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Component-based SHGC determination of BIPV glazing for product comparison

Helen Rose Wilson [a,*], Tilmann E. Kuhn [a], Hisashi Ishii [b], Daniel Valencia-Caballero [c], Nuria Martin Chivelet [d], Jinqing Peng [e], Rebecca Jing Yang [f], Yukun Zang [f], Hua Ge [g], Kai Ye [g], Jacob C. Jonsson [h], Konstantinos Kapsis [i]

[a] *Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany*
[b] *LIXIL Corporation, LIXIL Housing Technology, Technology Research Institute, Nakasato 3000, Noda City, Chiba, Japan*
[c] *TECNALIA, Basque Research and Technology Alliance (BRTA), Paseo Mikeletegi 2, San Sebastián 20009, Spain*
[d] *CIEMAT, Photovoltaic Solar Energy Unit, Avda. Complutense 40, 28040 Madrid, Spain*
[e] *College of Civil Engineering, Hunan University, Changsha 410082, Hunan, China*
[f] *RMIT University, Melbourne, VIC 3000, Australia*
[g] *Concordia University, 1455 de Maisonneuve Blvd. W., Montreal H3G 1M8, Canada*
[h] *Windows and Daylighting Group, LBNL, 1 Cyclotron Road, Mail Stop 90R3111, Berkeley, CA 94720-8134, USA*
[i] *University of Waterloo, 200 University Avenue West, CPH 3666, Waterloo, Ontario N2L 3G1, Canada*

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ABSTRACT

Building-integrated photovoltaic (BIPV) systems are intrinsically designed to generate electricity and to provide at least one building-related function. When BIPV modules act as glazing products in windows, skylights or curtain walls, their ability to control the transmission of solar energy into the building must be characterised by a Solar Heat Gain Coefficient (SHGC) or g value (also known as Total Solar Energy Transmittance – TSET – or "solar factor"). For the comparison of BIPV glazing products consisting of one PV laminate and possibly further, conventional glazing layers separated by gas-filled cavities, the procedures documented in international standards for architectural glazing (e.g. ISO 9050 and EN 410) form a suitable starting point. Easily implemented modifications to these procedures are proposed to take both optical inhomogeneity (if relevant) and extraction of electricity from BIPV glazing units into account. Geometrically complex glazing and shading devices, and light-scattering glazing layers, are outside the scope of the proposed methodology; SHGC determination for obliquely incident solar radiation is also excluded. For these cases, the experimental calorimetric approach documented in [ISO 19467:2017; ISO 19467-2:2021] is recommended.

The paper also presents results and conclusions from an implementation exercise and sensitivity study carried out by participants of the IEA-PVPS Task 15 on BIPV. The cell coverage ratio in the PV laminate, the thermal resistance offered by the glazing configuration, the choice of boundary conditions and the effect of extracting electricity were all identified as parameters which significantly affect the SHGC value determined for a given type of BIPV glazing. A practicable approach to accommodate the great variety of dimensions typical for BIPV glazing is also proposed. These findings should pave the way for modifying the existing component-based standards for architectural glazing to take the specific features of BIPV glazing into account.

1. Introduction

Since the 1970's, architectural glazing has evolved from single glazing to multiple-pane glazing units containing coated glass panes and gas-filled cavities that provide effective thermal insulation. With thermal transmittance values of 1.2 $Wm^{-2}K^{-1}$ and less being achieved by commercially available glazing units, they provide adequate thermal

* Corresponding author.
E-mail addresses: helen.rose.wilson@ise.fraunhofer.de, testlab-solarfacades@ise.fraunhofer.de (H.R. Wilson), tilmann.kuhn@ise.fraunhofer.de (T.E. Kuhn), hisashi.ishii@lixil.com (H. Ishii), daniel.valencia@tecnalia.com (D. Valencia-Caballero), nuria.martin@ciemat.es (N. Martin Chivelet), jallen.peng@gmail.com (J. Peng), rebecca.yang@rmit.edu.au (R.J. Yang), s3679970@student.rmit.edu.au (Y. Zang), hua.ge@concordia.ca (H. Ge), kai.ye@mail.concordia.ca (K. Ye), jcjonsson@lbl.gov (J.C. Jonsson), costa.kapsis@uwaterloo.ca (K. Kapsis).

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Nomenclature

AM	Air mass
BIPV	Building-integrated photovoltaics
CR	Coverage ratio
DGU	Double glazing unit
MPP	Maximum power point
OC	Open circuit
PV	Photovoltaic
RRT	Round robin test
SHGC	Solar heat gain coefficient (or g value)
TSET	Total solar energy transmittance (or g value)
A_{cell}	surface area covered by PV cells within the total PV module area
A_{inact}	surface area covered by electrically inactive material (e.g. transparent encapsulant) between PV cells within the total PV module area
$A_{intercon}$	surface area covered by interconnectors between PV cells within the total PV module area
A_{jb}	surface area covered by the junction box within the total PV module area
A_{mod}	total PV module area
g	Total Solar Energy Transmittance (or SHGC or solar factor)
h_{in}	heat transfer coefficient towards the inside (Wm^{-2} K^{-1})
h_{out}	heat transfer coefficient towards the outside (Wm^{-2} K^{-1})
q_i	secondary heat transfer factor of the glazing towards the inside
r_{cell}	ratio of surface area covered by PV cells to total PV module area (= cell coverage ratio CR)
r_{inact}	ratio of area covered by electrically inactive material (e.g. transparent encapsulant) between PV cells to total PV module area
$r_{intercon}$	ratio of total interconnector area to total PV module area
r_{jb}	ratio of junction box area to total PV module area
T_{in}	indoor glazing surface temperature (°C)
T_{out}	outdoor glazing surface temperature (°C)
U	thermal transmittance without irradiance (Wm^{-2} K^{-1})
α_e	solar direct absorptance
α_{e1}	solar direct absorptance of the outer pane within a double glazing unit
α_{e2}	solar direct absorptance of the second pane within a double glazing unit
$\alpha_i(\lambda)$	absorptance spectrum of the isolated *i*th glazing layer for radiation incident on the outdoor-facing surface
$\alpha'_i(\lambda)$	absorptance spectrum of the isolated *i*th glazing layer for radiation incident on the indoor-facing surface
ε_{in}	emissivity of an indoor-facing surface of a glazing layer
ε_{out}	emissivity of an outdoor-facing surface a glazing layer
Λ	total thermal conductance of a glazing unit (single or multiple-pane glazing)
η	power conversion efficiency of a PV device (irradiation of outdoor-facing surface)
η'	power conversion efficiency of a PV device (irradiation of indoor-facing surface)
ρ_e	solar direct reflectance
$\rho_i(\lambda)$	reflectance spectrum of the isolated *i*th glazing layer for radiation incident on the outdoor-facing surface
$\rho'_i(\lambda)$	reflectance spectrum of the isolated *i*th glazing layer for radiation incident on the indoor-facing surface
τ_e	solar direct transmittance
$\tau_i(\lambda)$	transmittance spectrum of the isolated *i*th glazing layer

insulation and are installed over large areas of building facades. Solar radiation that enters the building provides welcome natural lighting and reduces the demand for space heating in winter, but may cause overheating in summer. Already in the 1990′s, a new metric was introduced to quantify the total amount of solar radiation transmitted by glazing into the building [1–3]. This metric, variously designated as Total Solar Energy Transmittance (TSET), solar factor, Solar Heat Gain Coefficient (SHGC) or g value, takes account of both directly transmitted solar radiation and absorbed solar radiation that is transferred indoors as heat [4].

Semi-transparent building-integrated (BIPV) glazing represents a further development of architectural glazing which combines the classic optical and energy-transmitting functions of transparent areas and the shading functions of opaque areas with the electricity generation of PV cells. As has been documented in a number of experimental studies [5–9], the extraction of photovoltaically generated electricity from the BIPV glazing unit acts to lower the SHGC value of the window. In this paper, a component-based calculation method is proposed for BIPV glazing that can be readily integrated into SHGC determination methods that are already documented in standards for characterising and comparing glazing products under standardised boundary conditions. Like the underlying standards, application of the proposed method is limited to normally incident solar radiation and glazing products that consist of one PV laminate and conventional, planar glazing layers separated by gas-filled cavities. Fig. 3 shows an example of such a glazing configuration. If the PV laminate or the glazing layers contain air-permeable "holes" [10], they cannot be treated by the presented approach. The treatment of a BIPV glazing unit containing strongly light-scattering layers is also excluded from this approach. Development of a more sophisticated calculation-based dynamic approach that is based implicitly on [11] and is commensurate with the needs of building energy simulation has been introduced by Zhou et al. [12] but is not the topic addressed here. Geometrically complex glazing (including that containing strongly light-scattering layers) and shading devices, and SHGC determination for obliquely incident radiation, are outside the scope of the proposed methodology; for these cases, the experimental calorimetric approach documented in ISO 19467-1:2017 and ISO 19467-2:2017 [13,14] is recommended.

What is explicitly addressed in the proposed methodology are features commonly encountered in BIPV glazing units, namely optical inhomogeneity of the PV "glazing layer", analogously to Annex C of EN 410, and extraction of the photovoltaically generated electricity.

2. Principles of component-based SHGC determination for glazing product characterisation

The basic definition for SHGC, the fraction of incident solar radiation which is transmitted directly or by re-radiation through architectural glazing into the indoor space of a building, is expressed mathematically in Eq. (1) as

$$g = \tau_e + q_i \quad (1)$$

where g is the SHGC, τ_e is the solar direct transmittance of the glazing unit and q_i is the secondary heat transfer factor towards the inside. As documented in ISO 9050:2003 [15], EN 410:2011 [16] or NFRC 300-2023 [17], the transmittance spectrum for a glazing unit $\tau(\lambda)$ is calculated by multi-layer optical calculations from the transmittance and reflectance spectra of the component panes. All spectra are determined for radiation that is (near-)normally incident on the characterised sample. The solar direct transmittance for the glazing unit τ_e is calculated by weighting the transmittance spectrum by a specified solar spectrum, which is based on the spectral distributions for AM1.0 global in EN 410:2011 [16], AM1.5 global in ISO 9050:2003 [15] or AM1.5 direct in NFRC 300-2023 [17], respectively. Similarly, the solar direct absorptance for radiation incident on the outdoor-facing surface of the ith glazing layer within the glazing unit, α_{ei}, is also calculated by multi-layer optical calculations from the transmittance and reflectance spectra of the component panes (the "glazing layers") and weighting by the specified solar spectrum.

Each of the component glazing layers is characterised by its transmittance spectrum $\tau(\lambda)$ and reflectance spectra $\rho(\lambda)$ and $\rho'(\lambda)$ for radiation normally incident on the outdoor-facing and indoor-facing surfaces, respectively. The transmittance and reflectance spectra are measured for each glazing layer separately and serve as input data for the multi-layer calculations. For each individual glazing layer i in isolation (i.e. not within the glazing unit), the absorptance spectrum $\alpha_i(\lambda)$ for the outdoor-facing surface is calculated according to Eq. (2) as

$$\alpha_i(\lambda) = 1 - \tau_i(\lambda) - \rho_i(\lambda) \tag{2}$$

where $\tau_i(\lambda)$ is the transmittance spectrum of the ith glazing layer and $\rho_i(\lambda)$ is the reflectance spectrum for radiation incident on the outdoor-facing surface of the ith glazing layer. The analogous equation for the absorptance spectrum $\alpha'_i(\lambda)$ for the indoor-facing surface is given by Eq. (3) as

$$\alpha'_i(\lambda) = 1 - \tau_i(\lambda) - \rho'_i(\lambda) \tag{3}$$

where $\tau_i(\lambda)$ is the transmittance spectrum of the ith glazing layer and $\rho'_i(\lambda)$ is the reflectance spectrum for radiation incident on the indoor-facing surface of the ith glazing layer.

It is emphasised that Equations (2) and (3) refer to the absorptance spectra for the individual, isolated glazing layers. The absorptance spectra for the ith glazing layer within a multiple-pane glazing unit containing two or more layers are modified by the presence of the other panes and must be calculated using the multi-layer approach documented in e.g. [15,16] or [17].

As the spectra are determined for normally incident radiation, the multi-layer calculations are not valid for strongly scattering layers and the results obtained for slightly scattering layers will have a larger error than for the originally foreseen "glass-clear" transparent layers.

In the original versions of the standards EN 410 and ISO 9050 for conventional architectural glazing, it is assumed that all of the absorbed solar radiation is converted to heat and is transported by conduction, convection or radiation either to the outdoor or the indoor environment. The cited standards follow the conventions, methods and sets of boundary conditions set out in the parallel standards for calculating the steady-state thermal transmittance U for the centre of glass of architectural glazing, [18,19], for product comparison. One-dimensional heat transport through the glazing unit is assumed, neglecting any lateral flows or edge effects. The thermal resistance $1/U$ caused by the glazing unit between the outdoor and the indoor environment is modelled as the sum of resistances corresponding to external and internal surface heat transport, conduction through the solid glazing layers, and conduction, convection and radiation within the gas-filled cavities between panes. Thermal properties for glass, low-e coatings and the commonly used gases for inter-pane cavities are specified in these standards. For product comparison purposes, standardised values for the external and internal heat transfer coefficients are also provided. Based on the thermal properties of the component materials, the thicknesses of the component layers and the specified boundary conditions, the U value of a complete glazing unit can be calculated by applying a one-dimensional series resistance model. The same approach can be applied to calculate the partial resistances between the different glazing component surfaces.

Once the solar direct absorptance α_{ei} for each ith glazing layer within the glazing unit and the partition of thermal resistances, as defined above, are known, the proportion of incident solar radiation that is absorbed within the glazing unit and is transported indoors, q_i, can be calculated by the equations specified in EN 410 or ISO 9050. Corresponding to the U-value calculations, the form of the equations for q_i varies with the number of panes in the glazing unit. Specifically, for single glazing consisting only of a PV laminate, the equation specified in EN 410 or ISO 9050 for q_i is

$$q_i = a_e h_{in} / (h_{out} + h_{in}) \tag{4}$$

where α_e is the solar direct absorptance of the PV laminate as described above and h_{out} and h_{in} are the heat transfer coefficients towards the outside and inside, respectively, as specified in EN 673:2011 [18] or ISO 10292:1994 [19].

Making use of the definition of the thermal transmittance U from EN 673:2011 [18] or ISO 10292:1994 [19] as

$$1/U = 1/h_{out} + 1/\Lambda + 1/h_{in} \tag{5}$$

where h_{out} and h_{in} are defined as above and Λ is the total thermal conductance of the glazing, Eq. (4) for single glazing can be reformulated as

$$q_i = \alpha_e U / (h_{out}(1 - \mathrm{U}/\Lambda)) \tag{6}$$

Taking into account that the thermal conductance Λ of a PV laminate is about 20 times larger than the corresponding U value, Eq. (6) for a PV laminate can be approximated as

$$q_i \cong \alpha_e U / h_{out} \tag{7}$$

indicating a nearly linear dependence of q_i on α_e and U/h_{out}.

An analogous reformulation of the expression for q_i of double glazing from EN 410 or ISO 9050 results in the equation

$$q_i = \alpha_{e1} U / h_{out} \alpha_{e2} (U / h_{out} + \mathrm{U}/\Lambda) \tag{8}$$

where α_{e1} and α_{e2} are the solar direct absorptance values of the outer and inner panes within a double glazing unit, respectively, and the remaining terms are as defined above. Again, there is a linear dependence of q_i on α_{e1}, the absorptance in the outer pane (the most common position for the PV pane in double glazing), and on U/h_{out}.

3. Features of semi-transparent BIPV glazing

There are two main features of semi-transparent BIPV glazing which distinguish it from most conventional architectural glazing and which demand modifications in the approach to determine the SHGC value.

The defining property of BIPV glazing is its ability to convert incident solar radiation to electricity by the photovoltaic effect. This means that the assumption stated above for conventional architectural glazing, "that all of the absorbed solar radiation is converted to heat", no longer applies. When the PV layer of a BIPV glazing unit is connected to an external electric circuit, some of the absorbed solar radiation is extracted as electricity and removed from the glazing unit; the amount of heat which can be transported indoors is reduced, decreasing the SHGC value of the BIPV glazing unit.

As illustrated in Fig. 1 and Fig. 3, the second, frequently encountered property of semi-transparent BIPV glazing is optical inhomogeneity at a macroscopic level, meaning that different regions of the glazing unit are characterised by different transmittance and reflectance properties. Most commonly, the "photovoltaic glazing layer" consists of a PV glass-glass laminate or a glass-backsheet laminate, where one main area is occupied by crystalline silicon PV cells and a second significant area is transparent, with a transparent encapsulation material such as ethylene vinyl acetate (EVA) or polyvinyl butyral (PVB) embedded between the front and back covers. There may also be significant areas covered by metal interconnectors between the cells or by an electronic junction box that is exposed to solar radiation and thus is visible from outdoors. Phovoltaic glazing based on inorganic thin-film technology may also consist of different macroscopic areas alternating between coated and laser-ablated areas to provide areas for clear vision. (The fine laser-

Fig. 1. PV semi-transparent glazing manufactured by Onyx Solar and installed in the Kubik experimental building at Tecnalia facilities in Derio, Spain, within the BIPVBoost project.
Source: Eneko Setien, Tecnalia

ablated lines that are intrinsic to the construction of inorganic thin-film PV modules are not usually treated as "optically different" areas because of their small dimensions compared to the beam cross-sections used to determine optical properties spectrophotometrically. In this case, the PV laminate can be treated as optically homogeneous.) In principle, organic PV glazing with differently coloured PV regions may also be characterised by the proposed approach, providing that not only the optical properties but also the power conversion efficiency is available for each different PV region, and the different PV regions are not connected electrically in series.

An approach to take these features of BIPV modules into account is described in detail in the following two Sections 4 and 5. An overview of the procedure and references to the relevant Subsections is provided by Fig. 2.

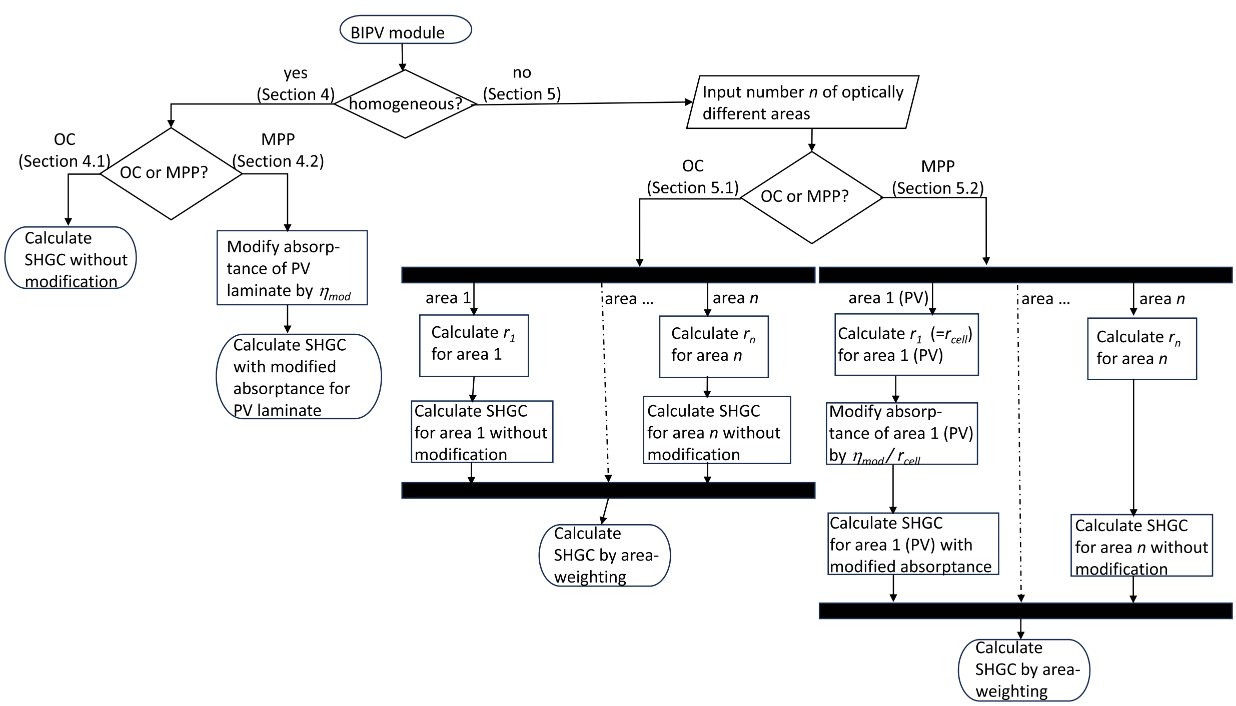

Fig. 2. Flow chart outlining the modifications needed to take optical inhomogeneity (if relevant) and extraction of electricity into account when calculating the SHGC of BIPV modules. Details are provided in the indicated Sections of this paper.

4. Proposed modification to SHGC determination to account for photovoltaic conversion of incident solar radiation on an optically homogeneous BIPV glazing unit

4.1. Open-circuit case

If the cells of a BIPV glazing unit are exposed to solar radiation but are not connected to an external circuit, i.e. are in the open circuit (OC) state, all of the absorbed solar radiation is converted to heat. If the whole area of the glazing unit can be considered to be homogeneous, as is often the case for organic and inorganic thin-film photovoltaics, the method for determining the SHGC of the BIPV glazing in the OC state is identical to that for non-photovoltaic glazing, based on measurements of the transmittance and reflectance spectra for the PV laminate and any other further panes of the glazing unit, i.e. no modification to the SHGC determination procedure is necessary.

4.2. Maximum-power-point case

Still considering the optically homogeneous case, but with the PV laminate connected to an external electric circuit, some of the absorbed solar radiation is converted photovoltaically into electricity and is extracted from the BIPV glazing. For a PV module in the form of a single PV laminate (i.e. not within a BIPV glazing unit), the photovoltaic conversion efficiency is defined in IEC TS 61836:2016 [20] as the "ratio of electric power generated by a PV device per unit area to its incident irradiance". Introducing the symbol η_{mod} for this quantity, the extraction of electricity from an optically homogeneous BIPV glazing unit can thus be taken into account by modifying Eq. (2). For the isolated *i*th layer that consists of the optically homogeneous PV laminate, the absorptance spectrum $\alpha_i(\lambda)$ for the outdoor-facing surface is given by Eq. (9):

$$\alpha_i(\lambda) = 1 - \tau_i(\lambda) - \rho_i(\lambda) - \eta_{mod,i} \tag{9}$$

where $\tau_i(\lambda)$ is now specifically the transmittance spectrum of the PV laminate, $\rho_i(\lambda)$ is the reflectance spectrum for radiation incident on the outdoor-facing surface of the PV laminate and $\eta_{mod,i}$ is the power conversion efficiency of the homogeneous PV module (i.e., the PV laminate).

Most commonly, the PV module will be the external layer of the BIPV glazing unit, in which case $i = 1$ in Eq. (9). However, Eq. (9) is also valid if the PV module is included in a different position and the glazing layers located between the solar radiation and the PV module feature spectrally constant optical properties, such that the use of a constant value for $\eta_{mod,i}$ is justifiable. This condition of spectral constancy is fulfilled sufficiently by panes of low-iron glass, which would be an advisable choice for panes positioned between the solar radiation and the PV module to minimize the loss in generated electricity due to absorption in the intervening panes. The condition of spectral constancy is not met e.g. by low-e coated glass. In this case, the spectrum of the radiation incident on the PV module differs significantly from that specified in [21] for determination of $\eta_{mod,i}$. In that case, the relevant value for $\eta_{mod,i}$ would have to be redetermined, taking the spectral response of the PV module into account. Considering firstly, that the spectral response is not usually supplied by PV module manufacturers, and secondly, that the PV module will be the outer pane in the great majority of BIPV multiple-pane glazing units, the authors have decided to retain Eq. (9) in the presented simple form. As a corollary, its use will lead to errors if it is applied to multiple-pane BIPV glazing with the PV module "behind" glazing layers with strong spectral variation of the transmittance. The magnitude of the error depends on the combination of the PV spectral response and the spectral variation of the glazing transmittance.

To obtain the SHGC value of the complete BIPV glazing unit, Eq. (2) is replaced by Eq. (9) for the *i*th layer that consists of the PV laminate in the multi-layer calculations documented in EN 410:2011 [16] or ISO 9050:2003 [15]. For monofacial PV laminates, Eq. (3) remains unchanged. For bifacial PV laminates, it would be necessary to differentiate between the values of $\eta_{mod,i}$ for irradiation of the outdoor-facing and indoor-facing surfaces. Equation (3) would need to be modified by subtracting the value of $\eta'_{mod,i}$ for irradiation of the indoor-facing surface. In addition, the use of a single value for $\eta'_{mod,i}$ is permissible only if the relative spectral distribution of the radiation incident on this indoor-facing surface agrees sufficiently with that of the solar spectrum used for spectral weighting. This would not be the case e.g. for solar radiation after reflection by a glass pane with a low-e coating.

The module photovoltaic conversion efficiency $\eta_{mod,i}$ is usually based on the maximum power point (MPP) value, meaning the point on the current-voltage characteristic for the module at which maximum power can be extracted. As noted in IEC TS 61836 [20], the photovoltaic conversion efficiency is "typically measured under standard test conditions (STC)", which are defined in the same document as "in-plane irradiance … = 1 000 Wm^{-2}, PV cell junction temperature (25 °C) and air mass (AM) = 1.5". Among these conditions, the PV cell temperature is the most influential parameter on PV efficiency in the solar-shading context and mainly depends on ambient temperature and solar irradiance (PV efficiency typically decreases between 0.4% and 0.2% for every degree increase in cell temperature) [22]. In BIPV applications, the PV cell junction temperature usually reaches values above 25 °C. In addition, the radiation is normally incident on the module during the test measurement, whereas the solar radiation is often obliquely incident on BIPV arrays, resulting in higher reflection losses. Standard test conditions are thus more favourable for photovoltaic electricity generation than those that are usually experienced in building-integrated applications, so for practical purposes concerning SHGC determination for product characterisation, the value of $\eta_{mod,i}$ can be considered to represent an upper limit for the electricity extracted from a BIPV glazing unit. In other words, the SHGC value determined according to the proposed method under MPP conditions will be lower than is frequently encountered in reality. Again, it is emphasized that this method is intended to enable product comparison under well-defined conditions; it is not intended for use in building energy simulations.

Although the photovoltaic conversion of radiation to electricity has a spectral dependence which is characterized by the spectral response of the photovoltaic device, the integral value of $\eta_{mod,i}$ is considered to be adequate for the purpose of product characterization addressed in this paper. (Exceptions have been noted in the discussion above on Eq. (9) and the special case of a bifacial PV laminate within a multi-layer BIPV glazing unit. In such cases, $\eta_{mod,i}$ or $\eta'_{mod,i}$ should be replaced by the suitably normalized spectral response function. This approach was described by Zhou et al. [12]. The conditions specified in IEC 60904-9:2020 [21] for the solar simulators that are used in measuring $\eta_{mod,i}$ include requirements on the spectral mismatch. According to those definitions, the solar spectra documented in EN 410:2011 [16] and ISO 9050:2003 [15] both satisfy the spectral mismatch requirements for a "category A" solar simulator. In other words, the value reported for $\eta_{mod,i}$ in the data sheet of a PV module would be very similar, within the category A tolerance values, to that obtained on the basis of the spectral response and the solar spectra documented in EN 410:2011 [16] and ISO 9050:2003 [15]. A further argument supporting the use of $\eta_{mod,i}$ in Eq. (9) is its widespread availability in PV module data sheets, whereas the spectral response of a PV module (as distinct from a "naked" solar cell) is not generally available.

Finally, once the modified absorptance $\alpha_i(\lambda)$ of the PV module in isolation has been obtained according to Eq. (9), the solar direct absorptance α_{ei} of the ith pane within a multi-pane BIPV glazing unit is determined by applying the multilayer optical calculations and spectral integration according to EN 410:2011 [16] or ISO 9050:2003 [15]. It is noted that computer programs to perform the multilayer optical calculations commonly use input files containing the spectra for $\tau(\lambda)$, $\rho(\lambda)$ and $\rho'(\lambda)$ of the individual glazing layers. A convenient method to ensure use of the modified value of $\alpha(\lambda)$ according to Eq. (9) is to add the η_{mod} value to the input $\rho(\lambda)$ values for the PV laminate. However, it must be remembered that this modified input file should be used only for calculation of the modified value of α_{ei} for use in the SHGC calculation; it should not be used for calculation of the purely optical properties such as solar direct transmittance or solar direct reflectance of the BIPV glazing unit.

The modified value of α_{ei} is then inserted into the relevant expression for the secondary heat transfer factor towards the inside q_i of the BIPV glazing unit, which varies according to the number of glazing layers in the unit. For the boundary conditions prescribed by the underlying standards [18] or [19] for the U value, the temperature change due to the extraction of electricity has a negligible effect on the U value and can be ignored [23]. Application of Eq. (1) with the modified value of q_i results in the SHGC value that applies for the MPP state, i.e. when electricity is extracted.

5. Proposed modifications to SHGC determination to account for inhomogeneous optical properties

Although conventional architectural glazing is usually optically homogeneous over its entire surface area, non-photovoltaic exceptions exist in the form of printed glazing. Ceramic prints are applied by screen-printing or digital methods, often as a means to reduce the SHGC value by reducing the solar direct transmittance, or to create translucent areas for daylighting functions, or for decorative purposes. As is documented by Appendix C to EN 410:2011 [16], a recognised method to calculate the optical characteristics and the SHGC of optically inhomogeneous glazing units is to determine the transmittance and reflectance spectra separately for each of the different regions, carry out the multi-pane calculations and then weight the contributions of the different regions to obtain the final, integrated results according to the relative area of each region. In accordance with the remainder of [16], this applies for normally incident radiation. This approach ignores the fact that regions with different solar direct absorptance values will heat to different temperatures when irradiated, which would cause lateral heat flow within the optically inhomogeneous layer, changing the transmission of heat through the glazing unit. This effect was considered to be small enough to be neglected in the existing Annex C of EN 410 for optically inhomogeneous, non-photovoltaic glazing, and the same assumption is made here for optically inhomogeneous BIPV glazing.

An optically inhomogeneous PV module – e.g. a laminate consisting of individual crystalline silicon solar cells separated by translucent or transparent regions – of total surface area A_{mod} typically contains different regions with the following surface areas:

A_{cell} the surface area covered by PV cells within the total module area.
A_{jb} the surface area covered by the junction box within the total PV module area.
(If the junction box is not exposed to solar radiation, $A_{jb} = 0$.)
$A_{intercon}$ the surface area covered by interconnectors between PV cells within the total PV module area.
A_{inact} the surface area covered by electrically inactive material (e.g. transparent encapsulant) between PV cells within the total PV module area.

It then follows that

$$A_{mod} = A_{cell} + A_{jb} + A_{intercon} + A_{inact} \quad (10)$$

The corresponding ratios of the component surface areas to the total surface area are:

$$r_{cell} = A_{cell}/A_{mod} \quad (11)$$

(also known as the cell coverage ratio CR)

$$r_{jb} = A_{jb}/A_{mod} \quad (12)$$

$$r_{intercon} = A_{intercon}/A_{mod} \quad (13)$$

$$r_{inact} = A_{inact}/A_{mod} \quad (14)$$

It then follows that

$$1 = r_{cell} + r_{jb} + r_{intercon} + r_{inact} \quad (15)$$

Separate transmittance and reflectance spectra are to be available for each of the component areas defined above. The thermal resistance from front to back of the PV laminate is considered to be constant over all of its optically different regions, as the insertion of highly conductive semiconductor cells or metal interconnectors will have a negligible effect on the thermal resistance caused by the dielectric glass, encapsulant or backsheet components. Depending on the required accuracy of the final optical and SHGC results, it may be possible to ignore the contribution of small areas such as interconnectors. Taking the case of interconnectors as a possible example, $A_{intercon}$ and $r_{intercon}$ would then be set equal to zero in Equations (10) and (15), respectively, and the "missing" area should be added to the A_{inact} and r_{inact} components. Ignoring the contribution of opaque interconnectors would mean that the solar direct transmittance corresponding to the "inactive" region is too high. As it will not be completely compensated by the resulting increase in secondary heat transfer towards the inside, the resulting SHGC value would be slightly higher than taking a non-zero value of $r_{intercon}$ into account, i.e. the error is on the conservative side, assuming that a lower SHGC is usually desired for solar-shading purposes. In [7], the effect of a region with a relative area less than 0.05 was found to be negligible on the SHGC value.

5.1. Open-circuit case

For the open-circuit case (OC), the optical properties and the SHGC value should be calculated according to the multi-layer calculation procedures of EN 410 [3,16] or ISO 9050 [2,15] separately for each PV laminate region combined with the remaining panes of the glazing configuration. The area weighting to obtain each optical property and SHGC value should be done using the final calculated properties for the different areas of the complete glazing configuration that correspond to the different regions of the PV laminate.

Thus, taking the solar direct reflectance of a BIPV triple glazed unit as an example,

$$\rho_{e,\ mod,\ triple\ glazing} = r_{cell} \times \rho_{e,\ cell,\ triple\ glazing} + r_{jb} \times \rho_{e,\ jb,\ triple\ glazing} + r_{intercon} \times \rho_{e,\ intercon,\ triple\ glazing} + r_{inact} \times \rho_{e,\ inact,\ triple\ glazing} \quad (16)$$

where

$\rho_{e,\ cell,\ triple\ glazing}$ is the solar direct reflectance of a hypothetical triple glazed unit in which the PV module area is covered completely by PV cells.

$\rho_{e,\ jb,\ triple\ glazing}$ is the solar direct reflectance of a hypothetical triple glazed unit in which the PV module area is covered completely by the junction box.

$\rho_{e,\ intercon,\ triple\ glazing}$ is the solar direct reflectance of a hypothetical triple glazed unit in which the PV module area is covered completely by interconnectors.

$\rho_{e,\ inact,\ triple\ glazing}$ is the solar direct reflectance of a hypothetical triple glazed unit in which the PV module area is covered completely by electrically inactive material (e.g. transparent encapsulant).

and the multi-layer calculation procedures for triple glazing are applied to calculate the solar direct reflectance,

$\rho_{e,\ xx,\ triple\ glazing}$, with "xx" referring to each PV component area separately.

NOTE: In the case of multiple-pane glazing, it is not correct to initially calculate area-weighted spectra for the optically inhomogeneous PV laminate and then use these spectra for subsequent calculations.

5.2. Maximum-power-point case

For the maximum-power-point case (MPP), the spectral optical properties (transmittance, reflectance and absorptance) remain unchanged and thus are equal to the optical properties for the OC case. However, to calculate the SHGC value for the MPP case, the effect of extracting electricity on the solar direct absorptance of the PV layer must be taken into account. The value of η_{mod}, as introduced in Section 4.2, is again the basis, as for the optically homogeneous case. However, when this value is reported in the data sheet for an optically inhomogeneous PV module, it refers to the whole module with its combination of PV cells and non-PV regions. To quantify the power conversion efficiency specifically for the area covered by PV cells in the module, the quantity $\eta_{cell,mod}$ is introduced and is defined by Eq. (17) as follows:

$$\eta_{cell,\ mod} = \eta_{mod} / r_{cell} \tag{17}$$

where η_{mod} is again the module (power) conversion efficiency as defined in IEC TS 61836 [20] and r_{cell} (equal to the cell coverage ratio CR) is as defined in Eq. (11). Both quantities in Eq. (17), η_{mod} and r_{cell}, must refer to the same PV module and will usually be documented in the electrical data sheet for the PV module in question. $\eta_{cell,mod}$ can also be understood as the photovoltaic conversion efficiency of a hypothetical PV module which is completely covered by solar cells, i.e. where r_{cell} $(= CR) = 1$.

For the solar cell region of the isolated, optically inhomogeneous PV laminate that is used as the ith glazing layer of the BIPV glazing unit, the absorptance spectrum $\alpha_{i,\ cell,\ MPP}(\lambda)$ for the outdoor-facing surface is given by Eq. (18):

$$\alpha_{i,\ cell,\ MPP}(\lambda) = 1 - \tau_{i,\ cell}(\lambda) - \rho_{i,\ cell}(\lambda) - \eta_{i,\ cell,\ mod} \tag{18}$$

where $\tau_{i,\ cell}(\lambda)$ is now specifically the transmittance spectrum of the cell region of the PV module, $\rho_{i,\ cell}(\lambda)$ is the reflectance spectrum for radiation incident on the outdoor-facing surface of the cell region of the PV laminate and $\eta_{i,cell,mod}$ is defined by Eq. (17). As above, the absorptance spectrum $\alpha'_{i,\ cell,\ MPP}(\lambda)$ for irradiance incident on the indoor-facing surface can be calculated analogously if that surface is photovoltaically active. The same restrictions on the validity of Eq. (9) and its equivalent for irradiation of an indoor-facing surface apply equally to Eq. (18) and its equivalent for irradiation of an indoor-facing surface.

The modified absorptance spectrum $\alpha_{i,\ cell,\ MPP}(\lambda)$ according to Eq. (18) is then used to determine the solar direct absorptance $\alpha_{ei,\ cell,\ MPP}$ of the solar cell region of the PV laminate as the ith pane within a multi-pane BIPV glazing unit by applying the multilayer optical calculations and spectral integration according to EN 410 [16] or ISO 9050 [15]. The modified value of $\alpha_{ei,\ cell,\ MPP}$ is then inserted into the relevant expression for the secondary heat transfer factor towards the inside $q_{i,\ cell,\ MPP}$ of the cell region of the BIPV glazing unit. Application of Eq. (1) with q_i replaced by $q_{i,\ cell,\ MPP}$ results in $g_{cell,\ MPP}$ as the SHGC value that applies for the cell region of the BIPV glazing unit in the MPP state, i.e. when electricity is extracted.

The SHGC values for all other regions of the BIPV glazing unit remain unchanged by the extraction of electricity from the cell region. The SHGC value for the complete BIPV glazing unit in the MPP state is then calculated by area weighting, using $g_{cell,\ MPP}$ as the component for the cell region. Taking the SHGC value $g_{mod,\ MPP,\ double\ glazing}$ of a BIPV double glazing unit as an example,

$$g_{mod,\ MPP,\ double\ glazing} = r_{cell} \times g_{cell,\ MPP,\ double\ glazing} + r_{jb} \times g_{jb,\ double\ glazing} + r_{intercon} \times g_{intercon,\ double\ glazing} + r_{inact} \times g_{inact,\ double\ glazing} \tag{19}$$

where

$g_{cell,\ MPP,\ double\ glazing}$ is the SHGC value of a hypothetical double glazed unit in which the PV module area is covered completely by PV cells in the MPP state.

$g_{jb,\ double\ glazing}$ is the SHGC value of a hypothetical double glazed unit in which the PV module area is covered completely by the junction box. (This value is zero if the junction box is not exposed to solar radiation.)

$g_{intercon,\ double\ glazing}$ is the SHGC value of a hypothetical double glazed unit in which the PV module area is covered completely by interconnectors.

$g_{inact,\ double\ glazing}$ is the SHGC value of a hypothetical double glazed unit in which the PV module area is covered completely by electrically inactive material (e.g. transparent encapsulant).

As BIPV glazing units are commonly manufactured with a wide range of heights, widths and cell coverage ratios, it is recommended that the SHGC values for 100% coverage of each of the optically different regions should be reported separately. Both the OC and MPP values should be reported for the PV cell regions. The overall SHGC value for any specific BIPV glazing unit can then be easily calculated, using the relevant area ratios for the optically different regions.

6. Application of modified SHGC determination procedure to realistic cases of BIPV glazing

The authors of this paper collaborated within the framework of IEA-PVPS Task 15, “Enabling framework for the development of BIPV” to develop and then apply the methodology described in the previous Sections to realistic cases of semi-transparent BIPV glazing units. Each participant calculated the SHGC values of specified BIPV glazing samples in the OC and MPP states under well-defined boundary conditions, most participants using the standard that is applicable to their global region for SHGC calculations as the individual starting point. Duplication in the choice of standards among the participants allowed cross-checking and verification of the individual results.

The exercise had three main goals:

- to determine the magnitude of the effect of electricity extraction on the SHGC value for different BIPV glazing configurations and solar cell coverage values.
- to compare the magnitude of the electricity extraction effect with that of other influences on the calculated SHGC value, such as the solar spectrum used for weighting or the heat transfer coefficients used to calculate thermal transmittance.
- to determine whether the effect of electricity extraction on the SHGC was large enough to warrant efforts to include it within international SHGC standards.

6.1. Specification of samples

A partly transparent, glass-glass PV laminate with monofacial crystalline silicon solar cells was taken as the starting point. To illustrate the effect of different cell coverage ratios, variants with a total of 36 cells or 72 cells were considered. Three different glazing configurations were considered to investigate the effect of different U values:

- the glass-glass PV laminate alone
- a BIPV double glazing unit (DGU 1) with the PV laminate as the outer layer, a 25.4 mm air-filled cavity and a glass pane with a pyrolytic low-e coating as the inner pane. (This corresponds to the BIPV double glazing unit that was investigated experimentally by Kapsis [7].)
- a BIPV double glazing unit (DGU 2) with the PV laminate as the outer layer, a 12 mm argon-filled cavity and a glass pane with a silver-based low-e coating as the inner pane

Fig. 3 illustrates the schematic configuration of the BIPV double glazing units.

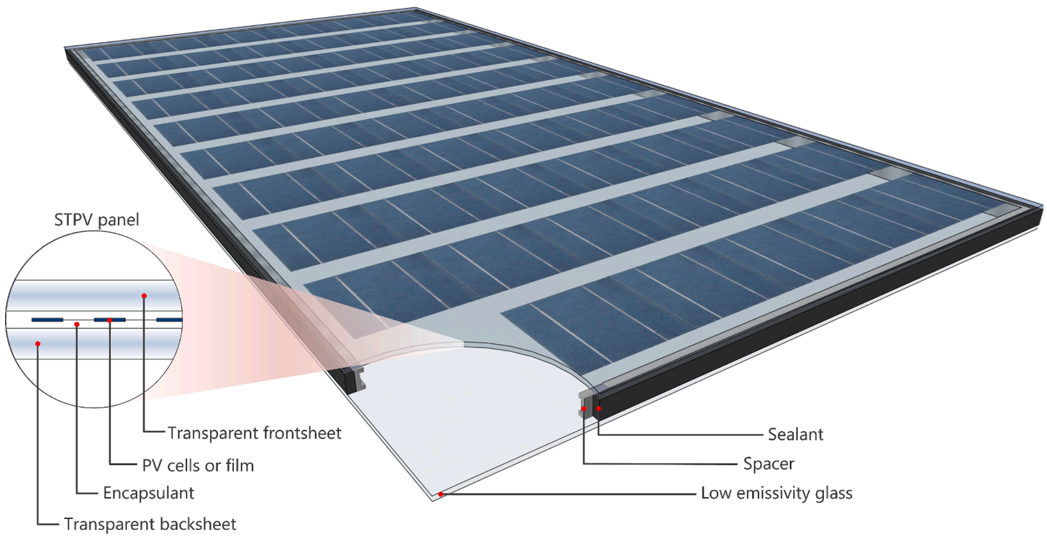

Fig. 3. Schematic diagram of a semi-transparent BIPV double glazing unit integrating a partly transparent, crystalline silicon, glass-glass PV laminate as the outer layer [7].

It is noted here that in many European countries, energy-saving regulations effectively require the use of triple glazing units in many buildings. Although triple glazing units were not included in the calculation exercise, the results allow conclusions about BIPV triple glazing units to be drawn and are presented later.

Parameters specifying the geometric configuration of the BIPV glazing units and the thermal properties of their components were fixed and are documented in Table 1. Transmittance and reflectance spectra for each of the glazing layers were provided to the participants; separate sets were provided for the solar cell region of the PV glass-glass laminate and the transparent region. The small areas corresponding to the interconnectors were not taken into account and the junction box was not exposed to solar radiation, so $r_{intercon}$ and r_{jb} were set equal to zero.

6.2. Variable parameters

For historical reasons, several different solar spectra are specified in standards for SHGC calculation, resulting in different values of the solar direct transmittance value τ_e of Eq. (1), which was thus one of the variable parameters in the joint exercise. These solar spectra are widely used in standards to characterise products for solar energy application, and are intended to represent "typical" spectra for use in product comparison. (A much wider range of spectral distributions is encountered at any given location in reality, depending on the solar altitude and atmospheric conditions.) A second variable is the approach taken by different standards to calculating the U value and its components, which are needed to determine the the secondary heat transfer factor of the glazing towards the inside, q_i, the second term of Eq. (1). The standards [19] and [18] apply the same static method, fixing the average temperature and the temperature difference between the outermost and innermost glazing layers. These two standards differ only in the specified values for the external and internal heat transfer coefficients, and are referenced by ISO 9050:2003 [15] and EN 410:2011 [16] respectively, the standards addressed by the proposed modification. By contrast, the ISO 15099:2003 standard [11] applies a dynamic heat-transfer calculation method, where the outdoor and indoor air temperatures are the specified boundary conditions and the heat transfer coefficients vary with the temperature of the glazing layers once thermal equilibrium has been achieved. To minimize differences caused by the different U-value calculation methods, all participants agreed to use the same sets of values for the external and internal heat transfer coefficients and to use the same value for the air and adjacent glazing surface temperature. Table 2 documents the participating institutions and the standards which they applied.

In total, the solar direct transmittance, U value, secondary heat transfer factor towards the inside and SHGC value were calculated by each participant for 48 variants. This resulted from two values each for the external and internal heat transfer coefficients, two electrical states (OC and MPP), three glazing configurations as specified in Section 6.1 and two different coverage ratios (corresponding to PV laminates with 36 and 72 solar cells). The values for these parameters, together with the fixed values of the outdoor and indoor temperatures, are listed in Table 3. The two values for the external heat transfer coefficient h_{out}, 25

Table 1
Geometrical and thermal parameters of the layers of the investigated BIPV glazing.

Parameter	Unit	Value
η_{mod} of 72-cell PV laminate (92.2% coverage)	[-]	0.15
efficiency $\eta_{cell,mod}$ of all-cell PV laminate (100% coverage)	[-]	0.1627
effective conductivity of PV laminate	$Wm^{-1}K^{-1}$	0.6
thickness of PV laminate	mm	5
ε_{out} of PV laminate	[-]	0.84
ε_{in} of PV laminate	[-]	0.84
effective conductivity of low-e-coated glass pane (1) NFRC ID 9924	$Wm^{-1}K^{-1}$	1
thickness of low-e-coated glass pane (1)	mm	5.64
ε_{out} of low-e-coated glass pane (1)	[-]	0.157
ε_{in} of low-e-coated glass pane (1)	[-]	0.84
effective conductivity of low-e-coated glass pane (2)	$Wm^{-1}K^{-1}$	1
thickness of low-e-coated glass pane (2)	mm	5.85
ε_{out} of low-e-coated glass pane (2)	[-]	0.028
ε_{in} of low-e-coated glass pane (2)	[-]	0.84

Table 2
Institutions participating in the comparative calculation exercise, the standards which they applied and the underlying solar spectra. AM = air mass, g = global, d = direct. See list of authors for the full names of the institutions.

	LIXIL, RMIT	CIEMAT, Tecnalia	Hunan U	ConcU, ISE, LBNL
Solar spectrum	AM 1.5g	AM 1.0g	AM1.5g	AM1.5d
U value	ISO 10292	EN 673	ISO 15099	ISO 15099
SHGC	ISO 9050	EN 410	JGJ / T 151–2008	ISO 15099 with NFRC 300

Table 3
Thermal boundary conditions applied and values of varied parameters.

T_{out}	T_{in}	h_{out}	h_{in}	Electrical state	Cell coverage ratio	Glazing configuration
°C	°C	$Wm^{-2}K^{-1}$	$Wm^{-2}K^{-1}$			
25.1	25.0	25	8.1	OC	0.922	PV laminate alone (glass-glass)
		12	6.6	MPP	0.461	PV laminate; 25.4 mm air; low-e pane 1
						PV laminate; 12 mm Ar; low-e pane 2

$Wm^{-2}K^{-1}$ and 12 $Wm^{-2}K^{-1}$, are typical of values specified by standards to represent "winter" and "summer" conditions, respectively. The two values for the internal heat transfer coefficient h_{in}, 8.1 $Wm^{-2}K^{-1}$ and 6.6 $Wm^{-2}K^{-1}$, span a range of values that could be typically encountered indoors.

6.3. Results

The first sets of results are for the solar direct transmittance of the BIPV glazing units, which varies with the cell coverage ratio and glazing configuration, but is independent of the electrical state (OC or MPP). As expected and presented in Table 4 for the investigated PV laminates with opaque crystalline silicon solar cells, the cell coverage ratio dominates in determining the solar direct transmittance value, followed by the transmittance-reducing effect of the low-e-coated panes in the two BIPV double glazing units. By comparison, the variation resulting from applying different solar spectra to determine the τ_e value for a given glazing configuration and CR value is relatively small. For the more densely covered samples, the maximum variation is 0.003. A maximum difference of 0.016 is observed for the lower CR value and the glass-glass PV laminate alone.

The calculated thermal transmittance U values depend only on the input values for the outdoor and indoor heat transfer coefficients, temperatures and thermal properties of the three different glazing configurations. They are considered to be independent of the electrical state (OC or MPP) and the cell coverage ratio CR as discussed in Section 4. Table 5 documents the results calculated according to the different U-value standards listed in Table 2. The U values from the different standards agree to two significant figures for a given set of input parameters and the boundary conditions specified for the exercise. The last three columns of Table 5 present values for the ratio U/h_{out}, which indicates the distribution between outward and inward flow of heat originating from the outermost glazing layer, i.e. the PV laminate for the discussed examples. The dominating influence on its value is the thermal resistance provided by the glazing itself; the relatively low thermal resistance of the glass-glass PV laminate leads to the highest values of U/h_{out}, indicating that the inward-flowing share of heat is greatest for this glazing configuration, in accordance with the discussion presented in Section 2. The U/h_{out} ratio is lowest for the second BIPV double glazing unit (DGU 2) with an argon-filled cavity and a soft low-e coating on the indoor pane, where the high thermal resistance of the glazing unit ensures that the inward heat flow is low. For each glazing configuration, the U/h_{out} ratio is lowest when the external heat transfer is high and the internal heat transfer is low, i.e. when relatively little heat flows inward through the glazing and into the indoor space. Conversely, the ratio is highest when the external heat transfer is low and the internal heat transfer is high. For the double glazing units, the ratio is effectively independent of the internal heat transfer coefficient due to the high thermal resistance of the glazing unit itself.

Table 4
Solar direct transmittance values obtained for the different BIPV glazing units, calculated using the different solar spectra specified by the applied international SHGC standards. AM = air mass, τ_e = solar direct transmittance, CR = (cell) coverage ratio, DGU = double glazing unit.

Glazing configuration, CR	τ_e **ISO 9050** (AM1.5g)	τ_e **EN 410** (AM1.0g)	τ_e **NFRC 300** (AM1.5d)
PV laminate, CR = 0.922	0.066	0.063	0.064
DGU 1, CR = 0.922	0.046	0.045	0.044
DGU 2, CR = 0.922	0.021	0.021	0.019
PV laminate, CR = 0.461	0.451	0.435	0.441
DGU 1, CR = 0.461	0.316	0.308	0.304
DGU 2, CR = 0.461	0.144	0.146	0.134

As expected from the discussion at the end of Section 2 and illustrated in Fig. 4(a) and (b), the U/h_{out} ratio is useful as an independent variable when analysing the variation of the secondary heat transfer factor towards the inside q_i among the different BIPV glazing variants. Considering first the case of BIPV glazing with the higher cell coverage ratio of $CR = 0.922$ shown in Fig. 4(a), a general trend of q_i increasing with the U/h_{out} ratio is observed for both the OC and the MPP cases. With this high cell coverage ratio, the heat absorbed in the solar cells of the PV laminate dominates the total amount of heat absorbed in the BIPV glazing units, and the share which flows inward is significantly higher for the poorly insulating PV laminate alone than for the BIPV double glazing units. The q_i value for the PV laminate alone also varies strongly with the choice of both outside and inside heat transfer coefficients, for the same reasons as discussed in the previous paragraph with respect to the U/h_{out} ratio. By contrast, the high thermal resistance of the double glazing units decouples the effect of heat transfer to the outdoors and the indoors: for a given value of the U/h_{out} ratio, which is predominantly determined by the h_{out} value, the q_i values increase significantly with the h_{in} value. As expected, the q_i value for a given glazing configuration and U/h_{out} ratio is higher for the OC state than for MPP, with the magnitude of the difference correlating with the magnitude of q_i in the OC state. For heat transfer coefficients similar to those specified by EN 410 [3,16] and ISO 9050 [2,15] to represent winter conditions, $h_{out} = 25$ $Wm^{-2}K^{-1}$ and $h_{in} = 8.1$ $Wm^{-2}K^{-1}$, the calculated difference in q_i caused by the extraction of electricity is 0.038 ± 0.001 for the PV laminate alone, whereas it is only 0.003 ± 0.001 for DGU 2. (Please note that the tolerance values indicate the range of values calculated by the participants using the methods of the different standards documented in Table 2; they should not be interpreted as uncertainty values.) For values that are more typical for summer conditions, $h_{out} = 12$ $Wm^{-2}K^{-1}$ and $h_{in} = 8.1$ $Wm^{-2}K^{-1}$, the calculated differences in q_i due to extraction of electricity for the densely covered PV laminate alone and the DGU 2 increase to 0.061 ± 0.001 and 0.016 ± 0.002, respectively.

Turning to the case of a lower cell coverage ratio of $CR = 0.461$, as may be more typical for applications requiring significant daylighting through a partly transparent BIPV glazing unit, the dependence of q_i on the U/h_{out} ratio is more complex, as illustrated by Fig. 4(b). The effect of reducing the cell coverage is easily explained for the PV laminate alone; halving the cell-covered area essentially halves the solar direct absorptance and thus the amount of heat flow to the inside for any given value of the U/h_{out} ratio. The difference in the q_i value caused by electricity extraction is also halved. For the BIPV double glazing units, however, the solar radiation that is absorbed in the low-e-coated indoor pane contributes significantly to the heat flowing inward when more than half of the outdoor pane, the PV laminate, is transparent. For the OC state, the combined contribution of heat generated in the PV cells and heat generated in the irradiated sections of the indoor pane results in q_i values that are higher for $CR = 0.461$ than for $CR = 0.922$. Again, the difference in q_i between the OC and MPP states, caused by extraction of electricity for a given glazing configuration and U/h_{out} ratio, is halved when the cell coverage ratio is halved.

Table 5
Input values for outdoor and indoor heat transfer coefficients (h_{out} and h_{in}, respectively) and the resulting thermal transmittance values U and U/h_{out} ratios for the three different glazing configurations (PV laminate alone, DGU 1 and DGU 2). DGU = double glazing unit. As discussed in the text, these values are assumed to be independent of the cell coverage ratio CR and the electrical state (OC or MPP).

h_{out}	h_{in}	U			U/h_{out}		
$Wm^{-2}K^{-1}$	$Wm^{-2}K^{-1}$	$Wm^{-2}K^{-1}$			[-]		
		PV laminate	DGU 1	DGU 2	PV laminate	DGU 1	DGU 2
25	6.6	5.0	1.4	1.2	0.20	0.06	0.05
25	8.1	5.8	1.4	1.3	0.23–0.24	0.06	0.05
12	6.6	4.1	1.3	1.2	0.34–0.35	0.11	0.10
12	8.1	4.6	1.4	1.2	0.39	0.11	0.10

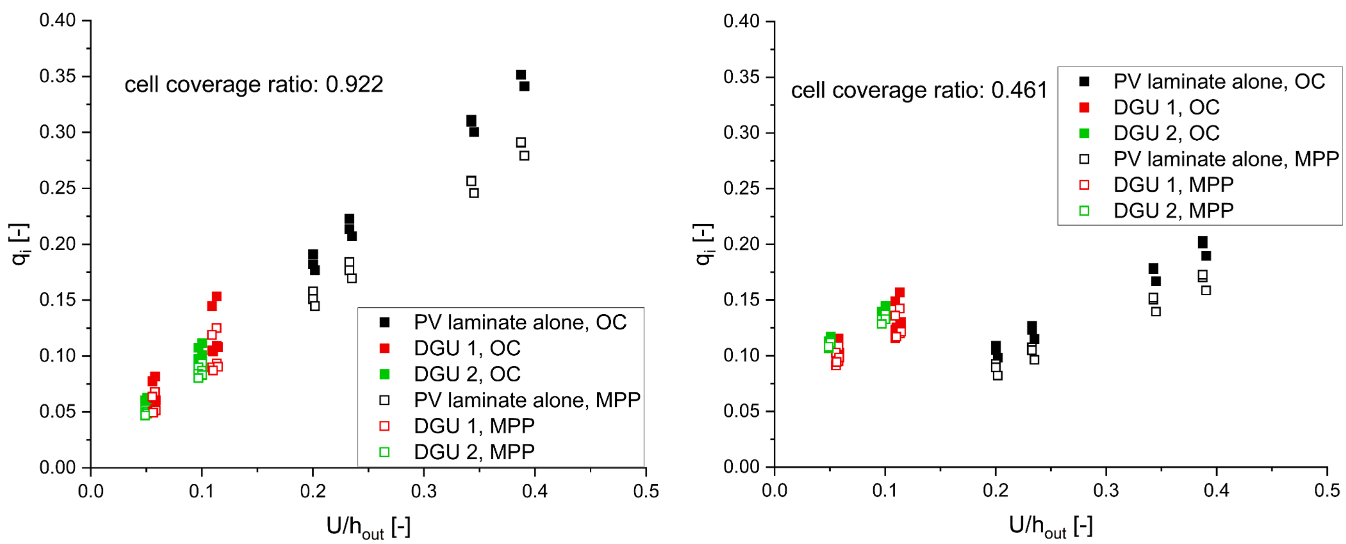

Fig. 4. Dependence of the secondary heat transfer factors toward the inside q_i on the U/h_{out} ratio for different BIPV glazing configurations in the OC and MPP electrical states and cell coverage ratios (a) of CR = 0.922 and (b) CR = 0.461. OC = open circuit, MPP = maximum power point, DGU = double glazing unit (as specified in Section 6.1 and Table 1).

The slight scatter of points in Fig. 4 for a given value of the U/h_{out} ratio, glazing configuration and electrical state is due to the fact that the participants used three different standards, NFRC 300 [17], EN 410 [16] and ISO 9050 [15], as the basis of the calculations. The previously mentioned differences in the solar spectrum cause slight variations in the determined value of the solar direct absorptance α_e and slightly different approaches are specified to calculate the U value; both effects contribute to the visible variation in q_i.

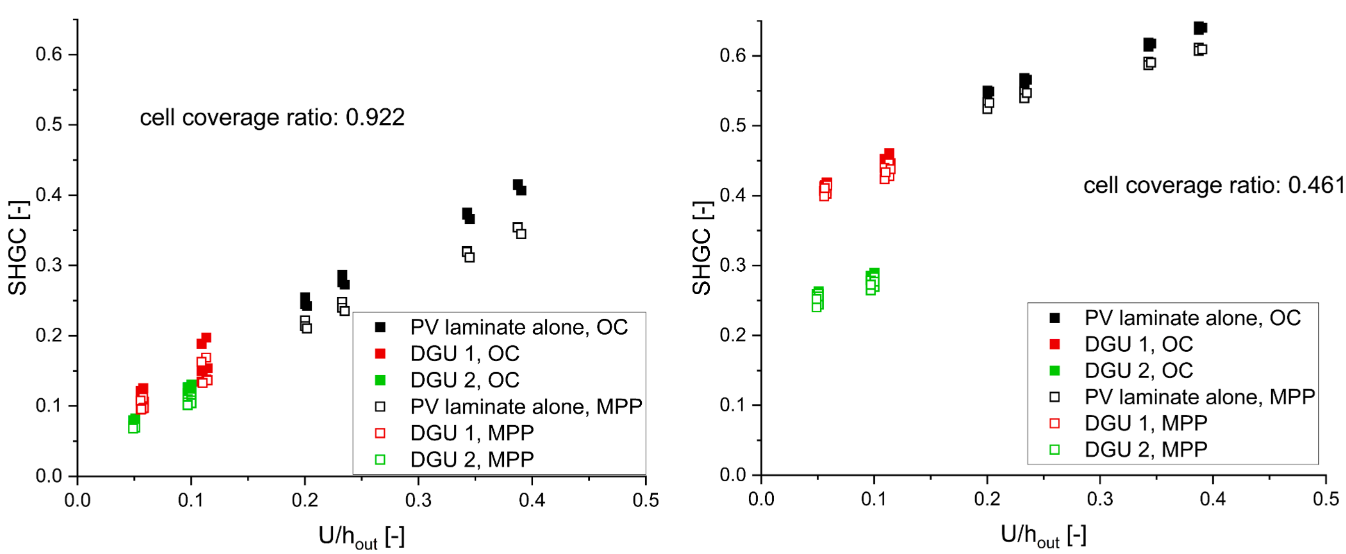

Fig. 5. Dependence of the solar heat gain coefficient SHGC on the U/h_{out} ratio for different BIPV glazing configurations in the OC and MPP electrical states and cell coverage ratios (a) of CR = 0.922 and (b) CR = 0.461. OC = open circuit, MPP = maximum power point, DGU = double glazing unit (as specified in Section 6.1 and Table 1).

The range of SHGC values calculated for the 48 parameter combinations explored in this sensitivity exercise are documented in Fig. 5(a) and (b), again plotted versus the U/h_{out} ratio. In accordance with Eq. (1), they were obtained as the sum of the solar direct transmittance values τ_e of Table 4 and the secondary heat transfer factors q_i toward the inside, from Fig. 4. In addition to the slight variations in q_i and U/h_{out} caused by the different underlying standards that were visible in Fig. 4, the different solar spectra also cause slight variations in the solar direct transmittance τ_e component of the SHGC plotted in Fig. 5.

For the low solar direct transmittance values of the configurations with CR=0.922, the SHGC behaviour is dominated by the q_i component and the same arguments apply as in the discussion of influences on q_i. However, for the investigated configurations with $CR = 0.461$, the solar direct transmittance contribution can represent up to two-thirds of the SHGC value. Clearly, the solar direct transmittance does not affect the magnitude of the difference in SHGC due to electricity extraction for a given glazing configuration and U/h_{out}; the difference in SHGC between the OC and MPP states is identically equal to the corresponding difference in q_i.

The results illustrated in Fig. 5 for "DGU 1" agree well, within experimental error, with the experimental results reported for the double glazing unit investigated by Kapsis [7], providing evidence of the validity of the component-based approach proposed here.

For the summer conditions characterized by $h_{out} = 12$ Wm^{-2}K^{-1} and $h_{in} = 8.1$ Wm^{-2}K^{-1}, Fig. 6 illustrates the dependence of the calculated SHGC of the different glazing configurations and electrical states on the cell coverage ratio CR. The SHGC values illustrated in Fig. 5 for $CR =$ 0.922 and 0.461 were used as inputs to define these linear functions. For clarity, only the results calculated according to ISO 9050 [15] are shown as an example. As expected, in the absence of solar cells ($CR = 0$), the SHGC values are identical for the "OC" and "MPP" electrical states, and the difference in SHGC for a given glazing configuration increases with the coverage ratio. This linear dependence of the SHGC on the coverage ratio for both electrical states has also been confirmed experimentally, e.g. by Kapsis [7].

For ease of consultation, the differences in SHGC due to electricity extraction are illustrated in Fig. 7 for the 24 investigated combinations of cell coverage ratio, glazing configuration and outside and inside heat transfer coefficients. Values between 0.062 and 0.003 were determined for the investigated variants. The largest difference of 0.062 was determined for the single glazing variant with $CR = 0.922$ under summer conditions. Values greater than 0.03 were determined only for the poorly insulating, single glazing variants consisting of the PV laminate alone.

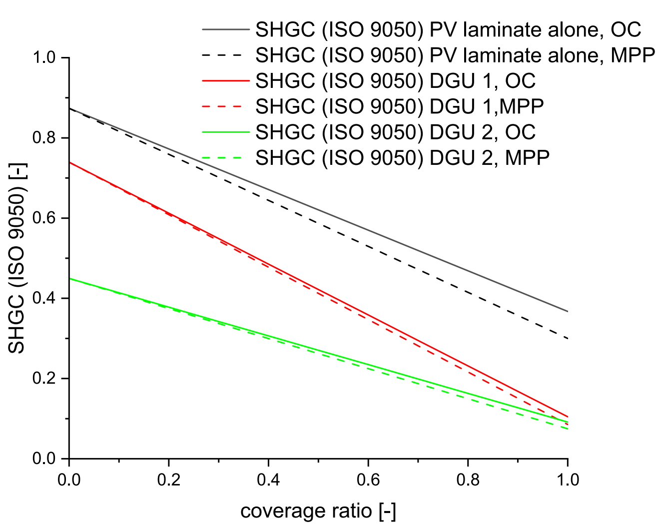

Fig. 6. Solar heat gain coefficient SHGC versus the cell coverage ratio CR for different BIPV glazing configurations in the OC and MPP electrical states, illustrating the linear dependence. OC = open circuit, MPP = maximum power point, DGU = double glazing unit (as specified in Section 6.1 and Table 1). For clarity, only the SHGC values calculated according to ISO 9050, with $h_{out} = 12$ Wm^{-2}K^{-1} and $h_{in} = 8.1$ Wm^{-2}K^{-1} (summer conditions) are shown as an example.

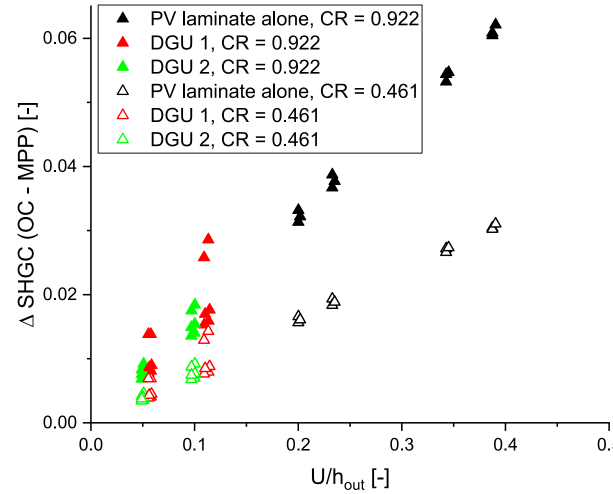

Fig. 7. Dependence of the difference between solar heat gain coefficient SHGCs in the OC and MPP electrical states on the U/h_{out} ratio for different BIPV glazing configurations and cell coverage ratios, $CR = 0.922$ (solid symbols) and $CR = 0.461$ (hollow symbols). OC = open circuit, MPP = maximum power point, DGU = double glazing unit (as specified in Section 6.1 and Table 1).

7. Discussion

Returning to the stated goals of the calculation exercise using the proposed calculation methodology, the results presented here for realistic cases of BIPV single and double glazing document that

- the magnitude of the effect of electricity extraction on the SHGC value for the investigated BIPV glazing configurations reached a value of up to about 0.06 for a PV laminate alone with a high cell coverage ratio. The value became typically less than 0.02 when BIPV double glazing units with one low-e coating and a high cell coverage ratio were considered. Comparable results have been obtained in experimental investigations, such as those reported by Kapsis [7]. However, it should also be remembered that the examples were calculated using a module power conversion efficiency of 15%. With current module power conversion efficiencies already exceeding 20%, the magnitude of the electricity extraction effect on the SHGC value shown in Fig. 7 can be expected to increase proportionately to the power conversion efficiency. However, it should also be remembered that the electricity extraction effect based on a given η_{mod} value for standard test conditions and the MPP represents an upper limit that will often not be reached in practice.
- the size of the electricity extraction effect on the calculated SHGC value for a given BIPV glazing unit, particularly for the double glazing units, is observed to be of the same order or magnitude as that caused by evaluation applying different solar spectra specified in different standards or the values used for the outdoor and indoor heat transfer coefficients when calculating the thermal transmittance. This underscores the importance of clearly stating the input parameters used when presenting calculated SHGC values – not only for BIPV glazing!
- the size of the determined effect of electricity extraction on the SHGC was considered to be large enough to warrant inclusion within international SHGC standards and is currently being addressed by the appropriate technical committees for architectural glazing within CEN and ISO.

The presented results also document the general trend of the effect of the reduction in SHGC value due to electricity extraction decreasing as the thermal insulation provided by a glazing unit improves. Considering that triple glazing units with two low-e-coated panes typically have a *U* value of 0.8 $Wm^{-2}K^{-1}$ or less, the trend shown in Fig. 7 indicates that the difference in SHGC value due to electricity extraction will be typically less than 0.01 for a BIPV triple glazing unit, which would usually be regarded as negligible.

Although the derivation of the proposed SHGC calculation approach has concentrated on semi-transparent BIPV glazing, where at least one region of the PV laminate layer has a non-zero solar direct transmittance, it is equally valid for a completely opaque BIPV glazing unit. In this case, the solar direct transmittance for the entire PV laminate layer would be set to zero. However, the q_i component will still ensure that the SHGC is greater than zero, and, in the case of a PV laminate alone, can reach a value of 0.30 or more.

8. Conclusion

A simple modification to existing methods to calculate the SHGC of conventional architectural glazing has been presented, which allows the effect on the SHGC value of extracting electricity from a BIPV glazing unit to be calculated. The only additional information needed to take electricity extraction from the PV component into account is the power conversion efficiency of the PV laminate and the coverage ratio of solar cells within it. As BIPV glazing units are commonly manufactured with a wide range of heights, widths and cell coverage ratios, it is recommended that the SHGC values for 100% coverage of each of the optically different regions should be reported separately. Both the OC and MPP values should be reported for the PV cell regions. The overall SHGC value for any specific BIPV glazing unit can then be easily calculated, using the relevant area ratios for the optically different regions.

Like the underlying calculation methods, the presented approach is intended for the comparison of BIPV glazing at the product level, not for dynamic calculation of the SHGC under variable boundary conditions within the building energy simulation context. As in the underlying calculations, the assumptions of normally incident solar radiation, essentially non-scattering, parallel and planar glazing layers, and simplified calculation of one-dimensional thermal transmission apply. Within these constraints, the authors are convinced that the presented approach is useful, allowing the SHGC of many widespread and diverse BIPV glazing products to be declared in both the OC and the MPP electrical states. They hope that this will support the dissemination of BIPV glazing and thus its contribution to increasing the share of electricity generated from renewable sources.

CRediT authorship contribution statement

Helen Rose Wilson: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Tilmann E. Kuhn:** Writing – review & editing. **Hisashi Ishii:** Validation. **Daniel Valencia-Caballero:** Validation, Methodology, Investigation. **Nuria Martin Chivelet:** Writing – review & editing, Validation, Investigation. **Jinqing Peng:** Validation. **Rebecca Jing Yang:** Writing – review & editing, Supervision. **Yukun Zang:** Writing – review & editing, Validation. **Hua Ge:** Writing – review & editing, Supervision. **Kai Ye:** Validation. **Jacob C. Jonsson:** Validation. **Konstantinos Kapsis:** Methodology.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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