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Quadruple glazing hourly temperature and temperature budged analysis

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Abstract

Insolated quadruple and other multipane glazing experiences notable higher temperatures compared to double or triple pane. Hourly temperature and temperature budged analysis teaches how these experienced temperatures are distributed among individual glass panes throughout the year on hourly basis. Analysis is based on ASHRAE characteristic year climatic data and optical/thermal properties of simulated glazing. Analysis takes into account glazing azimuth angle (vertical glazing is assumed), solar irradiance and local wind and its direction.

1. Quadruple glazing temperature limits

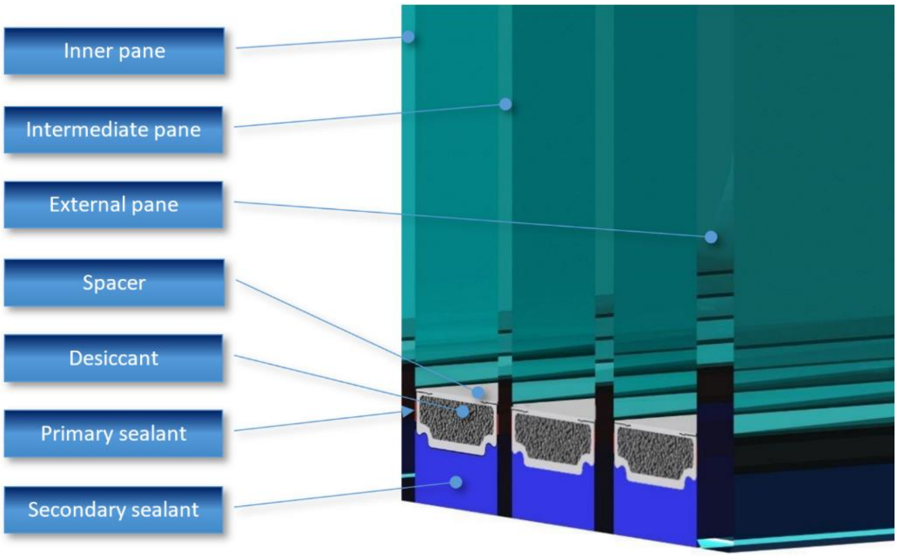

Figure 1: Quadruple-pane glazing set-up.

Multipane insulating glazing (MIG) comprising many glass panes is the final frontier of the gas insulated, sealed insulating glazing units. It promises many attractive feats such as the unprecedented comfort of living and passive building with zero heating which in turn resolves the need for seasonal energy storage in heating-dominated areas. To get to commercially viable multipane glazing, cost, building physics and longevity issues had to be addressed. With multipane glazing, building physics and glass-unit's longevity become inseparable matter. Multipane glass unit design must by design simultaneously shield building and intermediate glass panes from overheating. Optimally designed quadruple glazing has two annealed glass intermediate panes which must be guarded against exceeding safe temperature. There are two criteria:

1. Thermal break temperature difference limit and
2. Gas and vapour permeation limit.

Thermal break temperature difference limit is subject of absolute peak temperature that glazing unit might experience with reasonable expected climatic assumptions and plausible user behaviour. Thermal break temperature difference limit is subject to product design standard and is not part of this report.

The main result of this report are tables 1-4 where resultant annual gas loss is calculated to individual glass pane hourly temperatures accounting for temperature-dependent argon gas permeation.

2. Gas and vapour permeation limit

In the quadruple-pane glazing, we quantify water vapour permeation through the PIB sealant barrier, which influences the lifespan of the sealed glass unit. In our calculations, the least-squares exponential curve fitting method was used to fit the experimental vapour permeation data (Figure 2). As can be noticed, the PIB sealant significantly increases the vapour permeability with increased temperature. The water vapour permeation at room temperature is approximately 0.1 g/(m^2d) and increases to nearly 10 g/(m^2d) at 80 °C, that is 100-fold.

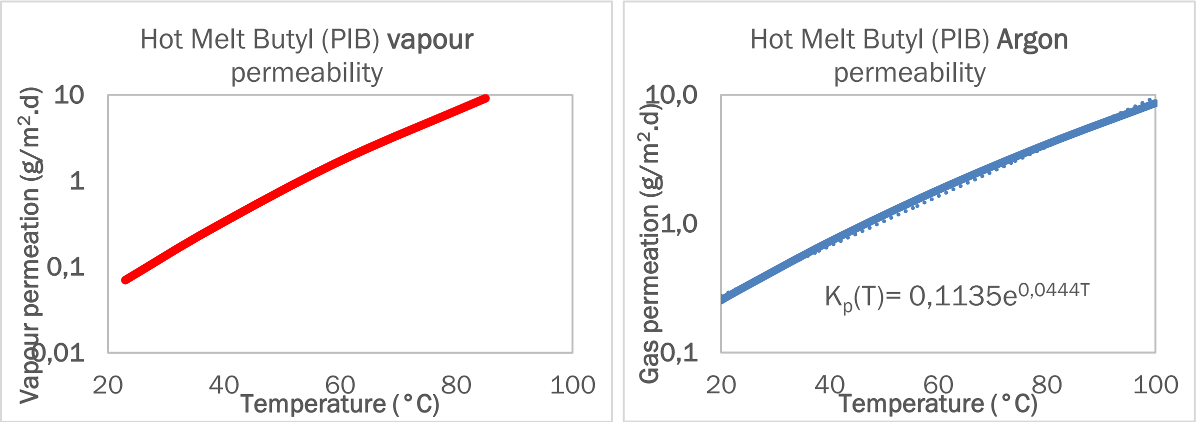

Figure 2. The PIB primary sealant increases the vapour permeability with increased temperature. Measured points per ASTM F 1249, 1 mm film, 100% relative humidity (left). The PIB primary sealant increases the gas permeability with temperature – calculated data from[1] (right). Curve fit for the temperature-dependent Argon gas los is indicated, T(°C).

In very much the same way argon/krypton gas is lost[2]. Gas or water vapor permeation roughly follows well-known Arrhenius exponential temperature relation. Argon/Krypton gas permeation is thought to increase 17-fold from 20°C to 80°C. More involved analysis requires free-volume molecular dynamics approach to determine temperature-dependent gas permeation characteristics[3,4].

An experience-based no-exceed limit is set at 80°C, but it is wise to design glass units that will not experience temperature above 70°C. To further understand the temperature limit, it has to be reviewed on day by day, hour per hour basis as one has also to account for the temperature exposure

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[1] Wolf, A. T. "Design and material selection factors that influence the service-life and utility value of dual-sealed insulating glass units." *Proceedings of 9th International Conference on Durability of Building Materials and Components*–9DBMC. 2002.

[2] Asphaug, Silje Kathrin, et al. "Accelerated ageing and durability of double-glazed sealed insulating window panes and impact on heating demand in buildings." *Energy and Buildings* 116 (2016): 395-402.

[3] Thornton, Aaron W., et al. "New relation between diffusion and free volume: I. Predicting gas diffusion." *Journal of Membrane Science* 338.1-2 (2009): 29-37.

[4] Thornton, Aaron W., et al. "New relation between diffusion and free volume: II. Predicting vacancy diffusion." *Journal of Membrane Science* 338.1-2 (2009): 38-42.

time. This is why we introduced the “temperature budget” analysis which gives us good information on time in hours each glass pane spends at a certain temperature level.

3. Temperature budget explained

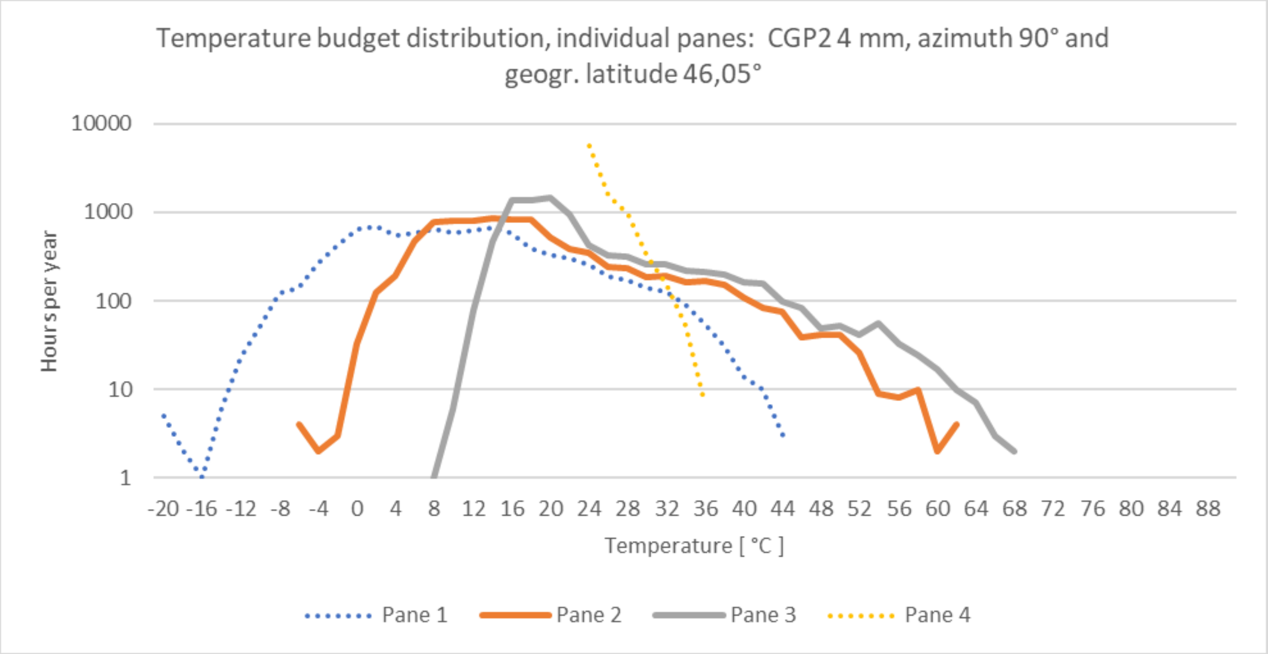

Figure 3: Example temperature budget distribution for quadruple glazing made of standard glazing. Configuration is south oriented (no shading, azimuth angle 90°) and for Ljubljana climate (geographical latitude 46,05°). Pane 1 is outdoors, pane 4 is indoors. Modelled glazing configuration experiences peak temperature of 68°C, at pane 3 on June, 30th at 17hrs. One has to consider that this peak temperature is modelled without indoors shading such as curtains, roller blinds and similar, which would elevate the 3rd glass pane temperature further toward 100°C.

Figure 3 shows a temperature budget distribution for quadruple glazing. Modelled glazing is standard, krypton filled glazing made of Guardian ClimaGuard Premuim 2 coated glass with temperature optimized coating arrangements. Coatings are on positions: 2, 5, 7. Thus, first intermediate pane is free of coatings and is also made of 4 mm EC (ExtraClear glass). This configuration offers low peak temperature for a non-solar-control configuration.

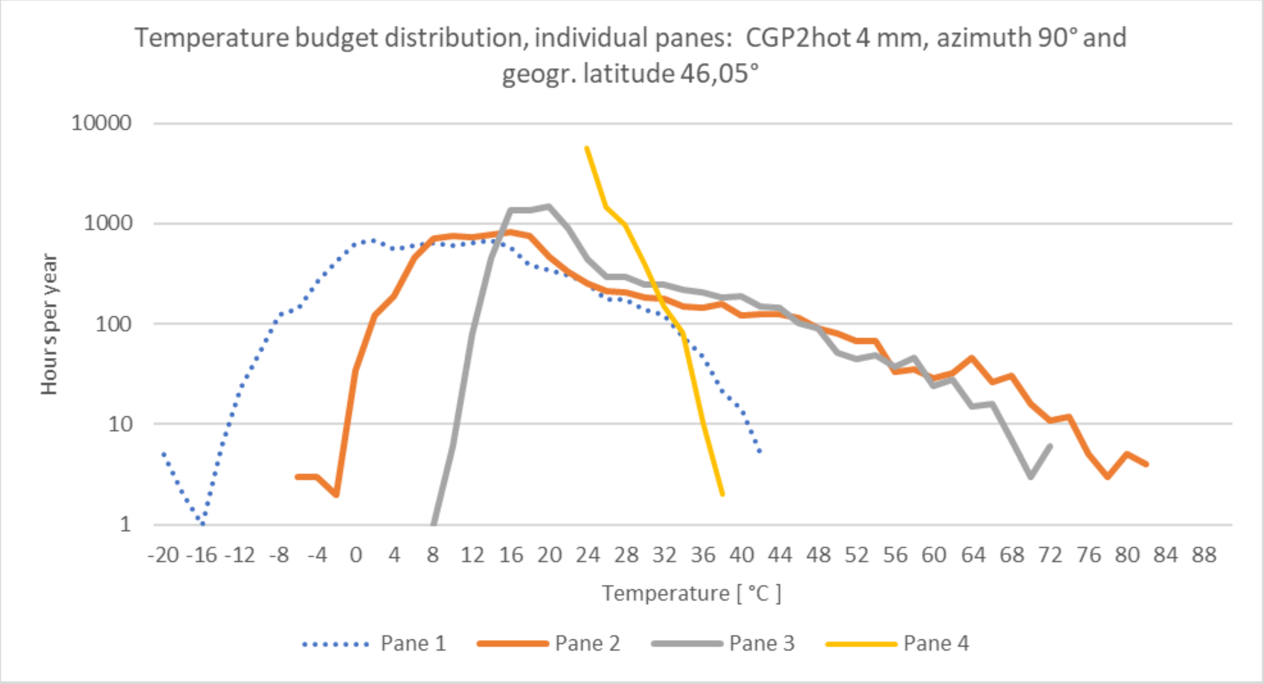

Figure 4: Example temperature budget distribution for quadruple glazing made of standard glazing. Configuration is south oriented (no shading, azimuth angle 90°) and for Ljubljana climate. Pane 1 is outdoors, pane 4 is indoors. Modelled glazing configuration experiences peak temperature of 82,4°C, at pane 2 on June, 30th at 15hrs.

Figure 4 modelled glazing is standard glazing made of Guardian ClimaGuard Premuim 2 coated glass with a traditional coating arrangement. Coatings are on positions: 3, 5, 7. Note that a small change of the first coating position from position 2 to position 3 results in a large peak temperature change. Peaking temperature moves from glass pane 3 to glass pane 2 and also a time of peak temperature changes.

Temperature budget diagrams show how many hours per year individual the glass pane experiences at a certain indicated temperature level. The peak temperature of both designs is over recommended level of 70°C. The optimized design (*Figure 3*) with a peak temperature of 67°C might be used as the temperature is below 80°C.

The detailed temperature budget distribution is intended to be used in conjunction with temperature-dependent gas and vapor permeation data (*Figure 2*), to simulate realistic annual gas loss and vapor ingress to the insulating glass unit.

Using temperature budgets and temperature-dependent Argon gas loss formula from *Figure 2* (right), we obtain annual gas loss rates indicated in the following tables.

Table 1: Simulated annual gas loss rate per chamber for a 1,2x1,6 m window, 16 mm spacers, PIB seal stretched to 0,6 mm and effective thickness of the PIB of 3 mm (Ljubljana climate, orientation due west).

Glazing config. descriptor	Outer chamber	Middle chamber	Inner chamber
CGP2 4 mm	0,36%	0,48%	0,53%
CGP2hot 4 mm	0,42%	0,56%	0,54%
Converlight dark + CG Dry	0,55%	0,56%	0,51%
SNX50UC+Dry 44.4 mm	0,39%	0,44%	0,49%
SN75EC HT 6 mm	0,33%	0,42%	0,49%
SNX60 UC 6 mm	0,32%	0,39%	0,47%

Table 2: Simulated annual gas loss rate per chamber for a 1,2x1,6 m window, 16 mm spacers, PIB seal stretched to 0,6 mm and effective thickness of the PIB of 3 mm (Ljubljana climate, orientation due south).

Glazing config. descriptor	Outer chamber	Middle chamber	Inner chamber
CGP2 4 mm	0,39%	0,57%	0,59%
CGP2hot 4 mm	0,53%	0,74%	0,63%
Converlight dark + CG Dry	0,82%	0,77%	0,55%
SNX50UC+Dry 44.4 mm	0,44%	0,49%	0,53%
SN75EC HT 6 mm	0,35%	0,46%	0,52%
SNX60 UC 6 mm	0,33%	0,41%	0,49%

Table 3: Simulated annual gas loss rate per chamber for a 1,2x1,6 m window, 16 mm spacers, PIB seal stretched to 0,6 mm and effective thickness of the PIB of 3 mm (Ljubljana climate, CGP2hot 4 mm).

CGP2hot 4 mm	Outer chamber	Middle chamber	Inner chamber
Due south	0,53%	0,74%	0,63%
Due east	0,40%	0,53%	0,53%
Due west	0,42%	0,56%	0,54%
Due north	0,37%	0,48%	0,51%

Table 4: Simulated annual gas loss rate per chamber for a 1,2x1,6 m window, 16 mm spacers, PIB seal stretched to 0,6 mm and effective thickness of the PIB of 3 mm (Due south, CGP2hot 4 mm).

CGP2hot 4 mm, south	Outer chamber	Middle chamber	Inner chamber
Ljubljana	0,53%	0,74%	0,63%
Munich	0,52%	0,74%	0,63%
Hamburg	0,44%	0,61%	0,58%
Oslo	0,43%	0,62%	0,58%

4. Temperature budget calculation method

Input information is glass configuration, orientation (azimuth angle) and ASHRAE hourly climate data (Figure 5).

Ljubljana	Time	TAir	WindX	WindY	IDirNorm	IDiffHor
	1	0,9	0	0	0	0
	2	0,9	1,48	-0,26	0	0
	3	0,8	2,1	0	0	0
	4	0,8	0,64	0,77	0	0
	5	0,7	0,12	0,99	0	0
	6	0,8	-0,45	0,89	0	0
	7	0,5	-0,87	0,5	0	0
	8	0,6	0	1,3	0	0
	9	0,6	1,47	0,85	0	9
	10	0,7	1,73	-1	0	34
	11	0,9	0,49	-1,63	0	58
	12	1,1	-0,58	-1,16	0	71
	13	1,3	-0,94	-0,34	0	72
	14	1,4	-0,96	0,29	0	61

Figure 5: Example climate data for Ljubljana (only first 14 hrs are shown out of 8784 hrs).

Glass configuration is reworked with Window 7.x program to obtain angular-dependent absorptances for individual glass panes (Figure 6).

QGU	**CGP2 4 mm**									
	EC 4 mm									
	CGP2 EC 4 mm									
	CGP2 EC 4 mm									
Abs1 :	0,135	0,137	0,147	0,155	0,159	0,169	0,196	0,234	0,22	0	0,173
Abs2 :	0,045	0,045	0,045	0,045	0,047	0,048	0,047	0,042	0,033	0	0,045
Abs3 :	0,061	0,063	0,068	0,072	0,073	0,076	0,082	0,081	0,051	0	0,073
Abs4 :	0,038	0,039	0,043	0,046	0,046	0,046	0,047	0,039	0,017	0	0,042

Figure 6: Window7.x calculated angular absorptances (Abs*n* for individual glass panes 1 to 4). Note that coated glass in Window7.x uses approximated relations[5,6,7] where there might be deviations from true values.

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[5] Finlayson, Elizabeth U., et al. *WINDOW 4.0: Documentation of calculation procedures*. No. LBL-33943; TA-309. Lawrence Berkeley Lab., CA (United States), 1993.

[6] Klems, Joseph H., M. Yazdanian, and G. O. Kelley. Measured performance of selective glazings. No. LBL-37747; Mo-337; CONF-951215-3. Lawrence Berkeley Lab., CA (United States), 1995.

[7] Roos, Arne, et al. "Angular-dependent optical properties of low-e and solar control windows—: Simulations versus measurements." Solar Energy 69 (2001): 15-26.

The next step is to calculate peak individual glass temperatures in Window 7.x at 880W and 24.1°C outdoors and 24°C indoors temperature. Other parameters: inside; fixed combined convection 7.5 W/m^{2}K and outside; fixed convection 7 W/m^{2}K, effective sky emissivity 0.9 (to accurate model low-e coated exterior surfaces).

Relative (normalized) angular absorptances are calculated next (Figure 7).

	0	10	20	30	40	50	60	70	80	90	Hemis
Abs1 :	1,00	1,01	1,09	1,15	1,18	1,25	1,45	1,73	1,63	0,00	1,28
Abs2 :	1,00	1,00	1,00	1,00	1,04	1,07	1,04	0,93	0,73	0,00	1,00
Abs3 :	1,00	1,03	1,11	1,18	1,20	1,25	1,34	1,33	0,84	0,00	1,20
Abs4 :	1,00	1,03	1,13	1,21	1,21	1,21	1,24	1,03	0,45	0,00	1,11

Figure 7: Relative (normalized) angular absorptances and hemispherical absorptance. Normalization is done against angle 0° in a way that normalized angular value shows how much more (or less) is energy absorption at certain angle compared to the normal at angle 0° where initial peak temperatures have been determined.

Angular absorptances are then employing curve fitting converted to four formulas:

$$abs_n(\theta) = \cos(\theta)^{P1} + P2.\sin(\theta)^{P3}.\cos(\theta)^{P4} + P5.\sin(\theta)^{P6}.\cos(\theta)^{P7}$$

where index *n* denotes 1..4, four individual glass panes, and angle $\boldsymbol{\theta}$ incidence angle of light.

CGP2 4 mm								
P1	P2	P3	P4	P5	P6	P7	Hemis	Tp.n
3,827	3,879	9,956	0,469	3,026	2,072	1,651	1,28	34,9
1,271	0,000	8,714	0,061	1,136	2,600	0,321	1,00	64,1
7,091	6,066	9,384	1,087	4,602	1,981	2,526	1,20	66,5
4,674	9,426	8,855	1,683	5,326	2,262	3,356	1,11	36

Figure 8: Curve fitting parameters Pn for the angular absorptance formula for each glass pane (listed as individual lines in table). "Hemis" denotes hemispherical parameter (not part of curve fitting) and Tp.n indicates previously calculated peak temperature of individual glass pane at 880 W (not part of curve fitting).

Figure 9 shows quality of achieved fit for relative angular absorptances.

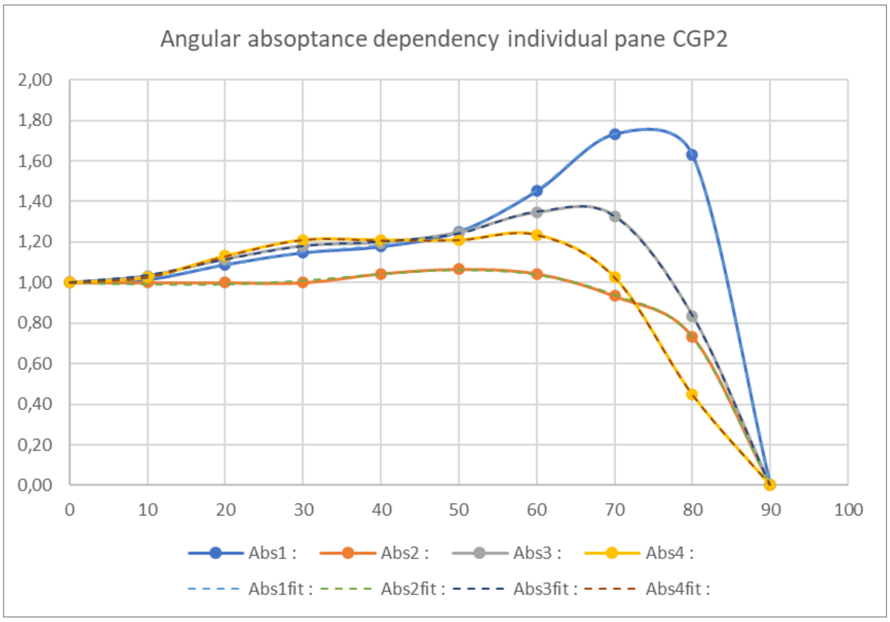
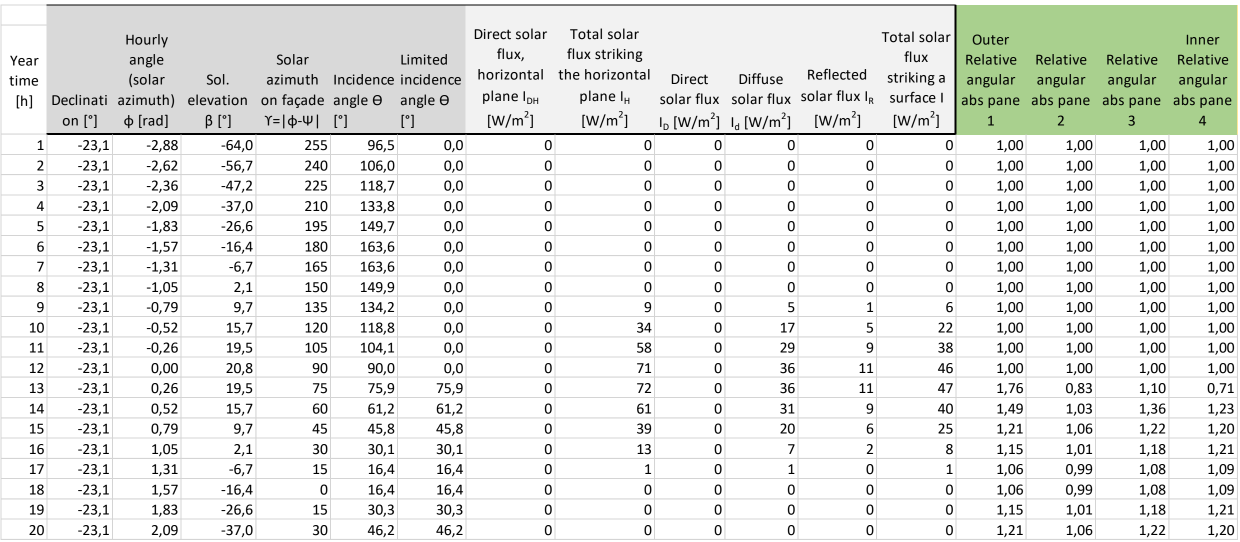


Figure 9: Formula calculated angular absorptance with fitted parameters P1-P7 (absnfit) compared to input data (absn).

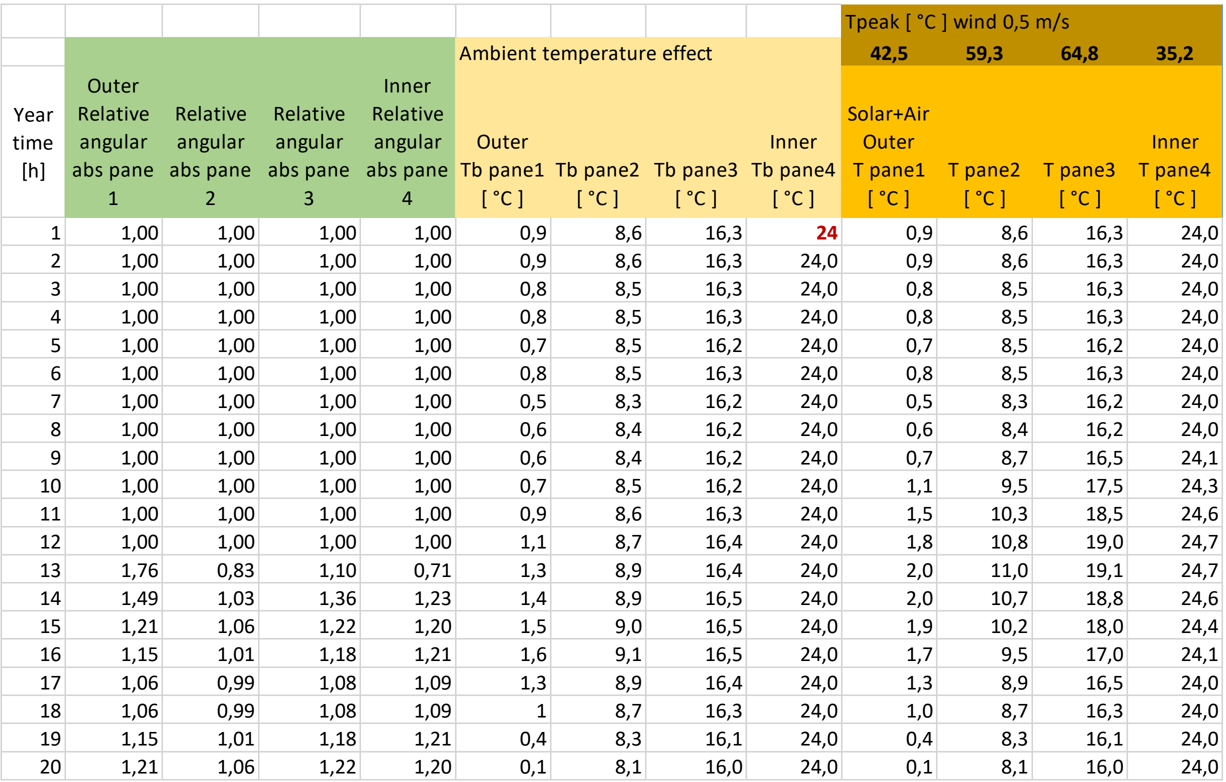
Using ASHRAE solar angle and radiation formulas, climate hourly data, and relative angular absorptances (formula based) hourly solar incidence radiation parameters are calculated (Figure 10).



Year time [h]	Declination [°]	Hourly angle (solar azimuth) ϕ [rad]	Sol. elevation β [°]	Solar azimuth on façade ϒ=|ϕ-Ψ|	Incidence angle ϴ [°]	Limited incidence angle ϴ [°]	Direct solar flux, horizontal plane I_{DH} [W/m^2]	Total solar flux striking the horizontal plane I_H [W/m^2]	Direct solar flux I_D [W/m^2]	Diffuse solar flux I_d [W/m^2]	Reflected solar flux I_R [W/m^2]	Total solar flux striking a surface I [W/m^2]	Outer Relative angular abs pane 1	Relative angular abs pane 2	Relative angular abs pane 3	Inner Relative angular abs pane 4
1	-23,1	-2,88	-64,0	255	96,5	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
2	-23,1	-2,62	-56,7	240	106,0	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
3	-23,1	-2,36	-47,2	225	118,7	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
4	-23,1	-2,09	-37,0	210	133,8	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
5	-23,1	-1,83	-26,6	195	149,7	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
6	-23,1	-1,57	-16,4	180	163,6	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
7	-23,1	-1,31	-6,7	165	163,6	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
8	-23,1	-1,05	2,1	150	149,9	0,0	0	0	0	0	0	0	1,00	1,00	1,00	1,00
9	-23,1	-0,79	9,7	135	134,2	0,0	0	9	0	5	1	6	1,00	1,00	1,00	1,00
10	-23,1	-0,52	15,7	120	118,8	0,0	0	34	0	17	5	22	1,00	1,00	1,00	1,00
11	-23,1	-0,26	19,5	105	104,1	0,0	0	58	0	29	9	38	1,00	1,00	1,00	1,00
12	-23,1	0,00	20,8	90	90,0	0,0	0	71	0	36	11	46	1,00	1,00	1,00	1,00
13	-23,1	0,26	19,5	75	75,9	75,9	0	72	0	36	11	47	1,76	0,83	1,10	0,71
14	-23,1	0,52	15,7	60	61,2	61,2	0	61	0	31	9	40	1,49	1,03	1,36	1,23
15	-23,1	0,79	9,7	45	45,8	45,8	0	39	0	20	6	25	1,21	1,06	1,22	1,20
16	-23,1	1,05	2,1	30	30,1	30,1	0	13	0	7	2	8	1,15	1,01	1,18	1,21
17	-23,1	1,31	-6,7	15	16,4	16,4	0	1	0	1	0	1	1,06	0,99	1,08	1,09
18	-23,1	1,57	-16,4	0	16,4	16,4	0	0	0	0	0	0	1,06	0,99	1,08	1,09
19	-23,1	1,83	-26,6	15	30,3	30,3	0	0	0	0	0	0	1,15	1,01	1,18	1,21
20	-23,1	2,09	-37,0	30	46,2	46,2	0	0	0	0	0	0	1,21	1,06	1,22	1,20

Figure 10: Example preview of solar parameters and relative absorptances depending on Limited incidence angle, ϴ, calculations for the first 20 hours in a simulated year.

With these parameters we further calculate hourly glass temperatures assuming constant external wind at 0,5 m/s (and corresponding constant convective heat dissipation).



									Tpeak [°C] wind 0,5 m/s			
					Ambient temperature effect				42,5	59,3	64,8	35,2
Year time [h]	Outer Relative angular abs pane 1	Relative angular abs pane 2	Relative angular abs pane 3	Inner Relative angular abs pane 4	Outer Tb pane1 [°C]	Tb pane2 [°C]	Tb pane3 [°C]	Inner Tb pane4 [°C]	Solar+Air Outer T pane1 [°C]	T pane2 [°C]	T pane3 [°C]	Inner T pane4 [°C]
1	1,00	1,00	1,00	1,00	0,9	8,6	16,3	24	0,9	8,6	16,3	24,0
2	1,00	1,00	1,00	1,00	0,9	8,6	16,3	24,0	0,9	8,6	16,3	24,0
3	1,00	1,00	1,00	1,00	0,8	8,5	16,3	24,0	0,8	8,5	16,3	24,0
4	1,00	1,00	1,00	1,00	0,8	8,5	16,3	24,0	0,8	8,5	16,3	24,0
5	1,00	1,00	1,00	1,00	0,7	8,5	16,2	24,0	0,7	8,5	16,2	24,0
6	1,00	1,00	1,00	1,00	0,8	8,5	16,3	24,0	0,8	8,5	16,3	24,0
7	1,00	1,00	1,00	1,00	0,5	8,3	16,2	24,0	0,5	8,3	16,2	24,0
8	1,00	1,00	1,00	1,00	0,6	8,4	16,2	24,0	0,6	8,4	16,2	24,0
9	1,00	1,00	1,00	1,00	0,6	8,4	16,2	24,0	0,7	8,7	16,5	24,1
10	1,00	1,00	1,00	1,00	0,7	8,5	16,2	24,0	1,1	9,5	17,5	24,3
11	1,00	1,00	1,00	1,00	0,9	8,6	16,3	24,0	1,5	10,3	18,5	24,6
12	1,00	1,00	1,00	1,00	1,1	8,7	16,4	24,0	1,8	10,8	19,0	24,7
13	1,76	0,83	1,10	0,71	1,3	8,9	16,4	24,0	2,0	11,0	19,1	24,7
14	1,49	1,03	1,36	1,23	1,4	8,9	16,5	24,0	2,0	10,7	18,8	24,6
15	1,21	1,06	1,22	1,20	1,5	9,0	16,5	24,0	1,9	10,2	18,0	24,4
16	1,15	1,01	1,18	1,21	1,6	9,1	16,5	24,0	1,7	9,5	17,0	24,1
17	1,06	0,99	1,08	1,09	1,3	8,9	16,4	24,0	1,3	8,9	16,5	24,0
18	1,06	0,99	1,08	1,09	1	8,7	16,3	24,0	1,0	8,7	16,3	24,0
19	1,15	1,01	1,18	1,21	0,4	8,3	16,1	24,0	0,4	8,3	16,1	24,0
20	1,21	1,06	1,22	1,20	0,1	8,1	16,0	24,0	0,1	8,1	16,0	24,0

Figure 11: Constant wind (0,5 m/s) hourly glass pane temperatures.

Where, **Tb pane1 = Tair** (from ASHRAE climate data), **Tb pane4 = 24°C** (indoors),

Tb pane2 = (Tb pane4 – Tb pane1)/3 + Tb pane1

Tb pane3 = (Tb pane4 – Tb pane1)/3*2 + Tb pane1

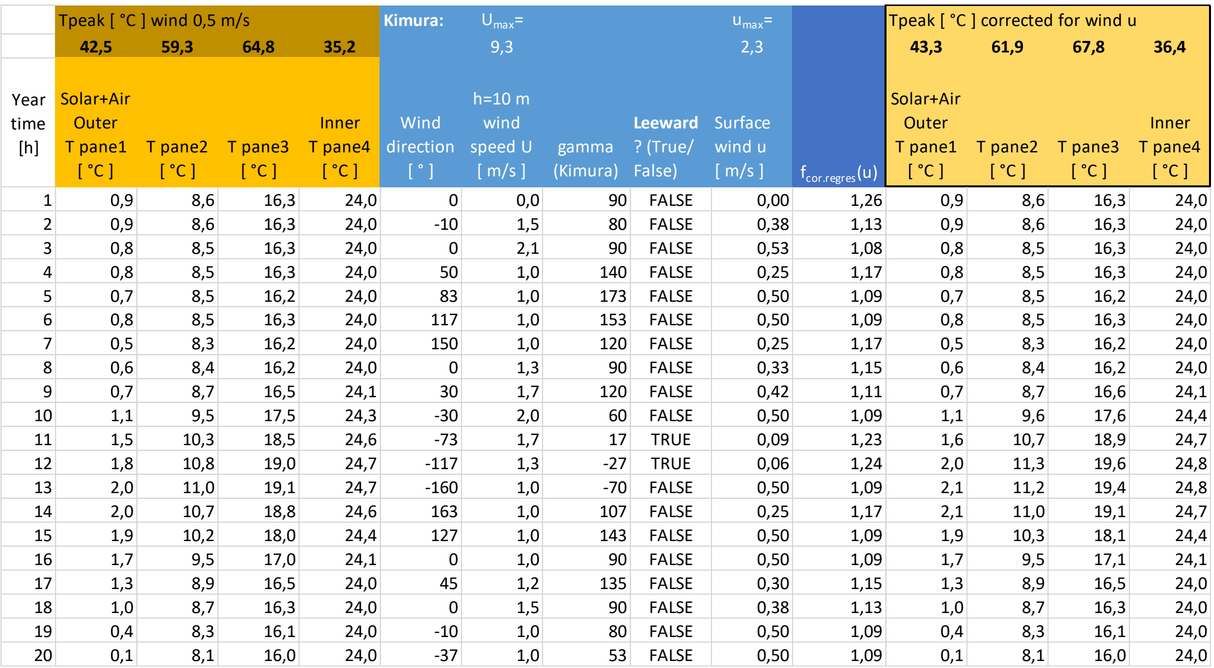
Tb pane temperatures account for the ambient temperature effect according to linear interpolation.

Tpane$_n$ temperatures (°C) are calculated according to the following scaling formula:

$$Tpane_n = Tb.pane_n + \left(\frac{I_R + I_d}{880W} * Hemis + \frac{I_D}{880W} * abs_n(\theta)\right) * (Tp.n - 24°C)$$

where $\boldsymbol{I_R}$, $\boldsymbol{I_d}$ and $\boldsymbol{I_D}$ are respective incident solar fluxes (Figure 10). The 880W is solar energy irradiance power where **Tp.n** (Figure 8) were calculated. $\boldsymbol{abs_n(\theta)}$ are relative angular absorptances (Figure 10). ***Hemis*** is a hemispherical relative absorptance (Figure 8).

These temperatures are further corrected for the effect of realistic wind according to[8].



	Tpeak [°C] wind 0,5 m/s				Kimura:	U_{max}=			u_{max}=		Tpeak [°C] corrected for wind u			
	42,5	**59,3**	**64,8**	**35,2**		9,3			2,3		**43,3**	**61,9**	**67,8**	**36,4**
Year time [h]	Solar+Air Outer T pane1 [°C]	T pane2 [°C]	T pane3 [°C]	Inner T pane4 [°C]	Wind direction [°]	h=10 m wind speed U [m/s]	gamma (Kimura)	**Leeward** ? (True/ False)	Surface wind u [m/s]	$f_{cor.regres}(u)$	Solar+Air Outer T pane1 [°C]	T pane2 [°C]	T pane3 [°C]	Inner T pane4 [°C]
1	0,9	8,6	16,3	24,0	0	0,0	90	FALSE	0,00	1,26	0,9	8,6	16,3	24,0
2	0,9	8,6	16,3	24,0	-10	1,5	80	FALSE	0,38	1,13	0,9	8,6	16,3	24,0
3	0,8	8,5	16,3	24,0	0	2,1	90	FALSE	0,53	1,08	0,8	8,5	16,3	24,0
4	0,8	8,5	16,3	24,0	50	1,0	140	FALSE	0,25	1,17	0,8	8,5	16,3	24,0
5	0,7	8,5	16,2	24,0	83	1,0	173	FALSE	0,50	1,09	0,7	8,5	16,2	24,0
6	0,8	8,5	16,3	24,0	117	1,0	153	FALSE	0,50	1,09	0,8	8,5	16,3	24,0
7	0,5	8,3	16,2	24,0	150	1,0	120	FALSE	0,25	1,17	0,5	8,3	16,2	24,0
8	0,6	8,4	16,2	24,0	0	1,3	90	FALSE	0,33	1,15	0,6	8,4	16,2	24,0
9	0,7	8,7	16,5	24,1	30	1,7	120	FALSE	0,42	1,11	0,7	8,7	16,6	24,1
10	1,1	9,5	17,5	24,3	-30	2,0	60	FALSE	0,50	1,09	1,1	9,6	17,6	24,4
11	1,5	10,3	18,5	24,6	-73	1,7	17	TRUE	0,09	1,23	1,6	10,7	18,9	24,7
12	1,8	10,8	19,0	24,7	-117	1,3	-27	TRUE	0,06	1,24	2,0	11,3	19,6	24,8
13	2,0	11,0	19,1	24,7	-160	1,0	-70	FALSE	0,50	1,09	2,1	11,2	19,4	24,8
14	2,0	10,7	18,8	24,6	163	1,0	107	FALSE	0,25	1,17	2,1	11,0	19,1	24,7
15	1,9	10,2	18,0	24,4	127	1,0	143	FALSE	0,50	1,09	1,9	10,3	18,1	24,4
16	1,7	9,5	17,0	24,1	0	1,0	90	FALSE	0,50	1,09	1,7	9,5	17,1	24,1
17	1,3	8,9	16,5	24,0	45	1,2	135	FALSE	0,30	1,15	1,3	8,9	16,5	24,0
18	1,0	8,7	16,3	24,0	0	1,5	90	FALSE	0,38	1,13	1,0	8,7	16,3	24,0
19	0,4	8,3	16,1	24,0	-10	1,0	80	FALSE	0,50	1,09	0,4	8,3	16,1	24,0
20	0,1	8,1	16,0	24,0	-37	1,0	53	FALSE	0,50	1,09	0,1	8,1	16,0	24,0

Figure 12: Kimura model based realistic wind external surface convection corrected hourly temperatures of individual glass panes. Wind direction and wind speed U (m/s), are calculated directly from ASHRAE data set (Figure 5), surface wind is according to Kimura model (formulas are quite complicated due to use of logical operators).

f$_{cor.regres}$(u) is regression calculated convection scaling factor (Figure 13) for the exterior glass pane. Here a modified formula for hourly temperature is used:

$$Tpane_1 = Tb.pane_1 + \left(\frac{I_R + I_d}{880W} * Hemis + \frac{I_D}{880W} * abs_1(\theta)\right) * (Tp.n - 24°C) * \mathrm{fcor.regres(u)}$$

Wind speed correction is applied only to the solar radiation component of the glass heating.

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[8] Kimura, Ken-Ichi. *Scientific basis of air conditioning*. Vol. 15. London: Applied Science Publishers, 1977.

Other panes use slightly reduced wind effect which was estimated by separate direct calculations in the window:

$$Tpane_2 = Tb.pane_2 + \left(\frac{I_R + I_d}{880W} * Hemis + \frac{I_D}{880W} * abs_2(\theta)\right) * (Tp.n - 24°C) * ((\mathrm{fcor.regres(u)} - 1) * 0{,}95 + 1)$$

$$Tpane_3 = Tb.pane_3 + \left(\frac{I_R + I_d}{880W} * Hemis + \frac{I_D}{880W} * abs_3(\theta)\right) * (Tp.n - 24°C) * ((\mathrm{fcor.regres(u)} - 1) * 0{,}9 + 1)$$

$$Tpane_4 = Tb.pane_4 + \left(\frac{I_R + I_d}{880W} * Hemis + \frac{I_D}{880W} * abs_4(\theta)\right) * (Tp.n - 24°C) * ((\mathrm{fcor.regres(u)} - 1) * 0{,}9 + 1)$$

Formulas for **Tpane3** and **Tpane4** are the same.

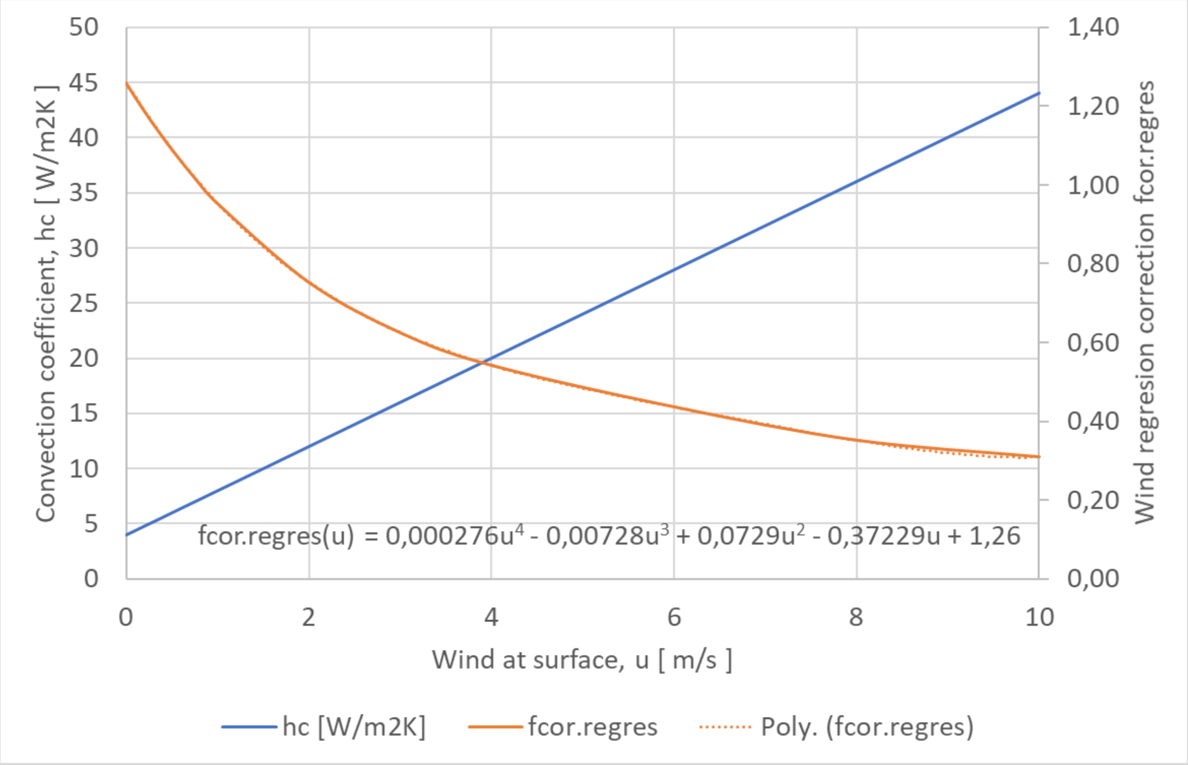

Figure 13: fcor.regres wind scaling temperature correction factor for the external glass pane from Kimura surface wind convention heat transfer data (regression formula on the diagram above).

5. Calculation biases

There are three main calculation biases:

1. The calculated unit has ideal PIB seal geometry, while in realistic products PIB is distributed with somewhat varying geometry;
2. PIB seal has fixed geometry in positive gas pressure stretched position, which overestimates gas loss in colder periods. However, in highly pressurized units experiencing temperatures above 80°C, such calculation underestimates real gas loss as the PIB seal might be stretched thin beyond the assumption in this report.
3. Real glazing units have temperature distribution across glass panes which depends on internal convection and foremost on the irradiated surface and local light reflections from the frame and even from spacers. **Dark spacers may further increase the bottom part temperature by an additional 5°C which would result in up to 30% increased gas loss** over that estimated in this report.
4. Calculation is summer biased as assumed radiation heat dissipation from exterior pane is calculated under summer daytime air humidity conditions and interior temperature is assumed constant at 24°C. This causes exterior pane temperatures in winter to be slightly higher (about 3°C in cold days).

6. Conclusions

Presented “Quadruple glazing hourly temperature and temperature budged analysis” method allows an idealized estimate of individual, hourly temperatures of glass panes in a glazing accounting for each glass pane optical properties, hourly solar and weather data. Exterior pane convection and radiation heat dissipation are accounted for.

The analysis is intended as dynamic feed-in dataset for the all-glass FEM simulation of glazing unit’s sealing system for the full year or multiyear simulations with emphasis on the summer gas permeation.