Embodied energy of windows in buildings: impact of architectural and technical choices part 2

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Abstract: - In this publication, the relationship that exists between embodied energy of building components and the global energy efficiency of building has been quantified. First, the embodied energy of multiple windows based on their typology has been compared. The aim was to evaluate the embodied energy and additional costs required for a triple glazing window, with the gain in energy consumption that its integration generates for a building. The study was performed on an existing case. Energy consumptions were obtained by in situ measurements and reinforced by building modeling using dynamic thermal simulation software. These allowed us to estimate the return on investment in terms of the embodied energy of building elements; it is a reasoning process expressing overall energy costs. The global economic aspect has also been studied over the lifetime of the windows. This study proves that an awareness of embodied energy allows us to draw results and conclusions on environmental impact and energy consumption that can be used by building designers and architects at a decision-making level.

Key-Words: - Embodied energy, triple and double glazed window, energy costs and savings, operational performance, return on investment

3 Results for studied windows in reference operational building

The reference building which has been studied was the "Maison du Pays" of Hochfelden in the region of Alsace in France. The building is situated at the base of a hill, built perpendicular to the slope in order to minimize the impact on the ground. The research of energy performance led us to create a compact building for the administration activity which detaches a volume for intermittent occupation which is the conference room. The studied building has an area of 2810 m², and is presented in Figures 6 and 7.

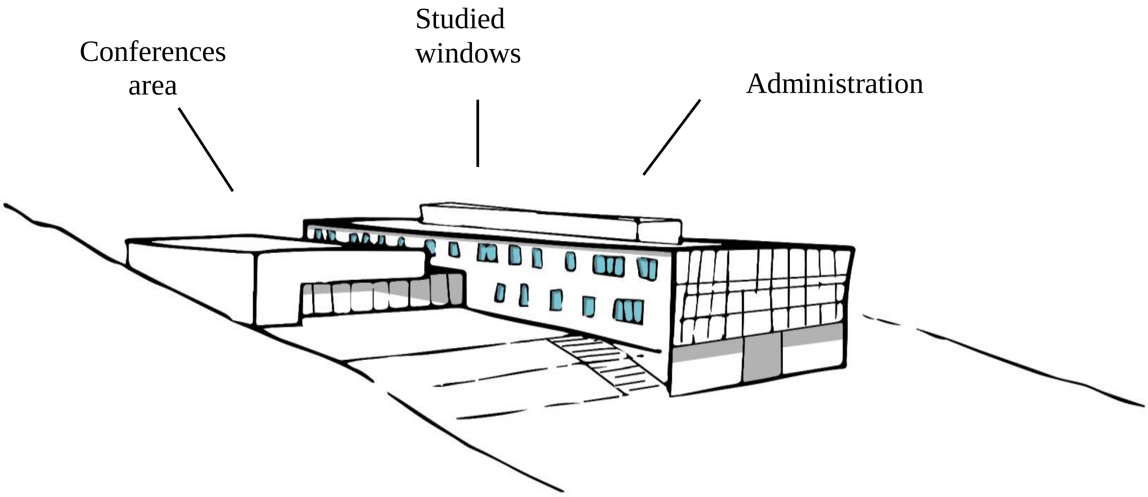

Fig. 6: Drawing picture of studied building, in Hochfelden, France

3.1 Dynamic thermal simulation of the reference building

A complete thermal study was conducted using the PLEIADES + COMFIE® v.3.5.2.1 software to simulate the building energy consumption [9]. The purpose was to calculate the building heating needs in order to estimate the energy consumption of the building in winter. Modeling was carried out by integrating scenarios as close as possible to the real scenario within one year of simulation. In order to be more realistic and precise, the entire construction was divided into 22 temperature zones. Then the results of the dynamic thermal simulation were compared with measurements in situ.

Fig. 7: Photo of studied building in Hochfelden, France

3.1.1 Input data, assumptions and boundary conditions for dynamic thermal simulation

The envelope consists of a supporting structure in honeycomb alveolar brick. The insulation is thus distributed.

In this study, specially investigated are the triple glazed windows with a wooden frame corresponding to existing windows of the administration building.

Heating is provided for 71% by geothermal heat pump water / water type (GHP) with a COP of 3.28 and for the rest of 29% is provided by an extra gas condensing boiler (GCB) with 99.7% PCS efficiency.

The weather file provided by the Pack Meteonorm Pleiades has been used. This is "Strasbourg moyen.try".

The building consumption monitoring revealed that the heating temperatures are well above the regulation temperature of 18°C and showed that in periods of vacation, there is no reduced temperature.

3.1.2 Results of dynamic thermal simulation

The heating needs have been calculated by thermodynamic simulation, using Pleiades + Comfie software, and the results are presented in the Table 5. The simulation was performed by integrating the most realistic scenarios possible, resulting in 69,656 kWh/year that is to say, 24.8 kWh/(m².year) for the heating demand of the analysed building.

Primary energy (PE) and final energy (FE) conversion factors used are those of the environmental database KBoB, namely 2.88 for electricity and 1.06 for gas [10]. It is interesting to note, that the real consumption of the building in operation during the year 2014 is higher than the one given by the results of the theoretical calculation carried out by thermodynamic simulation (TDS).

Table 5:
Energy consumption for heating the Hochfelden building

Heating requirement [kWh/year]	**69 656**	
Heating technical equipment	Geothermal Heat Pump (GHP) COP = 3.28	Gas Condensing Boiler η_{PCS} = 99.7%
Percentage assured by the technical equipment [%]	71	29
Quantity assured by the technical equipment [kWh/year]	49 456	20 200
Electricity Consumption [kWhFE/year]	15 078	-
Gas Consumption [kWhFE/year]	-	20 261
Final Energy Consumption [kWhFE/year]	35 339	
Primary Energy Consumption [kWhPE/an]	43 425	21 477
Energy Consumption for Heating [kWhPE/year]	**64 902**	

This is mostly due to the weather file used in the TDS software which is not exactly the same as the real weather time in Hochfelden during the measurement period. The imposed temperatures are not always respected and are regularly changed by the occupants. Also the automat regulation is sometimes incorrectly adjusted or has been disturbed, and the ventilation is not regulated.
Despite these, it may be estimate that the calculation of heating needs and of heat consumption has been performed correctly and the value found will be used for further study.

3.2 Analyze of the thermal performance and the embodied energy of different types of windows applied to the case of the control building

The aim is to estimate the investment payback in terms of embodied energy of building elements assessing the connection that exists between their energy performance and their embodied energy.
Thus, for one window element, the "grey" energy of double and triple glazing window has been calculated previously. It is now the moment to consider, by realizing a dynamic thermal simulation, which are the gains on heating consumption of the control building equipped with windows whose thermal performance is different (double or triple glazing). Finally, for a window life cycle, it is possible to compare its embodied energy with the gain of energy consumption induced in the operational building.
For clarity reason, we have chosen to present the thermal performance of double glazing and triple glazing in Table 6. Both types of windows have a wood frame. In order to determine the useful thermal characteristics of window-walls, we have paid attention to the requirements of the thermal regulations existing in France [11], [12], [13].
The calculation of the global heat transfer coefficient U_w of the window consists in three distinct parts:
1. The glazing current part of the window, U_g in [W/m²K], which means the transparent element, characterized by a transfer coefficient that defines the heat transfer in the central part without edge effects, and which is valid over the entire visible area of the packing element. The detailed calculation method of U_g is described in NF EN 673 standard.
2. The junction between glazing current part and the frame. It is characterized by a linear coefficient of thermal bridges characterizing the combined effect of the edge of the glazing element and the frame. This coefficient is applied to the perimeter of the visible part of the glazed element.
3. The frame: it is characterized by an average surface heat transfer coefficient U_f in [W/m²K] of the frame and it is valid over the entire surface of joinery. The surface coefficient of frame can be determined also by numerical calculation in accordance with standards [14] and [12].
To calculate the global coefficient of the window, U_w, in W/K.m², the three coefficients corresponding to the three areas must be determined. In our case, for the present study, the U_w coefficient has been calculated by a 3D numerical simulation of the complete wall using eq. 1.

$$U_w = \frac{\Phi}{\Delta T \cdot A_w} \; [W.K^{-1}.m^{-2}] \qquad \text{eq. 1}$$

With Φ - the heat transfer calculated through the entire surface in W.
ΔT - the temperature span between inside and outside of the considered surface, in K.
A_w – total surface of the widow, in m².

The numerical solutions have been verified in accordance with article 4.2 of the National and European norms [15].
The U_w heat transfer coefficient has been evaluated for the real situation of the control building according to its true dimensions and its real components (profiles, windows, materials).
In the administrative building, the triple glazed windows with wood frames were implemented. For the purpose of the study, these existing windows are compared to double-glazed windows as in Table 6. It is obviously that from thermal perspective, the triple glazing window with an U_w value of 1.21 W/(m² K) is more efficient than a double glazing window with an U_w of 1.55 W/(m²K). But if two other characteristics that are the solar factor and the light transmission are analyzed, it may be find that the performance of double glazing is better than that the one of triple glazing. This could be an advantage in winter season, but may induce overheat in summer time.
We think the energy efficient of windows has to be assessed differently to non-transparent construction elements, as their energy balance depends not only on the reduction of transmission losses, but also on the solar gain of the different windows and glass types for winter season. This implies that for a certain U_w value, different other criteria may be considered as the one depending on the orientation, shading, the g-value, window geometry and the ratio of solar heat gain to transmission and air renewal losses in the building [16].

Table 6:
Presentation of characteristics of double and triple glazing windows used in the administration building

Window	Frame	Glazing	Solar Factor	TL [-]	U_g [W/m²K]	U_f [W/m²K]	U_w [W/m²K]
Administration Triple Glazed	Wood Section (90*90) mm²	TGW 4/12/4/12/4 Faces 2 et 5 low emissivity 90% argon.	0.60	74	0.70	1.40	1.21
Administration Double Glazed	Wood Section (78*78) mm²	DGW 4/16/4 Face 3 low emissivity 90% argon.	0.63	80	1.10	1.60	1.55

3.2.1 Gain on heating consumption through the installation of triple glazed instead of double-glazed windows

The summary of results of dynamic thermal simulation of the building with a double glazed window (DGW) and a triple glazed window (TGW) is presented in Table 7.

Table 7:
Comparative of heating requirements for double and triple glazed windows.

Requirements	Total Heating	Unitary Heating
TGW U_w = 1.21 W/m²K Solar Factor = 60%	69 656 **[kWh]**	33 **[kWh/m²]**
DGW U_w = 1.55 W/m²K Solar Factor = 63%	73 199 **[kWh]**	35 **[kWh/m²]**

The use of triple glazing instead of double-glazed windows can save 5% on annual heating consumption. This is the equivalent of an energy gain of 3543 kWhFE / year thanks to triple glazing.
The spare of 5% on the heating needs must be converted into primary energy equivalent in order to be compared with the "grey" energy used for the production of the window. Primary energy conversion factors used are those of the KBoB database, namely 2.88 for electricity and 1.06 for gas. Also, in the control building, the heating is produced for 71% by a water-water type geothermal heat pump (GHP) and for 29% by an additional condensing gas boiler (CGB) as presented in the Table 8.

Table 8:
Consumption gap, due to triple glazing window, for the reference building heating requirements

	GHP COP = 3.28	**CGB** η_{PCS} = 99.7%
Percentage assured by the technical equipment [%]	71	29
Difference in heating requirements TGW / DGW [kWh]	3 543	
	2516	1027
Electricity Consumption [kWhFE]	767	-
Gas Consumption [kWhFE]	-	1 031
Consumption gap in primary energy for the heating needs [kWhPE/year]	2 209	1 092
	3 301	
Difference in primary energy consumption for the heating needs	**99 035** [kWhPE/30 years]	

The characteristic lifetime of a window is 30 years.
The introduction of triple glazing instead of double-glazed windows will allow earning 99,035 kWh primary energy (kWhPE) over the 30 years as presented in Table 8.

3.2.2 Return of investment in embodied energy

The embodied (grey) energy extra cost of triple glazing has been calculated and connected with the heating energy gain that allows this type of window.
For the Hochfelden reference building, the extra cost of grey energy of the 64 triple glazing windows in respect to the double glazing is about 10593 kWh. This is compared with the heating energy gain enabled by the triple glazed windows over a year which is of 3301 kWhPE/year. In this way, we may calculate the period of return of investment which is 3.2 years.
In conclusion, in just about 3 years, the gains in energy consumption for heating may cover the extra cost invested in embodied energy of triple glazing in relation to the double glazed windows. From an energy point of view, the introduction of triple glazing windows is clearly justified. The interval of time for the return of energy investment is rapid.

3.2.3 Return of investment in cost

Regarding the savings on the energy consumption, triple-glazed windows compared with double-glazed windows enable to earn 123 € per year for heating consumption. This annual saving is calculated and included in Table 9.
Hereafter is a summary of energy prices in France, in 2014, as given in the reference [17]:
- the average price for gas: 0.055 €HT/kWh;
- the average price for electricity: 0.086 €HT/kWh.
For the Hochfelden reference building, the extra cost of triple glazing in respect to the double glazing is compared with the savings in heating energy enabled by the triple glazed windows and has a value of 123 Euros per year, as shown in Table 9.
The added value for the implementation of TGW instead of DGW at Hochfelden was calculated equal to the value of 3980 €HT.

Table 9: Savings in heating consumption for the reference building due to triple glazing window.

	GHP COP = 3.28	**CGB** η_{PCS} = 99.7%
Percentage assured by the technical equipment	71%	29%
Difference in heating requirements TGW/DGW	3 543	
	2516 kWh	1027 kWh
Electricity Consumption	767 kWhFE	-
Gas Consumption	-	1031 kWhFE
Price of electricity	66 [€HT]	-
Price of gas	-	57€HT
Difference of energy costs for annual heating TGW/DGW	**123** [€HT/year]	

The saving on annual heating consumption of 123 Euros per year, thanks to triple glazing is relatively small compared to the added value required for the implementation of all triple glazing instead of double glazing windows in our reference building in 2014.
Moreover, the time to return on investment is 32.5 years. This is greater than the reference lifetime of a window which is about 30 years.

4 Return on investment in the embodied energy and manufacturing costs of triple-glazed windows compared to double glazing

The above study shows that if a decision is taken to install triple-glazed windows instead of double-glazed windows (both with the same wooden frame) the savings in heating consumption realized by triple glazing quickly covers the extra cost of energy required for their production when compared to double glazing. Figure 8 shows that the return on investment is 3.2 years. The lifetime of a window is estimated at 30 years. So, during its lifetime, the triple-glazed window will have saved 88,437 kWhPE of heating energy compared to the case where double glazing was installed.

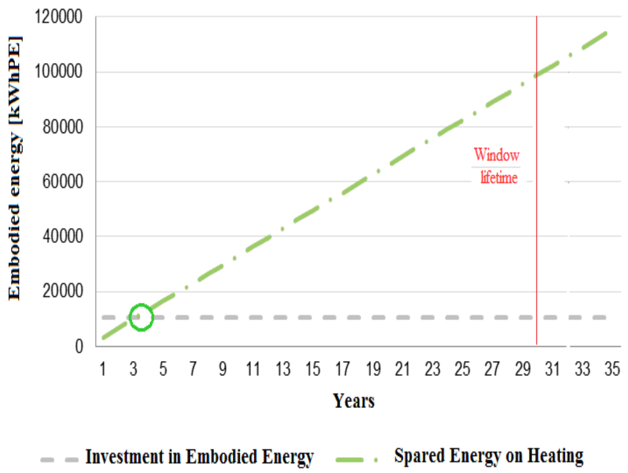

Fig. 8: Duration in years for return on investment expressed in equivalent embodied energy values

Meanwhile, from an economic point of view, the installation of triple-glazed as opposed to double-glazed windows proves unprofitable.
Indeed, Table 8 and Figure 9 show that the time to return on investment is 32.5 years. This is greater than the 30- years reference lifetime of the windows, so, when changing the triple-glazed windows after 30 years, there is still a surplus cost of 320 € not reflected in the heating consumption.

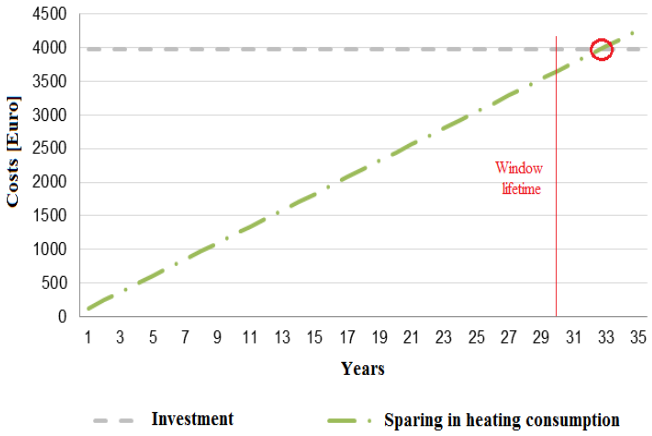

Fig. 9: Duration in years for return on investment expressed in equivalent cost of saved energy.

Ultimately, the conclusions drawn from studies of return on investment in cost and energy are in opposition. From an energy point of view, the installation of triple glazing clearly justifies itself compared to double glazing, with a rapid time to return on energy investment. On the other hand, the outcome of the economic analysis does not encourage the installation of triple glazing over double glazing; the cost is not profitable in terms of heating energy consumption savings over the lifetime of the window. This shows that the economic approach is disconnected from the energy approach, and that the cost difference between triple glazing and double glazing is not linked to the energy required for the manufacture of windows. Note that the use of triple glazing is still uncommon in France today, and it is known that what is rare is expensive. This suggests that by making triple glazing more popular and accessible the cost will become competitive and that one day it will become profitable from an economic point of view.

5 Conclusion

The aim of this publication was to demonstrate the correlation, and to quantify the embodied energy of building components and energy consumption of a building in operation. In this study, we focused on embodied energy of the transparent elements of buildings. Thus, for the specific window component, several alternatives with different energy performance we have been analysed. During the life time of a window, the embodied energy has been compared to the gain of energy consumption in building operation.
Considering the results obtained in the study on the typology and the geometry of the window, one can see that the reduction of window-frame surfaces can reduce the embodied (or "grey") energy costs required to manufacture the window, and, at the same time, increase daylight surface and improve the thermal performance of the inner surface.
As far as designers are concerned, studies of window geometry have produced two arguments for reducing energy expenditure required in their production:
- For the same glass surface, choose one large window rather than two smaller ones.
- Start moving towards a window shape with a reduced perimeter - a square rather than an oblong, for example.

So, looking at the geometry of windows can be seen as a way of reducing expenditure on the grey energy of buildings. However, addressing the geometry of apertures would obviously have an impact on the aesthetic and architectural aspect of a building.
Relating to the study carried out on the comparison between the energy consumption and economic benefits of double-glazed and triple-glazed windows (with a wooden frame), the conclusions are mixed.

From an energy point of view, the introduction of triple glazing is clearly justified, but the additional cost of grey energy needed for the production of triple-glazed windows (compared to double-glaze) can be quickly recovered by the savings made in the heat-energy consumption of the building.
On the other hand, the economic savings that triple-glazed windows allow become unprofitable when compared to the heating consumption over the 30-year lifetime of the window.
From an economic point of view, studies show that the choice of triple-glazed windows is clearly changing, helped by a stronger awareness of environmental impact. It may be hope that the more popular triple glazing becomes, the more competitive the price will be.

In summary, this study has only focused on the comparison between different types of windows, but can be extended to all components of a building. Beyond the quantitative findings of the analysis we have to remember that studies of return on investment in energy and cost over the lifetime of structural components should be included in the early stage of design of buildings.

Thinking about overall energy costs by factoring-in grey energy can become a decision-making tool for building designers.

This approach allows us to evaluate the energy impact of architectural and technical choices where structures are concerned and can lead to the design of more and more energy-efficient buildings.

At the moment it seems that the principles of life-cycle analysis and embodied energy are still only being promoted by pioneers in their field.

The larger issue is to educate and convince all stakeholders in the construction industry. A seal in building labelling will be one step forward for integration in thermal regulation. Incorporating a comprehensive vision of the embodied energy involved in the component parts of building construction will be unavoidable in the future.

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