HEAT TRANSFER CALCULATIONS IN LIFE CYCLE ASSESSMENT OF BUILDINGS AND EPBDII

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ABSTRACT

The present contribution aims at a typical example of a low-energy house to repeat the known facts in environmental assessment of buildings, emphasize the need to use transient calculations of energy demand not only to optimize building envelope and operation of buildings but also in the assessment of their life cycle. It also outlines a possible way of comparing the built and operational energy within the life cycle of buildings, as a contribution to the debate on the implementation of the second Energy Performance of Buildings Directive (EPBD II).

INTRODUCTION

The idea of energy certification of buildings and its implementation through the Energy Performance of Buildings Directive I and II (further EPBD I & II) is certainly a positive step towards improving the energy balance of buildings. The problem remains, however, the implementation of the EPBD into national legislations of European Union's member states. Criticism of the EPBD implementation involves various aspects. In this article we would like to focus on the following topics:

- Favouring simplified calculation procedures, despite the fact that the system of EPBD related CEN standards (CEN = European Committee for Standardization) provides tremendous opportunities for the use of sophisticated computational tools to enable detailed and physically more correct assessment of buildings and structures
- Single-sided orientation on the assessment of operational energy without considering built, gray, energy

Both aspects directly or indirectly lead to an overestimation of the portion of operational energy within the life cycle of buildings. The result is not only incorrect presentation of the environmental impact of the building, but also creation of an unsubstantiated idea that energy and physical criteria for buildings and their components can be tightened to zero (or even beyond), regardless of the environmental load in the production of construction materials and buildings themselves. These considerations are also known from other specialized publications (e.g. Peuportier, 2002), but we feel that in this technocratic and fast business world they often disappear and that it is necessary to repeat them from time to time. Therefore, the actual case study compares the expected energy demand of the detached house in the course of its service life and the energy input (embodied energy) necessary for its assembly and for the manufacture of individual building products. The operation of the building during its service life is described using computer aided building performance simulation. For comparison also a simplified "standardized" procedure of the base case was carried out. The input data related to embodied energy are based on information from classical works on life cycle analysis (Mötzl et al., 1999, Eyerer & Reinhardt, 1999, and Hegger et al., 2005).

In the past a few studies were published on coupling life cycle assessment of buildings and transient simulation, from among which particularly the study of Peuportier (2002) focusing on opportunities in renovation design should be mentioned. He performed a sensitivity analysis of various design options in terms of their effects on the environmental balance of the building. Unlike the said studies the presented study starts at the level of low-energy house and stresses the fact that towards ultra low- and nearly zero energy houses the portion of embodied (grey) energy on environmental balance of buildings dramatically increases.

OBJECT AND CALCULATION DESCRIPTION

The figs. 1 to 4 show the floor plans and the characteristic elevations of the detached house in consideration. The total heated floor area is 120 m^2, which corresponds with criteria for governmental housing subsidy. The basic versions are the heavy one (brick masonry combined with thermal insulation) and the lightweight one (thermally insulated timber framework), which are probably the most common wall systems used for houses in Central Europe. Each of the basic versions was then modelled and simulated with four other combinations of the thermal insulation thickness according to the table 1. The *U*-values of the windows remained in all calculations the same. The fig. 6 introduces picture of the two zone model of the case study house.

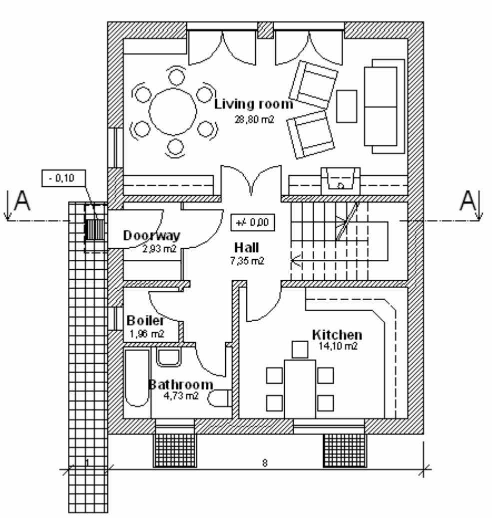

Figure 1 Ground floor

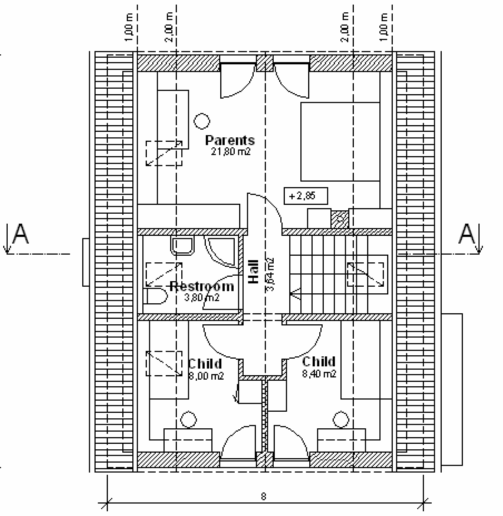

Figure 2 Attic

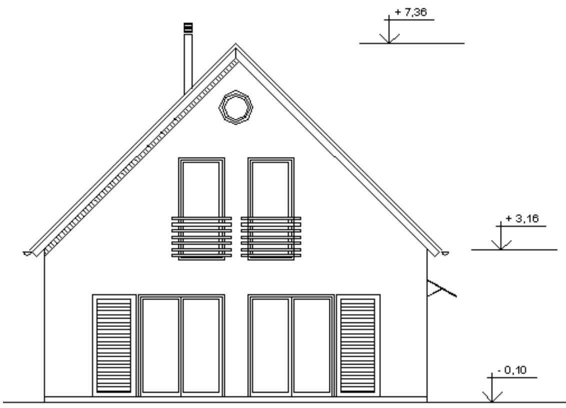

Figure 3 South elevation

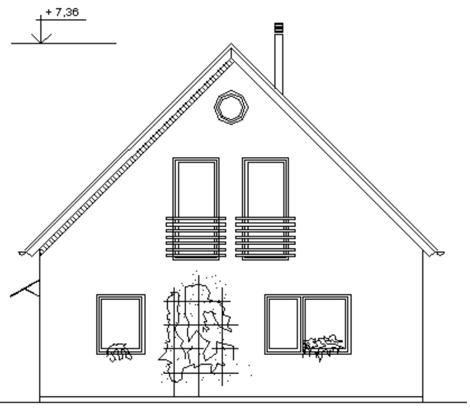

Figure 4 North elevation

Table 1
Combinations of the main building envelope components as modelled

		BRICKWORK HOUSE					LIGHTWEIGHT HOUSE				
MEAN *U*-VALUE:	[W /(m^2K)]	0.41	0.32	0.30	0.29	0.28	0.41	0.32	0.30	0.29	0.28
U-values of single components of the building envelope [W /(m^2K)]	Base plate	0.76	0.48	0.48	0.48	0.48	0.76	0.48	0.48	0.48	0.48
	Walls	0.25	0.19	0.15	0.13	0.11	0.25	0.19	0.15	0.13	0.11
	Roof	0.17	0.15	0.14	0.14	0.12	0.17	0.15	0.14	0.14	0.12
	Windows	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
	Entrance door	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Thermal insulation thickness [m]	Base plate	0.020	0.050	0.050	0.050	0.050	0.020	0.050	0.050	0.050	0.050
	Walls	0.100	0.150	0.200	0.250	0.300	0.140	0.190	0.240	0.280	0.330
	Roof	0.220	0.250	0.275	0.275	0.300	0.220	0.250	0.275	0.275	0.300

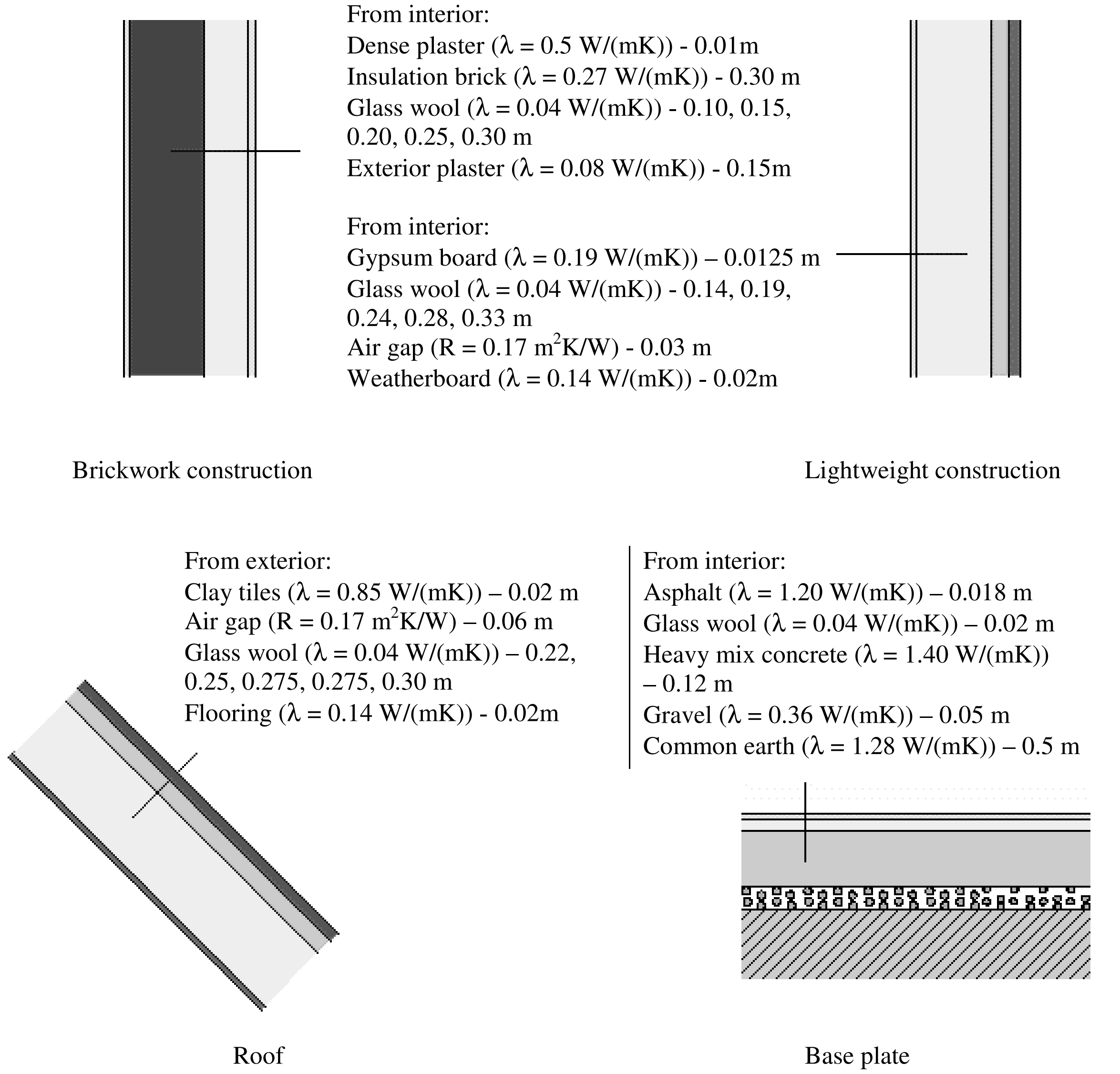

Figure 5 Composition of the main parts of the building envelope as modeled using Capsol's Wall Type Editor

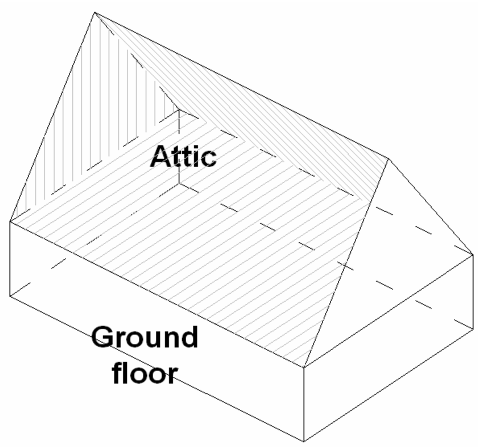

Figure 6 Division of the model in two thermal zones

The simulation was performed using software Capsol. Capsol is a computer program to calculate multi-zonal steady-state and dynamic heat transfer, including one dimensional heat conduction, convection, view factor based infrared radiation, multi-zonal ventilation and solar radiation. During the dynamic calculation a system of energy balance equations is built and solved each calculation time step, using a finite difference method. The ventilation heat losses were set to 0.5 air change rate per hour. The heat gains are represented by occupant ones only (4 persons). They stand also for heat gains due to equipment and artificial light in order to keep the model as simple as possible. The required indoor air temperature was set to 20°C and an ideal zone heat control was chosen. Figure 5 indicates the composition of the main parts of the building envelope - the foundation slab, the walls and the roof. For modeling the main parts of the building envelope, including the entrance doors and windows, was used the Capsol's Wall Type Editor (Capsol, 2002). Figure 6 shows the division of the model in two thermal zones. For "standardized" calculation simplified seasonal procedure described in EN ISO 13790 was used. The "standardized" calculation was performed only for the basic heavy version, which was subsequently constructed. Of course in both cases hourly climate data and seasonal ones, respectively, of the same place, Berlin, were used. This location was chosen because mostly German and Austrian ecological data of single products were used in this study.

In addition to the simulation of heat energy demand the total PEI (Primary Energy Input) and GWP (Global Warming Potential) values representing the embodied energy were calculated for each of the 10 combinations. The transportation of final products from the factory / the selling place to the client and the processes at the building site, e.g. the production of shuttering, the formworks or the use of machines, are not included in the total PEI and GWP values.

RESULTS AND THEIR INTERPRETATION

Fig. 7 shows the relationship between the improvements of the mean *U*-values by increasing the thermal insulation thickness on one side and the reduction of energy demand for heating on the other side. It is quite obvious that the "linear" reduction of the heat energy demand is achieved by the "geometrical" increase of the thermal insulation thickness. Somewhere between the mean *U*-Values of 0.30 and 0.32 W/(m^{2}K), which corresponds to approx. 17.5 cm of thermal insulation in the brick house and approximately 21 cm for the lightweight house, the rational increase of the thermal insulation thickness stops. Just to compare: to improve the mean *U*-Value from 0.41 to 0.32 W/(m^{2}K), and reduce the heat energy demand in the range of 1500 kWh/a, 5 cm of additional thermal insulation is necessary. A subsequent 5 cm increase of thermal insulation brings about an improvement of the *U*-Value of only 0.02 W/(m^{2}K) and the reduction of heat energy demand in the range of 300 – 400 kWh/a. From Fig. 5 it is obvious that:

- Increasing the thickness of the thermal insulation to extreme values does not stop the heat flow. This is resulting from the exponential nature of the equation for calculating thermal transmittance (see also Close, 1946). Thus, all efforts to build zero energy house based on zero heat loss must necessarily fail.
- Large conventional thermal insulation thickness is inefficient from both building physical and structural point of view (needs additional support structure, which also leads to a reduction in its effectiveness).

From the chart in Fig. 7 it is also clear that reducing the mean *U*-value is in positive correlation to the reduction of energy demand for heating. On the other hand, this reduction is achieved by increasing the thermal insulation thickness inadequately. The question therefore arises how to define the optimal thickness of conventional thermal insulation. The economic criteria are the first consideration, e.g. the ratio of thermal insulation prices and savings achieved (Close (1946), Puškár & Leuck (2011) and criticism by Kallenrode (2005)). The problem of economic criteria is their dependency on the volatility of the market situation, the energy policy of the given country and also the population's purchasing power. Much more meaningful metric, e.g. from the standard-setting perspective, is the primary energy required for production and installation of the thermal insulation. This primary energy can then be easily compared with the primary energy needed to operate the building, particularly for heating. Though, in case of heavy insulated lightweight buildings also the summer cooling can play an important role (Zöld, 2009, and Ostry and Novotny, 2010, respectively). The amount of primary energy is also the basis for comprehensive assessment of the impact of buildings on the environment during their life cycle. The comprehensive assessment is usually associated with an assessment of the building, respectively its components in terms of (Pfundstein, M., Gellert, R., Spitzner, M. H., Rudolphi, A, 2008):

- Global warming potential (GWP);
- CO_2 storage (in products made from renewable raw materials);
- Ozone depletion materials (ODP);
- Acidification potential (AP);
- Eutrophication potential (EP) or nutrification potential (NP) (excessive fertilisation);
- Photochemical ozone creation potential (POCP);
- Space requirements.

Although currently the assessment of the impact of buildings on the environment during their life cycle cannot be done routinely, the existing European standards establish general principles, content and form of such assessments the individually used methodologies should comply with. The quality of the methodology used and the total output therefore depends on the assessor, whereas probably the hardest decisions are the ones that give weight to different aspects, e.g. GWP, CO_2-storage etc. (different products namely comply with the various aspects in varying degrees).

Figures 8 and 9 are showing the relationship between the embodied equivalent CO_2 (GWP) emissions and CO_2 emissions due to the operation of the demonstration house. The other aspects are not treated because within the evaluation of energy performance of buildings the need for primary energy based on fossil fuels and the resulting CO_2 emissions are mainly taken into account. In terms of environmental impact is therefore the closest related aspect the GWP. Unlike the notion PEI, which is quite comprehensible, the notion GWP should be explained at this point. The GWP represents not only a production of net CO_2-emissions but also other greenhouse gases that contribute to the global warming, too, and have the same impact as a comparable amount of CO_2-emissions, e.g. methane, NO_x or particles. Hence, it is more the measure of all relevant greenhouse gases converted and added up to CO_2-equivalent emissions (Mötzl at al., 1999). The table 2 shows PEI and GWP values of individual materials/products used in the study. For the purposes of this study the data from the Austrian "Ökologischer Bauteilkatalog" (Mötzl at al., 1999), the German "Ökologische Bilanzierung von Baustoffen und Gebäuden" (Eyerer and Reinhardt, 1999) and the Baustoff-Atlas (Hegger at al., 2005) were used. The data have only indicative value since the study is rather demonstration of method than the precision of results. It should be noted, however, that for a particular object always an updated and location-related data should be used.

The energy demand for operation of the demonstration house was determined using Capsol based simulation model, while the scenario of its future use was chosen as much as equivalent to standardized boundary conditions, i.e. the possibility of movable window shading or the possibility of additional natural ventilation in case of high internal temperatures rise were not taken into account. Nor was anticipated the possibility of heat recovery in winter and the cooling in summer. The considered heat gains corresponded to the presence of 4 persons in the morning, evening and night hours during the week. The resulting calculated annual energy demand for heating was converted into primary energy demand and following CO_2-emissions using the conversion table published in "Der österreichische Gebäude-Energieausweis – Energiepassport" (Panzhauser et al., 1996). Of course, only the fossil-fuel-based CO_2-emissions were traced. As a primary energy source for heating the natural gas delivery was considered.

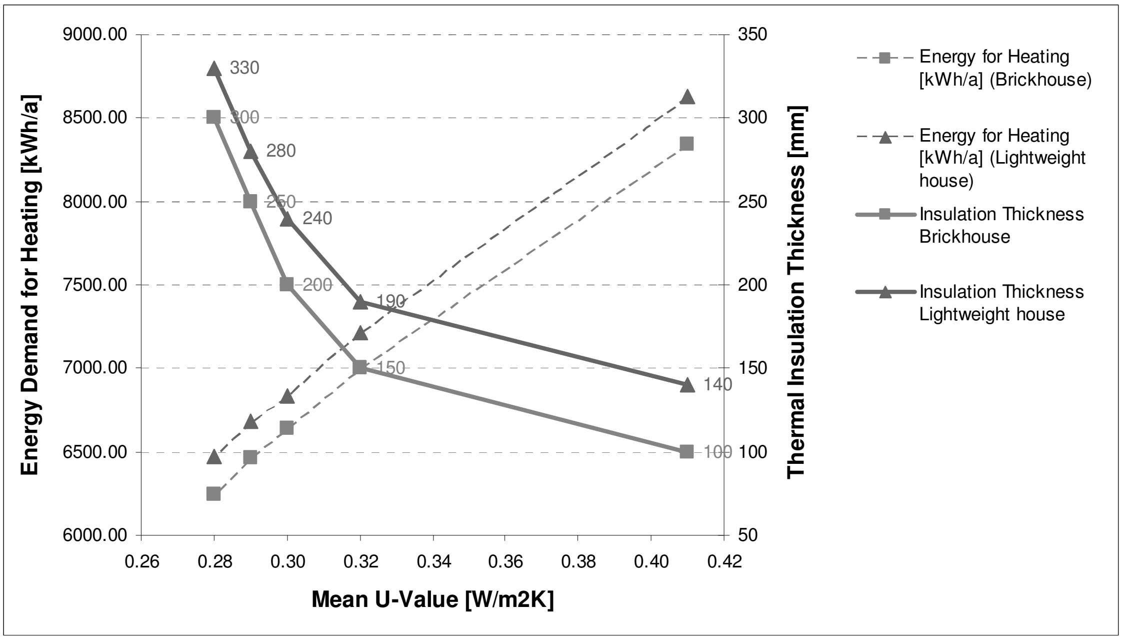

Figure 7 The effect of the mean U-value [W/(m^2.K)] improvement on the annual reduction of energy demand for heating [kWh/a] in dependence upon thermal insulation thickness [mm] (indicated on the secondary y-axis)

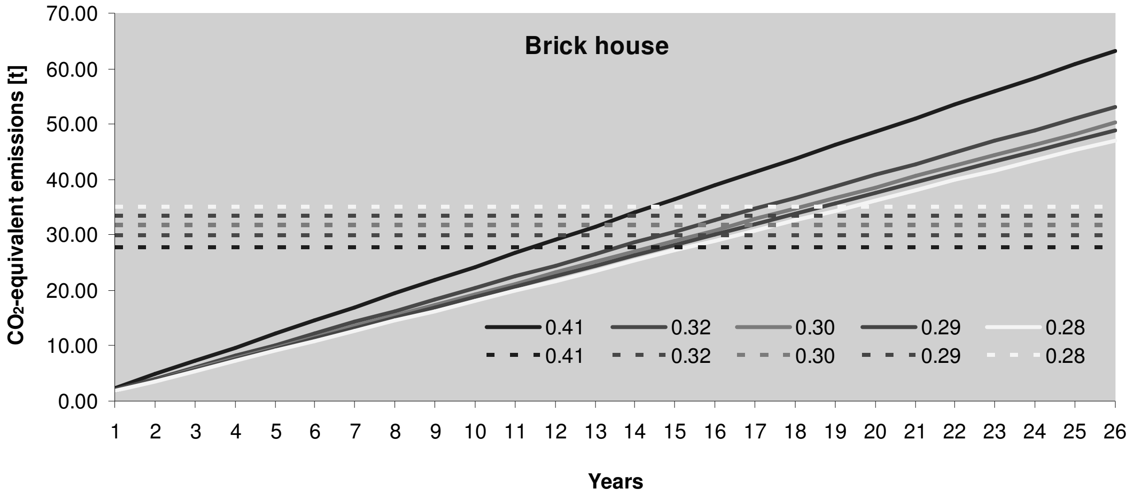

Figure 8 Relationship between the embodied equivalent CO_2 (GWP) emissions (dotted lines) and CO_2 emissions due to the operation (continuous lines) of the demonstration brick house for five mean U-values of the building envelope

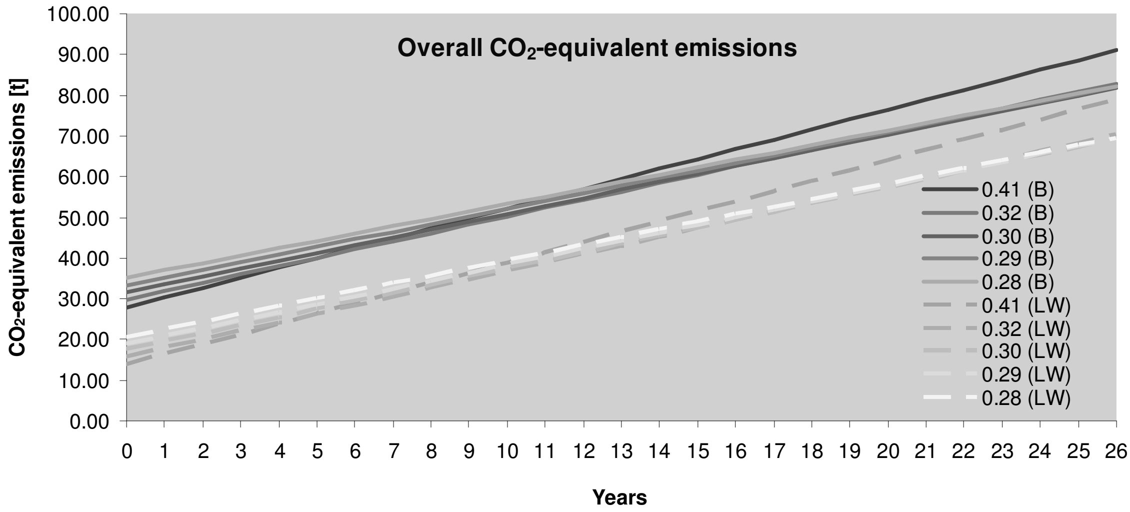

Figure 9 Course of overall CO_2-equivalent emissions for investigated demonstration objects – brick house (B) and lightweight house (LW)

CONCLUSIONS

From numerous studies on optimizing the thickness of thermal insulation in terms of investment cost and energy savings, it is clear that the linear energy saving is achieved by an exponential increase in the thickness of the insulation. The problem with these studies is that they usually assume positive correlation between the thickness of the insulation and its price. Given the fact that prices of thermal insulation and energy are subject to market fluctuations, trading strategies of suppliers and the country's energy policy and the purchasing power of its population, it is almost impossible to clearly determine the optimal thickness of the insulation on the relation of investment cost and energy savings. EPBDII also seeks to introduce at the national level of the Member States so called cost optimum for establishing criteria for assessing the energy quality of buildings. According to the authors, it is a completely unnecessary step that only obscures the situation, since existing standards related to the quality of the building envelope are in most states already so strict that further increases in the values of thermal resistance can no longer produce significant energy savings.

A much more convenient way for assessing the quality of the new envelope or the one of renovated buildings could be, also in terms of setting standards, comparing built and operational energy within the expected life cycle of the building under consideration. The standardized steady-state or quasi steady-state calculations lead, especially in case of low-energy and improved energy efficient buildings, to an overestimation of the portion of operational energy in total energy demand, as the heating season is in these cases fixed. Conversely, transient calculations help to better highlight a growing share of the built energy in total energy demand for the construction and operation of modern buildings.

The current exclusive focusing on the energy efficiency of the building operation leads to heavy insulated building envelopes and to the utilization of alternative renewable energy sources (mostly on a decentralized basis). In principle this trend is right, as the good insulated building envelope is a basic precondition for efficient use of energy, regardless if it comes from conventional or renewable sources. However, as the above case study tried to show, increasing the thickness of thermal insulation and the improvement of the mean *U*-value are effective to certain extent only. In spite of large effort there is no general formula for assessing the limits of the thermal insulation thickness in terms of its ratio to energy savings. The reasonable proportion must always be assessed individually. In this regard the computer aided building performance simulation seems to be the most suitable approach. At all events the consequence of low mean *U*-values of buildings is longer "payback time" of embodied energy and following CO_2-equivalent emissions. Though this situation is desirable, it should not be achieved at the expense of extraordinary high emissions of greenhouse gases due to the embodied energy. Hence it might have sense to introduce a reasonable system of limitations on the initial GWP values due to the fabrication of construction material and building products, when assessing the environmental quality of a building. The limitations should be based on building geometry and structured in classes similar to energy certification. An "environmental" building class is understood to be composed of an operational building class (from energy certification) and a building class based on embodied energy. The desired resulting "environmental" building class could then be achieved either by good operational performance or good values of embodied GWP or both. In order to achieve this vision two things are necessary:

- Reliable, freely available and regularly actualized national GWP and PEI data of individual building materials and products (see also recommendations of Regener project (1997));
- Research on relationship between embodied energy and building geometry that would enable creation of reasonable environmental building classes and related limits on embodied energy.

As a result a kind of simplified environmental building declaration similar to energy certificate could be introduced Europe-wide. However, this goal would require further research and above all an agreement of all relevant stakeholders.

Table 2
PEI and GWP values of individual materials/products used in the study (mostly based on databases in Mötzl at al., 1999, Eyerer and Reinhardt, 1999, and Hegger at al., 2005)

MATERIAL / PRODUCT	**PEI/UNIT** [MJ/kg]	**GWP/UNIT** [kg CO_2-equiv./kg]
Thermal ins. foundations (XPS)	101	3.6
Thermal ins. floor	17.5	1.2
Waterproofing	63	2.2
Anti-radon layer	200	13
Concrete	0.8	0.13
Plaster	1.46	0.22 (average)
Thermal ins. walls	17	1.4
Bricks	0.13	2.6
Steel	24	1.7
Chimney	338	27.2
Ceramic ceiling bricks	2.7	0.3
Ceramic roof tiles	3.6	0.35
Water-proof layer PE	75	1.82
Thermal ins. roof	17	1.4
Damp-proof layer	75	36
Roof timber/wood	3.47	-1.65 (average)
Windows – wood/aluminium	486	1.8
Wooden doors	1.35	-1.76
Gravel	1.64	0.002

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