THERMAL CHARACTERISTICS OF BIPV
(U-value and g-value)

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1) Introduction

One third of the worldwide total energy demand is consumed by building applications. In order to supply this demand, reduce this considerable consumption and still maintain the comfort of the building, Building Integrated Photovoltaic (BIPV) is one of the most well-disposed elements for building applications, thanks photovoltaic energy generating effect, thermal insulation and solar gain, and its multifunctional characteristics, respectively.

BIPV as an element integrated on building envelops have to comply the requirements of building products as defined in Construction Products Directive [CPD-89/106/EEC]. The thermal characteristics of BIPV are considered as one of the most important functions in total energy efficiency in building as defined in European Performance of Building Directive (EPBD); for instances: thermal insulation (U-value), sun control (g-value and Fc-value), etc.

To determine these thermal characteristics of BIPV, most manufacturers define their products specification based so far on conventional building products, since no specific research on PV in building products exist. With same module configuration like laminated glass, the U-value of PV-laminated glass is the same as conventional laminated glass. With respect to higher radiation absorption and representing higher operating temperature of BIPV compared to conventional building products, however, changes of the thermal characteristics have to be taken into account. The operating temperature of roof-integrated PV can reach 90°C. [Mei et al. 2009]

In this paper, the influences of PV-specific characteristics will be investigated on these relevant building functions in comparison with conventional building products; heat transmission coefficient (U-value), solar heat gain (g-value) and solar reduction ratio (Fc-value) in both summer and winter periods. The most significant coefficients related to operating temperature and corresponding surface temperatures are external and internal heat transfer coefficients ($\boldsymbol{h_e}$ and $\boldsymbol{h_i}$) and heat transmission coefficient in cavity ($\boldsymbol{h_s}$).

In the BMU research project "MULTIELEMENT, the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) together with 15 industrial partners study on the development of manufacturing, testing and installation methods of multifunctional photovoltaic devices / modules in buildings [Misara et al. 2009].

2) Thermal Characteristic

The heat transmission coefficient (U value) is a parameter of thermal insulation quality for building products, which means the amount of heat flow in Watt (W) is transported through one square meter of building products at a temperature difference of 1 K. The U-value is composed of the heat transmission coefficient of each layers ($\boldsymbol{d/\lambda}$) and the internal and external heat transfer coefficient ($\boldsymbol{h_i}$, $\boldsymbol{h_e}$) [EN-673].

In summer, the solar heat gain coefficient (g-value) is a parameter of total energy transmittance of transparent building products, like glazing. This consists of the direct transmission of solar radiation ($\boldsymbol{\tau_e}$) and the secondary heat dissipation toward the interior of the building ($\boldsymbol{q_i}$) [EN-410]. In winter, the solar reduction ratio (Fc-value) is a parameter of solar protection devices. It's a ratio of g-value of the solar protection device to the g-value of glazing without shading elements [DIN-4108-2]. Table 1describes the characteristics of their thermal relevant building functions along with their calculation methods.

For the determination of these parameters, the accurate values for the external and internal heat transfer coefficients ($\boldsymbol{h_i}$, $\boldsymbol{h_e}$), and the heat transmission coefficient in the gap ($\boldsymbol{h_s}$) are necessary. In order to determine or identify these coefficients, table 2 has described both summer and winter boundary conditions [EN-410 and EN-13363-2]. These coefficients depend on the operating temperature, surface temperature of the component, ambient temperature, tilt angle, emissivity of surface and the wind speed. The standard values of internal and external heat transfer coefficients can be obtained by EN410 and EN13363-2, while the heat transmission coefficient in the cavity (h_s) are defined in EN673 and measured in EN674, EN675 and EN12567. These coefficients have been considered under steady state boundary conditions.

Table 1 Thermal parameters of building products: U-value, g-value and Fc-value.

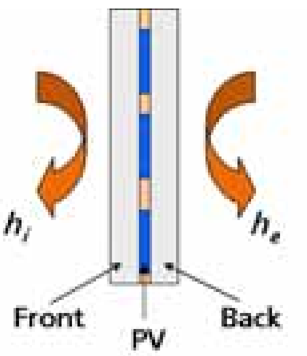
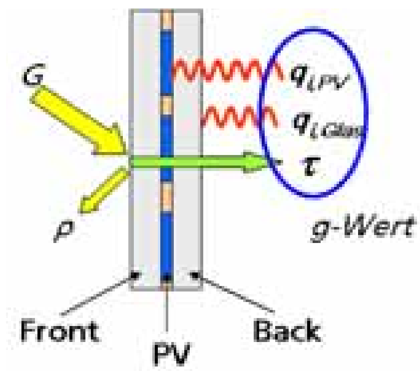
Heat transmission coefficient (U-value)	**Solar heat gain coefficient (g-value)** **Solar reduction ratio (Fc-value)**
$\frac{1}{U}=\frac{1}{h_e}+\frac{1}{h_t}+\frac{1}{h_i}$ (eq. 1) $\frac{1}{h_t}=\sum_1^N\frac{1}{h_s}+\sum_1^M\frac{d_j}{\lambda_j}$ (eq. 2)	$g=\tau_e+q_i$ (eq. 3) $q_i=\alpha_e\cdot\frac{h_i}{h_i+h_e}$ (eq. 4) $F_c=\frac{g_{total}}{g_{glas}}$ (eq. 5)
U = heat transmission coefficient [W/m²K] h_e = external heat transfer coefficient [W/m²K] h_t = total heat transmission coefficient [W/m²K] h_i = internal heat transfer coefficient [W/m²K] h_s = heat transfer coefficient in space [W/m²K] N = number of spaces M = number of material layers d_j = thickness of each material layer [m] λ_j = thermal conductivity of each material [W/mK]	g = solar heat gain coefficient [%] τ_e = energetic transmission of glazing [%] q_i = secondary heat dissipation toward the interior [%] α_e = Absorption of glazing [%] h_e = external heat transfer coefficient [W/m²K] h_i = internal heat transfer coefficient [W/m²K] F_C = solar reduction factor [-]
 	

Table 2 Boundary conditions for determination U-value, g-value and Fc-value in summer and winter [EN-410, EN-13363-2]

Winter (U-value, g-value)	**Summer (Fc-value)**
Outside ○ Solar irradiation 300 W/m² ○ Wind speed 4m/s ○ Ambient temperature 5°C	Outside ○ Solar irradiation 500 W/m² ○ Wind speed 1m/s ○ Ambient temperature 25°C
Inside ○ Vertical glazing ○ Wind speed 0m/s ○ Room temperature 20°C	Inside ○ Vertical glazing ○ Wind speed 0m/s ○ Room temperature 25°C
Heat transfer coefficient ○ Internal 1) = 7,7 W/m²K ○ External 2) = 25,0 W/m²K	Heat transfer coefficient ○ Internal 3) = 2,5 W/m²K ○ External 4) = 8,0 W/m²K
1) Convection = 2,5 W/m²K (horizontal heat flux) + Radiation = 5.2 W/m²K (at ~10°C) 2) Convection = 20,0 W/m²K (4 + 4x4m/s) + Radiation = ~5,0 W/m²K (at ~10°C) 3) Convection = 2,5 W/m²K (horizontal heat flux) + Radiation = ~0,0 W/m²K (same outside and inside temperature) 4) Convection = 8,0 W/m²K (4 + 4x1m/s) + Radiation ~0,0 W/m²K (same outside and inside surface temperature)	

With respect to thermal characteristics of BIPV modules, most of BIPV manufacturers assume their products based on conventional building products; for instance: PV-module has the same U-value as conventional building products with the same module configuration, the q_i in g-value depends on the coverage degree with PV cells together the ratios of internal and external heat transfer coefficient of the conventional glazing (eq.-3 and eq.-4).

3) Problem

With respect to building functions from manufacturers, the summer and winter boundary condition have not been taken into account. The manufacturers do consider their building functions based only on winter boundary condition (***h_i*** at 7.7 W/m²K and ***h_e*** at 25.0 W/m²K). To identify the U-value and g-value, the winter boundary condition has to be considered. However, the g-value as part of solar reduction ratio (Fc-value) needs to be considered based on summer boundary condition.

The above conditions are applied only to glass, not for PV modules. With respect to the higher degree of absorption of solar cells in comparison to conventional glazing, the heat sources can be found inside the BIPV-modules. This will increase the operating and surface temperature of BIPV-modules. Therefore, the heat transfer coefficient (***h_i***, ***h_e***) and the heat transmission coefficient in cavity (***h_s***) will be varied compared to conventional glazing without internal heat sources. The relevant building functions will be changed along with the deviation of these thermal parameters.

In EN 6496, the correlation of internal and external heat transfer coefficients and heat transmission coefficient has been defined under consideration of different operating temperature. With respect to winter and summer boundary conditions above, however, the operating temperature and surface temperature will be different based on individual module configuration and different percentage of PV cell coverage. A certain operating temperature of each module configuration is not known. Therefore, this building code is not applicable for BIPV applications.

For the building planers or architectures, there are no proper calculation methods so far for identifying these thermal parameters and corresponding relevant building functions of BIPV modules.

In this case, there are many measurements to identify these relevant building functions and corresponding thermal parameters; for instances U-value by Hot-Box (EN12567), Guarded Hot Plate (EN674) and Heat Flow Meter methods and g-Value by Calorimetric (EN410).

- <u>U-value measurement</u>: With respect to boundary conditions above, however, the solar irradiation and corresponding internal heat source of PV-specific characteristic has not been considered yet for BIPV applications. For conventional building products, the heat flux will flow only in one direction. In BIPV application with internal heat source, the heat flux will flow into both directs from internal heat source to both ambient sides.
- <u>g-value measurement</u>: The total energy transmittance can be measured without knowing the internal and external heat transfer coefficients. In order to measure these heat transfer coefficient, the heat flux plate is used together with temperature differences between surface and ambient temperature. With respect to different solar irradiation in boundary conditions, however, the heat flux plate could not measure under direct solar irradiation due to its sensitive against direct solar irradiation.

4) Objective

In order to evaluate the influences of PV specific characteristics together with both side surface temperatures and their corresponding thermal parameters, the temperature model has been developed based on power-balance model for different BIPV modules configurations and further validated based on different solar irradiations on vertical glazing.

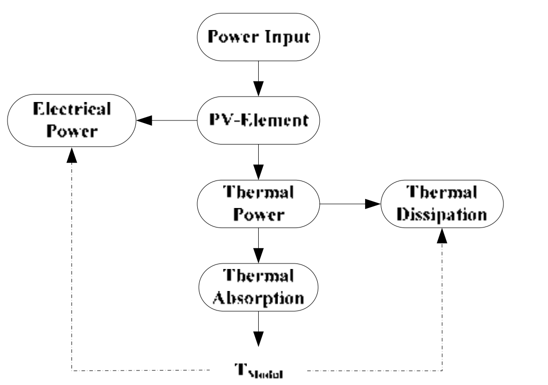
With respect to internal heat source inside the BIPV modules, the different solar irradiation can be emulated by feed-in power concept. Therefore, the new test infrastructure has been developed together with the measurement of heat transfer coefficients.

With good correlation between model and measured temperatures and thermal parameters, therefore, the relevant building functions can be further evaluated between BIPV module and conventional building products based on summer and winter boundary conditions for laminated glass, insulated glass and composited elements.

5) Temperature Models

<u>Power Balance Model</u>

In order to evaluate the influences of PV specific characteristics, the temperature model needs to be developed. There are many research works to evaluate the temperature of PV in implicit and explicit methods, which T_c can be calculated directly or from other parameters such as heat transfer coefficient, efficiency and others, respectively [Skoplaki and Palyvos 2009]. However, they do consider only on PV cell operating temperature in order to evaluate the electrical power yields of PV module. For identifying the relevant thermal characteristics on building functions, the surface temperature is needed, not operating temperature. Especially for BIPV module with high module configuration, the surface temperature will be totally different to standard PV module. This can be achieved by power balance model. This power balance is working on the concept of total power input and power output of the BIPV module. The power input is the short wavelength of solar radiation on the PV cell, which one part transmits through the module (in case of transparent module), one part reflects from the surface and the rest will be absorbed in modules [eq. 6]. This short wavelength absorption inside the module will be converted into electrical power through PV cell [eq. 7] and long wavelength thermal power. Under dynamic state, the rest long wavelength thermal power can be assumed into 2 parts; thermal dissipation power [eq. 8] and thermal absorption power [eq. 9] [Figure 1]. The thermal absorption part is related directly to thermal capacity of the modules and leads to time-lag of operating temperature under fluctuated solar irradiance in cloudy day. This time-lag could be more than 15 minutes for standard PV modules [Jones and Underwood 2001]. This is very important for energy management application and building simulation. The thermal absorption power will increase the module temperature until reaching the steady state. In order to solve the dynamic temperature model, the iteration method is needed. This increasing module temperature will decrease the electrical power and increase the thermal dissipation power [Misara et al. 2010].



Power Input

$$\left(1-\gamma_f-\alpha_f-\alpha_b\tau_{PV}\tau_f-\tau_b\tau_{PV}\tau_f\right)\cdot GA \quad \text{(eq. 6)}$$

Electrical Power

$$\left[\eta\cdot\left(1-\alpha_{coeff}\left(T_M-T_{STC}\right)\right)\cdot\tau_f\cdot GA\right] \quad \text{(eq. 7)}$$

Dissipation Power

$$\left[\sum_j^{f,b} h_j\left(T_M-T_j\right)A\right] \quad \text{(eq. 8)}$$

Absorption Power

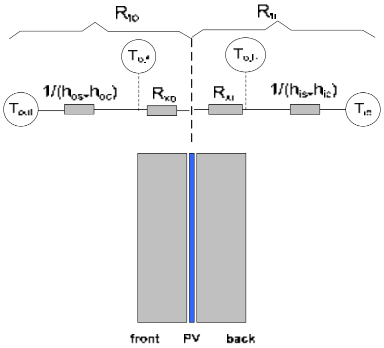
$$\left[C_M\left(\frac{\Delta T_M}{\Delta t}\right)\right] \quad \text{(eq. 9)}$$

τ	= transmission factor	G	= global irradiation (W/m²)
γ	= reflection factor	A	= module area (m²)
α	= absorption factor	η	= module efficiency (%)
f	= front layer	α_{coeff}	= temperature co-efficiency of module (%/K)
b	= back layer	T_{STC}	= Temperature at STC (25 °C)
PV	= PV layer	C_M	= module heat capacity (J/K)
		h_j	= external and internal heat transfer coefficient

Figure 1 Temperature model based on power balance along

For identifying the relevant building function, the steady state will be considered. Eq. 10 describes the equation of power balance model under steady state condition. The long wavelength thermal power will be balanced with dissipation thermal power, while the thermal absorption power is no longer available. The thermal dissipation power can be achieved through conduction heat transfer resistances ($\boldsymbol{R_{xo}}$), convection and radiation heat transfer coefficient ($\boldsymbol{h_c}$, $\boldsymbol{h_r}$) [Figure 2]. The conduction heat transfer resistances are the proportional of each material thickness (d in m) to the each material heat conductivity (λ in W/mK). These can also be assumed to be constant and independent from temperature. The convection heat transfer composes of natural and forced convection. The natural heat transfer coefficient depends mainly on temperature differences between surface and ambient temperature, module length, fluid characteristics, while the forced convection is depending mainly wind speed, module length and fluid conductivity. The radiation heat transfer coefficient depends on surface temperature, ambient temperature, emission, etc [Figure 3] [Quaschning 1996].

In terms of thermal dissipation, there are many research works related to convection and radiation heat transfers [Krauter et al. 2001, Mattei et al. 2006, de la Breteque et al. 2009]. However, they assumed that the surface temperature is equal to cell temperature. Knaup and King have described the backside surface temperature of standard glass-glass and glass-backsheet module with temperature decrement of 2-3°C along with the amount of solar irradiation [Knaup 1997, King 1997]. With respect to higher BIPV module configuration, the main focus of temperature models should be on surface temperature as describe in figure 2.



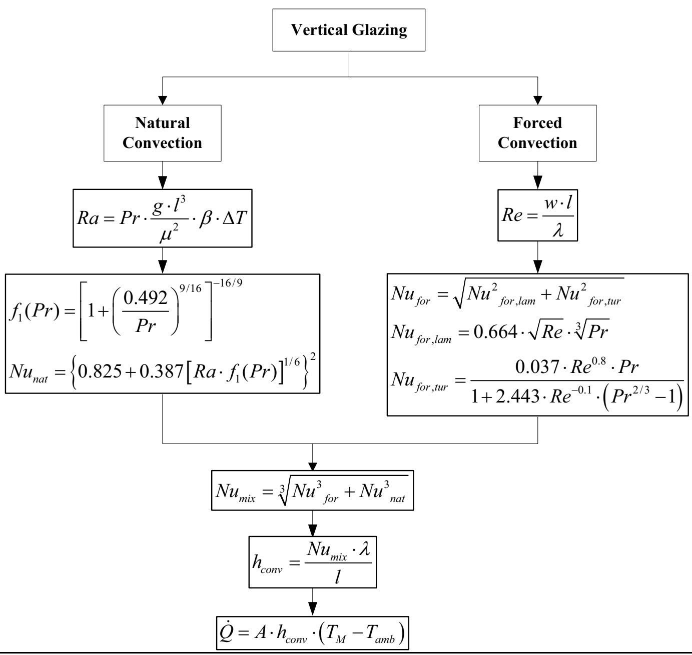
$R_{xi,\,xo}$	= conduction heat transfer resistance (m²K/W) = $\sum(d/\lambda)$
$1/(h_{ic}+h_{oc})$	= internal heat transfer resistance (convection + radiation) (m²K/W)
$1/(h_{or}+h_{or})$	= external heat transfer resistance (convection + radiation) (m²K/W)
$T_{o,b}$, $T_{o,f}$	= surface temperature – backside and frontside
T_{in}	= inside ambient temperature
T_{out}	= outside ambient temperature

$$\left(1-\gamma_f-\alpha_f-\alpha_b\tau_{PV}\tau_f-\tau_b\tau_{PV}\tau_f\right)\cdot GA = \left[\eta\cdot\left(1-\alpha_{coeff}\left(T_M-T_{STC}\right)\right)\cdot\tau_f\cdot GA\right]+ \left[\sum_j^{f,b}\left(\frac{1}{R_{x,j}}+h_j\right)\cdot\left(T_M-T_j\right)A\right] \qquad \text{(eq. 10)}$$

Figure 2 Correlation of heat transport elements (conduction, convection and radiation) along with module configuration.

Finally, the external and internal heat transfer coefficients are the combination of convection and radiation heat transfer coefficients on each side. In case of insulated glass, the heat transport in cavity is the combination of natural convection heat transfer coefficient and radiation heat transfer coefficient between two parallel surfaces [EN 673, VDI Wärmeatlas 2006].

Convection heat transfer coefficient – h_c



Ra	= Rayleigh number (-)
Pr	= Prandtl number (-)
g	= gravity (m/s²)
l	= length (m)
μ	= fluid viscosity (Pa.s)
β	= temperature^{-1} (1/K)
ΔT	= temperature difference (K)
Re	= Reynolds number (-)
w	= wind speed (m/s)
λ	= thermal conductivity (W/mK)
Nu	= Nusselt number (-)
A	= surface (m²)

Radiation heat transfer coefficient – h_r

$$h_r=\begin{bmatrix}0.5\cdot\varepsilon_M\cdot\sigma\cdot\varepsilon_E\cdot\left(1+\cos\alpha\right)\cdot\left(T_M^2+T_E^2\right)\cdot\left(T_M+T_E\right)+\\ 0.5\cdot\varepsilon_M\cdot\sigma\cdot\varepsilon_{sky}\cdot\left(1-\cos\alpha\right)\cdot\left(T_M^2+T_{sky}^2\right)\cdot\left(T_M+T_{sky}\right)\end{bmatrix} \qquad \text{(eq. 11)}$$

ε	= emissivity of surface (-)
σ	= Stefan–Boltzmann constant 5.669 × 10^{-8} W/(m² K⁴)
A	= tilt angle
T_M	= module temperature (K)
T_{amb}	= ambient temperature (K)
E	= Earth
Sky	= sky

Figure 3 heat transfer coefficient: convection and radiation

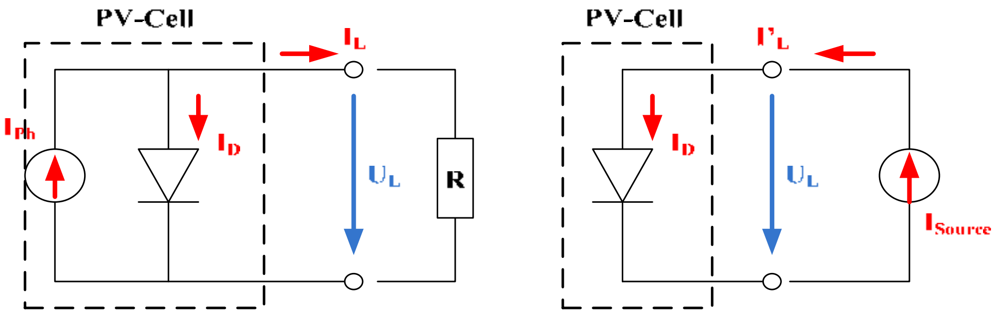
6) Feed-In Power Concept

Feed-in Power Concept

The characteristic of PV cell can be described with an equivalent circuit of single diode model (a current source in parallel with a single-diode) [Figure 4-a]. When exposed to light, a photo current (I_{ph}) is generated in proportional to the solar radiation. In the dark, the solar cell is not an active device; it acts as a diode and produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a current, so called diode dark current (I_D). [Rodrigues et al. 2010]

By operating the PV cell as a diode, the feed-in power concept is trying to emulate the amount of long wavelength thermal power absorbed in the module from solar irradiation [Figure 4-b]. Using an external power supply to feed the current back into the module, hence, the PV module acts like an electrical load. This feed-in power will heat up the module in dynamic state to increase the operating temperature until reaching the steady state condition (operating temperature is constant). Therefore, the different boundary conditions of solar irradiation can be achieved.

With respect to inapplicable of conventional test methods for identifying the relevant building functions as mentioned above, the internal heat source and the measurement of internal and external heat transfer coefficient can also be achieved with this feed-in power concept and heat flux plate measurement. In order to define U-value, the internal heat source of PV-module can be emulated, while the conventional measurement is not possible. For g-value, the external heat transfer coefficient can also be measured with heat flux plate because it has not been faced directly to the solar irradiation.



$$I_{Ph} = I_D + I_L \qquad I'_L = I_D$$

Figure 4 Equivalent circuit of PV Cell characteristic under solar irradiation (a) and without solar irradiation (b).

Test Method

Since there are 3 different solar irradiation defined in building codes and PV standard [Table 2], [IEC-61215], the solar irradiation of 300, 500 and 800 W/m² needs to be emulated with feed-in power concept. The solar irradiation of 800 W/m² can be found under Standard Operating Condition (SOC). In order to emulate the long wavelength thermal power, the amount of feed-in power can be calculated from power balance model (eq. 12).

$$G_{irradiation} = P_{thermal} + P_{electrical} + P_{transmission+reflection} \qquad \text{(eq. 12)}$$

With respect to the specification of PV module, the amount of feed-in thermal power needs to be calculated along with PV module's dimension. In the experiment, a polycrystalline PV module was used in glass-glass module configuration [Table 3]. The energetic components in the form of reflection together with transmission and the photovoltaic conversion are calculated using the technical data of the module. In order to compare the behaviour of the PV modules together with conventional glass, the amount of feed-in power was calculated together with the PV module dimension of 0.5 m² [Table 4]. With high transmission of conventional glazing and module dimension of 0.5 m², the feed-in powers for solar irradiation of 300W/m² and 500W/m² are 20W and 33W, respectively. For PV-Cell with high absorption, the feed-in power for solar irradiation of 300W/m², 500W/m² and 800 W/m² are 111W, 185W and 395W, respectively.

Table 3 PV-Module characteristics

Description	Conv. Glass	PV Module
Module efficiency $(\eta)PV$	0%	10%
Transmission/Reflection/Absorption	79%, 8%, 13%	8%, 8%, 84%
Module configuration	Glass-Glass	Glass-Glass
Number of PV solar cells	-	40
Cell technology	-	polycrystalline
Dimension	450x1070 mm.	450x1070 mm.

Table 1: Feed-in thermal power with different solar irradiation from conventional glazing and PV Modules

Scenarios			G		$P_{electric}$		Reflexion + Transmission		$P_{thermal}$	Feed-in Power
1	Glass-300		300 W	-	0 W (0%·300 W)	-	261 W ((8%+79%)·300 W)	=	**39 W**	**20 W**
2	Glass-500		500 W	-	0 W (0%·500 W)	-	435 W ((8%+79%)·500 W)	=	**65 W**	**33 W**
3	PV-300		300 W	-	30 W (10%·300 W)	-	48 W ((8%+8%)·300 W)	=	**222 W**	**111 W**
4	PV-500		500 W	-	50 W (10%·500 W)	-	80 W ((8%+8%)·500 W)	=	**370 W**	**185 W**
5	PV-800		800 W	-	80 W (10%·800 W)	-	128 W ((8%+8%)·800 W)	=	**592 W**	**395 W**

Positioning of sensors

With respect to experimental measurement with Infrared (IR) Camera, the module operating temperature is quite similar over module surface. Therefore, the temperature sensors and heat flux plates were placed centrally on the front and rear side of the PV component. [Figure 5]

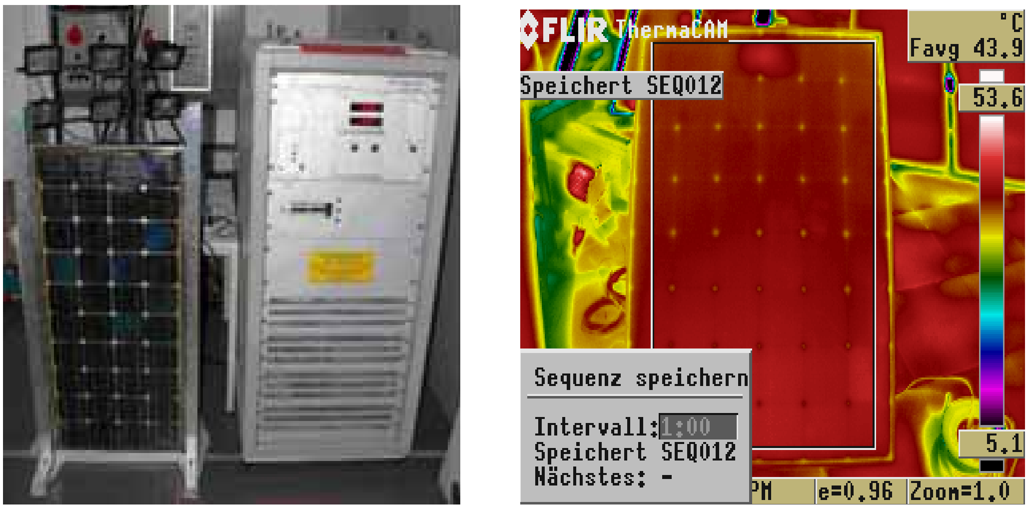


Fig. 5 (a) Test infrastructure of feed-in thermal power with polycrystalline PV module and external power supply (b) Experimental measurement with Infrared (IR) Camera

The internal and external heat transfer coefficient (h_i and h_e) are the proportional of measured heat flux from heat flux plates (q_i und q_e) to temperature different of operating module temperature (T_M) and ambient temperature (T_{amb}) [eq. 13]. These internal and external heat transfer coefficients represent both convection and radiation heat transfer. In case of convection heat transfer coefficient, only natural convection will be measured because the test was done under indoor condition without external wind speed.

$$h_{i,e} = \frac{q_{i,e}}{T_{M(i,e)} - T_{amb(i,e)}} \qquad \text{(eq. 13)}$$

7) Results

Figure 6 represents the surface temperature (a) and heat transfer coefficient (b) of PV module under different scenarios as mentioned in Table 4 under vertical mounting system and natural convetion. In case of conventional glazing, the surface temperatures under solar irradiation of 300 W/m² and 500 W/m² are 22.0 and 24.5 °C respectively. The differences are only 2-4 °C over ambient temperature. However, the surface temperatures of PV modules are 32°C, 42°C and 50°C under solar irradiation of 300W/m², 500W/m² and 800W/m². These represent the temperature differences between surface temperature and ambient temperature of 12°C, 22°C and 30°C, respectively.

With respect to higher operating temperature and corresponding surface temperature, therefore, the heat transfer coefficients will be higher . Regarding heat flux plate's specification, the temperature difference needs to be higher than 5°C. For conventional glazing, therefore, the heat transfer coefficient could not be measured due to lower temperature differences between surface temperature and ambient temperature (2°C and 4°C). In case of PV modules, the heat transfer coefficients of different PV module scenarios are 8.5 W/m²K, 9.5 W/m²K and 10.25 W/m²K under solar irradiation 300 W/m², 500 W/m² and 800 W/m², respectively. These values are much higher than standard values.

Table 5 shows the heat transfer coefficient of different scenarios of conventional glazing and PV modules based on different approaches; EN 410, EN 6496, temperature model and measurement. The normative values of conventional glazing (EN 410) without any consideration of higher operating surface are not applicable for PV modules. Although EN 6496 has defined the heat transfer coefficient as a function of operating temperature, these normative values are still not applicable for PV modules.

With good correlation between temperature model and measurement, therefore, it can be evaluated that the heat transfer coefficients were correctly considered in this simulation, so that the inherent model has been validated. Moreover, the effect of conduction heat transfer resistance of PV composite element has been further validated together with other tilt angle [Misara-2010].

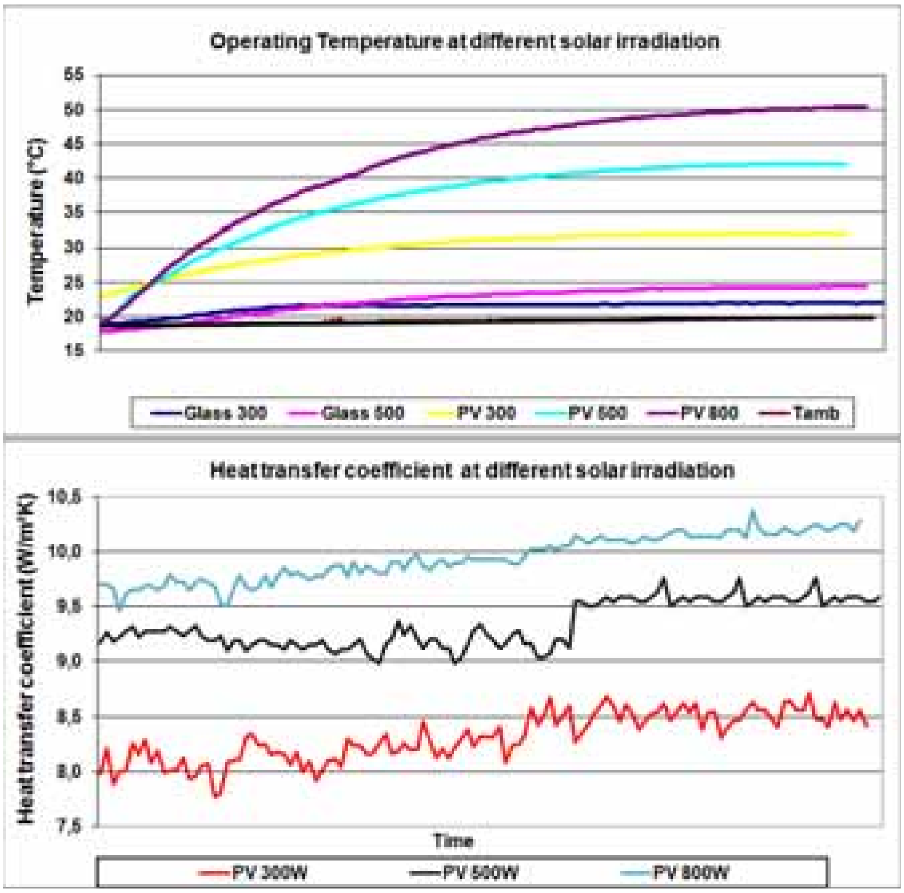


Fig 6 (a) operating temperature of conventional glass and PV Module with different solar irradiation under vertical installation and natural convection.
(b) measured heat transfer coefficient of PV module with different solar irradiation

Table 5 Comparison of heat transfer coefficient from EN 410, EN 6496, Models and measurement for conventional glazing and PV modules at different solar irradiation under vertical installation and natural convection

Scenarios		Module Temperature	Heat Transfer Coefficiency (W/m²K)			
			EN410	**EN6496**	**Model**	**Measurement**
1	Glass-300	22.0 °C	**7.70**	**7.70**	**7.30**	**-***
2	Glass-500	24.5 °C	**7.70**	**7.70**	**7.75**	**-***
3	PV-300	32.0 °C	**7.70**	**7.90**	**8.65**	**8.55**
4	PV-300	42.0 °C	**7.70**	**8.20**	**9.50**	**9.60**
5	PV-800	50.0 °C	**7.70**	**8.50**	**10.25**	**10.20**

* The heat flux could not measure with the temperature differences lower than 5 K.

8) Evaluation

By implementing this validated model for different PV module together with conventional building products (laminated glass, insulated glass and composite element), the operating temperature, surface temperature and corresponding heat transfer coefficients can be simulated based on winter and summer boundary conditions for identifying these thermal relevant building functions [Table 6].

The deviation of operating temperatures for PV modules is approximately 8-10 °C in winter and about 18-30 °C in summer compared to conventional building products. With respect to different PV module configurations, however, the deviation of operating temperatures in winter is less varied from 8°C to 10°C, because the influence of ambient temperature is mainly occupied on operating temperature. In summer, the deviation of operating temperature is higher because the influence of solar irradiation is occupied merely on operating temperature, while the influence of ambient temperature is no longer available.

The deviation of internal heat transfer coefficient (h_i) is around -7% to -12% for PV modules compared to conventional building products, while in summer the deviation is getting much higher from +17% to +39%. It can also be evaluated that the better thermal insulation of conventional building products is, the lower deviation of internal heat transfer coefficient is.

The external heat transfer coefficients (h_e) are quite similar for all configurations of PV-modules and conventional building products around 23,5 W/m²K in winter, while in summer the deviation of external heat transfer coefficients are around +6% to +10% compared to conventional building products.

The values in winter are much higher than that in summer, because the wind speed or forced convection is a major effect on external heat transfer coefficient. With higher wind speed of 4m/s in winter, the influence of forced convection represents around 99% on heat transfer coefficient. Therefore, the deviation on heat transfer coefficient is quite low.

In laminated glass and composite element, the heat transfer resistivity is quite constant and independent from temperature differences. For insulated glass, the heat transfer resistivity in cavity is -5% and -12% in winter and summer, respectively. With increasing operating temperature, the heat transport will be increased and leads to lower heat transfer resistivity in the cavity.

Table 6 Operating temperature, surface temperature and thermal parameters of different PV module configuration as well as %-deviation in comparison with conventional building products.

Boundary Conditions		Scenario 1			Scenario 2			Scenario 3		
		Laminated glass			Insulated glass			Composite element		
		Laminated	PV-laminated	Deviation	Insulated	PV-Insulated	Deviation	Composited	PV-Composited	Deviation
Operating temperatur(°C)	Winter	9,37	17,43	8,06	7,31	17,46	10,15	5,76	16,66	10,9
	Summer	26,08	44,46	18,38	26,35	51,84	25,49	26,66	57,09	30,43
Internal surface temperature(°C)	Winter	9,68	17,49	7,81	14,92	18,87	3,95	19,3	19,83	0,53
	Summer	26,06	43,79	17,73	25,62	36,26	10,64	25,09	26,43	1,34
Internal heat transfer coefficient(h_i) (W/m²K)	Winter	7,99	7,01	-12,27%	7,47	6,61	-11,51%	6,40	5,94	-7,19%
	Summer	6,91	9,59	38,78%	6,67	8,84	32,53%	6,06	7,07	16,67%
External surface temperature(°C)	Winter	9,02	16,42	7,4	7,13	16,44	9,31	5,70	15,72	10,02
	Summer	26,04	43,56	17,52	26,29	50,56	24,27	26,59	55,55	28,96
External heat transfer coefficient(h_e) (W/m²K)	Winter	23,50	23,58	0,34%	23,48	23,58	0,43%	23,47	23,57	0,43%
	Summer	12,27	13,01	6,03%	12,28	13,30	8,31%	12,29	13,51	9,93%
Heat transfer resistivity in cavity (1/h_c) (m²K/W)	Winter	0,0075	0,0075	0,00%	0,2030	0,1920	-5,42%	3,0379	3,0379	0,00%
	Summer	0,0075	0,0075	0,00%	0,1810	0,1590	-12,15%	3,0379	3,0379	0,00%

9) Building Functions

With respect to new thermal parameters in table 6 along with equations 1-5, the relevant building functions (U-, g- and Fc-Values) can be further evaluated under consideration of PV cell coverage. Figure 7 represents the calculation methods for identify the U-value and secondary heat dissipation toward the interior under consideration of percentage of PV cell coverage. At transparent area, the thermal parameters of conventional glazing will be taken into account, while the new thermal parameters will be considered at PV cell coverage area [Henze et al. 2009].

Table 7 shows the U-values of PV modules under consideration of different PV module configurations and percentage of PV cell coverage along with the standard values from manufacturer's specification. The calculations of these standard values are based on normative coefficients of conventional glazing. ($\boldsymbol{h_i}$ and $\boldsymbol{h_e}$ = 7,7 and 25 W/m²K).

With respect to the temperature differences between outside (5°C) and inside (20°C), the U-value will only be considered under winter condition, while the temperature differences between outside (25°C) and inside (25°C) in summer is zero. In winter, the U-values decrease for all PV modules configuration, up to -8.50% for laminated glass. The better thermal insulation of conventional building products is, the lower deviation of U-values is.

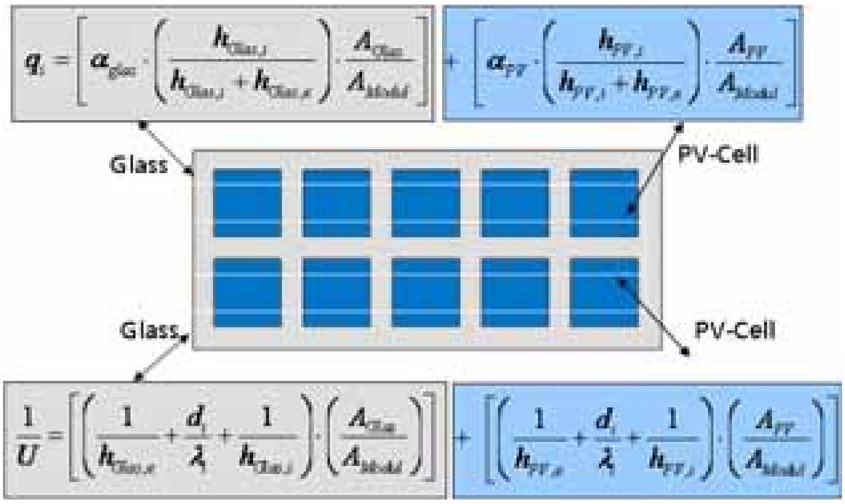


Figure 7 Calculation methods for identify the U-value and secondary heat transfer coefficient emitted inside under consideration of percentage of PV cell coverage

Table 7 Comparison of heat transfer coefficient (U-value) of different PV module configurations under consideration of new PV-specific thermal parameters and different percentage of PV cell coverage

PV-Coverage	U-Value		
	Laminated glass	Insulated glass	Composited element
	Winter	Winter	Winter
Manufacturer Values	5,7	2,7	0,312
0% (no PV)	5,707	0,000	0,309
50%	5,438	2,614	0,308
55%	5,412	2,612	0,308
60%	5,387	2,610	0,308
65%	5,362	2,607	0,308
70%	5,337	2,605	0,308
75%	5,313	2,603	0,308
80%	5,288	2,601	0,308
85%	5,264	2,599	0,308
90%	5,240	2,597	0,308
95%	5,217	2,595	0,308
% Deviation from Manufacturer Values	-8,48	-3,90	-1,32
% Deviation from building products (no PV)	-8,59	-1,54	-0,35

In order to utilize the solar energy in winter periods and protect the solar energy in summer, the solar heat gain coefficient (g-value) and solar reduction factor (Fc-value) will be considered under winter and summer boundary condition, respectively. Table 9 represents the solar heat gain coefficient (g-values) and solar reduction factor (Fc-values) for different PV module configurations with different percentage of PV cell coverage.

In winter, the solar heat gain coefficient (g-value) of the PV modules with new thermal parameters is worse than that with normative parameters (-9.5% for PV laminated glass and – 13% for insulating glass). That means the amount of solar heat gain in winter is lower than what people expected. Likewise, the solar reduction factor (Fc-value) of the PV modules with new thermal parameters is worse than that with normative with normative parameters (+52% for laminated glass and +43% for insulating glass). That means the amount of solar irradiation can be emitted inside the room more than what expected.

Tab. 9 Comparison of solar heat gain (g-value) in winter and solar reduction factor (Fc-value) in summer under consideration of new PV-specific thermal parameters and different percentage of PV cell coverage

PV Coverage	Laminated glass				Insulated glass			
	g-Value		Fc-Value		g-Value		Fc-Value	
	Winter		Summer		Winter		Summer	
	old	new	old	new	old	new	old	new
0%	0,820	0,820	1,000	1,000	0,702	0,695	1,000	1,000
50%	0,529	0,516	0,641	0,727	0,467	0,447	0,665	0,748
55%	0,500	0,485	0,609	0,700	0,444	0,422	0,632	0,723
60%	0,470	0,454	0,568	0,673	0,420	0,397	0,599	0,698
65%	0,440	0,423	0,533	0,645	0,397	0,372	0,565	0,672
70%	0,410	0,392	0,497	0,618	0,373	0,347	0,532	0,647
75%	0,381	0,361	0,461	0,591	0,350	0,322	0,498	0,622
80%	0,351	0,330	0,425	0,564	0,326	0,297	0,465	0,597
85%	0,321	0,299	0,389	0,536	0,303	0,272	0,431	0,572
90%	0,292	0,268	0,353	0,509	0,279	0,247	0,398	0,546
95%	0,262	0,237	0,317	0,482	0,256	0,222	0,364	0,521
% Deviation from new and old parameters	-9,666		51,012		-13,156		43,087	

10) Summary

In order to determine the relevant building functions of thermal insulation, solar shading and heat gain of BIPV-modules, the internal and external heat transfer coefficients at PV-Module's surfaces and heat conductivity in cavity are the most significant factors. With respect to higher absorption coefficient and corresponding higher operating temperature of PV modules, the surface temperature and its thermal characteristics have been changed respectively.

By validating with feed-in power concept, the normative values are applicable only for conventional building products, not PV module with higher operating temperature. The normative values are much lower than measured values. With good correlation between temperature model and measurement, therefore, it can be evaluated that the heat transfer coefficients were correctly considered in this simulation, so that the inherent model has been validated

In comparison with conventional building products, the lower deviation of external heat transfer coefficient ($\boldsymbol{h_e}$) can be obtained from BIPV-modules (<+1% in winter and +6% to +10% in summer). Meantime the greater deviation of internal heat transfer coefficient ($\boldsymbol{h_i}$) can be received (-12% to -7% in winter and +16% to +38% in summer). At the same time, the deviation of heat conductivity in the cavity ($\boldsymbol{h_s}$) is in the range of -5% in winter to -12% in summer.

Regarding all thermal characteristics above, the improvement on heat transmission coefficient (U-value) can be achieved at -9% for laminated glass, -2% for isolated glass and -1% for composite element under full PV coverage rate. The lower the heat transmission coefficient of the conventional construction, the less the improvement of the PV component cab be evaluated.

Under full PV coverage rate of BIPV module, the reduction of the energy transmittance (g-value) in winter can be obtained at -11% for laminated glass and -15% for isolated glass. At the same time, the reduction of the solar reduction ratio (F_c-value) in the summer can be received at +61% for laminated glass and +50% for isolated glass. The higher the construction of the PV component, the worse the energy transmittance (g-value) and the better the solar reduction ratio (F_c-value) can be estimated.

11) Outlook

With respect to internal heat source of PV modules, the existing testing methods (U-value and g-value) need to be adjusted. For identifying or calculating the relevant building functions of PV module, moreover, the new thermal parameters have to be taken into account; such as internal and external heat transfer coefficient and heat transfer coefficient in cavity of insulated glass.

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