The dynamic thermal response model and energy performance of multi-layer glass and BIPV facade structures

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Abstract

Despite the great progress made in the energy performance of buildings in recent decades, buildings remain significant energy consumers. Many advanced technologies for increase of energy efficiency have been developed, and strong commitments to increasing the energy performance of buildings have been adopted. The most well-known is the Recast of Energy Performance of Buildings Directive (EPBD), which requires that planners design buildings as nearly zero energy buildings (nZEB), highly energy efficient buildings in which a large share of energy demand is covered by renewable energy sources. In the present article, the evaluation methods and energy performance of advance facade building structures are presented. The structure consists of six-pane multi-layer glass with optional photovoltaic cells integrated in the outer glass layer (BIPV). The method for the determination of the dynamic thermal response model is presented, and the model is validated with experiments. Three indicators were developed (average daily heat flux $\dot{q}_{24}$ at inner surface of the facade structure, the autonomy factor AUT, the and utility factor UTI) to evaluate the all-year energy performance of such advanced building structures according to the heating and cooling energy needs and electricity production. Examples are shown for facade building structures located in three climate regions.

Keywords: all-glass buildings, building-integrated photovoltaics, dynamic thermal response, model of building structure, energy performance of building structures, CFD

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Nomenclature

A	area	(m ²)
AUT	autonomy factor	(h/year)
$\dot{E}$	PV electrical power	(W)
E'_{PV}	specific energy (electricity)	(kWh/m ² year)
$\dot{e}$	PV specific electrical power	(W/m ²)
$\dot{e}_{24}$	average daily PV specific electrical power	(W/m ²)
i	incident angle of solar irradiation	(°)
G	solar irradiation	(W/m ²)
g	total solar energy transmittance	(-)
k _G	solar irradiation correction factor	(-)

k_i	incident angle correction factor	(-)
k_T	temperature correction factor	(-)
$\dot{Q}$	heat flux	(W)
Q'	specific energy (heat)	(kWh/m ² year)
$\dot{q}$	specific heat flux	(W/m ²)
$\dot{q}_{24}$	average daily specific heat flux	(W/m ²)
T	temperature	(°C)
t	time	(h)
U	thermal transmittance	(W/m ² K)
UTI	utility factor	(%)
$a_x, b_x, c_x, d_x, e_x, f_x, g_x$	coefficients of approximation models (1)	
α	absorptivity	(-)
β	incident angle	(°)
ΔT	temperature difference	(°C)
τ	transmittivity	(-)

index

av	average
C	cooling
d	day
dir	direct
dif	diffuse (sky and ground)
ref	reference
g	glass
glob	global
H	heating
h	hour
i	at inner structure surface, indoor
o	outdoor
PV	photovoltaic
s	solar, solar generated
t	total, time
vis	visible

1. Introduction

The Recast of EPBD [1] requires that building planners design high energy performance buildings with a high share of renewable energy sources in delivered energy needed for the operation of the buildings. According to the directive, EU Member States prepared requirements and implemented national action plans for nearly zero-energy buildings (nZEB) as highly energy efficient buildings in which a large share of energy demand must be covered by renewable energy sources [2]. nZEB requirements will be a significant challenge for building designers, especially, when (very popular in contemporary architecture) all-glass buildings will be designed. Such buildings attract the views and express the openness of the company that owns the building [3]. To fulfil nZEB requirements in all-glass buildings, advanced technology, durability-proven and cost-effective glass facade building structures will be needed. In terms of energy efficiency, advanced technologies are distinguished by low thermal transmittance (U), high natural light transmittance (τ_{vis}), and climate-adapted total solar energy transmittance (g -value).

One technology for decreasing the heat transfer coefficient of transparent envelope building structures is multi-layer glazing. Lechowska et al. [4] analyse, using ANSYS FLUENT CFD computer code, the heat transmittance of a glazing prototype consisting of 11 ultra-thin glass panes. They report good agreement between 2D CFD simulations and experimental results. Such a building structure has thermal transmittance U 0.283 W/m²K at standard boundary conditions.

In the context of nZEB, energy production, in addition to natural heating and daylighting, is an important feature of glass facade structures. BIPV facade structures are among the most promising solutions. Ceron et al. [5] published an article about the state of the art of building-integrated photovoltaic products. They analysed roof and facade BIPV technology and defining BAPV (Building-Applied Photovoltaics) as PV systems consisting of PV modules installed on the building envelope and BIPV (Building-Integrated Photovoltaics) as PV systems in which PV modules replace conventional building envelope structures as multi-function devices. BIPV became the very popular object of research in the last decade.

In most cases, BIPV as double-skin facades [6] or BIPV in the form of insulating glazing were studied. Skandalos et al. [7], and Kapsis et al. [8] investigate thermal and energy performance of semi-transparent and opaque BIPV. Single- or double-glazed BIPV built with a-Si, p-Si, or m-Si PV cells with or without a ventilation cavity is the most common research in case of BIPV glazing [9, 10]. Such structures have a thermal transmittance in the range between 1 to 5 W/m²K. If the research was based on the experiments, small-scale experiments are commonly performed for the determination of optical and thermal properties of BIPV [9, 11, 12] with an area of BIPV ~ 1 m² placed in the wall of the test cell. The integration of PV cells into glass structures decreases the total solar energy transmittance or g-value of the glazing. Olivieri et al. [13] experimentally determined the g-value for the single glazed structure at different PV cells operation conditions (maximum power point, open circuit, shortcut).

Advanced glass facades, as well as BIPV facades, have an impact on several areas of living comfort in buildings and, consequently, the energy performance of such building structures are evaluated on case study objects or typical rooms, e.g. office buildings. The energy demands for heating, cooling and lighting are commonly investigated taking into account local or several climate conditions [14]. TRNSYS [15], EnergyPlus [16] or EcoDesigner Star [17] software tools are most often used for the simulation of the energy demand of the building.

It is common that heat transfer in glass building structures is modelled with an R-C model, assuming steady-state heat transfer [7, 18]. Such an approach is typical for most recognized building thermal response computer tools. Such an approach is adequate in case of a low number of glass panes because of the low attenuation and time delay of heat flux. For advanced heat transfer modelling, the computational fluid dynamic (CFD) technique has become widely used among researchers in the last decade as computer power increase, and techniques for the solution of Navier-Stokes set of equations have advanced. Fluid velocity and local heat transfer coefficients in the gap between glass panes were investigated by Medved et al. [19] and Han et al. [20]. Air velocities and the effect of the ventilation layer on the temperature of the PV model was studied in [21], considering the solar irradiation, the tilt of the PV module, and several geometric parameters. The steady-state CFD modelling using FLUENT software was performed to a developed empirical extension for the determination of PV cells temperature.

This paper aims to show the method for the characterization of the advanced multi-layer glass, and BIPV facade structures, taking into account the heat accumulation in glass panes that causes unsteady heat transfer. Such an advanced all-glass facade structure was developed by the company TRIMO [22], [23] and is available for large facade building structures (up to 3 m high and 1.2 m wide). An advanced small scale multi-layer glass structure with laminated PV cells was developed recently for the further research of nZEB integration.

In the present article, the energy balance of such facade structures is shown for different climate conditions and facade orientations, focusing on the energy balance of the structure itself without any interference whatsoever of the building except the heating and cooling temperature set points. It is shown that the accumulation of heat in the multi-layers of such building structures have significant effects on the heat transfer and cannot be neglected. The method for the determination of the dynamic thermal response model based on the set of virtual daily solar irradiation scenarios and transient CFD numerical simulations is presented. BIPV structures are optimized according to average daily heating and cooling heat flux and hour-by-hour autonomy factor. In this way, a multi-layer glass and BIPV facade structures can be evaluated and optimized in the first phase of design, and the developed dynamic thermal response model can be integrated into simulation tools [15–17] with improved accuracy of predicted energy use for the operation of the buildings.

2. Details about multi-layer glass and multi-layer BIPV facade structures

Multi-layer glass facade structure is a newly developed product of the company TRIMO [23]. The structure consists of up to six glass layers, five sealed cavities that are filled by air, and a noble gasses. All glass panes have a one-side low emissivity layer. To fulfil criteria of nearly zero energy buildings according to the required share of renewable energy carriers, glass facade structure was upgraded into a BIPV facade structure with encapsulated polycrystalline silicon PV cells inside two outer glass layers, as shown in Figure 1.

Fig. 1. Multi-layer glass facade structure in the all-glass building (left) [23], cross-section multi-layer BIPV facade structure studied in the article (right)

The energy balance of the multi-layer facade structure includes combined convective and longwave radiation heat flux ($\dot{Q}_i$) on the inner surface of the structure, transmitted shortwave solar irradiation flux ($\dot{Q}_s$) and, in the case of BIPV, the electricity power of PV cells ($\dot{E}_{PV}$). All fluxes are normalized on 1 m² of facade structure area and marked as $\dot{q}_i$, $\dot{q}_s$ and $\dot{e}_{PV}$. As already mentioned, our goal was to develop a method and indicators for the evaluation of energy performance of facade structure elements, rather than the building as a whole.

Fig. 2. Specific energy fluxes included in the energy balance of multi-layer glass (left) and BIPV facade structure (right)

Transparent envelope structures are commonly modelled by combining the radiative properties of single glass layers with empirical equations for the determination of heat fluxes on the surfaces, in glass panes, and in cavities. Such structures are modelled as structures without thermal mass. This approach leads to the determination of static thermal indicators, such as thermal transmittance (U), solar (τ_s) and light (τ_{vis}) transmittance, and total solar energy transmittance (g). Several computer programs have been developed for the determination of optical and static thermal properties of glass; WINDOW 7.6 software [25] was used in this study. In the case of multi-layer glass facade structures, the mass of glass significantly contributes to unsteady heat transfer and could not be neglected. As a consequence, both peak heat losses and heat gains are lower. Because solar heat gains during daylight time are present in each glass pane and are unequally distributed inside the structure, an adapted dynamic thermal response model must be developed for such building structures.

3. Determination of energy fluxes in multi-glass and BIPV building structures

3.1. Dynamic thermal response model of specific heat flux $\dot{q}_i$ at the inner surface of multi-layer glass and BIPV facade structures

The dynamic thermal response model of multi-layer glass and BIPV facade structures was developed in a four-step procedure, as shown in Fig. 3. The procedure consists of the determination of the radiative properties of the structure, definition of six daily solar irradiation scenarios as well as indoor and outdoor conditions, transient computational fluid dynamic modelling (CFD), and the development of a linear multi-parametric approximation model of normalized heat flux at the inner surface of the structure per m² of the building structure $\dot{q}_i$. Each step will be presented further on.

Fig. 3. Procedure for development of a dynamic thermal response model of heat flux at inner structure surface $\dot{q}_i$.

Optical and steady-state thermal properties of the multi-layer facade structure were determined using WINDOW software. User-defined properties of glass layers have been inserted according to the producer-provided data. Table 1 shows simulated data for the normal incident angle of solar irradiation.

Table 1. Optical and thermal properties of 6 layer glass facade structure determine by WINDOW 7.6. software for the normal incident angle of direct solar irradiation

multi-layer glass structure		outer glass 1	glass 2	glass 3	glass 4	glass 5	inner glass 6
solar absorptivity α_s		0.112	0.206	0.085	0.049	0.031	0.003
solar transmittivity τ_s		0.108					
visual transmittivity τ_{vis}		0.306					
thermal transmittance U		0.292 W/m ² K					
BIPV facade structure (values for BIPV ₁₀₀)	opaque	0.75	-	-	-	-	-
	transparent	0.045	0.082	0.034	0.020	0.012	0.001

The results from the WINDOW 7.6. simulations also show that the absorptivity and transmittivity of solar irradiation in multi-layer glass facade structures significantly depend on the incident angle. Several parametric approximation models were developed using CFD simulation data to include this feature in the dynamic thermal response model (for $\dot{q}_i$) and energy balance model of transferred solar irradiation (for $\dot{q}_s$) of the multi-glass and BIPV facade building structures. To keep the computer time needed for CFD simulations at a reasonable level while covering the expected range of climate conditions and facade orientations, in the second step of the procedure, six virtual solar irradiation scenarios were defined, covering a range of daily global solar irradiation ($G_{glob,\beta}$) on the vertical facade patterns as shown in Figure 4. Indoor and outdoor temperatures were set as constant during each of the transient simulations; indoor air temperature (T_i) was set at 20°C in all cases, and each solar irradiation scenario was modelled at three different outdoor air temperatures ($T_o = T_i - 20$ K, $T_o = T_i$, $T_o = T_i + 15$ K).

Fig. 4. Virtual daily solar irradiation scenarios modelled in CFD simulations

In the third step of the procedure, computational fluid dynamic simulations were performed. PHOENICS 2018 [26] software was used for transient CFD simulations. Specifications of domain

size, numerical models and boundary conditions are presented in Table 2. In total, 18 transient 24-hour CFD simulations were needed for glass and BIPV facade structure.

Table 2. Specifications of the CFD model

boundary conditions	<ul style="list-style-type: none"> - 2D geometry model was developed; - indoor air temperature T_i and outdoor air temperature T_o were constant during each of CFD simulation; - constant combined convective and radiation heat transfer coefficient were assumed (α_i 8 W/m²K, α_e 23 W/m²K); - the heat source is defined in middle of glass and BIPV layers; - PHOENICS InForm function is used for defining time-dependent heat sources (absorbed solar irradiation); emissivity of longwave radiation of low-e layer 0.034 and 0.88 for the glass surface.
size and physical properties of the structure	<ul style="list-style-type: none"> - structure is 3 m high (one story high), and 1.2 m wide, 6-layer facade structure (Fig. 1) was analysed; - properties of the glass and gases were taken from PHOENICS 2018 library; - inner cavity is filled by air, others are filled by argon (90%), properties of Ar was taken at reference temperature 20°C. All building structures are installed vertically; BIPV₁₀₀ is a structure with the maximum PV cell area, which corresponds to 60% of total structure area; - absorptivity of glass panes were taken from WINDOW 7.6, solar irradiation absorbtivity of PV cells α_s 0.75 was taken into account (this value was determined assuming the transmittivity of outer half glass layer 0.96, PV cells surface absorptivity 0.92 and ratio of heat generation 0.85) and efficiency of the PV cells $\eta_{PV,ref}$ 15% at reference conditions were assumed; as shown in Fig. 1, PV cells are laminated in the middle of (two half) outer glass layer with half thickness transmittivity 0.96.
Numerical solutions	<ul style="list-style-type: none"> - density difference buoyancy model was used; - Chen-Kim KE turbulence model was chosen; - Immersol radiation model solver was used, transparent fluid in cavities; - time step 300 s (heat source > 0 W/m²), otherwise 600 s; global convergence criterion 0.02%.
Simplifications	<ul style="list-style-type: none"> - adiabatic edge surfaces were assumed as case study CFD model of glass multi-layer structure with spacer shown no significant difference in $\dot{q}_i$ (Fig. 4); it was found that the heat flux at the inner surface of the structure in case of heat gains ($\dot{q}_i > 0$ W/m²) is insignificantly smaller as part of the heat is transferred through edge surfaces; - heat sources in each of the glass layers were modelled by incident angle correction factors; correction factors were determined with CFD simulations (Fig. 5) assuming absorptivity of each glass pane according to WINDOW 7.6 simulation results at specified angles of incidence;

Figure 5.: Heat flux at the inner surface of multi-layer glass structure in the case of the first virtual day solar irradiation scenario, shown in Fig. 4, at constant indoor and outdoor temperature $T_i=T_o=20^\circ\text{C}$ and different, but steady incident angles (note: cases are virtual; in case of incident angle $> 65^\circ$, beam radiation will be higher than extraterrestrial).

- instead of the checkboard structure (PV cell size $0.155 \times 0.155 \text{ m}$, edge distance 0.05 m , between cell distance 0.04 m), uniform distributed stripe shape PV cells were assumed in 2D CFD modelling as case study CFD simulations of 3D geometry glass structure with checkboard PV cells shown no significant difference in temperature of PV cells and in $\dot{q}_i$;
- PV cells are 2D objects, without encapsulation substance.

Two groups of results are gathered from CFD simulations. Heat flux $\dot{Q}_i$ at the inner surface of the structures was stored in each time step directly from CFD code and shown as specific heat flux $\dot{q}_i$ per 1 m^2 of structure area. In the case of the BIPV structure, the temperature of PV cells is also stored.

In the fourth step of the procedure, stepwise regression was used to build the approximation model of $\dot{q}_i$ for the multi-layer glass and BIPV facade structure. In the model, two independent variables were considered: solar irradiation ($G_{\text{glob},\beta}$) on the outer surface of facade structure and air temperatures difference ($\Delta T = T_i - T_o$). A statistical approach was implemented to determine the regressors of independent variables from two sets of CFD data. Regressors are history values of independent variables with a time step of one hour. The process is based on a pre-defined general model (Eq. 1), which was developed by stepwise selection of regressors [27] using Matlab using Statistics and Machine Learning Toolbox [28].

$$\begin{aligned} q_i(t) = & a_0 \cdot G_{\text{glob},\beta}(t) + a_1 \cdot G_{\text{glob},\beta}(t-1) + a_2 \cdot G_{\text{glob},\beta}(t-2) + a_3 \cdot G_{\text{glob},\beta}(t-3) + a_4 \\ & \cdot G_{\text{glob},\beta}(t-4) + a_5 \cdot G_{\text{glob},\beta}(t-5) + b_0 \cdot \Delta T(t) + b_1 \cdot \Delta T(t-1) + b_2 \\ & \cdot \Delta T(t-2) + b_3 \cdot \Delta T(t-3) + b_4 \cdot \Delta T(t-4) + b_5 \cdot \Delta T(t-5) + c_0 \end{aligned}$$

(1)

Further on, Matlab Statistics and Machine Learning Toolbox were used to determine the statistical significance of regressors according to p-values and F-statistics. If the regressor's p-value was < 0.05 , the regressor was kept; the regressor with the largest p-value among all regressors that have p-value above the 0.1 was removed step-by-step during the procedure from the general model by assigning zero value to the regressor's coefficient. The procedure

also takes into account the problem of collinearity, since it reduces the number of regressors to only those that are statistically significant. Coefficients of remaining regressors were determined using an inverse matrix operation.

The presented procedure was used to determine the dynamic thermal response models of heat flux $\dot{q}_i$ at the inner surface of the multi-layer glass and the BIPV facade structure with a maximum designed PV cells cover (BIPV₁₀₀). Because aesthetic and technology requirements, it was assumed that in case of BIPV₁₀₀ structure, the PV cells covers 0.6 m² of 1 m² of facade structure. The regressor coefficients for multi-layer glass and BIPV₁₀₀ facade structure shown in Fig. 1 are presented in Table 3.

Table 3. Coefficients of dynamic thermal response model of specific heat flux at the inner surface of the multilayer glass and BIPV₁₀₀ facade structure

Multi-layer glass structure		BIPV ₁₀₀ structure	
a ₀	-0.0035	a ₀	-0.0071
a ₁	-0.0352	a ₁	-0.0113
a ₂	-0.0227	a ₂	-0.0071
a ₃	-0.0238	a ₃	-0.0109
a ₄	0	a ₄	0
a ₅	-0.0308	a ₅	-0.0158
b ₀	0.3214	b ₀	0.2572
b ₁	0	b ₁	0
b ₂	0	b ₂	0
b ₃	0	b ₃	0
b ₄	0	b ₄	0
b ₅	0	b ₅	0.0526
c ₀	-0.8902	c ₀	-0.3896

In the case of the BIPV structure with lower PV cells area than the maximum one (e.g. BIPV₅₀, BIPV₂₅), the building structure is assumed to be virtually divided into the adequate part of the structure with maximum PV cells area (BIPV₁₀₀) and part of the multi-layer glass structure. Specific heat flux $\dot{q}_i$ at the inner surface of such a structure is determined by the sum of area weighted heat fluxes (Eq. 1) taking into account both sets of dynamic model coefficients (Table 3). Such an approach was validated by CFD simulations including cases of different locations of PV cells (bottom, top) in the facade structure.

The coefficients of the dynamic thermal response model shown in Table 3 were determined from the CFD simulation data, assuming that solar irradiation is perpendicular to the structure, meaning that incident angle (i) is equal to 0°. Because heat flux $\dot{q}_i$ depends on incident angle, solar irradiation at the time (t) was corrected by incident angle correction factor k_i :

$$G_{\text{glob},\beta,i}(t) = \left(G_{\text{dir},\beta}(t) \cdot \frac{k_i(i)}{k_i(0^\circ)} + G_{\text{dif},\beta}(t) \cdot \frac{k_i(55^\circ)}{k_i(0^\circ)} \right) \quad (2)$$

$$k_{i,(i)} = d_3 \cdot i^3 + d_2 \cdot i^2 + d_1 \cdot i + d_0 \quad (3)$$

Coefficients in the approximation model are d_0 0.098, d_1 $-1.638 \cdot 10^{-4}$, d_2 $2.072 \cdot 10^{-5}$, and d_3 $-3.500 \cdot 10^{-7}$. Value of incident angle correction factor is 0,098 at i 0°, is maximum at i 30° (0,103) and is zero at i equal to 90°. At hours when the incident angle is equal or above 90°, solar irradiation is diffuse, and an incident angle of 55° is assumed.

3.2. Specific solar heat flux $\dot{q}_s$ and total heat flux $\dot{q}_t$ at the inner surface of the multi-layer glass structures

Solar heat flux transmitted into the interior of the building is defined by the transmissivity of the multi-layer glass structure, which was determined using WINDOW 7.6 software. The dependence of the solar transmittance on the incident angle i of the solar irradiation was approximated by model:

$$\tau_{s,(i)} = e_2 \cdot i^2 + e_1 \cdot i + e_0 \quad (4)$$

The coefficients in the approximation model are $e_0 = 0.1121$, $e_1 = -1.63 \cdot 10^{-4}$ and $e_2 = -1.36 \cdot 10^{-5}$. In the case of the BIPV structures, the transmissivity of solar irradiation was determined by area-weighted averaging of PV cell area A_{PV} ($\tau_s = 0$) and the area of remaining multi-layer glass structure A_g (Eq. 5), taking into account the fact that in the structure with maximum PV cell area (BIPV₁₀₀), the PV cells occupied (only) 60% of the total structure. This corresponds to the ratio A_{PV} to A_g equal to 0.6. Specific solar heat flux is normalized to 1 m² of the building structure and defined by the equation:

$$\dot{q}_s(t) = (G_{dir,\beta}(t) \cdot \tau_{s,(i,dir,t)} + G_{dif,\beta}(t) \cdot \tau_{s,55^\circ}) \cdot \left(1 - \frac{A_{PV}}{A_{PV}+A_g}\right) \quad (5)$$

Global solar irradiation on the outer surface $G_{glob,\beta}$ of the building structure was modelled by TRNSYS computer code using Randel model and test reference years for selected geographic locations. Total specific heat flux $\dot{q}_t$ on the inner surface of the multi-layer building structure at time t is defined as the sum of $\dot{q}_i$ and $\dot{q}_s$:

$$\dot{q}_t(t) = \dot{q}_i(t) + \dot{q}_s(t) \quad (6)$$

3.3. Electrical power of BIPV structure $\dot{e}_{PV}$

Electrical power of PV cells per unit of BIPV building structure area is defined by the equation:

$$\dot{e}_{PV}(t) = G_{glob,\beta}(t) \cdot \eta_{PV,ref} \cdot k_G \cdot k_T \cdot \left(\frac{A_{PV}}{A_{PV}+A_g}\right) \quad (7)$$

Where $\eta_{PV,ref}$ is the reference efficiency of PV cells, k_G is the solar irradiation efficiency correction factor, and k_T temperature efficiency correction factor. The solar irradiation efficiency correction factor k_G is defined according to technology-specific data (polycrystalline silicon PV cell) as:

$$k_G = 1 \text{ if } G_{glob,\beta} \geq 200 \frac{W}{m^2} \text{ or } k_G = f_1 \cdot \ln(G_{glob,\beta}) - f_0 \text{ if } G_{glob,\beta} < 200 \frac{W}{m^2} \quad (8)$$

Coefficients are equal to $f_0 = 3.700 \cdot 10^{-3}$ and $f_1 = 2.900 \cdot 10^{-2}$. Temperature efficiency correction factor k_T was determined using the CFD simulation data of maximum daily PV cells temperature during first three virtual days presented in Fig. 4., assuming $T_o = T_i - 10K$, $T_o = T_i$ and $T_o = T_i + 10K$ constant air temperature boundary conditions. As the maximum daily PV temperature for the studied cases only slightly differs according to the position of the cell in BIPV, k_T was defined in the form of:

$$k_T = g_1 \cdot (g_2 \cdot G_{glob,\beta}(t) + g_3 \cdot T_i + g_4 \cdot T_e + g_5) + g_0 \quad (9)$$

Coefficients in approximation model are $g_0 = 1.153$, $g_1 = -6.120 \cdot 10^{-3}$, $g_2 = 3.195 \cdot 10^{-2}$, $g_3 = 6.70 \cdot 10^{-4}$, $g_4 = 9.871 \cdot 10^{-1}$, and $g_5 = 3.00 \cdot 10^{-5}$. k_G and k_T were assumed as equal for all PV cells in BIPV.

As a case study, specific heat fluxes and specific electrical power for south-orientated multi-layer glass and BIPV facade structured in the week around the spring solstice for three geographical locations are presented in Fig. 6. Meteorological data for Stockholm (latitude 59.3346°, longitude 18.0632°), Ljubljana (latitude 46.1264°, longitude 14.4981°) and Dubai (latitude 25.2770°, longitude 55.2962°) were taken from the METEONORM database [29].

Fig. 6. Modelled hour-by-hour specific heat fluxes for multi-layer glass (left) and BIPV facade structure (right) for meteorological data of Stockholm, Ljubljana, and Dubai for the period between 18 and 24 of March

4. Validation of static thermal properties and dynamic thermal response model of multi-layer glass and BIPV facade structure

For the validation of static thermal properties of multi-layer glass structures, in-situ measured transmittivity of solar irradiation τ_s and thermal transmittance U were compared to the modelled ones under steady-state conditions; the approximation model of specific heat flux at the inner surface of the structure $\dot{q}_i$ was tested for several consecutive days during dynamic environmental conditions. For the validation of WINDOW 7.6 model of solar transmittivity, the multi-layer glass structure was exposed to solar irradiation normal to the surface ($\pm 15^\circ$ during the experiment) to reduce the influence of reflected solar irradiation from surroundings. Two KIPP and ZONNEN model CM11 pyranometers were used, and measurement was performed in two consecutive days (17 and 18 May 2018) in time intervals ± 1 hour around solar noon. Results are shown in Figure 7.

Fig. 7. In-situ determine transmittivity of solar irradiation τ_{sol} for 6 layer glass structure at an incident angle of direct solar irradiation $\pm 15^\circ$

The results are slightly above modelled values (0.110 at incident angle 10°) as ground reflected solar irradiation reflected on the inner surface towards to the sensor could not be avoided completely and has some influence on measured value. However, we conclude that results are close enough to use WINDOW 7.6 software data in further numerical simulations.

A small-scale six-layer multi-layer glass facade structure with a height of 1.2 m and width of 0.8 m was installed in the south wall of a thermostatted lab cell ($4 \times 3 \times 3$ m) as shown in Figure 8. The coordinates of the lab cell are latitude 46.1264° , longitude 14.4981° . The cell was thermostatted to a temperature of 25°C with an amplitude that did not exceed Category A of thermal comfort [30]. Air and surface temperatures were measured with T-type thermocouple sensors. The heat flux sensor (140×140 mm) was installed in the centre of the inner glass surface. The heat flux meter was shaded with a highly reflective foil between the glass and heat flux meter, and all sun-exposed temperature sensors were shaded with a high reflective shield. Solar irradiation was measured on the vertical plane of the glass structure and with a meteorological station installed at the top of the temperature-controlled cell. Measurement data were collected using an Agilent 34901A board and Agilent 34970A data logger. After the first set of experiments performed to validate thermal transmittance (U) and dynamic thermal response model of specific heat flux $\dot{q}_i$ of multi-layer glass structure, virtual PV cells were installed on the outer glass of the multi-layer structure for validation of the dynamic thermal response model of specific heat flux $\dot{q}_i$ of BIPV₁₀₀. PV cells only act as shading devices not as an electricity generation devices. Adequate adaptation of the CFD code was made for this part of the experiment.

Fig. 8. Thermostatted lab-cell with experimental BIPV₁₀₀ (left, middle) and meteorological station at the top of the lab cell (right).

Thermal transmittance (U) was evaluated by measurements in the night period, ending 1 hour before sunrise. As an example, results are shown in Fig. 9 for experiments performed during the nights of 2nd of June (multi-layer glass structure) and 9th of July 2018 (BIPV₁₀₀). Experimental results are determined from measured specific heat flux and temperature difference data, modelled values by approximation model of $\dot{q}_i$ (eq. 1), taking into account measured air temperature differences.

Fig. 9. Measured and modelled thermal transmittance (U) for multi-layer glass and BIPV₁₀₀ structure

From Fig. 9 it can be seen that accumulated heat in the evaluated building structures during the night after a sunny day cause the thermal transmittance to be lower than design (stead) values determined by WINDOW 7.6 software and laboratory experiments of the producer. In Fig 10. measured specific heat flux at the inner surface $\dot{q}_i$ is shown for selected days from the experiments period in May and June 2018 and compared to the results of the dynamic thermal response model (Eq. 1). For the case of multi-layer glass building structure, a comparison with a numerical model in which the mass of the glass is not taken into account is also shown.

Fig. 10. Comparison of in-situ and modelled specific heat flux at the inner surface of the multi-layer glass (left) and experimental BIPV₁₀₀ structure (right); RMSE of a dynamic model of the multi-layer glass structure is 4.02 W/m², RMSE of a dynamic model of BIPV₁₀₀ is 2.11 W/m²

It can be concluded that the developed dynamic thermal response model is significantly more accurate, during the night period as well as during the daylight time. This fact confirms the assumption that the accumulation of heat must not be ignored. Some discrepancies between experimental and modelled specific heat flux could be explained by measurement error, which is in the range of $\pm 15\%$ according to the standard error evaluation procedure [31] of the small size of experimental structure in comparison to production size, leading to enhanced influence of the spacer heat bridge or gradual solarization of inner glass pane layers, which is more pronounced in the case of small structures. Nevertheless, we conclude that the presented dynamic thermal response model is adequate and can, therefore, be used for all evaluations of annual multi-layer glass and BIPV facade structure energy balances.

6. Energy balance model

Energy flux models were used to determine the energy balance of the multi-layer glass and BIPV building structures. In the first step of the energy balance, the average daily heat flux and average electricity power of BIPV were determined with the following equations:

$$\dot{q}_{24} = \frac{1}{24} \int_0^{24} (\dot{q}_i(t) + \dot{q}_s(t)) \cdot dt \rightarrow \frac{1}{24} \sum_{h=1}^{24} (\dot{q}_{i,h} + \dot{q}_{s,h}) \quad (10)$$

$$\dot{e}_{PV,24} = \frac{1}{24} \int_0^{24} (\dot{e}_{PV}(t)) \cdot dt \rightarrow \frac{1}{24} \sum_{h=1}^{24} \dot{e}_{PV,h} \quad (11)$$

Although we aimed to evaluate energy balance for the multi-layer facade structure without any interferences regarding the type and usage profile of the building, it was assumed that heat gains and losses could be utilized by the accumulation of heat in the building itself but only for 24 hours. Therefore, it is assumed that neither heat gains, nor heat losses of multi-layer glass and BIPV building structures, can be summarized over several consecutive days. This rule is based on the assumption that if the indoor temperature during the period of heating rises above the indoor comfort limit, the user will activate shading, increase ventilation heat losses, or switch on mechanical cooling. In all these cases, part of the heat gains of multi-layer glass and BIPV structure will be wasted. In contrast, if the heat losses during night-time were too low to maintain the cooling setpoint temperature below the thermal comfort limit during the following day, heat gains must be extracted from the building with additional energy use. Accordingly, the following criteria were implemented in the energy balance model:

- if daily average total heat flux $\dot{q}_{24}$ at the inner surface of the evaluated building structure determined by approximation models presented in Chapter 3. Taking into account heating indoor air temperature set-point is $\dot{q}_{24} \leq 0$ than $\dot{q}_{24,H}$ is set to zero as the structure is neutral regarding heating,
- and if daily average total heat flux $\dot{q}_{24}$ at the inner surface is determined by approximation models taking into account cooling air temperature set-point is $\dot{q}_{24} \geq 0$ than $\dot{q}_{24,C}$ is set to zero as the structure is neutral regarding cooling.

Fig. 11 demonstrates the application of this rule in the case of a multi-layer glass structure for one week for steady heating setpoint air temperature $T_{i,H}$ 22°C and cooling setpoint air temperature $T_{i,C}$ 26°C. In the days when $\dot{q}_{24,H}$ and $\dot{q}_{24,C}$ are equal to zero, the building structure does not cause the need for heating and cooling of the building.

Fig. 11. Total heat fluxes at the inner surface of the multi-layer building structure at a heating set-point temperature ($T_{i,H}$ 22°C) and cooling set-point temperature ($T_{i,C}$ 26°C) and daily average heat fluxes at heating ($\dot{q}_{24,H}$) and cooling ($\dot{q}_{24,C}$) conditions for selected one week period.

6.1. All year energy performance evaluation

For evaluation of the energy performance of the presented multi-layer glass and BIPV facade structure, an hour-by-hour energy balance was made over the year for three geographical locations (Stockholm, Ljubljana, Dubai), different facade orientations (south, west, north and east) and BIPV structures with different PV cell coverage (BIPV₁₀₀, BIPV₇₅, BIPV₅₀, BIPV₂₅). Note that BIPV₁₀₀ structure has an area of PV cells 0.6 m² per 1 m² of the structure; BIPV₂₅ has an area of PV cell only 0.15 m² per m² of the structure. Fig. 12 shown average daily energy fluxes $\dot{q}_{24,H}$ and $\dot{q}_{24,C}$ in case of a west-orientated BIPV₇₅ facade structure in selected geographical locations over a one-year period and indoor air set-point temperature $T_{i,H}$ 22°C and set-point temperature $T_{i,C}$ 26°C.

Fig. 12. Average daily heat fluxes determine for west-orientated BIPV₇₅ facade structures in case of $T_{i,H}$ 22°C and $T_{i,C}$ 26°C.

Summary of energy performance evaluation for evaluated structures is presented as yearly energy balance data in kWh per m² of the structure in Fig.13.

$$Q'_H = \sum_{n=1}^{365} \dot{q}_{24,H,n} \cdot 24 \frac{\text{h}}{\text{day}}; Q'_C = \sum_{n=1}^{365} |\dot{q}_{24,C,n}| \cdot 24 \frac{\text{h}}{\text{day}}; E'_{PV} = \sum_{m=1}^{8760} \dot{e}_{PV,m} \quad (12, 13, 14)$$

6.2. All-year autonomy and utility factor

If the building is connected to the electricity grid, a surplus of produced electricity can be stored in the grid; if the goal is to design a (true) energy self-sufficient building, electricity consumption must be synchronized with electricity production. This can be done directly with batteries. E-mobility could significantly contribute to this goal as well. Nevertheless, as the presented article focused on the energy performance of multi-layer glass and BIPV facade building structures, two additional all-year indicators were developed to characterize BIPV structures: autonomy factor (AUT) and utility factor (UTI). Both indicators are determined using hour-to-hour simulation data and expressed as whole-year values. The autonomy factor is determined by the balance of produced electricity and energy needs for heating and cooling “caused” by building’s structure. The value of AUT equal to 8760 hours per year (h/a) means that such a BIPV structure is completely independent of other energy sources regarding heating and cooling needs. The reversible operating heat pump as heat and cold generator that cover heat gains and sinks of facade structure. The average yearly coefficient of performance $COP_{av,H}$ equal to 4 and $COP_{av,C}$ equal to 3 were assumed. The whole year AUT is defined as the sum of hourly autonomy factors by the following equations and conditions:

$$AUT = \sum_{h=1}^{8760} AUT_h; AUT_h = 1 \text{ if } \frac{\dot{e}_{PV,h}}{\dot{q}_{t,H,h} \cdot \frac{1}{COP_{av,H}} + |\dot{q}_{t,C,h}| \cdot \frac{1}{COP_{av,C}}} \geq 1 \text{ otherwise } AUT_h = 0 \quad (15)$$

AUT indicates how many hours the building structure is energy neutral (according to heating and cooling needs), and utility factor UTI indicates the percentages of electricity produced by BIPV that is available to other building service systems while providing electricity to cover the heating and cooling needs of the BIPV structure itself. As well as AUT, UTI is determined by hour-by-hour balance and expressed as a whole-year value and determined by the following equations and conditions:

$$UTI = \frac{\sum_{h=1}^{8760} \left[\dot{e}_{PV,h} - \left(\dot{q}_{t,H,h} \cdot \frac{1}{COP_{av,H}} + |\dot{q}_{t,C,h}| \cdot \frac{1}{COP_{av,C}} \right) \right] \cdot f_{PV,h}}{\sum_{h=1}^{8760} \dot{e}_{PV,h}}$$

$$f_{PV,h} = 1 \text{ if } \dot{e}_{PV,h} - \left(\dot{q}_{t,H,h} \cdot \frac{1}{COP_{av,H}} + |\dot{q}_{t,C,h}| \cdot \frac{1}{COP_{av,C}} \right) > 0 \text{ otherwise } f_{PV,h} = 0$$

(16)

Values of AUT and UTI for multi-glass and BIPV structures, different facade orientations and selected sites are presented in Fig.13.

Fig. 13. Yearly energy balance of multi-layer glass and BIPV facade structures normalized per 1 m² of structure area (left), autonomy and utility factors for selected sites, orientations and design of BIPV (right)

7. Discussion

The research aimed to evaluate the energy performance of the advanced transparent facade structure consisting of six glass panes. The pilot BIPV with PV cells integrated into the outer

glass layer was evaluated as well. Such multi-layer glass structures have a steady state (nominal) thermal transmittance of $0.292 \text{ W/m}^2\text{K}$, which is a value that is lower than required in general for facade structures in the majority of EU countries. After the first set of experiments, it was found that differences between experimental and numerical simulated data using commercial software tools in heat flux at the inner surface of the structures, which define the energy balance of the structure in our research, were significantly large. In our study, two such tools were used: WINDOW 7.6 and TRNSYS. The reason is in the modelling of such a multi-layer glass structure without taking into account the mass of the structure. Differences were observed both in the maximum day-time heat flux at the inner surface of the structure ($\dot{q}_i$) and in thermal transmittance (U) during night-time. At the time of the experiment, the maximum day-time heat flux was lower, between 10 W/m^2 to 20 W/m^2 , 40% to 60% in comparison to the massless model, and the average night-time thermal transmittance was not above $0.230 \text{ W/m}^2\text{K}$. To improve the accuracy of the energy balance, the procedure for the determination of the dynamic heat response model of a multi-layer glass and BIPV facade structure was developed, including CFD modelling and developing a multi-parameter approximation model of heat flux in the form of a time-series. The approximation model involves five-hour historical values of perpendicular solar irradiation and air temperature difference. Two models, one for multi-glass and one for BIPV₁₀₀ structures, were developed. The BIPV₁₀₀ structure has a maximum designed PV cells area, which corresponds to 60% of the total structure area. Such a structure also enables comfort daylighting. From additional sets of CFD simulations, it was found that BIPV structures with smaller PV cell areas but the same raster of PV cell could be modelled by the principle of aggregation, taking into account proportion of glass and BIPV structure area. At each time step, approximated $\dot{q}_i$ was corrected with incident angle correction factor k_i to compensate for the influence of direct and diffuse solar irradiation incident angle on the absorptivity of each glass pane. Approximation model of $\dot{q}_i$ was validated for multi-layer glass and BIPV with virtual PV cells by in-situ experiments.

From the energy balance of multi-layer glass structures, it can be concluded that for all sites and facade orientations, all-year specific energy needs for cooling Q'_C are higher than specific energy needs for heating Q'_H . In Dubai, no heating is needed at all to cover heat losses of evaluated facade structures.

Regarding the facade orientation, specific energy needs for heating are in the range between 7 to $17 \text{ kWh/m}^2\text{a}$ for building in Stockholm and 4 to $13 \text{ kWh/m}^2\text{a}$ for building in Ljubljana, while specific energy needs for cooling are in the range between 120 to $38 \text{ kWh/m}^2\text{a}$ (Stockholm), 105 to $26 \text{ kWh/m}^2\text{a}$ (Ljubljana) and 190 to $60 \text{ kWh/m}^2\text{a}$ (Dubai). Higher cooling needs in Stockholm in comparison to Ljubljana are due to both higher solar irradiation on the vertical facades and lower incident solar irradiation angles. High cooling needs indicate that techniques of natural or free cooling will have a significant influence on further improvement of buildings energy efficiency towards energy self-sufficient buildings.

Shading by PV cells in BIPV structures has a much higher influence on decreasing of whole-year specific energy needs for cooling than on increase whole-year specific energy needs for heating. For all presented sites, BIPV₁₀₀ produces more electricity than the specific energy needs for heating and cooling; in Ljubljana, even BIPV₇₅ produces a sufficient amount of electricity regardless of facade orientation. This is the same for the north facades of building in Dubai. BIPV₅₀ covers approximately half of heating and cooling needs at all sites, while electricity produced by BIPV₂₅ covers heating needs only (Stockholm, Ljubljana). Interpolating results presented in Fig. 13 (left), building designers can make a basic analysis of the energy performance of a building and can optimize the design of the multi-layer glass and BIPV structures.

For determination of true energy self-sufficiency (regarding heating and cooling) of the building built with evaluated facade structures, hour-by-hour analysis is needed. From Fig. 13 (right) it can be seen that BIPV₁₀₀ can provide autonomy for approximately 4800 (Dubai), 4000 (Ljubljana) and 3800 (Stockholm) hours per year. The highest autonomy is provided by BIPV₁₀₀ installed on east and north facades because of lower energy demands for cooling. The autonomy of BIPV₇₅ is only 100 to 200 hours per year shorter regardless of facade orientation; BIPV₅₀ provides energy balance autonomy for 3600 (Dubai), 3400 (Ljubljana) and 3100 (Stockholm) hours per year. Please note that, for example, BIPV₅₀ has a share of the transparent part 70% of the total area of the structure. From the AUT data, the optimum facade orientation in a particular site is visible, especially in case of structures with lower PV cells coverage.

Despite the high transparency of the evaluated facade structures required for adequate daylighting of the building, even in the case of BIPV₁₀₀, electricity is needed for the operation of other building service systems, such as ventilation. To indicate the surplus of produced electricity for heating and cooling related to facade structures, the UTI factor was introduced and evaluated with an hour-by-hour balance. From Fig. 13 (right) it can be seen that approximate 80% of total produced electricity by BIPV₁₀₀ can be supplied to other building services, and even in the case of BIPV₇₅, this share is above 60%. In the majority of cases, BIPV installed on north facade has highest UTI due to lowest “self-consumption” of electricity. Differences in UTI between the sites can be observed but not to the extent that limits the implementation of evaluated facade structures.

8. Conclusion

Short-term daily solar irradiation and temperature conditions scenarios were defined as transient boundary conditions in CFD simulations of dynamic heat transfer in multi-layer glass and BIPV facade structures, enabling both time-efficient CFD modelling and developing a dynamic model of heat flux at the inner surface of such structures. The model was verified with experiments on the six-layer glass and BIPV with virtual PV cells showing that the proposed approach is significantly more accurate than massless dynamic models. A more accurate model for the determination of transmitted short wavelength solar direct and diffuse irradiation was introduced for multi-layer glass and BIPV structures as well. Experiments and numerical simulations showed that thermal transmittance of evaluated facade structures can be compared to require thermal transmittance of opaque facade structures in the majority of national regulations, meaning that presented facade structures enable formal all-glass building design. Indicators to support designer decisions were developed and evaluated. A set of indicators includes average daily energy flux (combine heat and solar transmitted irradiation) at the inner surface of the structure used for whole year energy balance evaluation, autonomy factor that indicates the number of hours in the year during which electricity production by BIPV is equal or higher than heating and cooling needs of the structure itself and a utility factor that indicates the availability of produced electricity by BIPV to other building service system. Our opinion is that the presented study provides a solid basis for further research of advance technologies for nearly zero energy buildings and beyond. Although the models shown in the article were solely developed to evaluate the energy performance of facade structures, models can be integrated into computer tools for the determination of dynamic thermal response of the buildings to provide more accurate analysis of an all-glass building with advanced multi-layer glass and BIPV facade structures.

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