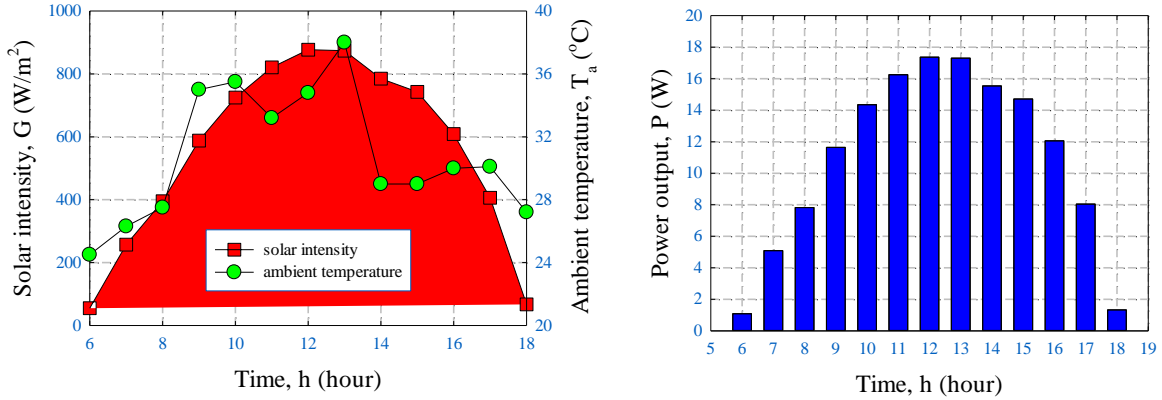


Figure 10. Electricity production performance of TRPVG-Ar16 for a specific whole day test

Electricity production performance of TRPVG-Ar16 is also evaluated in this research for a typical whole day test in July 2019 from 6am in the early morning to 6pm in the evening. The variations of ambient temperature and solar intensity during the test day are illustrated in Figure 10. In the same plot, electricity production values for each hour are depicted. The results reveal that 143.59 W electrical power can be achieved from a unit area of 0.198 m<sup>2</sup>. This figure corresponds to an electrical power output of 725.2 W from per m<sup>2</sup>. Incoming available radiative power from sun is measured to be 7202 W. In other words, for standard test conditions, novel PV glass is found to produce 100.69 W electrical power, which needs to be underlined.

### 5. CONCLUSIONS

In the present paper, a successful solar glass technology named TRPVG-Ar16 is proposed, and it is analyzed experimentally in the way of electricity production, acoustic, optical and thermal resistance performance. TRPVG-Ar16 differs from commercial fenestration products in terms of several points like notable heat insulation ability at a slim thickness, renewable energy production potential, free of charge cleaning, acoustic, optical and energy saving features. This specific study focuses on the



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optical, acoustic and thermal insulation performance through an experimental methodology. Following bullet points are derived from the research:

- Novel PV glass is a good sound insulator for buildings. The experiments conducted in the test house reveal that a promising noise reduction, 14.3% for the worst case and 37.1% for the best case, is achieved via this novel PV glazing material.
- TRPVG-Ar16 is capable of absorbing 100% of UVC and UVA light. This feature is of vital importance not only for health and thermal comfort of residents but also for the lifetime of household items like furniture.
- Effective control of solar thermal radiation is significant for cooling demand of buildings. 91.9% of incoming solar radiation is found to be blocked through TRPVG-Ar16.
- Visible light transmittance is also a crucial performance parameter regarding fenestration products. Especially in harsh climatic conditions like in the Middle East, thermal comfort in indoor conditions is considerably affected by high light intensity levels. TRPVG-Ar16 is observed to prevent 88.1% of visible light from entering indoor environment.
- TRPVG-Ar16 is also a good thermal insulator. The temperature difference throughout the novel PV glass is determined to be in the range of 6.1-36.5 °C, which is promising.
- For readers' interest, current experimental U-value of TRPVG-Ar16 is 1.135 W/m<sup>2</sup>K, which is notably better than most of the glazing products in market.
- TRPVG-Ar16 can clean itself via a special TiO<sub>2</sub> nano coating on the surfaces of a-Si PV cells. This coating also rejects excessive heat and provides better electrical performance.
- TRPVG-Ar16 can produce an electricity over 100 W from unit module area at standard test conditions.

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