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RESEARCH ARTICLE

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A comparison of the use of traditional glazing and a novel concentrated photovoltaic glazing (CoPVG) for building solar gain analysis using IESVE

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Abstract

The aim of this study is to compare the difference in solar gain for an internal space when a novel Concentrated Photovoltaic Glazing (CoPVG) unit is compared against traditional glazing modules. The CoPVG is an innovative glazing system developed by Ulster University, that takes advantage of Total Internal Reflection (TIR) to direct solar radiation into the internal space during periods of low solar altitude (around winter) harnessing the thermal contribution of solar gain and daylight. During periods of higher solar altitude (around summer), the solar radiation is mostly directed onto embedded photovoltaic cells. Previous work assessed the concept's optical functionality, through experimental measurement and computational ray-tracing. Dynamic simulation in Matrix Laboratory (MATLAB) using a series of codes to represent the optical function of the CoPVG's and Integrated Environmental Solutions Virtual Environment (IESVE) was validated by the experimental data. This work investigates methodologies in determining the transmissivty of the system in a dynamic simulation approach using ray tracing and Radiance in IESVE for visualisation, thereby building on the versability of this software to allow building designers and consultants to investigate energy and economic benefits of this system and systems like it in real building applications. The impact of integrating CoPVG as a replacement to traditonal glazing on a sun-facing building facade is assessed and the solar gain in the adjaciant space is compared throughout the year. During the summer months the integrated system reduces solar gain in the space by 34% but only 11% in the winter months, representing a reduction in the overall annual building energy needs. The study presents the potential economic and environmental savings provided by reduced cooling.

Keywords Photovoltaics, BIPV, Smart buildings, IESVE: solar gain, Daylighting

1 Introduction

Overheating in buildings can occur at various times of the year, regardless of the geographical location, including regions with traditionally cooler climates and further from the equator (Policy commons, 2016). Lomas et al. (2017) assessed overheating in buildings and its negative affect on occupant's health. Common health risks due to overheating are de-hydration, fluid retention and lack of concentration (Zero Carbon Hub, 2018) whilst exposure to daylight is known to have a positive effect on the occupants. The balance between daylighting and overheating is crucial when determining the the correct balance of acceptable gain. Brembilla et al. (2020) investigated this balance in low-energy building design, comparing different levels of solar radiation in models to predict daylighting and overheating with different shading components.

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It was found that the use of an external louvre shuttering device was favoured over roof eaves or overhangs due to the prevalent effect of blocking solar gain during the summer months (contributing to overheating) whilst enabling positive solar gain during winter.

Various factors contribute to overheating in buildings including its design (Mylona, 2017). Work carried out by Sepúlveda et al. (2021) used prediction models to assess levels of daylighting and overheating prior to construction. The building's glazing and its properties are a significant element leading to solar gain and overheating. Daylighting control technologies used in adaptive facades, such as PV windows with adjustable transmission and window integrated PV, was reviewed by Alkhatib et al. (2021). The study indicated that both systems have the potential to lower heat gain during the winter.

Building integrated solar technologies refer to those that replace traditional building materials such as cladding. Modelling approaches have been carried out on building integrated phtotovoltaics (BIPV) systems using various forms of thermal analysis (Assoa et al., 2017). The study implemented seasonal conditions and differing solar irradiance on the BIPV and simulated their influence on performance. Various model approaches have been validated including lumped and linear (for temperature) or a combination of the two. The combination model was then further improved, taking into account wind direction and the convective heat transfer co-efficient. Concepts and applications for dynamic facades have been investigated through research and developmnent and their augmentation with solar technologies (Zhang et al., 2015). The location and size of active solar façade systems are affected by the incident solar radiation, accessible surface/solar fraction and storage volume (Frontini et al., 2012). Building features can impact how the building operates both internally and externally, impacting indoor thermal comfort, lighting, energy usage and external aesthetics.

Glazing has a significant impact on a building's lighting and thermal comfort and should be assessed prior to the building construction. A higher ratio of glazed facade is directly linked to positive artificial lighting energy consumption but leads to a higher cooling loads (U.S. Department of Energy, 2012) due to excessive overheating. A balance is key and therefore the building's fabric is a crucial element in determining building heating and cooling loads through heat loss and heat gain of the building itself. Software tools such as Integrated Environmental Solutions Virtual Environment (IESVE) visually and thermally assess a building based on its location and construction. The software utilises building physics and steady state heat balance equations. It is a commercial tool used for building overheating analysis. Given the significant increase in the cost of commercial gas from October 2021, as shown in Fig. 1 (commercial gas tariffs in the UK), it highlights the need for energy efficient buildings and how to reduce energy usage for space heating and cooling.

A study by Lau et al. (2016) investigated the energy savings for cooling using horizontal and vertical shading devices and different glazing thickness and configurations for a large office building using IESVE for hot climates. The results indicated that the optimal configuration for the shading device was a combination of vertical and horizontal devices for North and South facades with double glazing. The study showed a range of configurations, however did not apply or account for varying geographical locations which would have been accessible given the use of the IESVE software in this case.

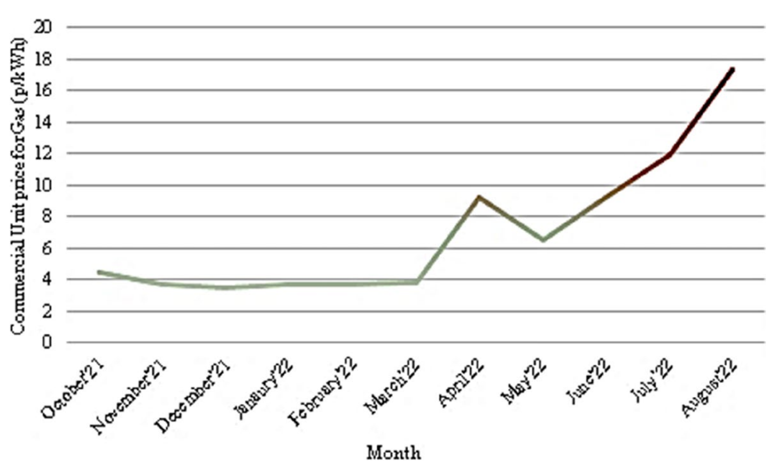


Fig. 1 The current price of commercial gas in the UK (GO Power, 2022)

The utilisation of computational tools for lighting modelling has become an essential component in the design process Radwan et al. (2020). These technologies facilitate the ability of architects and designers to forecast amounts of natural light, simulate various measures for controlling daylight, and assess their effectiveness inside virtual environments. The study demonstrates the application of simulation tools, namely Radiance and Daysim, in the precise evaluation of daylight availability and the enhancement of design choices (Pastan et al.; 2019). The utilisation of simulation and modelling techniques enables professionals to make well-informed decisions that optimise the advantages derived from natural sunlight.

A review of PV glazing systems carried out by Skandalos and Karamanis (2015) concluded that further research should be carried out on the transmittance of the PV glazing systems and building thermal control. Windows with embedded PV offer local electricity production whilst potentially providing daylight and internal temperature control**.** A dynamic simulation code was developed to investigate case study buildings in various climatic conditions to assess building envelope energy performance (Buonomano and Palombo, 2014). The study assessed the different glazing configurations and how the building performed when these are changed. The simulation was carried out using Balance Evaluation System Testing (BESTEST) and compared in EnergyPlus and TRNSYS.

The integration of photovoltaic (PV) glass into the building energy system is facilitated using energy models (Wang et al., 2023). The researchers conduct simulations to model the power generation of photovoltaic (PV) modules and evaluate the extent to which this energy production compensates for the electricity consumption of the building. The inclusion of financial analysis components in certain software packages enables the estimation of the return on investment for photovoltaic (PV) glazing systems (Albatayneh et al., 2022). The studies take into account many elements, including the expenses associated with installation, the possible reduction in electricity prices, and the possibility of receiving incentives or rebates.

Thermal assessment of a Concentrated Photovoltaic Evacuated Glazing system (CoPEG) was carried out by Zacharopoulos et al. (2017). Two incidence angles and solar intensities were used in the experimental work for winter and summer months. An incidence angle of 20° with a higher solar intensity (775 W/m^2) for winter and an incidence angle of 55° with a lower solar intensity (503 W/m^2) for summer. The experimental results showed that at 55° incidence angle, an increase in radiation reaching the PV surface was recorded.

The current study is based on the CoPEG technology with the vacuum element removed. The aims of this study where to demonstrate how this variant PV glazing system – the Concentrated PhotoVoltaic Glazing (CoPVG) - can contribute to daylight and internal temperature control and combat the effects of overheating in buildings. This work is validated through experimental work and previous dynamic simulation modelling. Previous work assessed the system's optical functionality; through ray tracing, dynamic thermal simulation in MATLAB and Integrated Environmental Solutions Virtual Environment (IESVE), validated through experimental analysis conducted at the Centre for Sustainable Technology, Ulster University. Two methodological approaches were used in IESVE to model the CoPVG's optical properties. The use of dynamic modelling to evaluate the CoPVG system's optical properties and subsequent characterisation using IESVE is highly novel, allowing investigation of how the determined optical properties impact the internal space of the building. This work focused on the way the system interacted with incident solar radiation and corresponding solar gain and building overheating throughout the year (note: the work did not consider the PV electrical output). The incident solar radiation, transmissivity and angle of the PV cells are fundamental to its optical performance and thus solar gain and internal air temperatures. Other variables include glazing type, direct radiation/shading ratio and environmental conditions. The novelty of the work described in this paper is the modelling techniques developed in the commerical software tool, its validation and its implication for the commerial encouragement of the innovative façade technologies needed in today's modern buildings. The graphical user interface allows the building and its components to be visually presented, and determines the impact of the building's glazing elements on the internal space conditions. IESVE's wide acceptance in the industry, allows building designers and consultants to readily use these incorporated techniques to assess the CoPVG and similar developing facades, so that their impact on boundary pushing Net Zero buildings and subsequent energy savings can be evaluated.

2 Description of the CoPVG system

The CoPVG module is a passive low-concentrating PV glazing concept, constructed of individual prisms and PV cells integrated onto a vertical glazing panel, with the PV portion at 28° to the vertical and the glazed transparent portion at 14.7° to the vertical, with a concentration ratio of 2.69. The CoPVG utilises Total Internal Reflection (TIR) to direct solar radiation into a building during periods of low solar altitude (around winter) During periods of higher solar altitude (around summer), the solar radiation is directed onto the PV cell, reducing unwanted solar gain and producing electrical energy via the PV cells. This passive control methodology can reduce the thermal energy requirements in a building throughout the year, whilst augmenting power supply. The PV cell angles and thus prisms are crucial to achieving optimal annual performance at specific azimuth and incident angles. Figure 2 illustrates the CoPVG system prism and construction configuration. The system's operation for transmissivity was previously studied by (Barone et al., 2022a) using ray tracing. The different incident and azimuth angles used and their resulting transmissivity with the system is shown in Table 1. These values were expanded for this study and developed into an entire year for the transmissivity of the system, by building the system in IESVE. Using the software enabled a time of year to be determined for each transmissivity value. A clear sunny day was selected for each month and used to further study the systems' "switching angles" – when the transmissivity changes from high to low transmissivity. Switching angles were determined throughout the year, using the software. Data taken from the results in IESVE for a clear sunny day in September are shown in Table 2. The values for transmissivity that are highlighted indicate the switching angles.

This methodology involved calculating the solar flux (kWh/m^2) incident on the exterior south (sun) facing façade and relating it to the total solar flux incident on all the interior space surfaces with a glazing tranmission set to 1. This procedure was then set-up as a new "window type" in the Apache construction properties - CoPVG.

Figure 3a and b, visually illustrate the CoPVG prototype's optical switching operation, between periods of low and high solar altitudes. Figure 3a demonstrates the system's high transmissivity when low solar altitude angles occur (allowing light in). Figure 3b shows that low transmissivity occurs during high solar altitude periods (concentrating the light onto the PV cell and not into the building).

3 Methodology

This study aims to compare the differences in solar gain in buildings with traditional glazing against buildings with the integrated CoPVG system using a computational modelling technique. Previous work carried out on the similar CoPEG will be used to validate the work in this study and modelling of the CoPVG system will be carried out using the commercial Integrated Environmental Solutions Virtual Environment (IESVE) design tool. IESVE is an industry recognised graphical, thermal building modelling and simulation software and as such widens the parameters for integration investigation. When a virtual proxy shading device is built within the model to represent the CoPVG, its operation is simulated, and the optical impact observed when subjected to various solar altitude angles and how it either directs or prevents solar radiation transmission into a building. Less transmission occurs in the summer when most of the solar energy is directed onto the PV cell and kept out of the building.

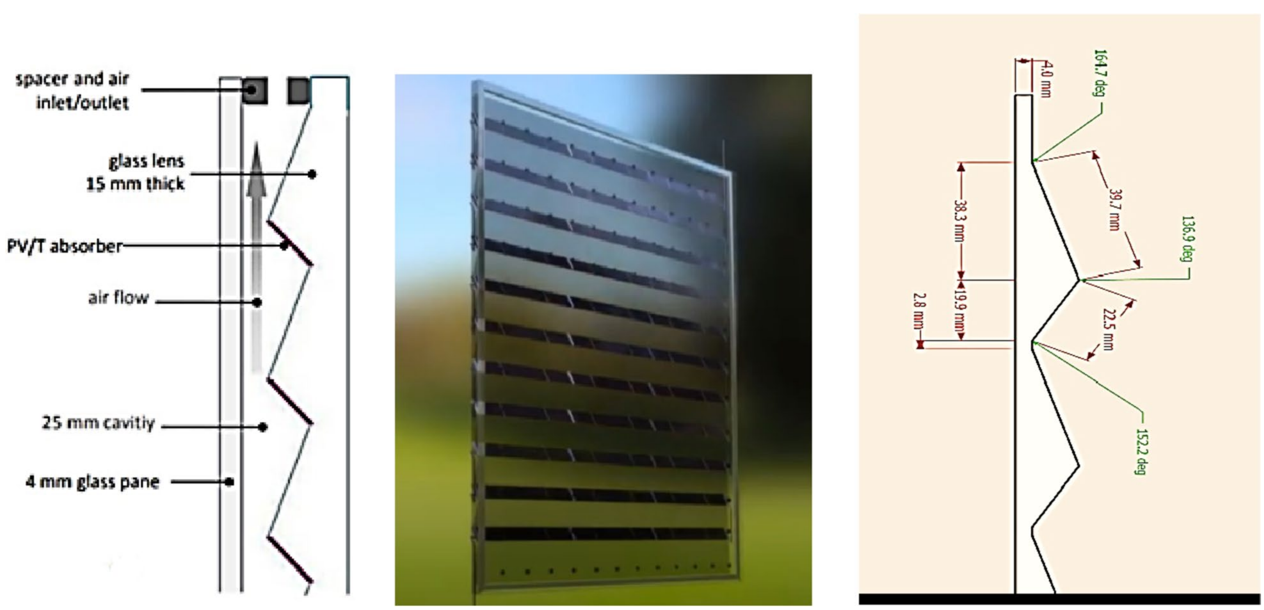


Fig. 2 The design of the CoPVG technology showing its prismatic configuration and relative position of PV cells within the system (Barone et al., 2022b)

Table 1 Angles of incidence and azimuth from CoPEG ray tracing

Angle of Incidence (°)	Azimuth Angle (°)	Transmissivity of the CoPEG (%)	Time of Year-from IESVE
0	80	65.2	
2.5	80	61.8	
5	80	61.1	
7.5	80	60.4	
10	80	59.7	
12.5	80	58.9	Start of Jan.-Midday
15	80	58.1	Mid Jan.-Midday
17.5	80	57.3	Start of Jan.-1pm
20	80	56.2	Start of Jan.-1pm
22.5	80	55.1	Mid Feb.-Midday
25	80	53.7	
27.5	80	52.1	Start of March-Midday
30	80	49.7	Start of March-1pm
32.5	80	46.1	Mid-March-Midday
35	80	38.6	Mid-March-1pm
37.5	80	1.4	End of March-Midday
40	80	1.4	End of March-1pm
42.5	80	1.5	Mid-Sept.-2pm
45	80	1.5	End of Aug.-1pm
47.5	80	1.5	End of Aug.-1pm
50	80	1.6	Start of May-1pm
52.5	80	1.5	Start of May-1pm
55	80	1.6	End of May-1pm
57.5	80	1.6	

During the winter months, with a higher transmissivity, most solar radiation is directed into the building, becoming useful, augmenting thermal and artificial lighting energy requirements.

3.1 Integrated environmental solutions virtual environment (IESVE)

IESVE is a commercially available building simulation tool used to assess the thermal properties of a building's envelope (IESVE Guide, 2015). SunCast, an IESVE application, can be used to predict the annual position of the sun, based on a geographical data file base. Apache is a graphical user interface application in IESVE. The features of Apache permits users to edit the construction type and associated properties within the dynamic model and produce building load calculations such as energy usage, heating and cooling loads. The database used in Apache is CIBSE and ASHRAE's current building regulation construction properties. This database is configured for each of the building's elements (glazing, external and internal walls, doors, roofs, skylights and partition walls). For each element the properties can be viewed and edited as shown in Table 3. Various profiles, or time schedules, can be set up to assign the building's heating, cooling and

Table 2 A clear sunny day in September was selected from the annual data from the IESVE results for the CoPVG's transmissivity

Date-Sept.22nd	Transmissivity (%)	Occurrence
08:00	0.5	
09:00	0.6	
10:00	0	
11:00	1.2	
12:00	32.9	Before Switching Angle
13:00	37.7	Switching angle
14:00	1.4	After Switching Angle
15:00	1.4	
16:00	1.3	
17:00	0	
18:00	0.4	

ventilation operation. Shading devices, such as blinds and external louvres can be assigned to a profile relating to when the shading device can be lowered or raised. The profile relating to the CoPVG was set-up using both louvres and blinds, which lowered and raised depending upon direct and diffuse solar radiation variation throughout the year.

The baseline system was input into IESVE as traditional glazing, as shown in Table 3, with an external louvre/blind element application. The external louvre and internal blind were set to yearly profiles using direct and diffuse radiation commands.

The values for transmission of the external louvre were calculated by using the data from Table 1 and obtaining an average for each angle of incidence for the entire year. These are shown in Fig. 4. In a similar manner for the blinds profile this was set up daily to monthly, monthly to yearly. The proxy switching angle was on the basis of if direct is greater than the diffuse the blind would open and vice versa if diffuse was greater than direct the blind would open. This command was input to the IES software as a yearly command via a formula.

The model was run in APACHE and focused on the state of the internal and external shading devices, to validate these commands. Each shade state was analysed against direct and diffuse radiation and the solar flux internal surfaces values were compared against this data to determine what affects the shade state had.

The solar irradiance for the blinds profile was set to continuously variable, meaning that the blinds only operated depending according to its schedule in IESVE. The formulas input to the schedules commanded the blinds to open or shut. This was input to eliminate any conflicting values for direct and diffuse radiation. The operation profile of the louvre using the formula indicated that if diffuse was greater than direct the louvre would shut.

3.2 Validation using previous CoPEG modelling using MATLAB

The CoPEG was previously modelled in the software MATLAB and DeTect by Barone et al. (2022a). The parameters of the space modelled, its HVAC systems, location and building construction make-up are listed in Table 4. The adapted model's glazed surface is south facing with a window to wall ratio (WWR) of 50%. For the purpose of comparison, a traditional glazing unit and that which incorporates the properties of the CoPEG are used for yearly simulations from January 1st to December 31st.

The information was input into IESVE to replicate this data. Figure 5 shows the dimensional properties of the office space used for the study in MATLAB. Figure 6 illustrates the integrated CoPEG in the IESVE model. The results for the monthly electric space heating and cooling are shown in Fig. 7. The total yearly energy consumption for heating and cooling is 622.4kWh.

Extracting the data from Fig. 8, for Naples and CoPEG, the results from the MATLAB and DeTect model show a total yearly energy consumption from heating and cooling of 616kWh. Comparing this to the results from the IESVE model (622.4kWh), the variation is less than 1% for the total yearly electrical energy for heating and cooling. For this study, only the CoPEG in Fig. 8 was compared to highlight the good correlation between the

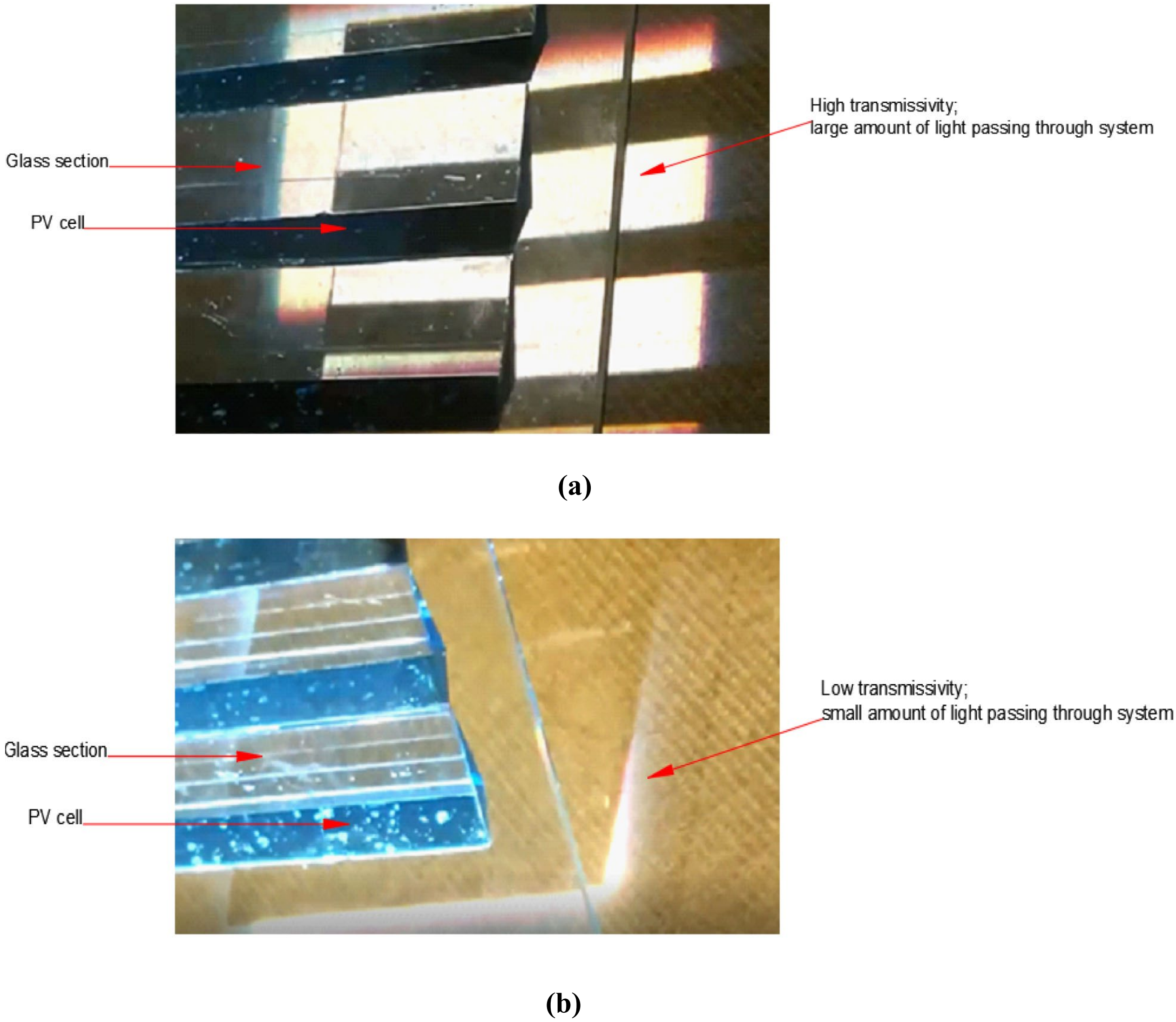


Fig.3 **(a)** A CoPVG prototype under low solar altitude showing high transmissivity **(b)** A CoPVG prototype under high solar altitude, showing low transmissivity

Table 3 The glazing parameters of traditional glazing in Apache IESVE from the current CIBSE construction database (The IES Construction Database Guide, 2015)

Material	Thickness (mm)	Conductivity (W/m.K)	Convection co-efficient(W/m^2.K)	Resistance (m^2.K/W)	Transmittance	Outside Reflectance	Inside Reflectance	Refractive Index	Outside Emissivity	Inside Emissivity
Outer pane	6	1.06		0.0057	0.409	0.289	0.414	1.526	0.837	0.042
Cavity	12		1.4033	0.6183						
Inner pane	6	1.06		0.0057	0.783	0.072	0.072	1.526	0.837	0.837

modelled processes. The other presented units were used for comparative purposes in the other study and therefore not of benefit to this study. The Insulated Glazing Unit (IGU), Semi-Transparent Photovoltaic (STPV) and Concentrated Photovoltaic Thermal Glazing were therefore not used for model validation and calibration relevant to the IES model.

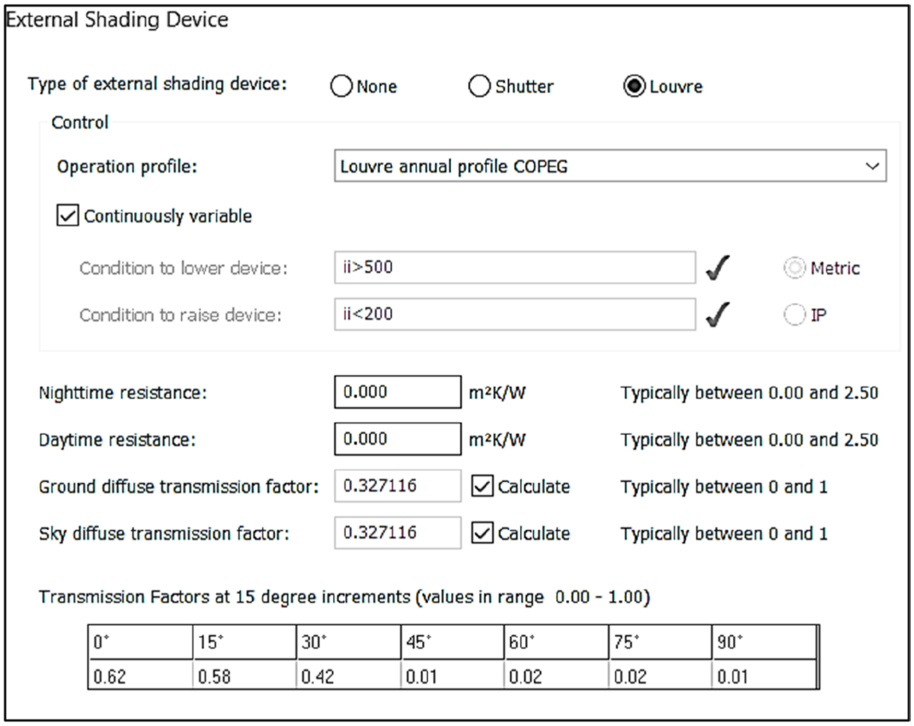


Fig. 4 The input data for the transmission factors for the external louvre

Table 4 The parameters in MATLAB adapted for the comparative model for IESVE

Orientation of glazing	South
Building Type	Office
Location	Naples
U-values (W/m^{2}K)	
External Wall	1.32
Floor	1.1
Ceiling	1.1
CoPEG	1.45
Occupancy	4 people @95 W/person
Lighting	9 W/m^2
HVAC (electrical)	ASHP/C: COP 3
	Coupled Fan Coil Unit constant air temp. 20&26 °C
Operation	8 hours per day, only weekdays
Room Dimensions (m)	10(W) × 3.6 (D) × 3(H)
Glazing Dimensions (m)	10(W) × 1.5(H)
Sill Height	0.9
WWR (%)	50

The results presented in Fig. 9 indicate the good correlation between the MATLAB model and IESVE model for 14 European locations. The largest discrepancy in heating and cooling energy demand between the two software is Tampere. The overall discrepancies in the models are due to the prolific information on the heating and cooling days throughout the year. These values were based on the climatic conditions for each location. The profiles for heating and cooling were set up in IESVE on a daily, weekly and annual profile for 8 hours per day, weekdays only. This method was based on the information in MATLAB. The MATLAB methodology uses a different weather file, whereas IESVE uses a Test Reference Year (TRY) which is more accurate and has accounted for the entirety of the year.

4 Modelling the CoPVG in IESVE for Belfast and Naples

The good corelation between the results from the IESVE model and the previously confirmed MATLAB model validated the use of IESVE to model the CoPVG system. The new simulations in this study investigate the use of traditional glazing with the CoPVG and the impact of integrating the CoPVG onto a south facing façade with regards to the heating and cooling loads in a building. The study uses two locations, Belfast, United Kingdom and Naples, Italy.

4.1 Methodology for modelling the CoPVG

The data from Section 3.1 for the CoPVG proxy was linked to the SunCast application to carry out ray tracing,

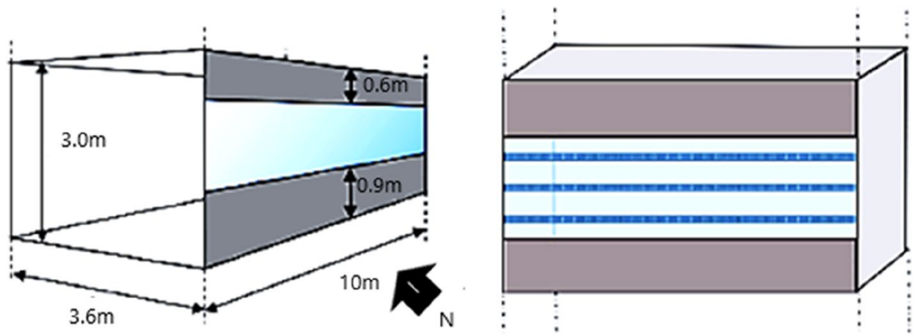


Fig. 5 The dimensional properties of the MATLAB model showing the integration of the CoPEG at 50% WWR

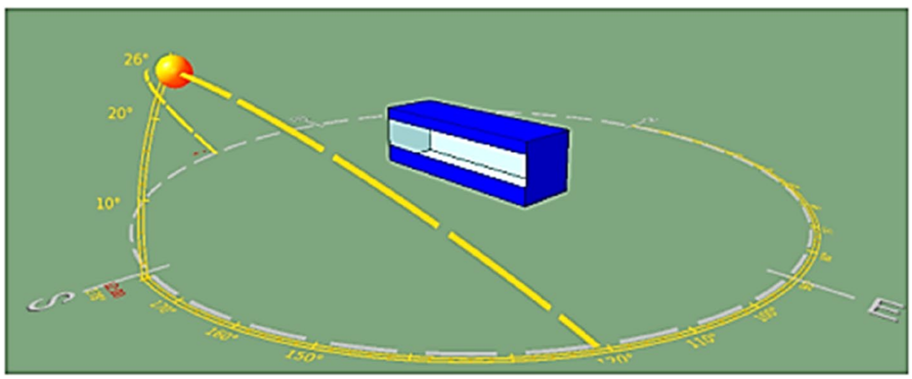


Fig. 6 The IESVE model replicate, showing WWR and office space modelled

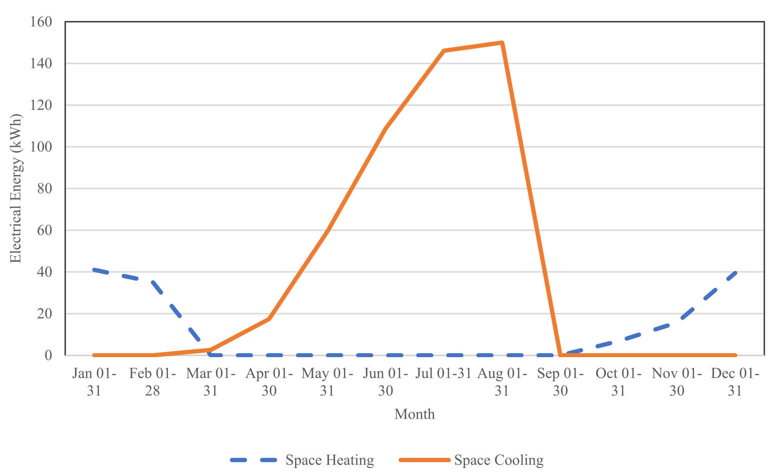


Fig. 7 The monthly totals for electrical heating and cooling usage for Naples. (IESVE model)

using two rays with perpendicular polarisations to calculate the annual transmittance. Absorption for all inner building surfaces is set to zero, to avoid discrepancies in transmissivity. Sky diffuse radiation is set to isotropic. Two models were developed using dynamic modelling in IESVE to assess the potential for overheating in a notional building internal space for traditional glazing system and the CoPVG.

Two dynamic models, Model 1 using tradiitonal glazing and Model 2 using the CoPVG,were simulated to assess and compare the impact of an integrated CoPVG system on a building's south facing façade with

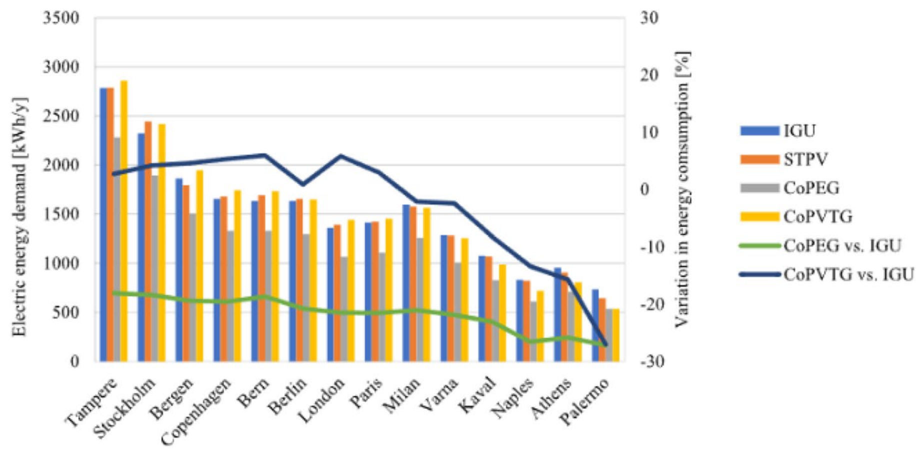


Fig. 8 The yearly electric energy usage for heating and cooling in various locations (MATLAB and DeTect model). (Barone et al. 2022b)

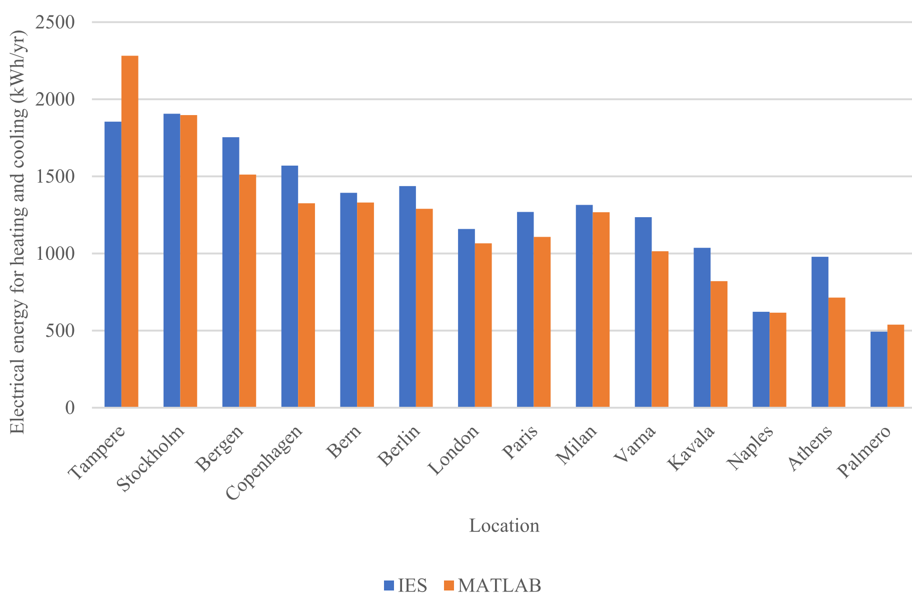


Fig. 9 The annual electrical consumption for heating and cooling for various locations and comparisons to the IESVE and MATLAB models

traditional glazing and measure differences in unwanted solar gain and building overheating, as presented in Fig. 10. The building fabric envelope was of traditional construction with a glazing transmittance set to 0.80, as determined by the maximum transmissivity of the system. The heating and cooling profiles were switched to continuously off, to determine the solar gain, minimising any affect of auxillary heating and/or cooling in the room. To determine the annual heating and cooling energy consumption, the profiles for heating and cooling were to set continuosly on.

Model 1: was a base line configuration with a traditional single glazed window with no active heating. The simulation was run on a time step of 6 minutes, with a 60 minute reporting interval. This had been previously used to provide accuracy when switching angles were occurring for the system.

Model 2: was set up as model 1, but the traditional glazing properties were replaced with the CoPVG properties (in the window construction parameters).

Each model represented a "typical" office space. Table 5 shows the input parameters used in the models and Fig. 10 graphically represents the two models - (a) Model 1 and (b) Model 2, depicting traditional glazing on a south facing façade office space and the same space with a CoPVG system, respectively. The solar absorptance

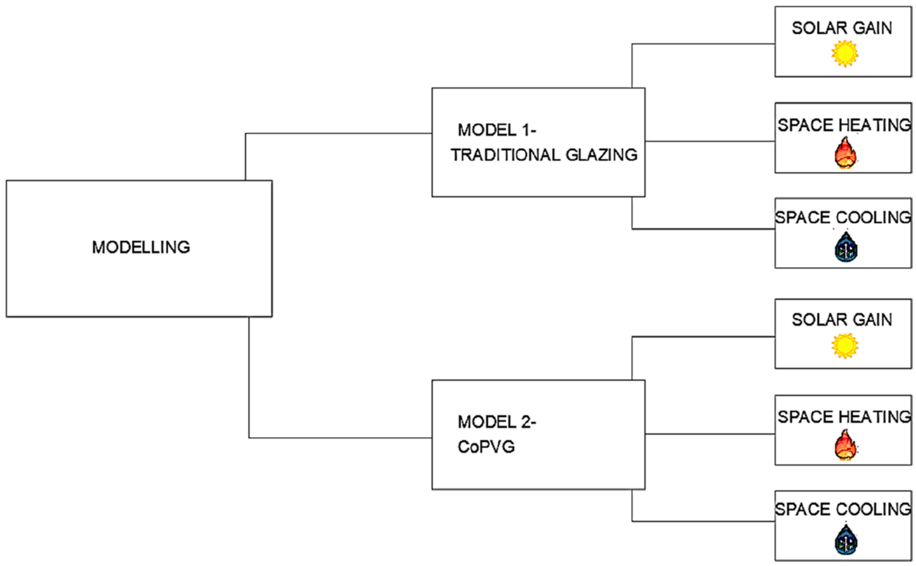


Fig. 10 Process modelling approaches used for the comparison of models using traditional glazing and the CoPVG

Table 5 Input parameters for the IESVE model in Belfast for the CoPVG and traditional glazing

Parameters	Model 1&2 Inputs
Room dimensions	10 m × 7 m × 2.7 m
Room type	Office
Gas boiler for space heating	95% efficiency
Air conditioning SCoP	2.5
Room Heating & Cooling set-points	19 °C,23 °C
Room orientation	South
Area/Type of glazing	19.2m^2 Traditional glazing
Area/Type of glazing	19.2m^2 Glazing with the CoPVG proxy
Location	Belfast, UK
Internal surfaces	solar absorption set to 0.5
U-value (W/m^2.K)	Traditional Glazing:2.7, CoPVG:2.7, floor:0.2, roof:0.18, ext.wall:0.26.
Improved U-value for glazing elements(W/m^2.K)	Traditional Glazing:1.2, CoPVG:0.8
Wall and glazing surface inclination	90° from horizontal, south-façade
Glazing transmissivity	Set to 0.80 or 80%

(SA) on all internal surfaces was set to 0.5, based on typical SA values for internal room surfaces. The transmissivity of the glazing was set to 0.8, based on typical glazing transmissivity in the software. The models were simulated in the visualisation application to show the luminous affects on the office room surfaces. Figure 11 shows the luminous affect for a typical month from each season with traditional glazing and with the CoPVG.

Two locations were selected for investigation on solar gain, cooling and heating energy. As previously discussed (section 3), the CoPEG system applied to an office space, in Naples, has been investigated and subsequent results and good agreement have been used to validate the modelling of the CoPVG system in IESVE, for Belfast (and Naples) in this new study. The building energy input has been changed to gas (to reflect the use of gas in Belfast as the dominant heating source) over electrical space heating which is common in Naples. Belfast and Naples were selected in this study, because they have different cliamtic conditions, as presented in Fig. 18. Belfast experiences mild summers and cold winters, thus it is a predominantly heating based climate. Naples experience hot summers and milder winters. The majority of the buiding energy in Naples is used for space cooling.

4.2 Modelling for Belfast

The annual solar gain in the space will be determined using traditional glazing (U-value 2.7 W/m^{2}K) and compared with gains in a space with the CoPVG system set at a Window/Wall Ratio (WWR) of 1. Energy and cost related affects of integration will be determined and compared with the traditonal glazing for space heating and cooling loads and related carbon emissions.

A represntative day from each month was selected for each dynamic model. Each day was a clear sunny day as previously determined by assessing the yearly weather data file from IESVE. The models are graphically illustrated,

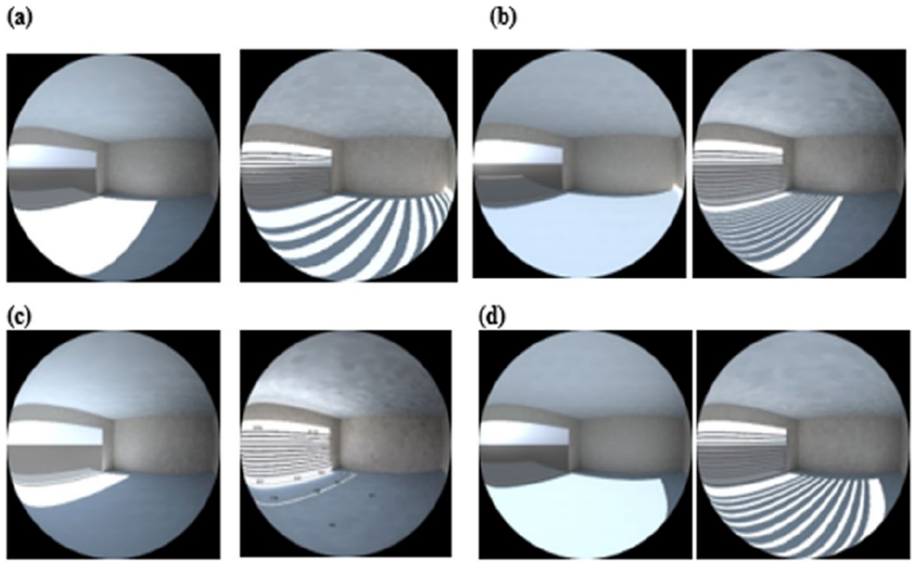


Fig. 11 Inside the modelled room with and without the CoPVG component: **(a)** January 21st at midday; solar altitude:15°, solar azimuth:171.3°. **(b)** March 21st; solar altitude: 35.1°, solar azimuth:170°. **(c)** July 21st; solar altitude:51.8°, solar azimuth:144.1°. **(d)** October 21st; solar altitude: 23.3°, solar azimuth: 161.5°

shown in Fig. 12, for the year and compared to show how the optical properties of the system impacted solar gain shown in Fig. 13. During periods of low solar altitude, the solar gain is approximately the same for the models with and without the CoPVG. During periods of high solar altitude solar gain is reduced in the CoPVG model, reflecting how the system redirects solar radiation onto the PV via the prismatic TIR, hence keeping it out of the building.

5 Results

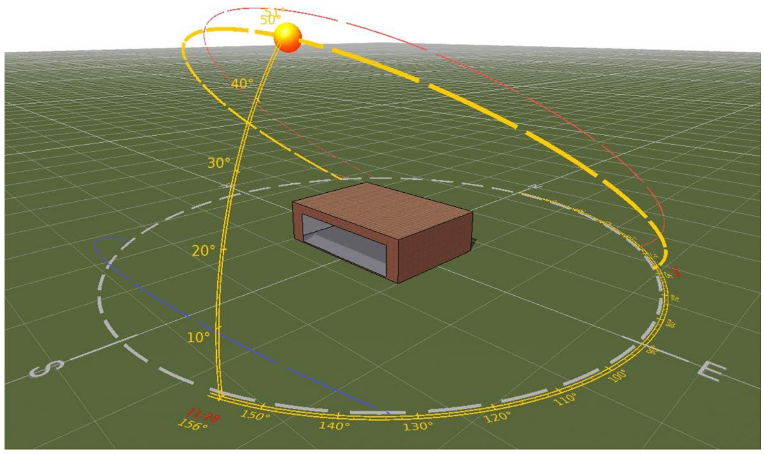
Figure 13 illustrates the annual monthly solar space solar gains for models 1 and 2. Model 1, without the CoPVG, produces a minimum and maximum solar gain of 294.6kWh and 1102.2kWh for December and May, respectively. Model 2, with the CoPVG, the minimum and maximum values of space solar gain are 188.1kWh and 543.7kWh in December and May, repsectively. The greatest difference in solar gain occurs in May at 558.5kWh. These values indicate that the CoPVG system is positively impacting solar overheating by blocking solar radiation during these months. The smallest difference in solar gain occurs in December, January and February, which may be beneficial for the space heating demand, as discussed in section 3.

5.1 Internal air temperatures with and without the CoPVG for Belfast

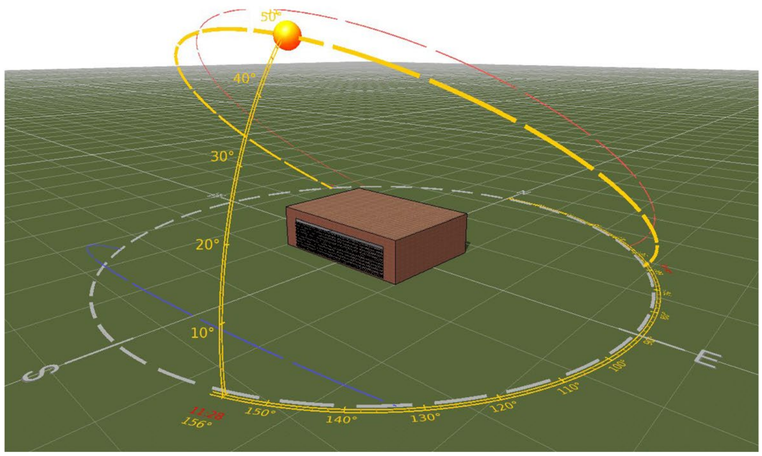
The internal air temperature of the modelled space was determined as per the solar gain models (using Apache dynamic simulations and monthly figures). Model 1 had a minimum internal air temperature of 3.11 °C, occurring on the 10th February at 07:30 and a maximum value of 31.83 °C on 1st June at 14:30. Model 2, with the CoPVG showed a minimum value of 2.78 °C on the 10th February at 07:30. The maximum value was 29.79 °C on the 1st June at 14:30. Figure 14 illustrates the internal space air temperatures for the CoPVG (model 2).

5.1.1 The effects on cooling and heating energy for Belfast using the CoPVG

Every building must maintain a level of thermal comfort for its occupant's health and overall well-being. Even in colder climates, space cooling can be a necessity during summer months**.** Current global energy prices have significantly increased energy costs for both domestic and non-domestic buildings (Department of Business, Energy & Industrial strategy, 2022). This increasing energy cost must be reduced and mirrors the parallel need to reduce fossil fuel energy and associated carbon emissions, through smart technologies and various other forms of sustainable energy production. From solar gain analysis, a yearly total reduction in energy use of 45% was observed with the integrated CoPVG. The average reduction in solar gain for the summer and spring "cooling season" months was 47% but the average solar gain reduction in the winter and autumn "heating season" months was 40%,



(a)Model 1- Traditional glazing



(b)Model 2- the CoPVG system

Fig. 12 Graphical representation of models 1 using traditional glazing and 2 using the CoPVG from IESVE Suncast application

meaning that the heating load input would need to be slightly higher in the winter and autumn months, to compensate. The seasonal impact of the integrated CoPVG on internal space thermal conditioning was evaluated in terms of solar gain and internal air temperature and related economic cost and carbon emission consequences presented. Assuming a traditional gas fired boiler efficiency of 95% for heating and an electrical air conditioning system with a seasonal CoP of 2.5, the most recent prices were used to calculate the building energy costs for a typical office in Belfast, UK. The room set-points were a constant 19 °C heating and 23 °C for cooling. The total carbon emissions presented for space heating is derived from the total energy used for the gas boiler, considering its efficiency and how much kWh are being used. The carbon emissions for space cooling is the total electrical energy used for the air conditioning unit in the room.

The total monthly space cooling energy usage is shown in Fig. 15a, with and without the CoPVG. The results show that the maximum difference in space cooling energy consumption occurs during the summer. These figures reflect on the system's principal operation. The largest difference in space cooling reduction occurs in May at 194.8kWh, which in monetary terms translates to a month cost reduction of £57.50 (£0.2952/kWh ×194.8kWh). The values for the winter and autumn months are lower, due to the lack of a space cooling requirement. During the cooling months between April to September, the average monthly usage was 66.01kWh when the CoPVG was used. For traditional glazing, the average usage for these months was 186.6kWh. The average monthly reduction in the "cooling period" over the year is 120.59kWh. In monetary value this translates to a £35.60 saving per month on average or £213.59 over the year.

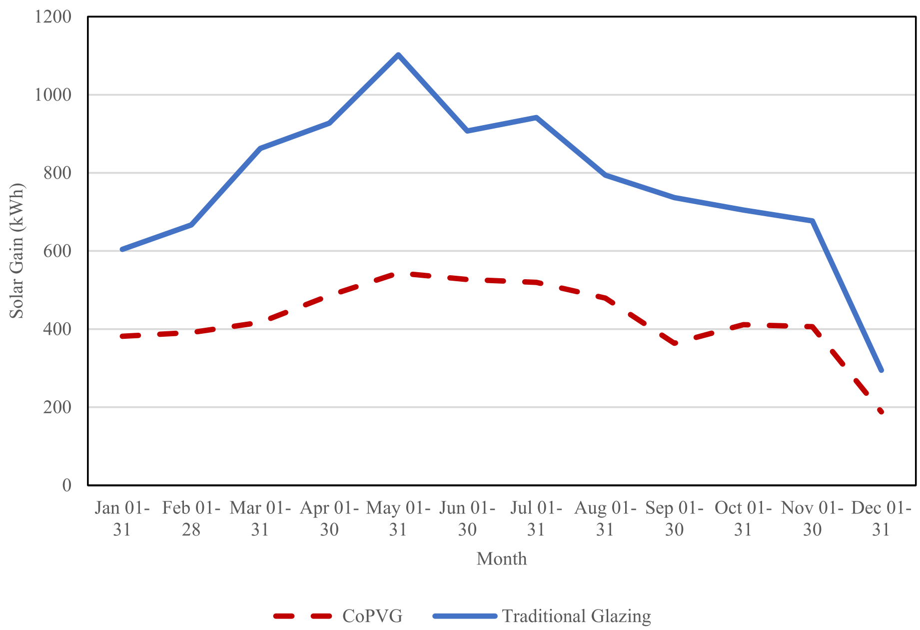


Fig. 13 Monthly values of solar gain in the room with and without the CoPVG, from models 1 and 2

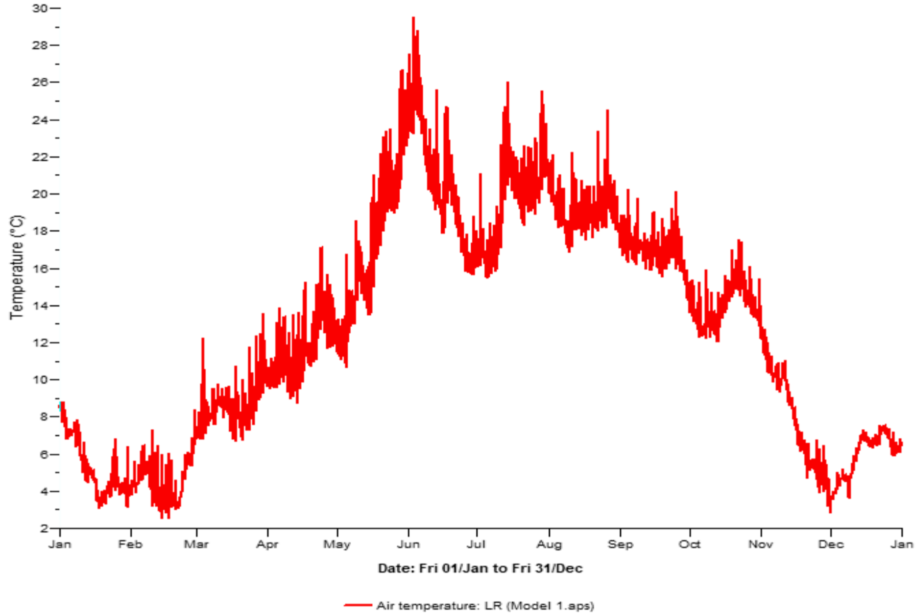


Fig. 14 The daily internal space air temperatures from model 2 (with the CoPVG system) over an entire year

Figure 15b shows the monthly space heating energy usage over the year. The results show that there is an increase in space heating when the CoPVG is applied, compared to traditional glazing. The largest difference in space heating usage occurs in March (374.9kWh) equating to a maximum cost differential of £64.33 (£0.1716/kWh ×374.9kWh). During the average "heating season" in Belfast (October to March), the average heating for this period was 802.34kWh using the CoPVG. With traditional glazing the average space heating for the same period was 602.48kWh. This increase in fuel translates to an average additional cost

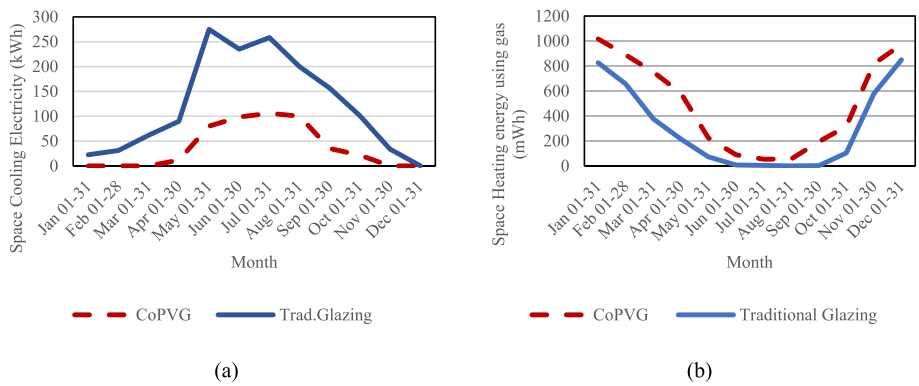


Fig. 15 The monthly totals for (**a**) space cooling energy and (**b**) space heating energy with and without the CoPVG for the room in Belfast

of £34.30 (199.86kWh x £0.1716kWh) per month when the CoPVG is applied.

Table 6 summarises the total impact on heating and cooling loads when the CoPVG is applied, indicating the kWh reduction and surplus and associated costs. It is evident that the current base CoPVG prototype, whilst demonstrating gains during the summer season, exhibits excessive additional heating during the winter. As such, this indicates that an improved U value based on the CoPEG design is necessary. The subsequent following section highlights the improvement in the traditional glazing U-value to something nearing an industry standard and the parallel improvement in the CoPVG to an optimised version (Improved U-value (IU) CoPVG).

5.1.2 Improving the U-values for Belfast

Building U-values make a significant difference in energy loss through the building fabric. The highest energy loss in any building element is through its glazing. The following section will demonstrate how the thermal improvement of the glazing U-values and integration of CoPVG will impact the building's energy usage for cooling and heating loads throughout the year. Fig. 16 represents the traditional glazing and the CoPVG, model 1 and 2 respectively. The simulations were conducted as previous, for both traditional glazing and the CoPVG, but now using improved U-values.

The parameters presented in Table 5 were simulated in IESVE to determine the space cooling and heating loads for the improved systems using Improved U-values (IU). The traditional glazing's U-value was improved from 2.7 to 1.2 W/m^{2}K and the CoPVG's U-value was improved from 2.7 to 0.8 W/m^{2}K using the construction database in IESVE (IESVE, 2015). These values were derived from the current U-values for typical glazing

Table 6 A summary of the differences of cooling and heating when using CoPVG compared to traditional glazing and associated monthly yearly costs in Belfast (Energy and Gas bill statement, 2021)

Month	Cooling Reduction (kWh) (−)	Heating Surplus (kWh) (+)	Electricity Tariff (£/kWh)	Gas Tariff(£/kWh)	Cooling Savings (£)	Heating Surplus (£)
Jan 01–31	22.5	190.9	0.2952	0.1716	6.64	32.76
Feb 01–28	31.2	232.9	0.2952	0.1716	9.21	39.97
Mar 01–31	61.9	374.9	0.2952	0.1716	18.27	64.33
Apr 01–30	78.2	368.6	0.2952	0.1716	23.09	63.25
May 01–31	194.8	151.3	0.2952	0.1716	57.50	25.96
Jun 01–30	136.4	81.8	0.2952	0.1716	40.27	14.04
Jul 01–31	152.5	49.3	0.2952	0.1716	45.02	8.46
Aug 01–31	99.7	55.8	0.2952	0.1716	29.43	9.58
Sep 01–30	121.6	191.3	0.2952	0.1716	35.90	32.83
Oct 01–31	79.5	214.1	0.2952	0.1716	23.47	36.74
Nov 01–30	33.8	238.4	0.2952	0.1716	9.98	40.91
Dec 01–31	0.3	123	0.2952	0.1716	0.09	21.11
Summed total	1012.4	2272.5	0.2952	0.1716	298.86	389.96

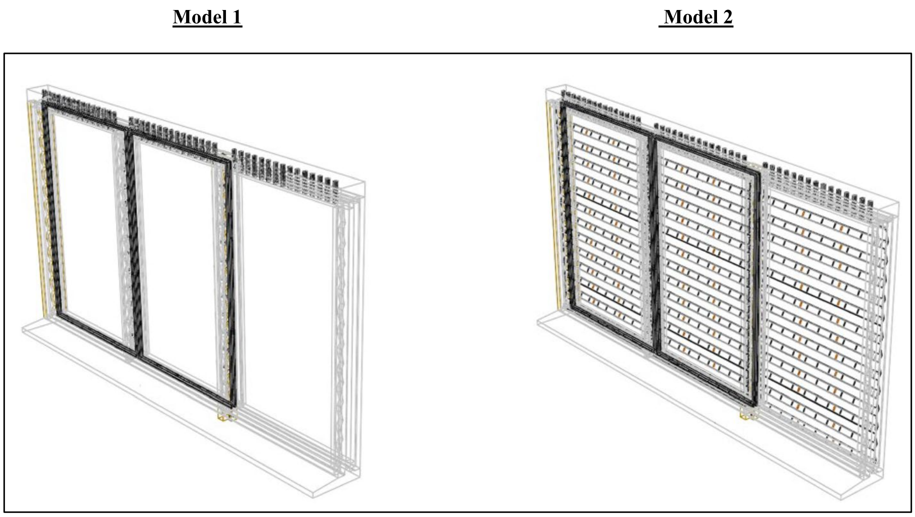


Fig. 16 A graphical representation of the traditional glazing and the CoPVG

and triple glazing and the new combined results for the old and improved U-value values are shown in Fig. 17 and Table 7.

The results from Fig. 17 and Table 7 show the improvement in the CoPVG (IU) compared to both traditional glazing (2.7 W/m^{2}K and 1.2 W/m^{2}K) and the initial CoPVG prototype (2.7 W/m^{2}K). The IU CoPVG reduces space heating by 60% and 36% compared to the original CoPVG and traditional glazing (2.7 W/m^{2}K), respectively.

The IU CoPVG requires 2365.5kWh heating opposed to the 1666.4kWh for the IU traditional glazing equating to a deficit of 699.1kWh at £119.96 (699.1kWh x £0.1716kWh). However, space cooling resulted in a significant saving, with the IU CoPVG requiring 987.9kWh of cooling opposed to the 1691kWh for the IU traditional glazing. The energy saving was 703.1kWh resulting in a cost saving of £207.55 (£0.2952/kWh × 703.1kWh).

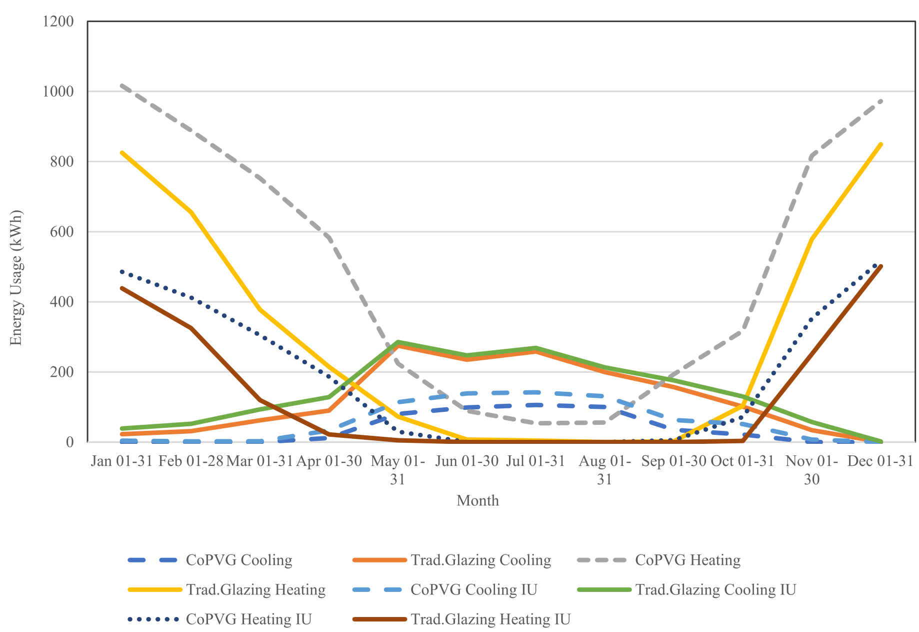


Fig. 17 Comparisons of energy usage for heating and cooling using improved U-values for the CoPVG and traditional glazing in Belfast

Table 7 Annual energy usage for heating and cooling using improved U-values for the CoPVG and traditional glazing for Belfast

Month	CoPVG Cooling (kWh)	Trad.Glazing Cooling (kWh)	CoPVG Heating (kWh)	Trad.Glazing Heating (kWh)	CoPVG Cooling IU (kWh)	Trad.Glazing Cooling IU (kWh)	CoPVG Heating IU (kWh)	Trad.Glazing Heating IU (kWh)
U-value (W/m^{2}K)	2.7	2.7	2.7	2.7	0.8	1.2	0.8	1.2
Jan 01–31	0	22.5	1016.2	825.3	3.9	38.7	485.5	438.8
Feb 01–28	0	31.2	888.5	655.6	2	52.2	412.1	325.2
Mar 01–31	0	61.9	752.4	377.5	2.5	93.1	304.8	119.7
Apr 01–30	11.5	89.7	583.4	214.8	33.1	128.1	186.7	21.9
May 01–31	80.1	274.9	224.1	72.8	113.8	285.4	29.9	5.2
Jun 01–30	98.6	235	89	7.2	138.7	247.1	0	0
Jul 01–31	105.9	258.4	53.6	4.3	142	268.5	0	0
Aug 01–31	100	199.7	55.8	0	130.5	213	0	0
Sep 01–30	35.1	156.7	193.7	2.4	62.9	175.9	5.6	0
Oct 01–31	21.7	101.2	317.7	103.6	51.4	129.9	71.5	3.3
Nov 01–30	0.1	33.9	817	578.6	7.1	57.3	352.4	251
Dec 01–31	0	0.3	972.3	849.3	0	1.8	517.1	501.3
Summed Total	452.9	1465.3	5963.7	3691.2	687.9	1691.0	2365.5	1666.4
Total Carbon Emissions (kgCO_2)	116.8	378	1538.60	952.3	177.5	436.3	610.3	429.9

The annual carbon emissions, shown in Table 7, are a reflection of the trends shown in total energy usage. The summed monthly total for electrical energy used for space cooling and heating are associated with a carbon impact factor of 0.258kgCO_2/kWh (Carbon Intensity, 2021). The annual carbon emissions for space cooling with traditional glazing was 378kgCO_2. With the integration of the CoPVG there is a 261.2kgCO_2 (69%) reduction in carbon emissions.

The revised performances and associated costs represent a small annual nett gain in the annual energy variables for Belfast when applying the IU CoPVG. However, given the significant savings that the CoPVG exhibits in reducing cooling loads, the potential of the CoPVG technology is not necessarily appropriate for a building in a heating dominated climate, but is more suited to a building in a cooling dominated climate, such as Naples, Italy.

5.2 Modelling in Naples

The previous section and results were based on a building located in Belfast, UK. This section will investigate the effects of an integrated CoPVG in a different geographical location - Naples Italy, with different climatic conditions. The model is set-up, as with the first investigation for Belfast, using input parameters that are considered base values (U-value 2.7 W/m^{2}K) as shown in Table 8, to determine the impact on space cooling and heating. The space heating is generated from natural gas and electrical air conditioning, as is typical in Italy. Figure 18 illustrates the difference in yearly ambient temperatures for Belfast and Naples. On average, monthly temperature in Naples are 50% higher than Belfast throughout the year.

Table 8 Input parameters for the IESVE model in Naples for the CoPVG and traditional glazing

Parameters	Model 1&2 Inputs
Room dimensions	10 × 7 × 2.7 m
Room type	Office
Gas boiler for space heating	95% efficiency
Air conditioning SCoP	2.5
Room Heating & Cooling set-points	19 °C,23 °C
Room orientation	South
Area/Type of glazing	19.2m^2 Traditional glazing
Area/Type of glazing	19.2m^2 Glazing with the CoPVG proxy
Location	Naples, Italy
Internal surfaces	solar absorption set to 0.5
U-value (W/m^{2}K)	Traditional Glazing:2.7, CoPVG:2.7, floor:0.2, roof:0.18, ext.wall:0.26.
Improved u-value for glazed elements(W/m^{2}K)	Traditional Glazing:1.2, CoPVG:0.8
Wall and glazing surface inclination	90° from horizontal, south-façade
Glazing transmissivity	Set to 0.80 or 80%

These annual ambient temperatures reflect the need for either space heating or space cooling in each location, with Naples generally requiring more space cooling for a

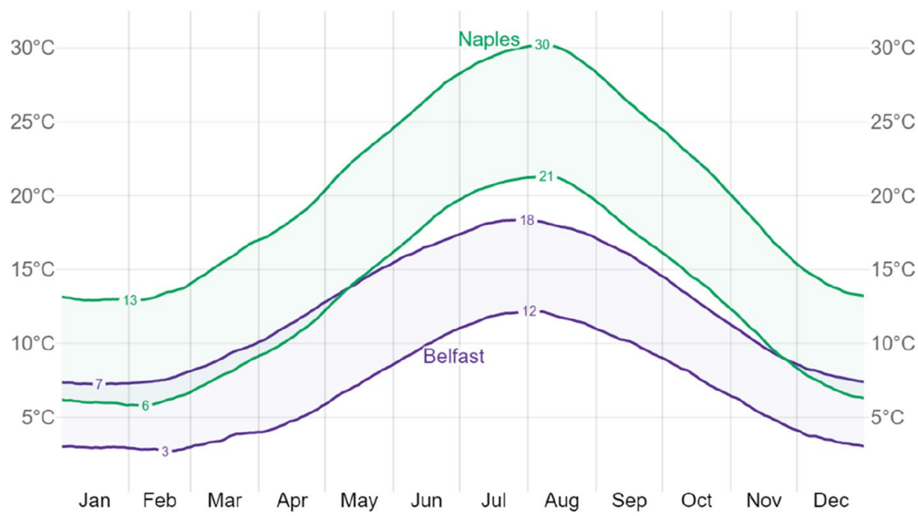


Fig. 18 The annual ambient air temperatures for Belfast and Naples. (Weatherspark, 2022)

larger portion of the year compared to Belfast where the main energy requirement is space heating.

5.2.1 Solar gain in Naples

Consistent with the previous section and the CoPVG in Belfast, the integration of the CoPVG on a south facing façade in Naples Italy, resulted in a reduction in the solar gain into the building throughout the year.

Figure 19 shows the monthly solar gain for the building in Naples. The largest monthly difference in solar gain occurs in August (852.3kWh) whilst the smallest solar gain is January (325.9kWh). These figures, as previous, reflect the savings in electrical cost (cooling loads), and increase in gas costs (heating loads). Figure 20a illustrates the monthly space cooling for both systems. The peak monthly total for space cooling occurs in August, relative to the solar gain. The CoPVG again directly reduces solar gain in the space, thus reducing the space cooling load.

The demand for space heating, as previously shown in Belfast, had increased with the integration of the CoPVG. Figure 20b shows a zero value for space heating for April to October in Naples, resulting in a minimal increase in heating for Naples, relative to Belfast. Table 9 shows the annual kWh loads and costs related to the reduction in space cooling and increase in space heating when the CoPVG is compared to traditional glazing in Naples. The total reduction in the space cooling load is 2554.3kWh equating to £789.28 and the deficit in space heating is 1204.5kWh equating to £142.13, based on the most

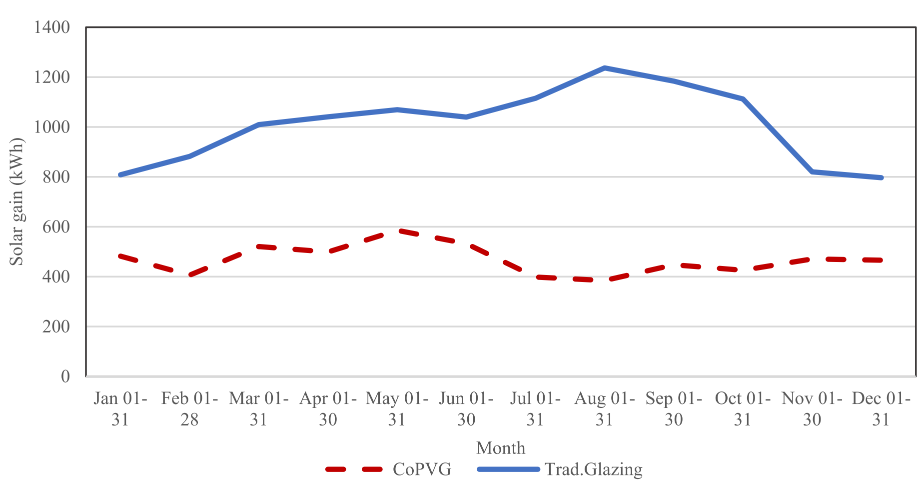


Fig. 19 Monthly solar gain for the CoPVG and traditional glazing on a south facing facade in Naples

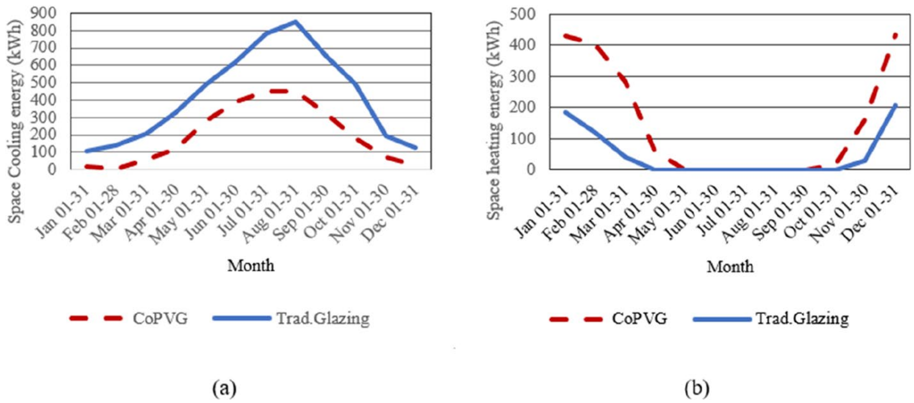


Fig. 20 Monthly space cooling energy (**a**) and space heating energy (**b**) totals using the CoPVG and traditional glazing for Naples

Table 9 A summary of the differences of cooling and heating when using the CoPVG compared to traditional glazing and associated monthly yearly costs in Naples

Month	Cooling Reduction (kWh) (−)	Heating Surplus (kWh) (+)	Cooling Savings (£)	Heating Surplus (£)
Jan 01–31	86.9	244.9	26.85	28.90
Feb 01–28	134.2	284.5	41.47	33.57
Mar 01–31	158.1	241.4	48.85	28.49
Apr 01–30	205.9	58.9	63.62	6.95
May 01–31	186.9	0.1	57.75	0.01
Jun 01–30	214.5	0	66.28	0
Jul 01–31	329.6	0	101.85	0
Aug 01–31	399.1	0	123.32	0
Sep 01–30	315.9	0	97.61	0
Oct 01–31	305.7	18.3	94.46	2.16
Nov 01–30	120.5	129	37.23	15.22
Dec 01–31	97.1	227.4	30.00	26.83
Summed total	2554.3	1204.5	789.28	142.13

recent commercial tariffs for electricity and gas in Naples at €0.309 (£0.27) and €0.118 (£0.10), respectively.

5.2.2 Improving the U-values for Naples

As was investigated in Belfast, the U-value for both traditional glazing and the CoPVG is improved for the Naples models. The U-values improved from 2.7 W/m^{2}K to 1.2 W/m^{2}K (for Model 1 using double glazing) and 0.8 W/m^{2}K (for Model 2 for the improved CoPVG), using the input parameters from Table 8.

Figure 21a illustrates the monthly space cooling loads for the improved CoPVG and traditional glazing systems in Naples, whilst Fig. 21b illustrates the space heating. The improved U-value significantly reduces the space heating demand when compared to the original CoPVG, but as previously seen, the biggest gains are presented in cooling load savings. Figure 22 presents the combined annual energy loads, illustrating the impact on the building's thermal performance.

From Fig. 22 and Table 10 it is evident that the highest annual energy load is in cooling and with traditional glazing (U-value of 2.7 W/m^{2}K). A 55% reduction in cooling loads is produced by applying the IU CoPVG (0.8 W/m^{2}K) over the base case, traditional glazing and a 33% improvement in heating. Comparing the improved systems, we again see the impact that the CoPVG makes on the cooling load. The IU CoPVG requires 2250.9kWh cooling opposed to the 4558.6kWh for the IU traditional glazing. For space heating, the difference is less dramatic, with the IU CoPVG requiring 390.5kWh opposed to the 114.1kWh for the IU traditional glazing.

The annual carbon emissions for space cooling with traditional glazing was (4981kWh ×0. 226 kg.CO_2e/kWh) 1125.7 kg of CO_2 per year. With the integration of the CoPVG (2370.4kWh ×0. 226 kg.CO_2e/kWh) 535.7 kg of CO_2 per year there is a reduction in carbon emissions of 590 kg of CO_2 per year (52% reduction).

Table 11 shows the differences in energy used and the subsequent savings/additional costs. Based on the most recent commercial tariffs for electricity and gas in Naples at €0.309 (£0.27) and £0.118 (£0.10), respectively, there is only a slight increase in heating costs, 276.4kWh equating to £32.62, but a substantial saving in cooling loads, 2307.7kWh at £713.08. The cooling savings is significantly higher than the heating deficit, yielding a £681 gain, highlighting the use of the CoPVG for cooling dominated climates.

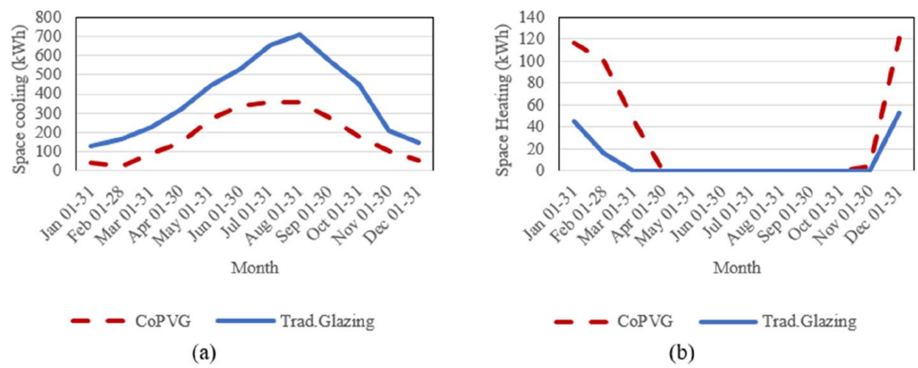


Fig. 21 Monthly comparisons of space cooling energy (**a**) and space heating energy (**b**) with the IU CoPVG and IU traditional glazing in Naples

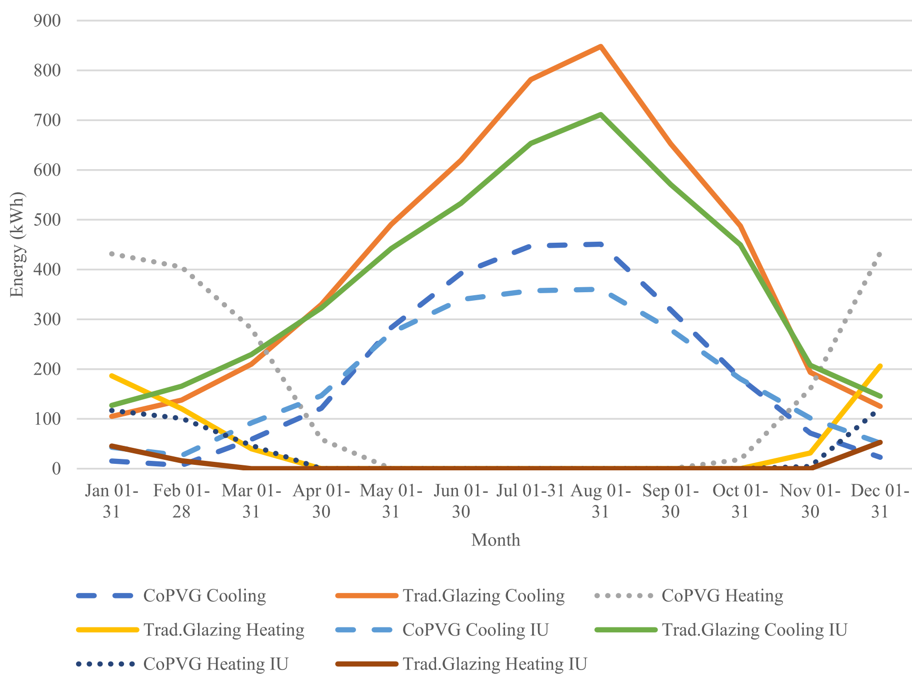


Fig. 22 Energy usage for the CoPVG integration with low and high U-values and the use of traditional glazing with high and low U-values for Naples

5.3 Comparing the CoPVG for Belfast and Naples

Figure 23 illustrates the combined energy costs for heating and cooling for both Belfast and Naples using the improved configurations. It is noticeable that the dominant use of energy is depicted from the space cooling in Naples using traditional glazing. The integration of the CoPVG significantly reduces these monthly totals and overall annual with the largest savings for cooling of £713.08. Table 12 shows a summary in the carbon emissions reduction (−) and surplus (+) per year for both Naples and Belfast. The data is taken from comparing the use of traditional glazing and the CoPVG both with improved U-values. Consistent with the energy figures, cooling in Naples shows the largest reduction in carbon emissions.

6 Conclusion

The results from the study are shown to validate the use of the CoPVG system when it is simulated using the commercial tool - IESVE. This validation has enabled the system's parameters, such as U-values, geographical location, etc. to be changed and compared (with traditional glazing), and the impact on a building's heating and/or cooling energy usage determined.

Table 10 Annual energy usage for heating and cooling using improved U-values for the CoPVG and traditional glazing for Naples

Month	CoPVG Cooling (kWh)	Trad.Glazing Cooling (kWh)	CoPVG Heating (kWh)	Trad.Glazing Heating (kWh)	CoPVG Cooling IU (kWh)	Trad.Glazing Cooling IU (kWh)	CoPVG Heating IU (kWh)	Trad.Glazing Heating IU (kWh)
U-value (W/m^{2}K)	2.7	2.7	2.7	2.7	0.8	1.2	0.8	1.2
Jan 01–31	15.3	105	431.4	186.5	42.9	127.1	116.9	45.4
Feb 01–28	6.7	137.6	404.9	120.4	26.3	165.7	100.8	15.8
Mar 01–31	58.9	210	281.2	39.8	92	229.5	46.9	0
Apr 01–30	121.3	329.7	58.9	0	146.7	322.9	0	0
May 01–31	283.1	490.7	0.1	0	273.1	442	0	0
Jun 01–30	392.2	619.4	0	0	339.8	533	0	0
Jul 01–31	447.3	781.7	0	0	357.3	653.4	0	0
Aug 01–31	450.9	848.1	0	0	360.3	711.3	0	0
Sep 01–30	319.2	652.6	0	0	279.4	570.8	0	0
Oct 01–31	181.2	487.6	18.3	0	180.5	449.7	0	0
Nov 01–30	71.5	193.4	160.4	31.4	101.4	207.8	4.4	0
Dec 01–31	22.8	125.2	433.6	206.2	51.2	145.4	121.5	52.9
Summed Total	2370.4	4981	1788.8	584.3	2250.9	4558.6	390.5	114.1
Total Carbon Emissions (kgCO_2)	535.7	1125.7	404.3	132.1	508.7	1030.2	88.3	25.8

Table 11 A summary of cooling and heating when using CoPVG compared to traditional glazing and associated monthly cooling and heating costs for a room in Naples using improved U-values for the CoPVG (0.8 W/m^{2}K) and traditional glazing (1.2 W/m^{2}K)

Month	Cooling reduction (kWh) (−)	Heating surplus (kWh) (+)	Cooling savings (£)	Heating Surplus (£)
Jan 01–31	84.2	71.5	26.02	8.44
Feb 01–28	139.4	85	43.07	10.03
Mar 01–31	137.5	46.9	42.49	5.53
Apr 01–30	176.2	0	54.45	0
May 01–31	168.9	0	52.19	0
Jun 01–30	193.2	0	59.70	0
Jul 01–31	296.1	0	91.49	0
Aug 01–31	351	0	108.46	0
Sep 01–30	291.4	0	90.04	0
Oct 01–31	269.2	0	83.18	0
Nov 01–30	106.4	4.4	32.88	0.52
Dec 01–31	94.2	68.6	29.11	8.09
Total	2307.7	276.4	713.08	32.62

The results have shown that the integration of the CoPVG has the best cost saving potential for buildings in reducing cooling loads when integrated into a south facing façade.

In Belfast, the benefits are marginal, even with the IU CoPVG format. A building with the IU CoPVG requires 2365.5kWh heating opposed to the 1666.4kWh for IU traditional glazing equating to a heating deficit of 699.1kWh (£119.96 at current prices). The same system comparison requires 987.9kWh of cooling opposed to 1691kWh for the IU traditional glazing, giving an energy saving of 703.1kWh (£207.55 at current prices). The savings are better when the IU CoPVG format is compared to traditional double glazing, with a 36% improvement in heating usage and 53% improvement in space cooling.

The fact that the system has been shown to operate more effectively in a cooling dominated climate is demonstrated by the analysis of the system in Naples. Comparing the two improved versions (IU CoPVG and IU glazing, 0.8 W/m^{2}K and 1.2 W/m^{2}K, respectively), the building with the IU CoPVG requires 390.5kWh heating opposed to the 114.1kWh for IU traditional glazing equating to a heating deficit of 276.4kWh (£32.62 at current prices). The same system comparison requires 2250.9kWh of cooling opposed to 4558.6kWh for the IU traditional glazing, giving an energy saving of 2307.7.1kWh (£713.08 at current prices). The proportional savings in Carbon Emissions (kgCO2) mirror this outcome, indicating the greatest potential savings occur in a cooling dominated region.

In conclusion, the IU CoPVG, installed with a WWR of 1, covering 19.2m^2 yields a potential £681 per year in savings (35.50 £/m^2). If these numbers are extrapolated, it is possible to determine the economic payback parameters for the IU CoPVG and therefore the permissible additional cost per unit installed compared

Fig. 23 Monthly cooling and heating costs for using the CoPVG and traditional glazing improved U-value for Belfast and Naples

Table 12 The differences in carbon emissions per annum for space heating and cooling in Belfast and Naples with and without the CoPVG

Carbon Emissions difference with improved u-values	Belfast Cooling	Belfast Heating	Naples Cooling	Naples Heating
Total Difference (kgCO2/year)	(–) 258.8	(+) 180.4	(–) 521.5	(+) 62.5

traditional façade window costs over the unit's operational lifespan. Further work will include the full techno-economic evaluation of the IU CoPVG over a range of differing climatic locations, various WWRs, areas of deployment and impact of façade orientations coupled with a wider investigation looking at comparisons with other traditional shading devices.

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Conflict of interest

We declare that we have no conflict of interest in conducting this research. We have no financial or personal connections that could potentially bias our findings or influence our interpretation of the results. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Authors' contributions

Roma Chang: Model development, formal analysis, investigation, data curation, writing-original draft, visualisation. Jayanta Deb Mondol: Technology development, methodology, supervision, review & editing. Aggelos Zacharopoulos: Conceptualisation, technology development, methodology. Mervyn Smyth: Methodology, writing- review & editing, visualisation, supervision. Adrian Pugsley: Model development, methodology, writing- review & editing, supervision.

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Availability of data and materials

Data are available upon request. Please email chang-r@ulster.ac.uk.

Declarations

Ethics approval and consent to participate

All authors were fully informed of the study to make fully informed decisions in the participation of this research.

Consent for publication

All authors have consented to the participation of this publication.

Competing interests

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

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