University of Ljubljana
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Multipane glazing vs. triple glazing (TGU) and closed cavity facade (CCF) in office and single house buildings

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Abstract

This report shows new opportunities and improvements concerning the performance of the multipane glazing. Main advantages of quadruple glazing are:

- reduced heating demand,
- improved thermal comfort without use of external shading devices, and
- reduced purchased energy supply.

The detailed comparison shows advantageous photovoltaic (PV) autarky because energy demand is reduced in winter and slightly increased in daytime summer when PV energy supply is better. Plane quadruple-pane glazing (QGU) also outperforms triple-pane arrangement with externally modulated venetians on all parameters which may offer investment cost savings against externally shaded façade options such as double skin glass façade (DSGF) and closed cavity facade (CCF) (performance of open-air external shades is better than those of closed types such as DSGF or CCF). Simplified maintenance is another advantage of a clean external shade-free QGU façade design.

Figure 1: DEg 8, office building in Oslo, Norway, enveloped in quadruple glazed façade.

Multipane glazing is best modelled with a software (SW) package that can model glazing units with its individual glass panes. One such SW is IDA-ICE (or ESBO) from EQUA (Sweden). A while ago a decision was made that quadruple glazing standardization procedure incorporates introduction of pre-calculated multipane glazing units to the IDA-ICE SW database for use with other consultants in building design and energy performance evaluation.

1. Integration of quadruple glazing Q-Air into IDA-ICE

Multipane glazing is best modelled with a software (SW) package that can model glazing units with its individual glass panes. One such SW is IDA-ICE (or ESBO) from EQUA (Sweden). A while ago a decision was made that quadruple glazing standardization procedure incorporates introduction of pre-calculated multipane glazing units to the IDA-ICE SW database for use with other consultants in building design and energy performance evaluation.

Reflex quadruple and quintuple glazing are now listed in IDA-ICE building physics software (Figure 2).

This program support requires pre-engineered glazing units to be fully optically defined with tabulated optical values for both side reflectances and transmittance tabulated per unit of wavelength. Lawrence Berkeley National Laboratory International Glazing Database Data File Format was used to prepare the optical data that was supplied by Guardian under appropriate non-disclosure agreements. Review of respective spectral data and glazing configuration a decision was made which information will be available to IDA-ICE client users to maintain the needed secrecy of certain know how embodied in the combined spectral glass and glazing data.

Initially twelve glazing units will be supported in the IDA-ICE, four Q-Air 3 standard argon-filled quadruples, four krypton-filled quadruples and four krypton-filled quintuples with Ug values of just 0,22 W/m^{2}K.

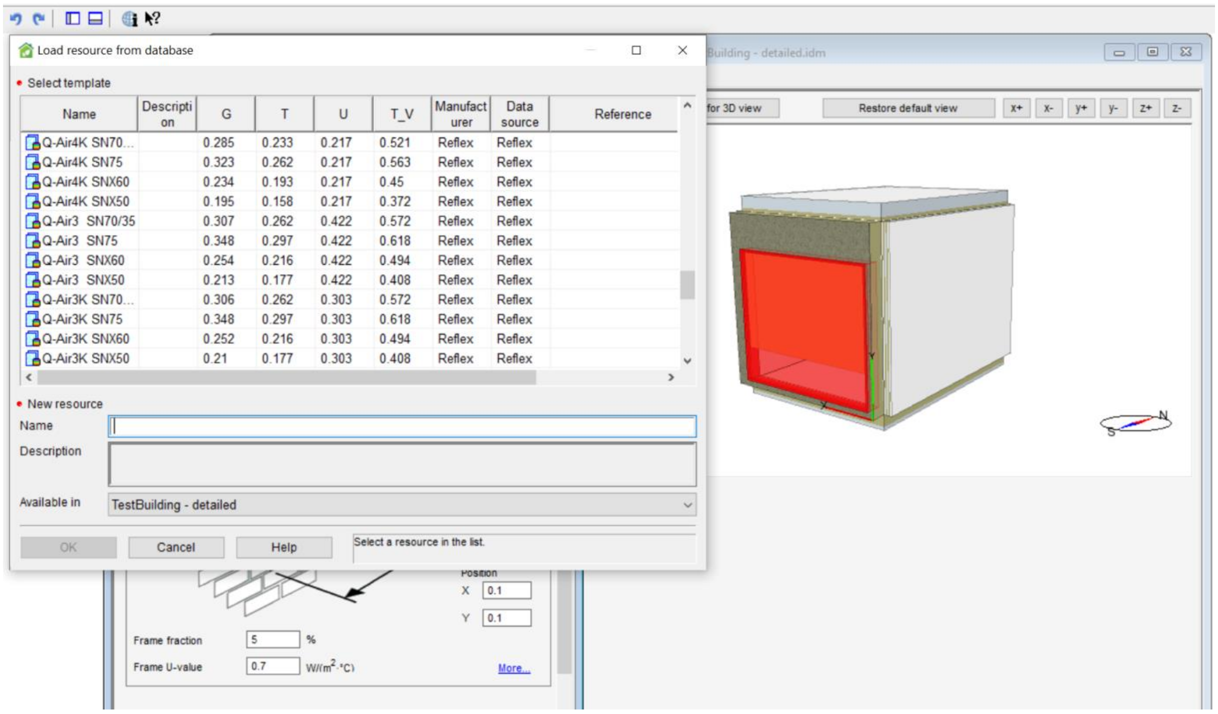


Figure 2: IDA-ICE environment showing the implemented Q-Air configurations

2. Office buildings

2.1. Office model building description

A two-room, 4x50 m, single floor building in an office arrangement with north-south orientation with three main glazing configurations as shown on **Error! Reference source not found.**.

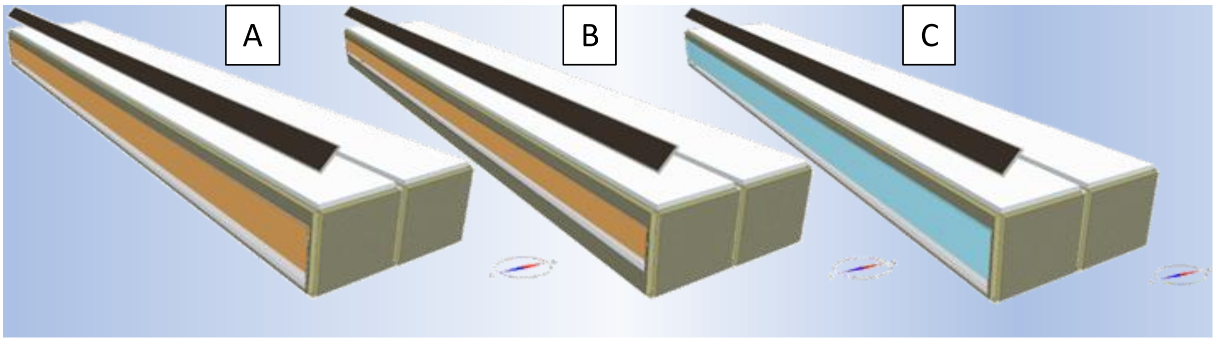


Figure 3: Glazing configurations. (A) fully glazed (100%); (B) partially glazed (70%, used also as label in charts as TGU/QGU 70%); (C) fully glazed with external venetians.

The test building is also equipped with a 60 m^2 roof photovoltaic (PV) system tilted at 45° (**Error! Reference source not found.**). Simulated PV system efficiency is 16%. Shading is modulated to 500 lux in all configurations while shading kicks-in at solar radiation of 100W/m^2. Average daylights are comparably at about 1000 lux on all configurations.

The primary heating mode of the building is a heat pump, while QGU uses add-on direct electric floor heating (heating demand is low in QGU buildings). Cooling is a fan coil or chilled beam. U value of walls is 0,14 W/m^2K. U-values of window's glazing are 0,30 and 0,58 W/m^2K for QGU and TGU respectively. Interior roller shading, having 39% visible light transmittance and 59% visible light reflectance is modelled with QGU. All QGU glazing is equipped with spectrally selective solar control glazing with system g values given in the tables below. The window frame is 0,7 W/m^2K and is modelled at 5% of the window area. Simulation is done in an all-electric configuration, so all energy supply values are in terms of electric energy. Domestic hot water was not modelled. Software used: hourly simulations with IDA-ICE 4.9.

Building thermal comfort is given in terms of Fanger's predicted percentage of dissatisfied (PPD), which as the name suggests determines the percentage of dissatisfied occupants. Usually, maximal hourly value is given as occupants value building comfort by its most discomforting period.

2.2. *Office building data*

Occupants 0,1 /m^2	U_{wall} = 0,14 W/m^2K
Lights 5W/m^2	Frame fraction 5%
Infiltration 0,015 ACH	Frame U_f = 0,7W/m^2K
Daylight shade modulation set 500 lux	Window opening 10%
Fan eff. 80%	Shade trigger 100W solar radiation
Window opening*: Yes	Primary heating mode: Heat pump
Cooling COP = 3	Shading program: Daylight-GetHeat-MinCool
VAV control: temperature+CO_2	TGU U_g=0,58 W/m^2K
CO_2 limit 900 ppm	QGU U_g=0,30 W/m^2K
Equipment 6W/m^2 "flexible hours with night use"	5GU U_g=0,22 W/m^2K
PV efficiency 16%	CCF U_g=0,48 W/m^2K
	Zone VAV variable air volume air supply

*Note on “Window opening”. PID temperature-controlled *window opening* was used even in façade designs such as CCF to simulate bypass cooling in the AHU. A bypass cooling where outside air is used directly for cooling is an option present in modern HVAC but not in the ESBO program. Shading program is listed and used if applicable to the shading devices that permit modulation.

2.3. Office building results and model data (QGU vs. TGU and 5GU)

Place	Type	Main wall Glazing [%]	g value South	g value North	Shade VIS reflectance South	Shade VIS reflectance North	Tset occupied south	Tset occupied north	Energy return eff.	VAV ventilation range [ACH]	Cooloing method	Heating method	Annual Cooling [kWh/m²]	Annual heating [kWh/m²]	Sys. Total delivered net energy [kWh/m²]	Fanger PPD max.	Total used electric [kWh/m²]	Purchased grid electric [kWh/m²]	Autarky
Ljubljana	QGU	100%	0,25	0,35	0,6	-	22-24,5	22,5-24,5	85%	0,3-2	Chilled beam	Electric floor h.	21,1	3,7	-3,0	10,3%	29,9	14,2	52,5%
Ljubljana	TGU	100%	0,27	0,35	0,6	-	**22,5-24,5**	22,5-24,5	85%	0,3-2	Fan Coil	Fan Coil	21,8	9,9	2,8	12,1%	32,8	16,6	49,4%
Ljubljana	TGU	100%	0,27	0,35	Ext.Venetia	enetians	22,5-24,5	22,5-24,5	85%	0,3-2	Fan Coil	Fan Coil	15,9	10,8	-1,4	12,2%	30,8	16,0	48,1%
Stockholm	QGU	100%	0,31	0,42	0,6	-	22-24,5	22,5-24,5	85%	0,3-2	Chilled beam	Electric floor h.	8,0	8,6	-5,4	11,4%	27,6	14,3	48,2%
Stockholm	QGU	70%	0,31	0,42	0,6	-	22-24,5	22,5-24,5	85%	0,3-2	Chilled beam	Electric floor h.	6,7	7,7	-7,5	10,5%	26,5	13,4	49,4%
Stockholm	TGU	100%	0,27	0,35	0,6	-	**22,5-24,5**	22,5-24,5	85%	0,3-2	Fan Coil	Fan Coil	6,5	19,1	-0,1	13,7%	30,2	16,9	44,0%
Stockholm	TGU	70%	0,31	0,54	0,6	-	22,5-24,5	22,5-24,5	85%	0,3-2	Fan Coil	Fan Coil	5,5	15,0	-4,1	13,2%	28,2	15,1	46,5%
Ljubljana	QGU	100%	0,25	0,35	0,6	-	22-24,5	**22,5-24,5**	85% CO2	0,3-4	Chilled beam	AHU	35,0	2,3	3,4	10,5%	33,1	15,6	52,9%
Ljubljana	TGU	100%	0,27	0,35	0,6	-	22,5-24,5	22,5-24,5	85% CO2	0,3-4	Chilled beam	AHU	34,5	7,0	8,0	11,4%	35,4	17,7	50,0%
Stockholm	QGU	100%	0,31	0,42	0,6	-	22-24,5	22,5-24,5	85% CO2	0,3-4	Chilled beam	AHU	19,0	5,1	-4,7	11,5%	27,9	12,8	54,1%
Stockholm	QGU	**70%**	0,31	0,42	0,6	-	22-24,5	22,5-24,5	85% CO2	0,3-4	Chilled beam	AHU	18,3	4,6	-5,5	11,4%	27,5	12,5	54,5%
Stockholm	TGU	100%	0,27	0,35	0,6	-	22,5-24,5	22,5-24,5	85% CO2	0,3-4	Chilled beam	AHU	15,7	13,8	1,9	12,4%	31,2	16,5	47,1%
Stockholm	**5GU**	100%	0,28	0,32	0,6	-	22-24,5	22,5-24,5	85% CO2	0,3-4	Chilled beam	AHU	17,4	3,9	-7,2	11,0%	26,6	12,0	54,9%
Stockholm	**5GU**	100%	0,28	0,39	0,6	-	22-24,5	22,5-24,5	85%	0,3-2	Chilled beam	Electric floor h.	7,4	6,5	-9,3	10,5%	25,6	12,6	50,8%

TGU	Triple-pane glazing unit
QGU	Quadruple-pane glazing unit
5GU	Quintuple glazing unit

In the detailed results more options were analyzed. Air handling unit (AHU) heating only was modeled where all add on heating arrangements are removed and heating is exclusively through air supply. Here CO_2 air handling unit was simulated which recirculates air until set CO_2 limit is reached and only then fresh air is supplied. Such cost-cutting arrangement is feasible with multipane glazing on the expense of some thermal comfort reduction (Fanger PPD increases).

Autarky is annual energy self-sufficiency expressed in % of the total energy need covered by the PV supply on the 15-minute interval basis.

5GU, quintuple glazing was also analyzed and is given for Stockholm for comparison.

2.4. Office building results and model data (QGU vs. CCF)

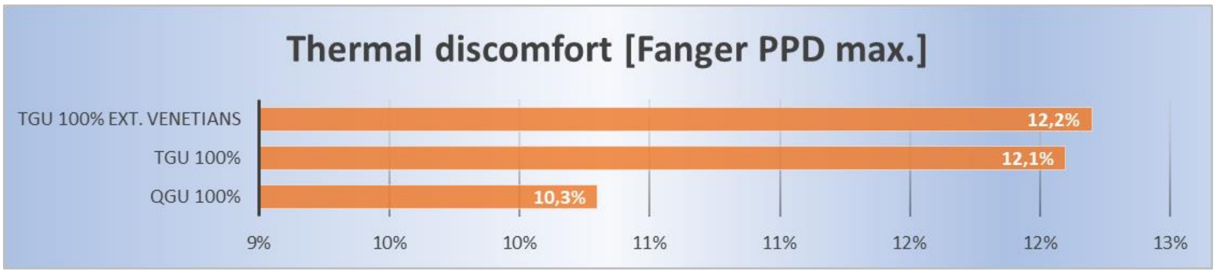
Place	Type	g value South	g value North	Shade VIS reflectance South	Shade VIS reflectance North	Tset occupied south	Tset occupied north	VAV ventilation range [ACH]	Annual Cooling [kWh/m²]	Annual heating [kWh/m²]	Sys. Total delivered net energy [kWh/m²]	Total used electric [kWh/m²]	Purchased grid electric [kWh/m²]	Autarky	Daylight average [lux]	Fanger PPD max.
Ljubljana	CCF	0,54	0,54	0,75/60°	0,75/60°	22,5-24,5	22,5-24,5	0,3-2	28,0	10,3	21,5	42,2	23,8	43,6%	589	10,0%
Ljubljana	QGU	0,21	0,35	0,6	0,6	22-24,5	22,5-24,5	0,3-2	40,9	4,4	23,6	43,2	21,5	50,2%	749	10,8%
Stockholm	CCF	0,54	0,54	0,75/60°	0,75/60°	22,5-24,5	22,5-24,5	0,3-2	18,9	20,4	29,9	45,2	27,6	38,9%	633	10,7%
Stockholm	QGU	0,21	0,35	0,6	0,6	22,5-24,5	22,5-24,5	0,3-2	34,4	10,5	26,8	43,6	22,2	49,1%	870	10,5%

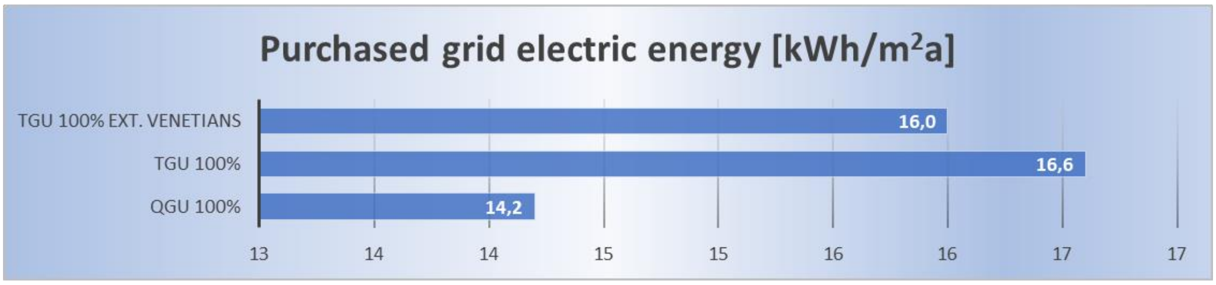
CCF	Closed cavity facade (fully glazed, Fig. 2a)
QGU	Quadruple-pane glazing unit (fully glazed, Fig. 2a)

In the detailed results more options were analyzed. Standard air handling unit with heat return efficiency of 85% was modelled.

2.5. *Office building result summary - QGU vs. TGU*

Office building quick comparison – Ljubljana, Slovenia (46° geographical latitude):





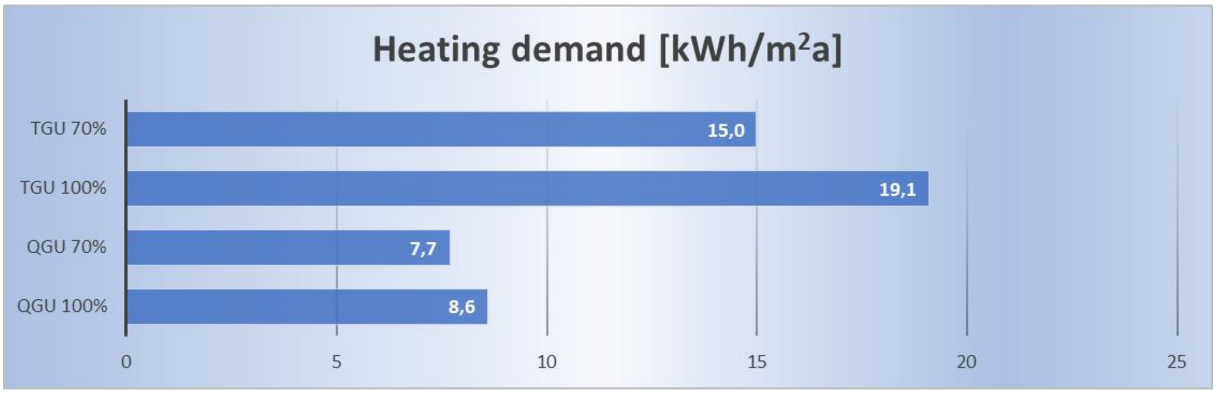
TGU	Triple-pane glazing unit
QGU	Quadruple-pane glazing unit

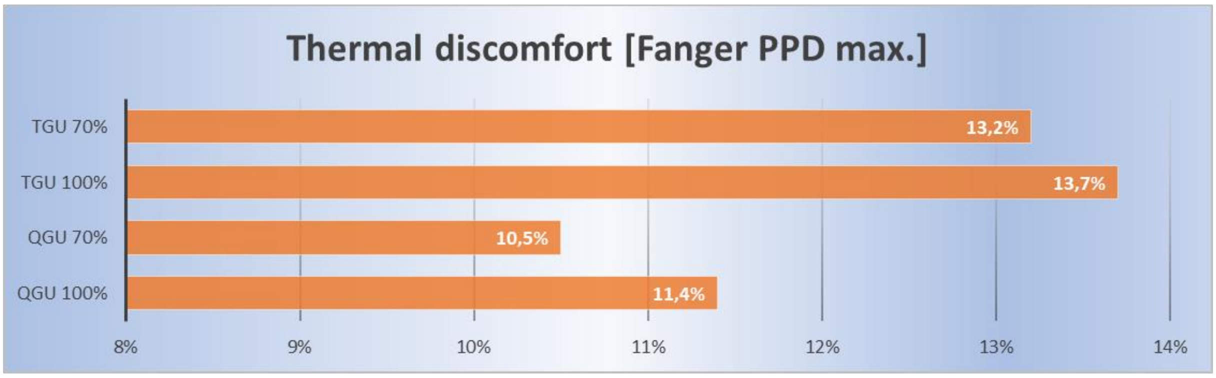
Triple-pane glazing solutions (with and without modulated external shades) for high volume to envelope ratios (business, office buildings) can be designed to offer quite comparable performance to quadruple panes for a mild climate such as in Ljubljana. This is mainly because heat exchange through the envelope can be limited with modest interventions such as low g glazing and winter does not exceed internal heat source gains by much.

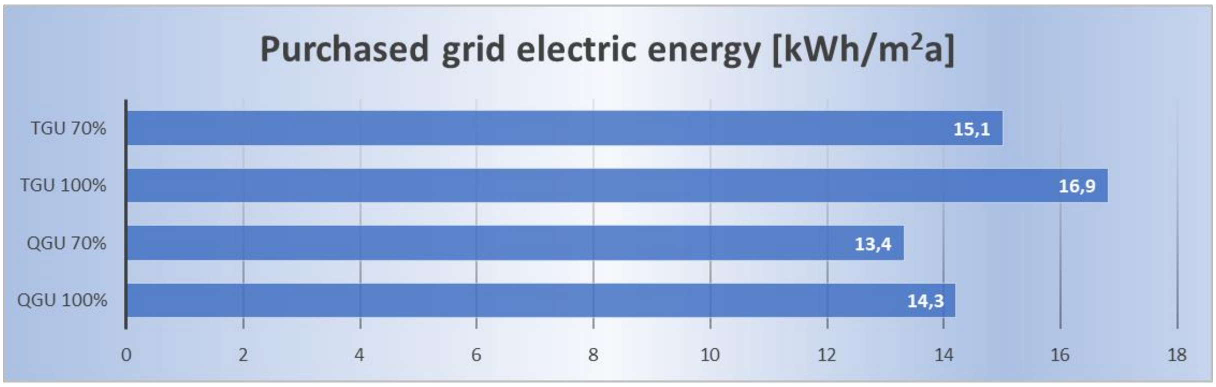
Adding quadruple glazing brings one quickly to the nearly-zero or even null heating as internal heat generation is plenty. Heating demand change is only 5 kWh/m2a typically.

Delivered grid energy reduction is thus small. The only notable gains are tentative null heating and notable improvement in winter comfort.

Office building quick comparison – Stockholm, Sweden (59° geographical latitude):







TGU	Triple-pane glazing unit
QGU	Quadruple-pane glazing unit

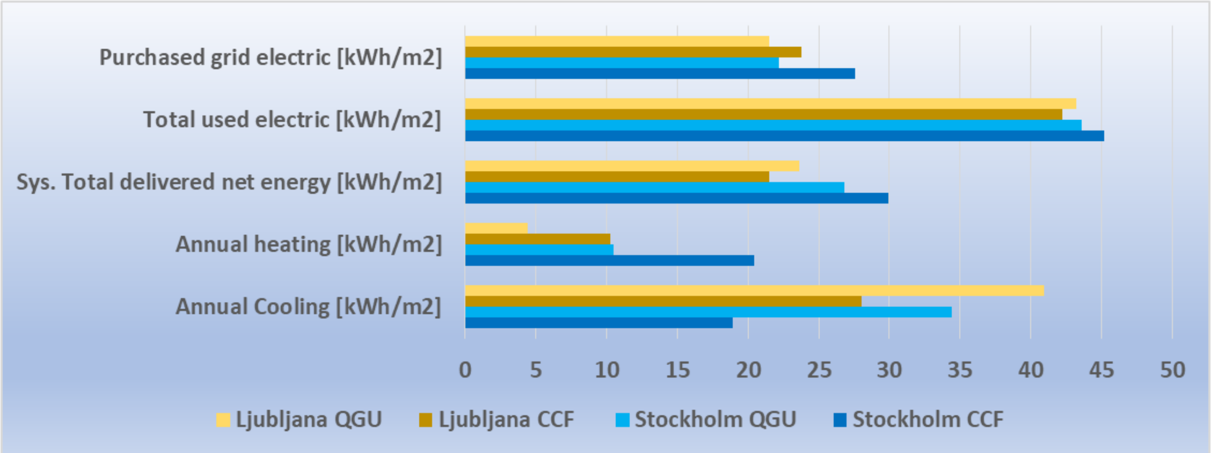
Quad-pane glazing solutions in Nordic countries can offer notable conventional heating savings. This is in short due to much more pronounced cold winters.

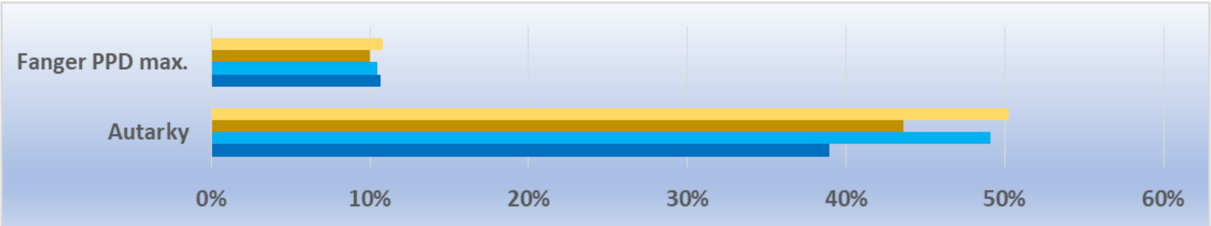
Adding quadruple glazing does not bring one quickly to the nearly-zero or even null heating despite internal heat generation is plenty. Heating demand change is 10 kWh/m2a typically. To achieve heating demand of about 5 kWh/m2a, quintuple glazing should be applied. With quintuple glazing PV autarky can be pushed all the way up to 55% without any employment of storage systems.

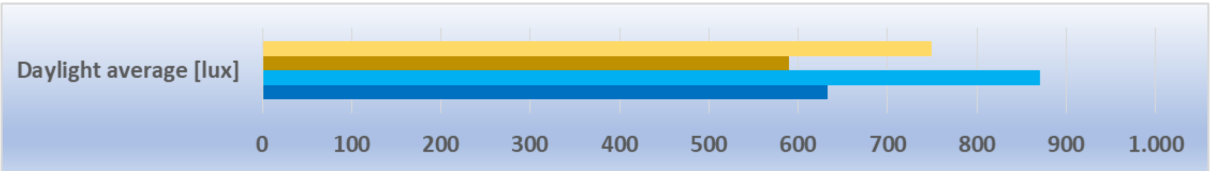
Delivered grid energy reduction is of about 15% (on top of photovoltaic collector). The notable gains are improvements in winter comfort.

2.6. *Office building result summary - QGU vs. CCF*

Ljubljana, Slovenia (46° geographical latitude), Stockholm, Sweden (59° geographical latitude):







CCF	Closed cavity facade
QGU	Quadruple-pane glazing unit

Quadruple-pane glazing solutions (without modulated external shades) for high volume to envelope ratios (business, office buildings) can be designed to offer comparable performance to CCF facades in all relevant (heating dominated) climates. This is mainly because reduced winter heat loss with pure quadruple panes offsets some weakness in cooling. With the PV attached this pronounced cooling is advantageous as PV works better in the summer.

Quadruple-panes are in most cases 50% less cost-intensive investment and offer higher comfort, more uninterrupted contact with the environment.

3. Single house

3.1. Single house model building description

A two-room, 10x10 m, two-floor building in a single home arrangement as shown on Figure 4.

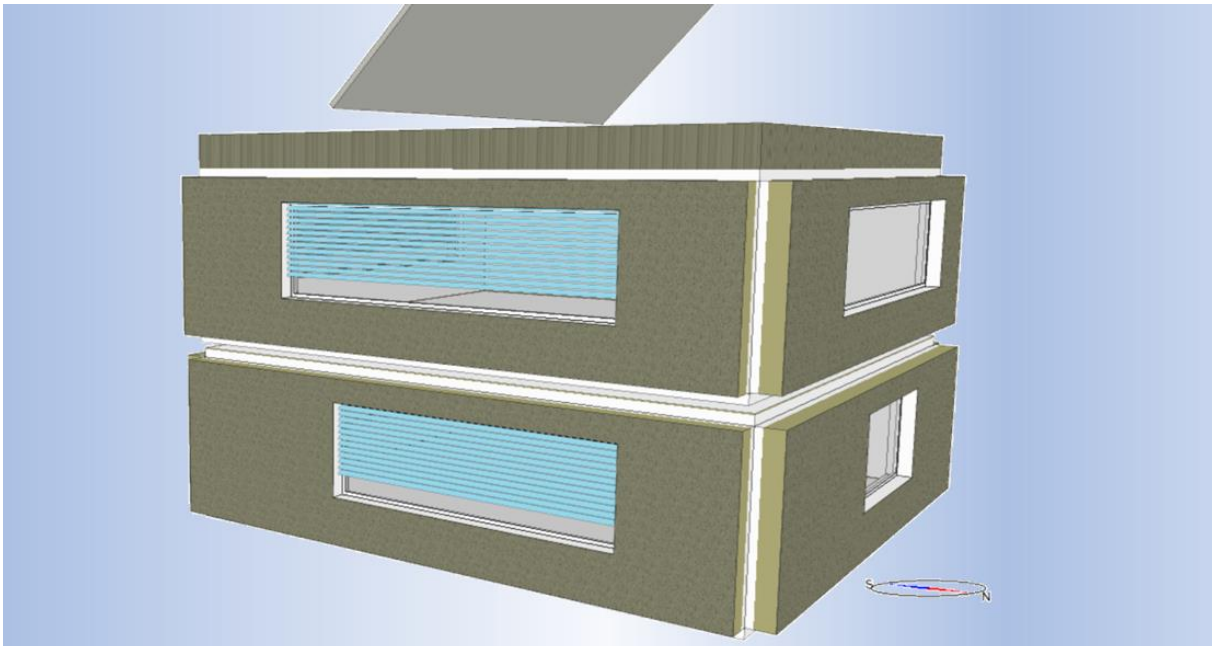


Figure 4: Single house configuration with expected window to envelope ratio of 16,8%. West wall has no windows, northern windows have no shading. Upper ceiling has U-value 0,06 W/m2K, walls U-value varies with location (indicated in the table below).

The test building is also equipped with a 40 m^2 roof photovoltaic (PV) system tilted at 45° (**Error! Reference source not found.**). Simulated PV system efficiency is 16%. Shading is modulated to 500 lux in all configurations while shading kicks-in at solar radiation of 100W/m^2. Average daylights are comparably at about 450 lux on all configurations.

The primary heating mode of the building is a heat pump floor heating. Cooling is arranged through ventilation. U-values of window's glazing are 0,30 and 0,58 W/m2K for QGU and TGU respectively. Interior roller shading is modelled with QGU. The window frame is modelled at 10% of the window area. Simulation is done in an all-electric configuration, so all energy supply values are in terms of electric energy. Domestic hot water was modelled at 27 l per person day as per[1]. Software used: hourly simulations with IDA-ICE 4.9.

[1] Ratajczak, Katarzyna, et al. "Real Domestic Hot Water Consumption in Residential Buildings and Its Impact on Buildings' Energy Performance—Case Study in Poland." *Energies* 14.16 (2021): 5010.

3.2. Single house building data

Occupants 0,02 /m²	U_{wall} = varies
Lights 1W/m²	Frame fraction 10%
Infiltration 0,02 ACH	Frame U_f = varies
Daylight shade modulation set 500 lux	Window opening 10%
Fan eff. 80%	Shade trigger 100W solar radiation
Window opening: Yes	Primary heating mode: Heat pump
Cooling COP = 3	Shading program: Daylight-GetHeat-MinCool
VAV control: temperature+CO_2	TGU U_g=0,58 W/m²K
CO_2 limit 900 ppm	QGU U_g=0,30 W/m²K
Equipment 5W/m² "House living modified 23-6h = 0.2"	Ventilation energy return eff. 93%
PV efficiency 16%	DHW 27 l/day person, daytime only
Zone VAV variable air volume air supply	Window to envelope ratio 16,8%

3.3. Single house building results and model data

Place	Type	Frame Uf [W/m²K]	U wall [W/m²K]	g value South/East	g value North	Shade VIS reflec South/East	Shade VIS reflec North	PV azimuth	VAV range [ACH]	Annual cooling [kWh/m²]	Annual heating [kWh/m²]	Total used electric [kWh/m²]	Purchased grid electric [kWh/m²]	Sys. Total prim. delivered [kWh/m²a]	Fanger PPD max.	Autarky
Ljubljana	QGU	0,7	0,17	0,35	0,42	0,59	w/o	20	0,2-1	21	4	33,9	18	-14,6	10,00%	46,9%
Ljubljana	TGU passive	0,9	0,17	0,6	0,54	xternal	w/o	0	0,2-1	19,6	8	34,9	20,4	-14	10,00%	41,5%
Stockholm	QGU	0,7	0,12	0,35	0,42	0,59	w/o	20	0,2-1	8,8	15,8	31	16,5	-17,6	10,40%	46,8%
Stockholm	TGU passive	0,9	0,12	0,6	0,6	xternal	w/o	0	0,2-1	8,1	19,9	32,3	19,2	-16,1	10,30%	40,6%

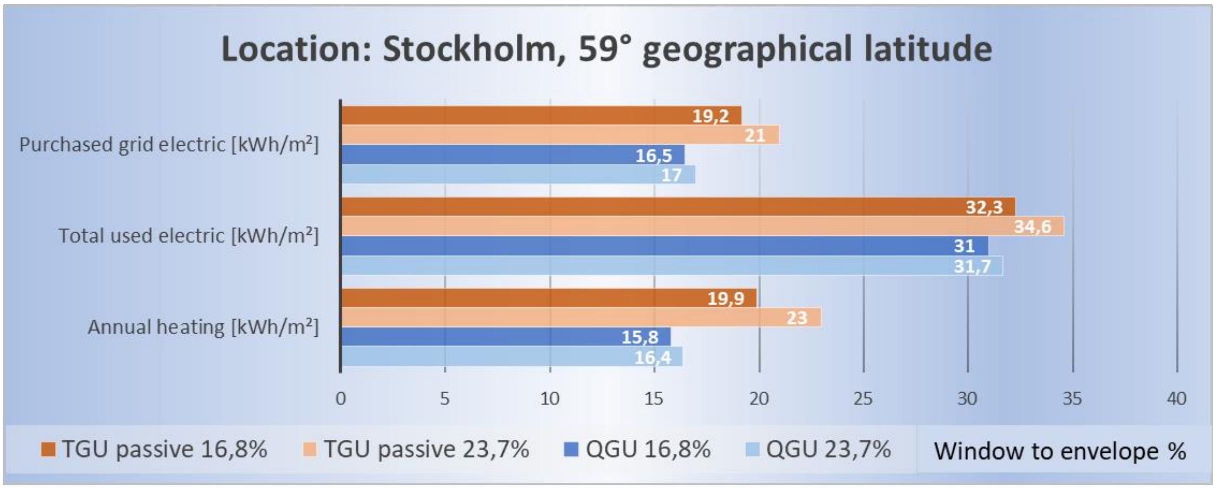
QGU	Quadruple-pane glazing units
TGU passive	Passive-house with triple-pane glazing units

Building thermal comfort is given in terms of Fanger's predicted percentage of dissatisfied (PPD), which as the name suggests determines the percentage of dissatisfied occupants. Usually, maximal hourly value is given as occupants value building comfort by its most discomforting period.

Autarky is annual energy self-sufficiency expressed in % of the total energy need covered by the PV supply on the 15-minute interval basis. Higher autarky means lower energy storage requirement. All buildings have sufficient PV supply on the net basis to cover all building needs as indicated by “Sys. Total prim. delivered” where negative sign indicates annual surplus value.

Triple-pane Passive-house (best available) level glazing system with external modulated shading is compared to quadruple-pane (QGU) without external shading. The two systems operate relatively comparably with the following advantages of QGU: 6% more PV autarky, about 4 kWh/m²a less heating demand, about 2 kWh/m²a less purchased energy from the grid, where the main advantage is that these feats are achievable without external robotized shade modulations. Also note that with QGU alone it is not yet possible to achieve “zero-heating” in Stockholm-like climate.

3.4. *Single house buildings – varied glazing fraction*



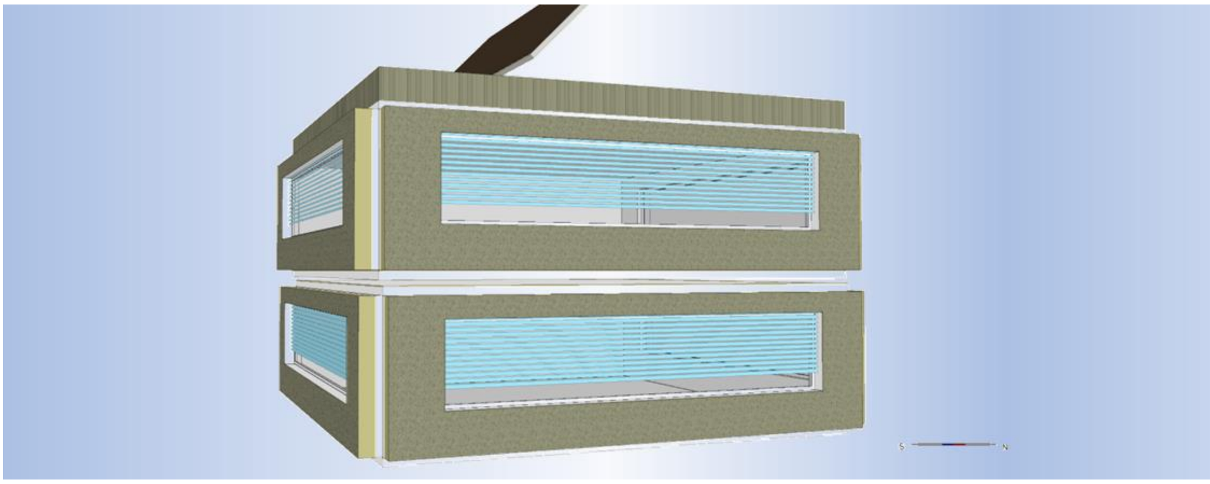
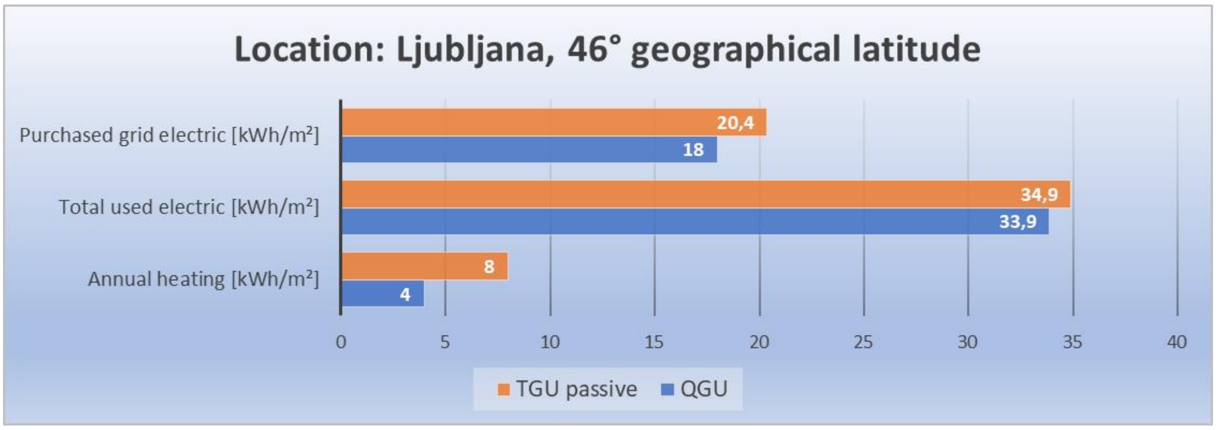


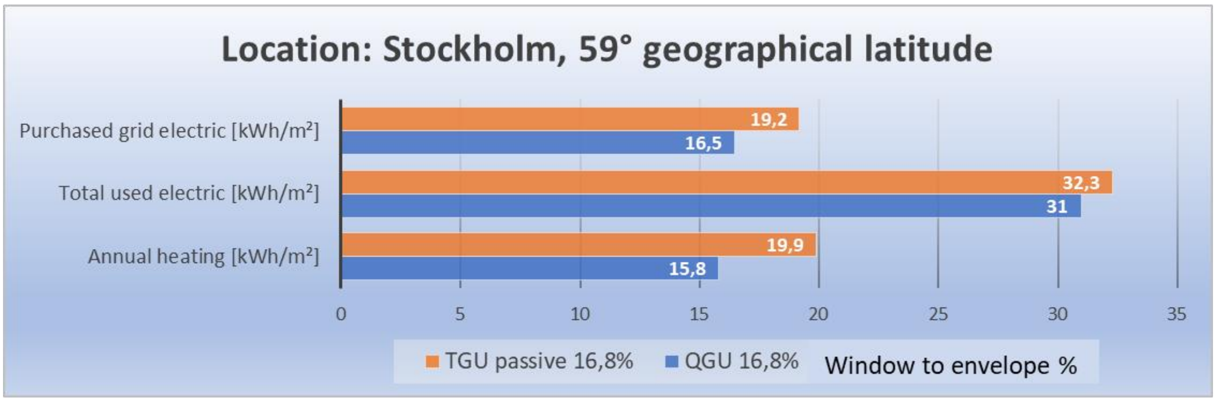
Figure 5: **Single house configuration with expected window to envelope ratio of 23,7%. West wall has no windows, northern windows have no shading. Upper ceiling has U-value 0,06 W/m^{2}K.**

Type	**Window / envelope [%]**	Frame Uf [W/m^{2}K]	U wall [W/m^{2}K]	g value South/ East	g value North	Shade VIS reflec South/ East	Shade VIS reflec North	PV azimuth	VAV range [ACH]	**Annual cooling [kWh/m^2]**	**Annual heating [kWh/m^2]**	**Total used electric [kWh/m^2]**	**Purchased grid electric [kWh/m^2]**	**Sys. Total prim. delivered [kWh/m^{2}a]**	**Fanger PPD max.**	**Autarky**
QGU 16,8%	16,80%	0,7	0,12	0,35	0,42	0,59	w/o	20	0,2-1	8,8	15,8	31	16,5	-17,6	10,40%	46,8%
QGU 23,7%	**23,70%**	0,7	0,12	0,35	0,42	0,59	w/o	20	0,2-1	9,1	16,4	31,7	17	-16,3	10,40%	46,4%
TGU passive 16,8%	16,80%	0,9	0,12	0,6	0,6	xternal	w/o	0	0,2-1	8,1	19,9	32,3	19,2	-16,1	10,30%	40,6%
TGU passive 23,7%	**23,70%**	0,9	0,12	0,6	0,6	xternal	w/o	0	0,2-1	8,8	23	34,6	21	-11,5	10,20%	39,3%

Use of QGU entails perhaps less obvious advantage in fraction of glazed surfaces. QGU can have large glazing fractions without notable thermal performance degradation. While increasing glazing to envelope (whole envelope including floor and ceiling) ratio from 16.8% to 23.7%, QGU increases heating demand by 0,6 kWh/m^{2}a, and triple-pane (TGU) by 3,1 kWh/m^{2}a. QGU can be used to facilitate Passive and "zero-heating" at any glazing ratio, while TGU is bound by legal heating demand limits rules to certain limited glazing fractions.

3.5. Single house building result summary





TGU passive	Passive-house with triple-pane glazing units
QGU	Quadruple-pane glazing units

4. Conclusions

Since quadruple-pane (QGU) glazing without external shading can compete with triple-pane with external modulated shadings on the cost basis, it makes sense to consider it due to many advantages:

- reduced heating demand;
- increased autarky ratio without application of energy storage;
- unlimited glazing without increased energy demand or loss of comfort;
- improved thermal comfort without use of external shading devices, and
- reduced purchased energy supply.