Optimum glazing in the regions of Europe considering the embedded energy

On behalf of
Compagnie de SAINT-GOBAIN,
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Content

1 Introduction

It is evident, that the U-value of glazing will decrease by increasing the number of panes and low-e-coatings, so the transmission losses through the glazing will decrease (just as the cooling load in cooling climates). At the same time, the g-value decreases too, so the solar gains are decreasing as well. In addition, the embedded energy increases with the overall thickness of the used glass, inert gas and the numbers of coatings.
The task of this study was there for to determine an overall energy balance (transmission losses, solar gains and embedded energy) over the life cycle of a glazing to carry out the best option in terms of the overall energy balance for the regions of Europe.

2 Methodology and input-data

2.1 Embedded energy

The data of embedded energy where taken from [Waltjen 1999][1], only the non-renewable energy was considered, see Table 1.

From these data, PHI calculated the embedded energy of a double, a triple and a quadruple single glazing. Under considering a service life of 25 years, it was possible to determine the primary energy per year, needed to produce the glazing, see Table 2.

[1] IBO (Hrsg.): Waltjen, Mötzel, Mück, Torghele, Zegler: Ökologischer Bauteilkatalog, Bewertete gängige Konstruktionen. Springer Verlag/Wien, 1999

Material	PEI (ne) kWh/kg	Density kg/m³	Source
Glass, uncoated	4	2500	IBO, cited in Waltjen 1999
Glass, coated	4,17	2500	IBO, cited in Waltjen 1999
Argon	1,11	1,78	Ökoinventare, cited in Waltjen 1999
Krypton	26,94	3,75	Ökoinventare, cited in Waltjen 1999

Table 1: Embedded energy of materials and density.

Glazing Setting	**Double low-E** 4/16A/C4		**Triple low-E** 4C/18A/4/18A/C4		**Quadruple low-E** 4/12K/C4/12K/C4/12K/C4	
	mm	kWh/m²	mm	kWh/m²	mm	kWh/m²
Glass uncoated	4	40,00	4	40,00	4	40,00
Glass coated (C)	4	41,70	8	83,40	12	125,10
Argon (A)	16	0,03	36	0,07		
Krypton (K)					36	3,64
Summ	24	81,73	48	123,47	52	168,74
kWh/(m²a) @ 25a	**3,27**		**4,94**		**6,75**	

Table 2: Embedded energy of the used glazings

2.2 Transmission losses and solar gains

Both, transmission losses and solar gains depending on the thermal parameters of the glazing (U- and g-value), on the climate data of the building site and on the thermal properties of the building.

2.2.1 Thermal properties of the glazing

Five different glazing, one double-low-e glazing, one g-value optimized and one U-value optimized triple-low-e glazing as well as one g-value optimized quadruple and one U-value optimized quadruple glazing were considered, see Figure 1.

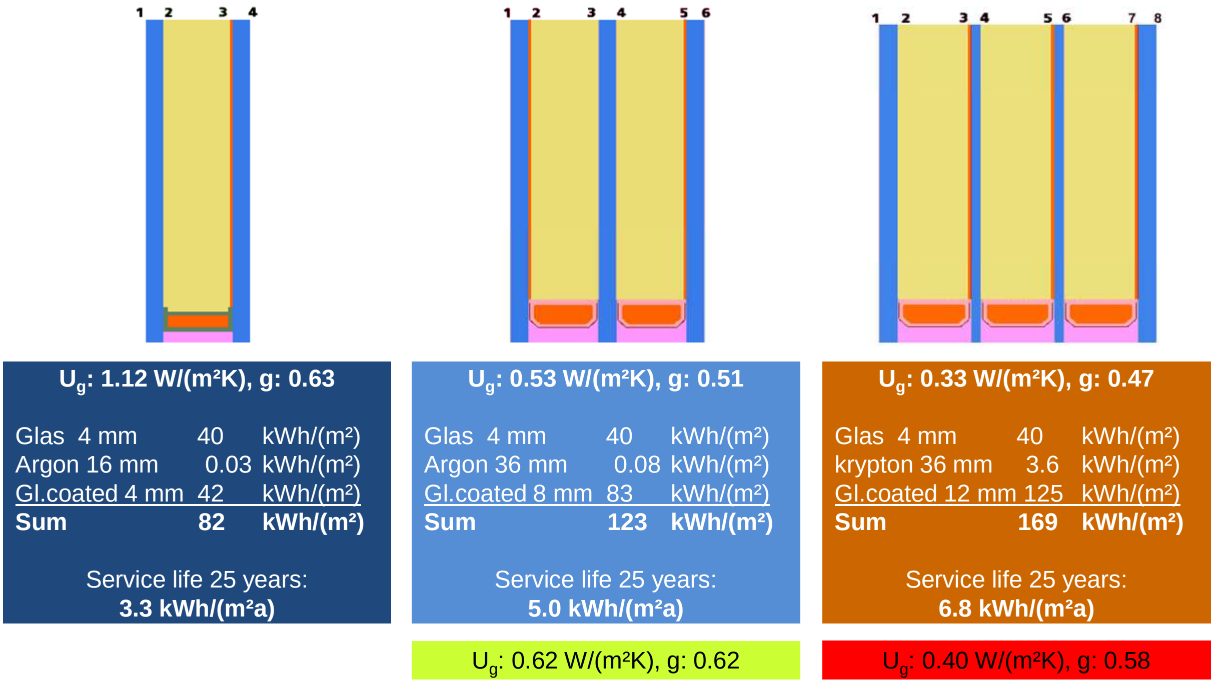

Figure 1: Considered glazing

2.2.2 Thermal properties of the glazing

In order to be able to generate a set of climate data for any point on the surface of the Earth, it is important to obtain the corresponding data at low cost and little effort from a single source. Satellite data from the NASA, which are continually available via the EOSWEB interface ([NASA 2009][2]) without cost and which were processed by the Passive House Institute, are ideal for this purpose. This data has a spatial resolution of 1 degree, which equates to a distance of up to 111 km. We use 1289 data sets for the areas of land in Europe which are located west of 35° East. The spatial resolution of the data is not adequate everywhere. Systematic errors can be expected particularly in mountainous regions such as the Alps, where the climate can change drastically within the distance of a few kilometres. The climate also changes radically near coasts within the space of a grid cell.

2.2.3 Thermal properties of the building: Methodology for calculating economic feasibility

The data basis and methodology for the following considerations were first applied in [Schnieders et.al. 2011][3] for defining an economically optimum construction in any chosen climate. On account on the current task, these analyses are largely limited to Europe. In order to help the reader understand the reasons behind this, relevant parts of the text from [Schnieders et.al. 2011] have been reproduced or adopted with slight changes below. If buildings and components are optimised from an economic point of view with reference to their energy demand for heating and cooling, then the necessary extra investment should be put into relation to the saved energy costs. The most appropriate method for this is that known as the net present value method, where each expenditure or income within the life cycle of the building is discounted to the beginning of the period under consideration using the chosen capital interest rate. This takes into account the fact that because of the interest due on the capital, costs which are incurred at a later point in time (here: energy costs) are weighted as being less than the costs which arise at the beginning of the period under consideration (here: investment for construction). More information about this method can be found for example in [Kah 2008][4], [Feist 1997][5], [Feist 2005][6] and [Feist 2013][7].

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[2] http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi, 5.10.0

[3] Schnieders, Feist, Krick, Rongen, Schulz et.al.: Passive Houses for different climate zones. Passivhaus Institut, Darmstadt, November 2011.

[4] Kah, Oliver, Wolfgang Feist, Rainer Pfluger, Jürgen Schnieders, Berthold Kaufmann, Tanja Schulz, Zeno Bastian: Bewertung energetischer Anforderungen im Lichte steigender Energiepreise für die EnEV und die KfW-Förderung. Passivhaus Institut, Darmstadt 2008.

[5] Feist, Wolfgang (Hrsg.): Arbeitskreis kostengünstige Passivhäuser, Protokollband Nr. 11, Kostengünstige Passivhäuser, Darmstadt, Passivhaus Institut, Dezember 1997

Since the cost of products for construction, labour and energy varies greatly in different countries in Europe, such considerations can only serve as a guideline. Research on energy and construction costs for the affected countries was far beyond the scope of the present study in any case; other optimums may result in individual cases and at current prices. Besides the window, the chosen cost estimates are based on the assessment of the authors with reference to average prices throughout the period under consideration. Economies of scale due to the higher number of items, also for products which were exotic up till now, have already been priced in.

Example building: The energy demand for a sample building on the basis of the geometry and orientation of the end-of-terrace house in Darmstadt-Kranichstein (Germany), which was built to the Passive House Standard, see Figure 2. The building faces exactly south and is moderately shaded; most of the windows are on the south side (30 m² south-facing windows with a living area of 156 m²). Details of this building are provided in the sample file in [PHPP 2007]. The new construction situation was assumed for this building in which any type of e.g. shading and glazing can be chosen, and the heating or cooling system respectively depends on the building characteristics.

Figure 2: Building used for the simulation

Boundary conditions for the economic feasibility calculation: The boundary conditions summarized in Table 3 and Table 4 were used for the calculations. All prices are retail prices including VAT. The present value of the energy service "comfortable temperature-controlled interior space" is obtained from the invested costs and the capitalised energy costs over the 40-year period under consideration. The house is cost-optimised if this value is minimal. For glazing and windows, please see Figure 3.

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[6] Feist, Wolfgang (Hrsg.): Arbeitskreis kostengünstige Passivhäuser, Protokollband Nr. 29, Hochwärmegedämmte Dachkonstruktionen, Darmstadt, Passivhaus Institut, Juni 2005

[7] Feist, Wolfgang (Ed.): Ökonomische Bewertung von Energieeffizienzmaßnahmen, Protokollband Nr. 42 des Arbeitskreises kostengünstige Passivhäuser. Passivhaus Institut, Darmstadt 2013

Four ventilation strategies were examined for each of these window and glazing types: Exhaust air system without HRV/ERV, with night-time ventilation via tilted windows across several storeys ($n = 0.46\ h^{-1}$ for a temperature difference of 1 K), Exhaust air system without HRV/ERV, without night-time ventilation, Supply and extract air system with 90 % HRV, with night-time ventilation as above, Supply and extract air system with HRV as above and 80 % ERV, without night-time ventilation.

The economically optimum U-values of the opaque exterior building components were determined for the best ventilation strategy in terms of cost. Apart from this, an economically optimal level of airtightness was specified, whereby an overall amount of € 5 per square metre of living area was set for improvement from $n_{50} = 0.6\ h^{-1}$ to $0.35\ h^{-1}$ and from $0.35\ h^{-1}$ to $0.25\ h^{-1}$. In principle, values worse than $0.6\ h^{-1}$ were not permitted here in order to guarantee faultless functioning of the ventilation system, structural integrity etc. Better values were interpolated or extrapolated using a hyperbola. The economic optimums of U-values and airtightness depend on the length of the heating or cooling periods and thus on the mechanical systems of the building and the quality of windows used, therefore they must be redefined for each variant.

The first economic optimum is obtained in this way. If passive cooling is not sufficient for the thus calculated building, then shading equipment is additionally taken into account in the comparison.

Finally, a search was made for a functioning Passive House. If the heating load or the sensible cooling load of the building which was optimised as previously described was higher than 10 W/m², then thermal protection was improved for the cases with supply air and extract air systems in such a way that both these limits were undercut. In this case a discount was made for a simplified building services system (e.g. supply air heating or cooling, but also other systems will be reduced in cost) according to **Table 4**.

Table 3: Boundary conditions of the economic analysis

Real interest[1]	2.5 %
Usage period of exterior building components	40 years
Price of additional insulation for wall and basement ceiling[2], λ = 0.035 W/(mK)	€ 1/cm/m²
Price of additional insulation for roof	€ 0.50/cm/m²
Average price of final energy[4]	9.2 cents/kWh
Efficiency factor of heat generator	92 %

1 This is a typical value for the mortgage interest rate, taking into account the rate of inflation (see [Feist 2013]).

2 The basement ceiling can in principle be insulated at a low price similar to that for the roof; however, there is often insufficient space available, so one would have to use materials with a smaller thermal conductivity, which costs even more than exterior wall insulation. With the value set here, we have adopted the middle course between the two.

3 A loss of living area has been priced in for interior insulation. With an overall price of € 1500 per m² living area and a room height of 2.50 m, this gives an additional square meter price of € 6 per centimetre of thermal insulation. In principle, the approach for loss of living area would only be justified from the point when the interior surface temperature allows the placing of furniture next to the exterior wall, otherwise a gain in living area would have to be assumed as a matter of principle. However, like the general increase in residential quality due to increased comfort, this has not been taken into account here so that the ascertained insulation thicknesses are rather too low.

4 The average real price during the period under consideration, inc. taxes and duties. If local energy prices are significantly lower, this is either due to subventions, or the locally produced energy could have been sold more profitably on the world market. In such cases, this has to do with a macroeconomic rather than a microeconomic analysis, but price adjustments during the usage period of a building are particularly likely in these cases. Further increases in energy prices during the period under consideration have not been included since in the long term, the substitution of increasingly scarce fossil fuels with renewable energy sources for a price slightly higher than the current price level is likely. Useful cooling energy for cooling and dehumidification is included with the same price as that for heating energy.

Table 4: Cost assumptions for mechanical services in € per square metre living area

	Costs [€/m²]
Extract air or supply air system	15
Supply air and extract air system with HRV	40
Additional costs for ERV	5
Heat or cold air distribution, in case heating or cooling load is greater than 10 W/m²	20

2.2.4 Window data and prices

Drawings of the used window profiles and installation situation, the thermal properties of the used materials and glasses as well as the consumer prices of the windows were provided by the pro Passivhausfenster GmbH member Lorber, see Figure 3.

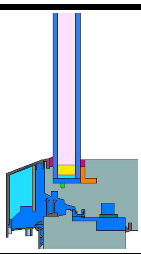
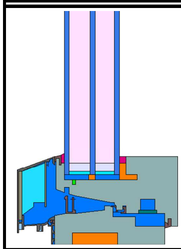
<table>
<tr><th colspan="2" rowspan="2">Window</th><th>Ug</th><th>g</th><th>Kranichstein</th></tr>
<tr><th>W/(m²K)</th><th>-</th><th>€/m²</th></tr>
<tr><td></td><td>2WS compact</td><td>1,10</td><td>0,63</td><td>431</td></tr>
<tr><td rowspan="4"></td><td>3WS compact</td><td>0,53</td><td>0,53</td><td>454</td></tr>
<tr><td>3WS+ compact</td><td>0,61</td><td>0,6</td><td>461</td></tr>
<tr><td>4WS compact</td><td>0,35</td><td>0,42</td><td rowspan="2">536</td></tr>
<tr><td>4WS+ compact</td><td>0,46</td><td>0,59</td></tr>
</table>

Figure 3: Used windows with the thermal properties of the glazing and prices per square meter.

The thermal data of the window profiles and the installation situations were calculated based on two-dimensional thermal flow analyses by the Passive house institute, see

[Krick 2014][8]. Figure 4 shows the most relevant properties of the considered window frames.

pro passivhausfenster smartwin compact double		Bottom Unten	Top Oben	Side Seitl.	Bottom fixed Unten fest	Top fixed Oben fest	Side fixed Seitl. fest
Temperaturfactor $f_{Rsi=0,25m^2k/W}$ Temperaturfaktor $f_{Rsi=0,25m^2k/W}$		0,59	0,63	0,63	0,61	0,63	0,63
Frame width b_f Rahmenbreite	mm	0,076	0,067	0,067	0,076	0,067	0,067
U-value frame U_f Rahmen-U-Wert	W/(m²K)	1,21	0,84	0,84	0,96	0,67	0,67
Ψ-glass edge Ψ_g Glasrand-Ψ-Wert	W/(mK)	0,032	0,032	0,032	0,033	0,035	0,035
Ψ_{opaque} Ψ_{opak}	W/(mK)	0,101			0,089		
Passiv House efficiency class Passivhaus Effizienzklasse		phA			phA		
U_W @U_g = 0,70 W/(m²K)	W/(m²K)	1,155			1,122		

pro Passivhausfenster smartwin compact triple		Bottom Unten	Top Oben	Side Seitl.	Bottom fixed Unten fest	Top fixed Oben fest	Side fixed Seitl. fest
Temperaturfactor $f_{Rsi=0,25m^2k/W}$ Temperaturfaktor $f_{Rsi=0,25m^2k/W}$		0,72	0,74	0,74	0,74	0,76	0,76
Frame width b_f Rahmenbreite	mm	0,076	0,067	0,067	0,076	0,067	0,067
U-value frame U_f Rahmen-U-Wert	W/(m²K)	0,94	0,70	0,70	0,70	0,53	0,53
Ψ-glass edge Ψ_g Glasrand-Ψ-Wert	W/(mK)	0,020	0,021	0,021	0,020	0,021	0,021
Ψ_{opaque} Ψ_{opak}	W/(mK)	0,076			0,062		
Passiv House efficiency class Passivhaus Effizienzklasse		phA			phA+		
U_W @U_g = 0,70 W/(m²K)	W/(m²K)	0,768			0,730		

Figure 4: Most relevant properties of smartwin compact double and triple.

For the results of the study regarding the economic optimum windows in Europe, please see [Krick 2014-1][9]

2.2.5 Annual heating energy demand

For any considered location and each glazing, the annual heating energy demand (Q [kWh/(m²a)] was calculated point out point out the best option for each location:

$$Q_E + Q_T - Q_S = Q$$

Where is:

Q_E [kWh/(m²a)]: Annual fraction of embedded energy, see 2.1.

Q_T [kWh/(m²a)]: Transmission losses of the glazing: U_g multiplied by the head degree hours of the optimized building at the specific location.

Q_S [kWh/(m²a)]: Useful solar gains: The sum of the solar radiation of any month with significant heating demand of the optimized building at its specific location multiplied with the g-value.

The lower Q, the better: Minimum Q = optimum.

3 Results

3.1 Catching the comfort criterion

If a certain level of thermal insulation is reached, high thermal comfort can be achieved by avoiding unpleasant heat radiation losses and cold down drafts. The Passive house institute

[8] Krick, Benjamin: Certification report for smartwin compact, PHI Darmstadt, 2014

[9] Krick, Benjamin: smartwin compact: Economic optimum in the regions of Europe, PHI Darmstadt, 2014

has carried out, that this level is reached, when the temperature difference between the inner surface of the building and the operative room temperature is less than 4.2 K (Passive House comfort criterion, see for instance [Feist 1998][10]). From that, the needed minimum U-value of the thermal envelop can be calculated depending on the design outside temperature. As design outside temperature, the average temperature of the coldest day in a reference year is taken into account.

At given U-values for the various glazing, frames and installation situations, the achievable U-values of the different Settings can by determined. By putting together this U-values, the local design outside temperature and the comfort criterion can be defined where which glazing should be used all over Europe, see Figure 5: The map shows, that in most parts of Europe triple glazing is to be used. In the north and east, quadruple glazing should be chosen and only in Mediterranean areas and in regions directly influenced by the Gulf Stream, double glazing might be used.

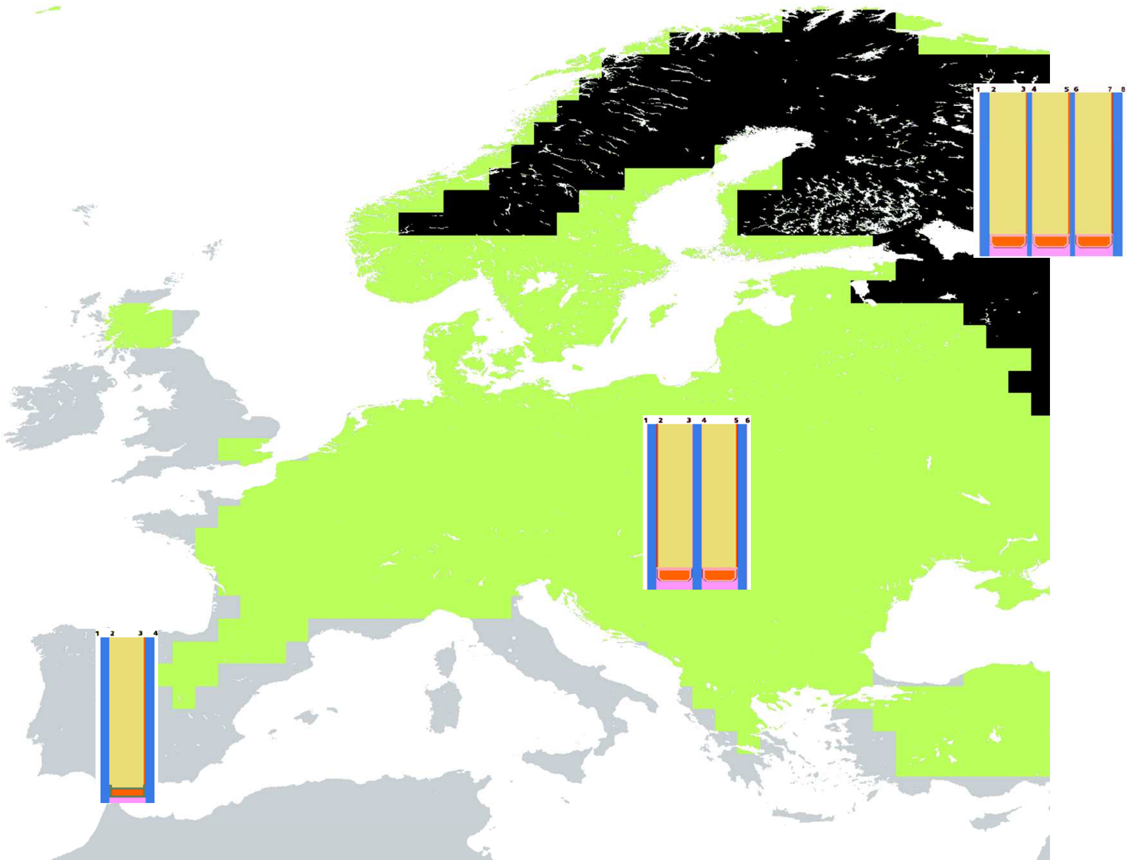


Figure 5: Glazing to be used in Europe for catching only the comfort- and hygiene criterion. Be aware, that this is not the economic optimum!

3.2 Specific locations

Figure 6 shows the useful solar gains, the transmission losses and the embedded energy for each of the considered glazing, oriented north at the climates of London, Frankfurt and

[10] Feist, Wolfgang; Fenster: Schlüsselfunktion für das Passivhaus-Konzept, 14. Arbeitskreis kostengünstige Passivhäuser, Passivhaus Institut Darmstadt; Dezember 1998

Rome. It is clearly visible, that the embedded energy is minor compared to gains and losses for the locations of London and Frankfurt. The same is valid for Rome, looking to the double glazing. For the quadruple glazing in Rome, the losses are (depending on the climate) so low, that the embedded energy roughly equals the losses. The red bar shows, that the U-value optimized quadruple glazing is the optimum for any of the chosen locations at north orientation. Because in Rome, there is no heating demand in any month, there are no useful solar gains too. So solar gains are not displayed.

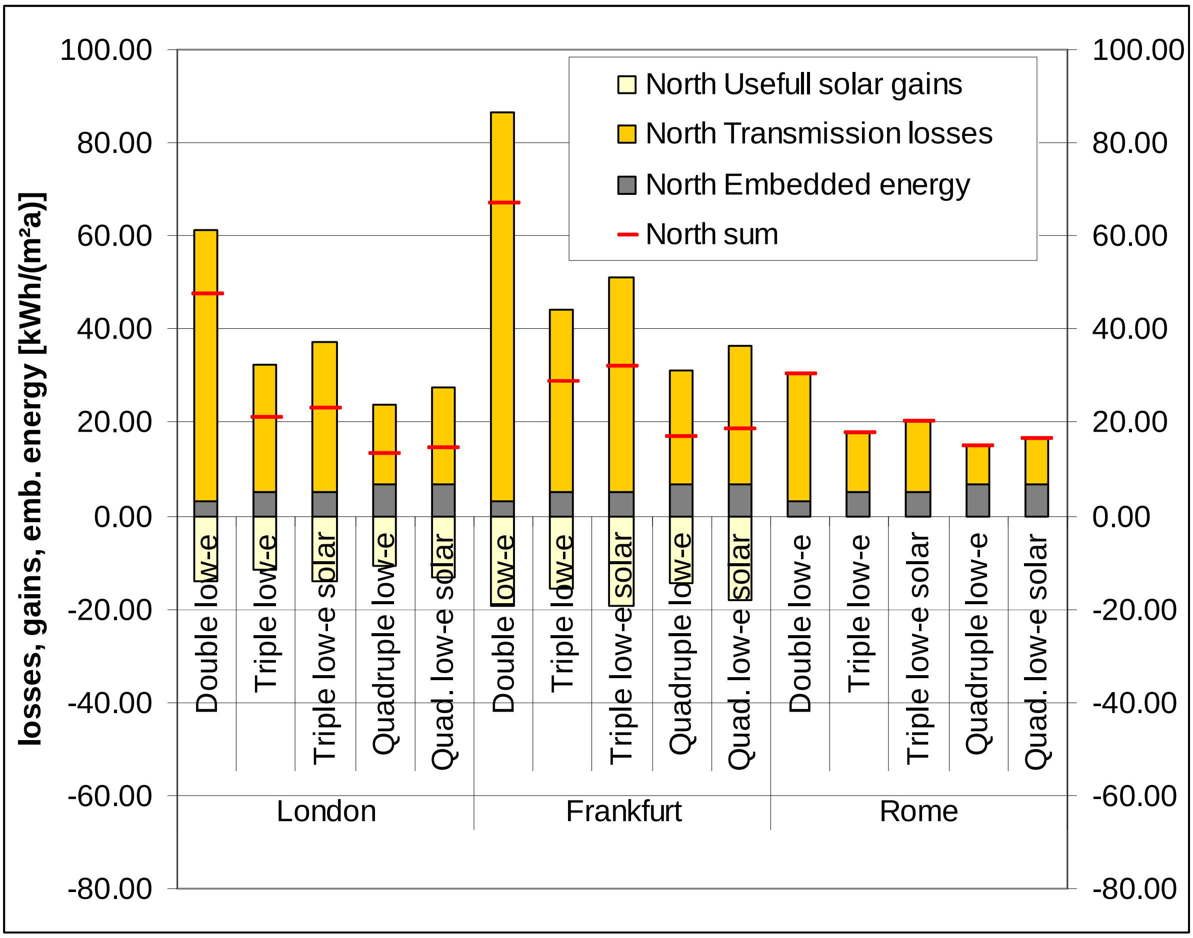


Figure 6: Gains, losses and embedded energy for **north faced** glazing at specific locations.

It is evident, that the solar gains are much higher for a south orientated glazing, see Figure 7. Because of this, the share of the embodied energy of the overall energy is even lower as for the north oriented glazing, the optimum is the solar optimized quadruple glazing. The red bar displays net solar losses only for double glazing in the heating climates.
Cooling is not considered here. Because more solar gains means more cooling, energy can be saved by better u-values and lower g-values. This would lead the way even more towards triple (and quadruple) glazing in cooling climates.

According to the here considered parameters, quadruple glazing seems to be the best option for all displayed locations in that chapter. It has to be mentioned, that the differences between triple- and quadruple glazing are not very high, so it might be, that (especially in warmer climates) a more detailed dynamic simulation will identify triple glazing as the better option. In addition, nowadays quadruple glazing should use krypton, which is a rare and thus expensive element. So the use of quadruple glazing should be reserved for special situations and very cold climates.

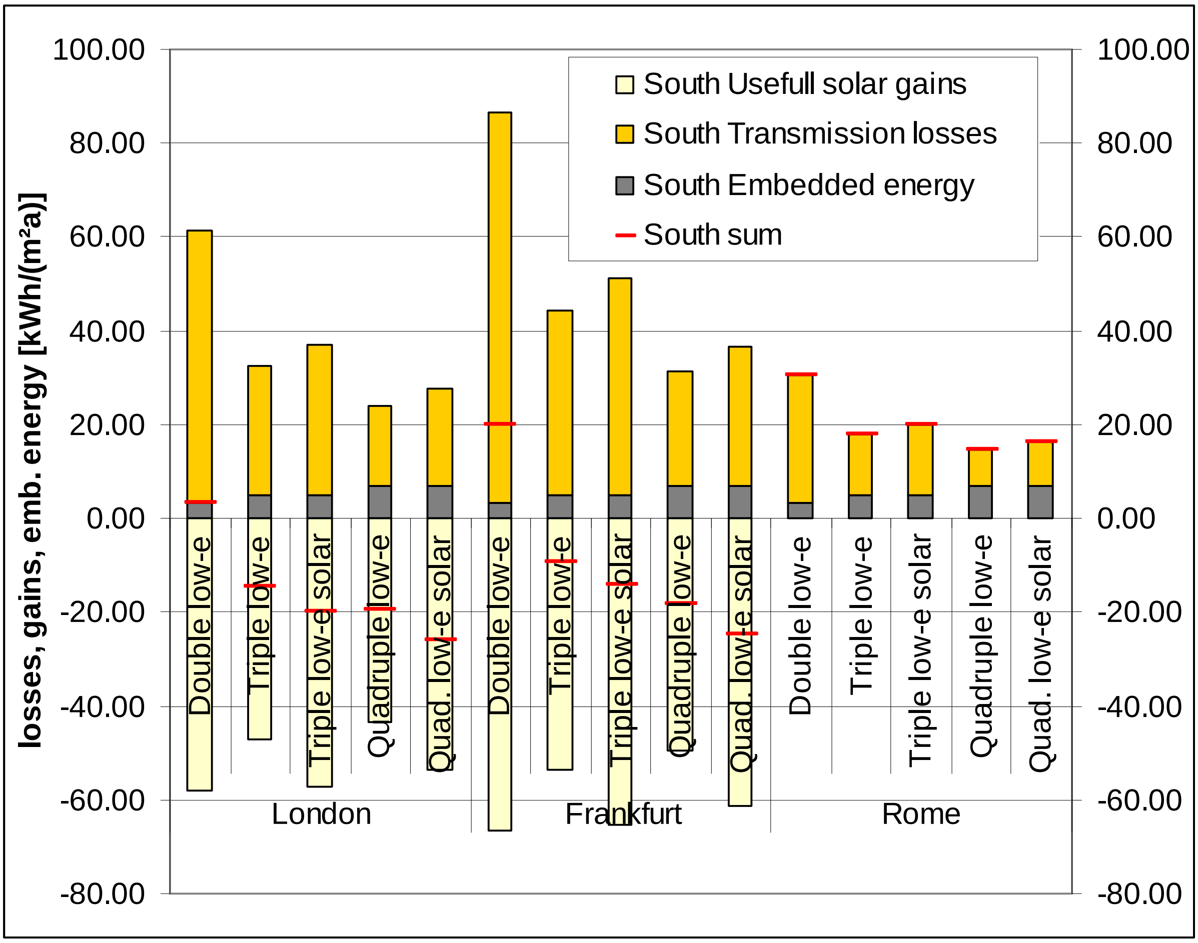


Figure 7: Gains, losses and embedded energy for **south faced** glazing at specific locations.

3.3 Optimum glazing in the regions of Europe

Figure 8 shows a map of Europe with the optimum glazing (regarding embedded energy, solar gains and losses) for north- (left) and south oriented (right) glazing. All over Europe, quadruple glazing is the option of choice. For north orientation the U-value optimized, and for south orientation, the g-value optimized variant is dominant. The including of cooling demand would lead in tendency to U-value optimized glazing for south orientation in the south of Europe.

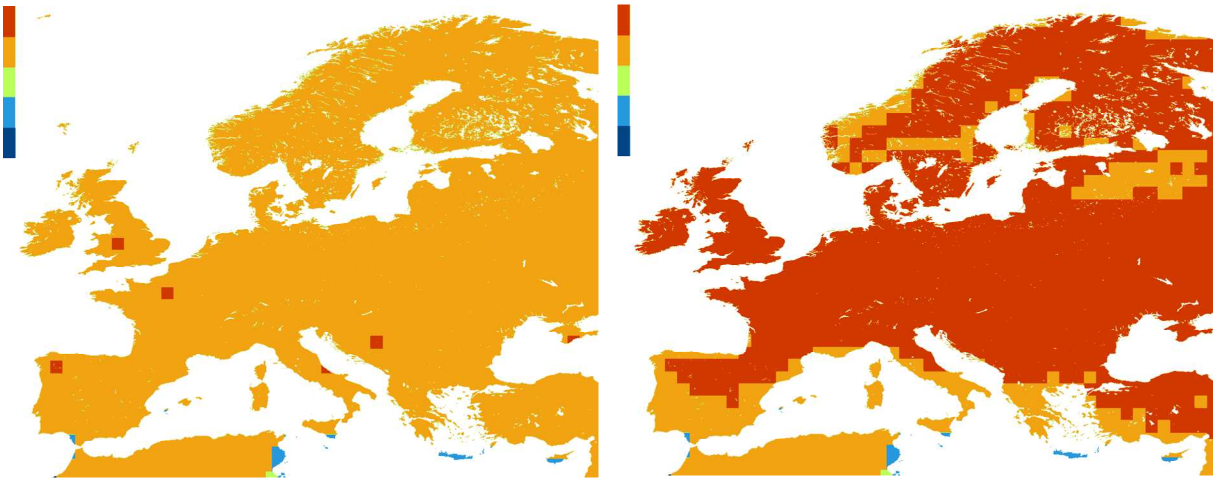


Figure 8: Optimum glazing regarding embedded energy, solar gains and losses all over Europe for north- (left) and south oriented (right) glazing.

Quadruple glazing is not a common option yet and might be not in future because of the lack of Krypton gas and limited thicknesses of gas-gaps, see [Krick 2014-2][11]. So the study was done again without quadruple glazing. The result does not surprise: U-value optimized triple glazing all over Europe for north-faced glazing and usually solar optimized triple glazing for south fazed glazing, see Figure 9.

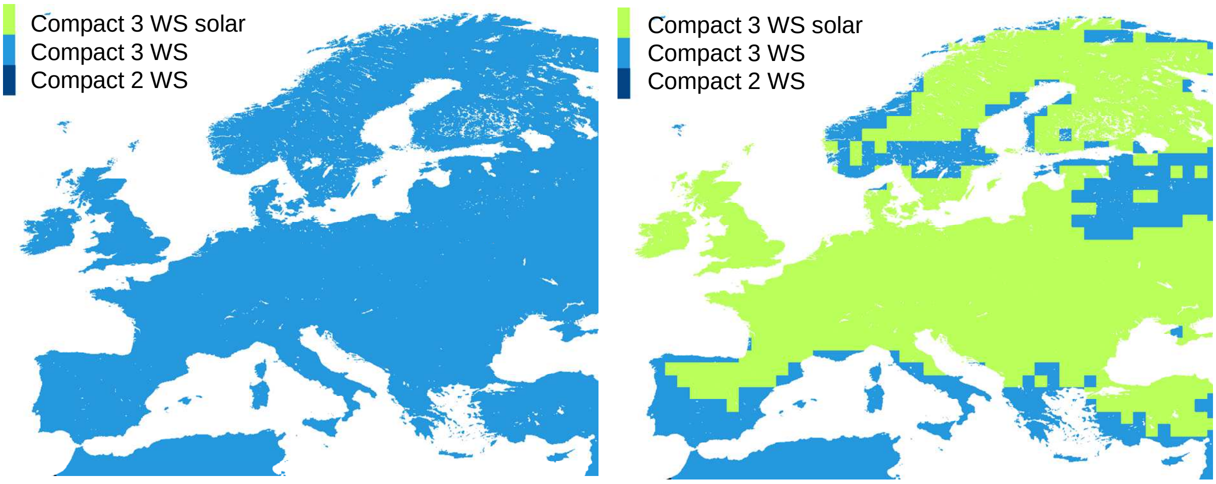


Figure 9: Optimum glazing (without quadruple glazing) regarding embedded energy, solar gains and losses all over Europe for north- (left) and south oriented (right) glazing.

[11] Krick, Benjamin: PHI window certification: previous success and new climate zones. In: Conference proceedings of the 18th International Passive House Conference in Aachen, PHI Darmstadt, 2014

4 Summary

It was clearly determined, that embedded energy plays a minor role in the overall use of the energy balance of windows. The optimum glazing for Europe regarding embedded energy, solar gains and transmission losses is quadruple glazing, which is not available jet on large scale and might not be even in the future. So quadruple glazing should be reserved for special situations and very cold climates, as long as krypton has to be used.

Taking into account economic aspects, usually triple glazing will be the optimum, only in the very north and east of Europe, quadruple glazing would be the best choice, while double glazing plays, even in the south, a minor role.