# ENVIRONMENTAL ASSESSMENT OF A LOW-ENERGY HOUSE

**Roman Rabenseifer**

## Summary

The paper shows the life cycle of a low-energy detached house from the viewpoint of $CO_2$-emissions. It compares the energy use in the course of its service life in relation to energy input necessary for its assembly and manufacturing of single building products. The service life is described using both the standardized calculation methods for energy balance of buildings and the open software tools, e.g. esp-r, as well. The input data related to embodied energy are based on information originating from selected recent works on life cycle analysis.

The paper discusses the limits of the building envelope improvements in terms of thermal insulation thickness and the sense of the building environmental assessment.

## 1 Introduction

The European countries, the economy of which is based on export of industrial products and services and completely dependent on imports of fossil fuels, systematically support the improvement of energy efficiency of buildings. They do it in two basic ways:

- Normatively and legislatively, using restrictions in order to ensure the basic quality of buildings from the viewpoint of energy effectiveness, e.g. by requiring more and more improved and detailed investigation of the future energy demand for heating and hot water preparation and by suitable systems of criteria,
- Motivating, using various state and communal programs, usually the aim of which is the effective use of energy from fossil fuels and the development of alternative and ecological energy sources (solar radiation, water, wind).

These two basic instruments focus almost entirely on building performance after its assembly on the building site. Explained in terms of the life cycle of a building, the mentioned policy does not take into consideration the energy needed either for production of the building materials or for assembly of a building or for its dismantling. The main argument for this exclusive concentration on the service life of a building is that 40 % of the total energy consumption is caused by operation of the buildings. The remaining 60 %

fall on industry and transportation, whereas 20 % out these 60 % are supposed to be caused by production of building materials, building processes, renovation and dismantling of the buildings. The following case study wants to show that this argumentation is no longer valid for buildings built in compliance with existing standards or even in a low-energy way. As the energy supply needed for the operation of such buildings is quite low, a significant rise of the building industry portion within this imaginary scheme should be a consequence.

In this context several questions occur, e.g.:

- Whether the perception of buildings as power plants using renewable sources of energy is justified in relation to energy inputs and $CO_2$-emissions,
- Whether the currently used energy demand calculations should not be complemented by information on energy inputs needed for building assembly and manufacturing,
- Whether alternative and lasting (sustainable) building materials would be a kind of solution and what is the optimal insulation of the building envelope,
- Whether it is possible in the design phase to consider the questions of $CO_2$-emissions due to the life cycle of buildings at all?

The presented study tries to find answers to the above questions. However it does not reserve the right either on completeness or absolute correctness. It is far more an attempt to realize to which extent the so called low-energy design (in the sense of highly insulated building envelope) is meaningful and where is the limit to the overflow of material – and related production energy and financial resources.

**Keywords:** Energy, $CO_2$-emissions, life cycle of buildings, service life, assessment

## 2 Methodology

The crucial problem of the presented comparison of $CO_2$-emissions due to the expected building operation on the one side and due to the built-in energy on the other side was the gathering of reliable data regarding the $CO_2$-emissions due to the production of building materials. Usually, the building industry does not record information on kilograms or tons of $CO_2$-emissions per building product, e.g. brick or window. Under circumstances these values could have been derived from the annual reports of single companies, if they had been at our disposal and had included the $CO_2$-emissions and the number of products per year. Unfortunately this was not the case. Therefore, some research in the libraries and on the internet was necessary. This effort showed that there had been serious research on this topic done, particularly in the German speaking countries. From a number of serious sources first of all the use of information in the Austrian Ökologischer Bauteilkatalog [1], the German Ökologische Bilanzierung von Baustoffen und Gebäuden [2] and on the website www.architektur.tu-darmstadt.de/ee [3] was made. The majority of the relevant values in all three cited publications are identical. Where differences occur (mostly steel, iron and aluminium based products) the newer information was taken. The necessary energy input for the production of building materials used for the assembly of the case study building and the related $CO_2$-emissions were calculated using the PEI (Primary Energy Input [MJ per unit of material or product]) and the GWP (Global Warming Potential [kg$CO_2$-eq. per unit of material or product]) values in the cited publications.

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 single $CO_2$-emissions but also other greenhouse gases that contribute to the global warming as well and have the same impact as 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 [1].

The energy demand for heating (operation) of the case study building was calculated using the software esp-r – a kind of open software for integrated building simulation [4]. Just for the verification purposes also a calculation according to the German energy conservation decree EnEV2004 [5] was performed – primarily in order to get a plausible initial range of heating power for esp-r model and as a kind of reference. The calculations were based on climate data for Berlin. The resulting calculated annual energy demand was converted into primary energy demand and following $CO_2$-emissions using the conversion table published in “Der österreichische Gebäude-Energieausweis – Energiepassport” written by Professor Panzhauser et all [6]. However, the same conversion coefficients are introduced in esp-r, too. Of course, only the fossil-fuels-based $CO_2$-emissions were traced. As a primary energy source for heating the natural gas delivery was taken into account.

## 3 Case study

The construction of detached houses (up to 120 m$^2$) and apartment buildings (having flats with up to 80 m$^2$) is in Germany and many other countries, e.g. Slovakia very often supported by the state under the fulfilment of certain conditions. One of these conditions represents the compliance of the project with the building regulations, e.g. the minimum thermal resistances of the main building envelope components, the highest allowed transmission heat loss (thermal-coupling coefficient (HT’)) of the entire building envelope and maximum heat or even primary energy demand. The **Fig. 1** and **Fig. 2** show the floor plans, the cross section and the characteristic elevation of the family house in consideration, the basic versions of which meet the above mentioned standard requirements both for Germany and for Slovakia as well. The basic versions were the heavy one (brick masonry combined with thermal insulation) and the lightweight one (thermally insulated timber frame-work).

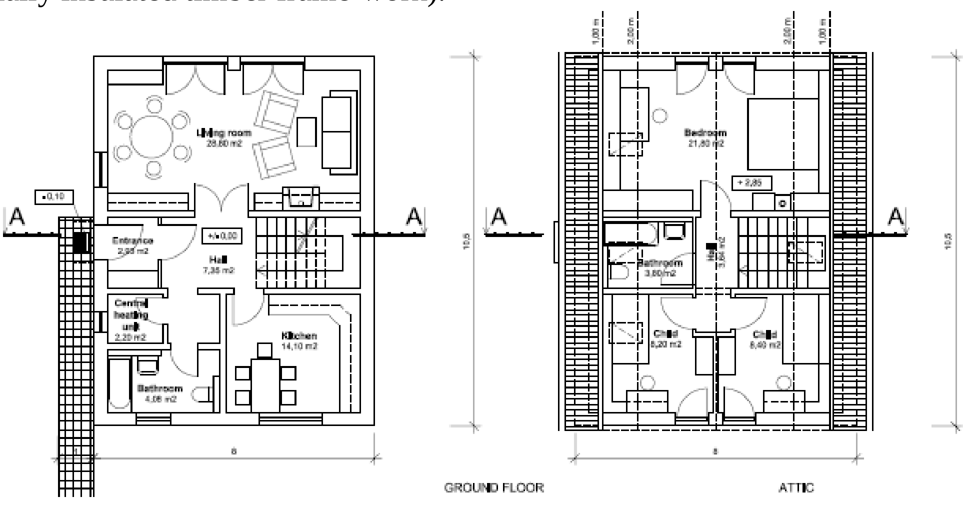


**Fig. 1** Floor plans of the investigated detached house

Each of the basic versions was then modelled and simulated with four other combinations of the thermal insulation thickness according to the **Tab. 1**.

**Tab. 1** Combinations of building envelope elements modelled

| | | Brick house | | | | | Lightweight house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean U-Value: | [W/(m$^2$K)] | 0.41 | 0.32 | 0.30 | 0.29 | 0.28 | 0.41 | 0.32 | 0.30 | 0.29 | 0.28 |
| | | | | | | | | | | | |
| U-values of single parts of the building envelope [W /(m$^2$K)] | 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 |
| | | | | | | | | | | | |
| Therm. ins. thickness [m] | Base plate | 0.02 | 0.05 | 0.05 | 0.05 | 0.05 | 0.02 | 0.05 | 0.05 | 0.05 | 0.05 |
| | Walls | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.14 | 0.19 | 0.24 | 0.28 | 0.33 |
| | Roof | 0.22 | 0.25 | 0.27 | 0.27 | 0.30 | 0.22 | 0.25 | 0.27 | 0.27 | 0.30 |

The U-values of the windows remained in all calculations the same. The simulations were performed using esp-r. The **Fig. 3** introduces pictures of the one zone model of the case study house generated by the Radiance [7] module within esp-r. The ventilation heat losses were set to 0.5 air change per hour. The heat gains are represented by occupant sensible ones only (**Fig. 4**). They stand also for heat gains due to equipment and 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.

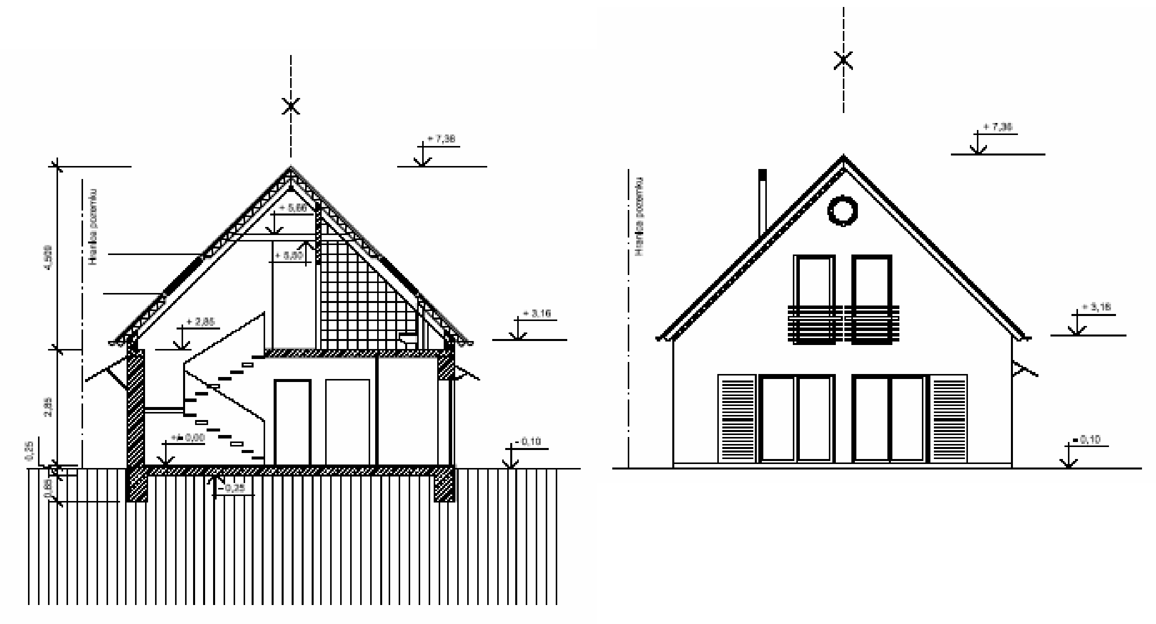

**Fig. 2** An elevation and the cross-section of the investigated detached house

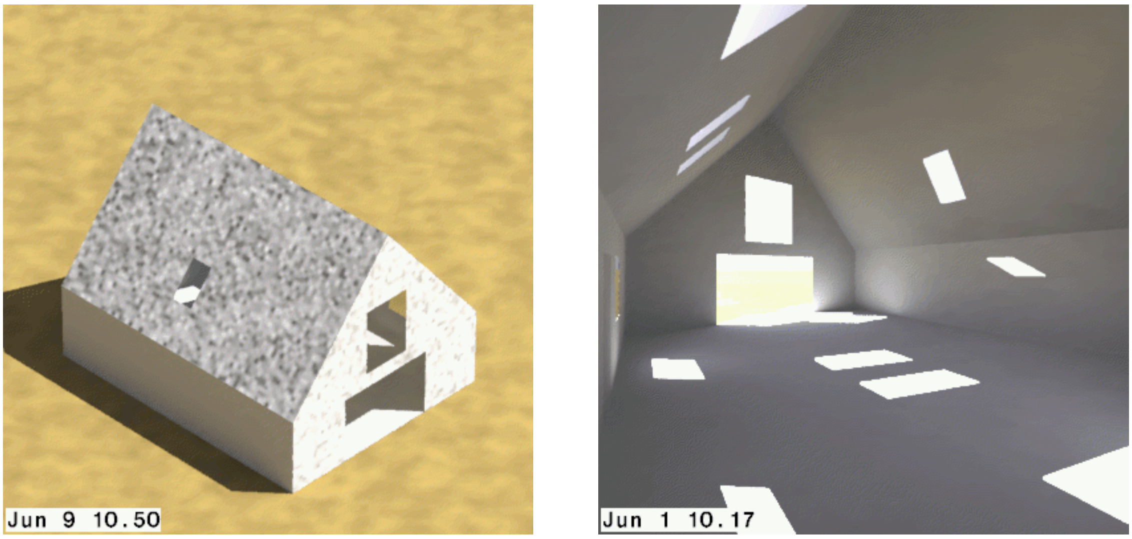


**Fig. 3** Visualization of the one zone model of the case study house

In addition to the simulation of the heat energy demand an ecological balance model (**fig. 5**) for each of the 10 combinations (5 for each basic version) has been set up and the PEI and GWP values calculated. In the balance models 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 were not considered.

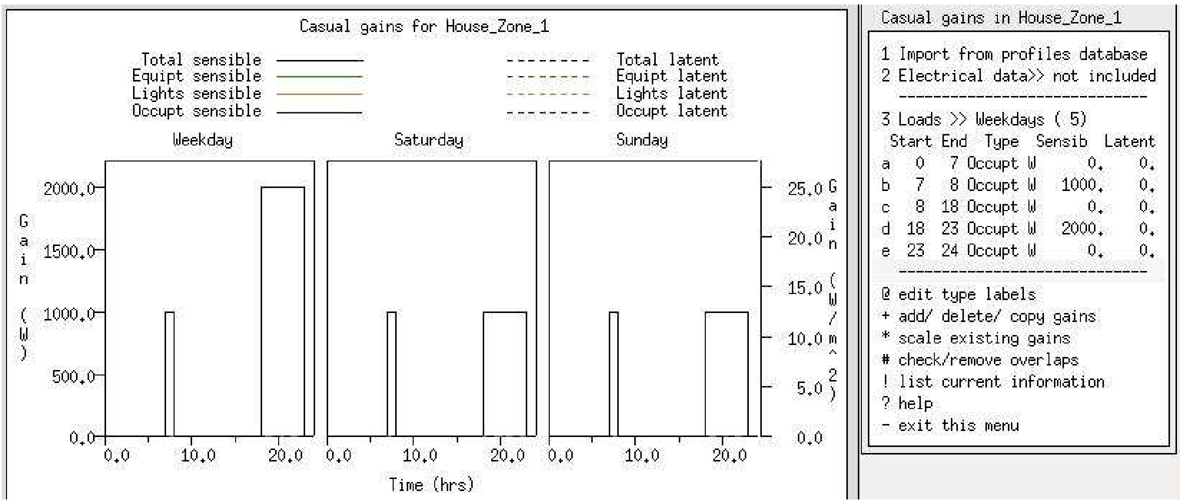


**Fig. 4** Heat gains distribution over the week

## 4 Interpretation of results

The diagram 1 (F**ig. 6**) shows the comparison of the $CO_2$-emissions due the energy demand for heating between the heavy (also called "brick house") and lightweight variant of the case study house (the compared bars are always for the same mean U-Values of the building envelope). The brick house performs slightly better due to the higher thermal capacity. This difference would be probably higher if the ceiling between ground floor and attic was simulated.

| ECOLOGICAL DATA PROFILE: | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Envelope element / Layer | Thickness d | Area A | Volume V | Weigth | Density ρ(D) | Density ρ | PEI/unit D | PEI / kg material | PEI Total | GWP 100 (1994) kg $CO_2$ eq. / unit (D) | GWP 100 (1994) kg $CO_2$ eq. / kg mat. |
| | [m] | [m²] | [m³] | [kg] | [kg/m³] | [kg/m³] | | [MJ/kg] | [MJ] | [kg $CO_2$-eq./kg] | [kg $CO_2$-eq./kg] |
| Foundations | | | | | | | | | | | |
| thermal insulation horizontal (Rockwool) | 0.02000 | 66.600 | 1.665 | | 85.000 | 85.000 | 17.500 | 17.500 | 2476.688 | 1.200 | 1.200 |
| thermal insulation vertical (XPS) | 0.05000 | 50.400 | 2.520 | | 37.000 | 37.000 | 101.000 | 101.000 | 9417.240 | 3.600 | 3.600 |
| waterproofing (PVC,0,002 m; 1kg/m2) | | 80.000 | | 80.000 | 1500.000 | 1500.000 | 63.000 | 53.000 | 4240.000 | 2.200 | 2.200 |
| antiradon layer (aluminium,0%Rec.,0,24 kg/m2) | | 80.000 | | 19.200 | 2700.000 | 2700.000 | 200.000 | 714.000 | 13708.800 | 13.000 | 36.000 |
| normal concrete (slab + foundations) | | | 42.000 | | 2000.000 | 2000.000 | 0.800 | 0.800 | 67200.000 | 13.000 | 0.130 |
| normal concrete - floor (8 x 10 x 0,03 m) | | | 2.400 | | 2000.000 | 2000.000 | 0.800 | 0.800 | 3840.000 | 13.000 | 0.130 |
| gravel | | | 6.000 | | 2500.000 | 1800.000 | 1.640 | 0.100 | 1080.000 | 0.002 | 0.000 |
| Total: | | | | | | | | | 101962.728 | | |
| Walls | | | | | | | | | | | |
| exterior plaster (Silikatputz) | | 160.000 | 0.480 | | 1500.000 | 1800.000 | 1.783 | 1.500 | 1296.000 | 0.299 | 0.200 |
| thermal insulation (Rockwool) | 0.10000 | 160.000 | 16.000 | | 149.000 | 149.000 | 17.000 | 17.000 | 40528.000 | 1.400 | 1.400 |
| 30 cm bricks | 0.30000 | | 27.800 | | 750.000 | 750.000 | 2.600 | 2.600 | 54210.000 | 1.300 | 0.130 |
| 25 cm bricks | 0.25000 | | 8.860 | | 750.000 | 750.000 | 2.600 | 2.600 | 17277.000 | 1.300 | 0.130 |
| 17,5 cm bricks | 0.17500 | | 3.520 | | 750.000 | 750.000 | 2.600 | 2.600 | 6864.000 | 1.300 | 0.130 |
| premade brick carrier ((0,12 x 0,065) | | | 0.257 | | 1887.000 | 1887.000 | 3.500 | 3.500 | 1699.998 | 0.300 | 0.300 |
| above windows and doors) | | | | | | | | | | | |
| normal concrete | | | 1.000 | | 2000.000 | 2000.000 | 0.800 | 0.800 | 1600.000 | 0.130 | 0.130 |
| reinforced concrete | | | 1.110 | | 2400.000 | 2400.000 | 0.800 | 0.800 | 2131.200 | 0.130 | 0.130 |
| reinforcing steel | | | | 100.000 | 7850.000 | | 24.000 | 36.000 | 3600.000 | 1.700 | 2.400 |
| thermal insulation (XPS, d = 0,05 m) | 0.05000 | 5.000 | 0.250 | | 37.000 | 37.000 | 101.000 | 101.000 | 934.250 | 3.600 | 3.600 |
| chimney (75,1 kg/m²) | | 1.88 | | 140.81 | | | 338 | 338.000 | 633.75 | 27.200 | 27.200 |
| interior plaster (Kalkputz, d = 0.002m) | | 350.000 | 0.700 | | 1300.000 | 1200.000 | 1.136 | 1.500 | 1260.000 | 0.136 | 0.200 |
| Total: | | | | | | | | | 132034.198 | | |
| Ceiling | | | | | | | | | | | |
| Ceiling facing bricks | | | 5.760 | | | 750.000 | | 2.600 | 11232.000 | | 0.130 |
| ceramic ceiling bricks [100 kg/m²] | | 70.000 | | 7000.000 | | | | 2.700 | 18900.000 | | 0.300 |
| ceramic ceiling carrier [16 kg/m] x 108 m | | | | 1728.000 | | | | 3.500 | 6048.000 | | 0.300 |
| reinforced concrete | | | 0.530 | | | 2400.000 | | 0.800 | 1017.600 | | 0.130 |
| normal concrete (8 x 10 x 0,05 m) | | | 4 | | | 2000.000 | | 0.800 | 6400.000 | | 0.130 |
| reinforcing steel | | | | 370.000 | 7850.000 | | 24.000 | 36.000 | 13320.000 | 1.700 | 2.400 |
| Total: | | | | | | | | | 56917.600 | | |

**Fig. 5** Ecological balance model of one of the 10 combinations in tabular form

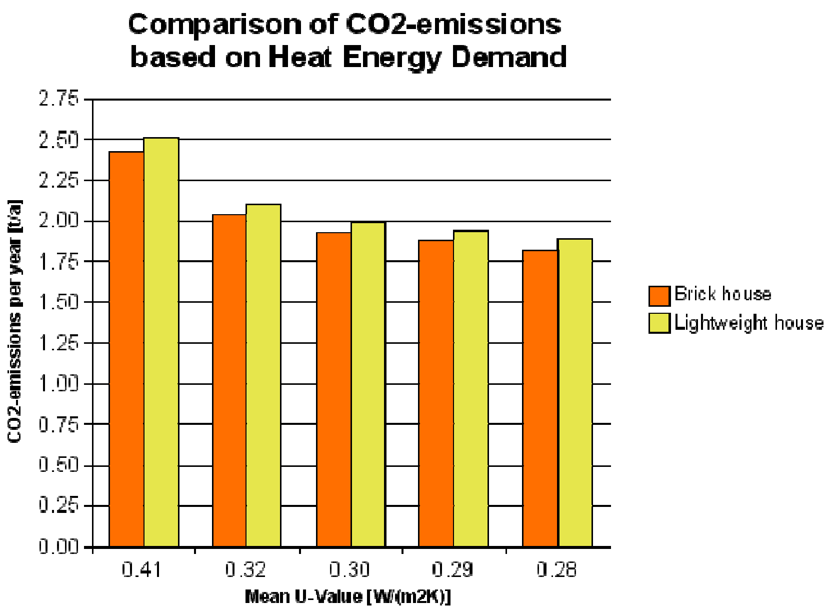


**Fig. 6** Diagram 1: Comparison of the $CO_2$-emissions based on energy demand for heating against the mean U-value of the heavy ("brick house") and lightweight variant of the building envelope.

Unlike this information, which is already quite known, the diagram 2 (F**ig. 7**) explains the relationship between the improvements of the mean U-values by increasing the heat insulation thicknesses 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 heat insulation thickness. Somewhere between the mean U-Values 0.30 and 0.32 W/(m$^2$K), which corresponds to approx. 17.5 cm of thermal insulation of the brick house and approx. 21 cm of the lightweight house, stops then the rational increase of the thermal insulation thickness. Just to compare: for the improvement of the mean U-Value from 0.41 to 0.32 W/(m$^2$K) and the reduction of heat energy demand in the range of 1500 kWh/a 5 cm of an additional thermal insulation is necessary. But the next increase of the thermal insulation by 5 cm brings about the improvement of the U-Value by just 0.02 W/(m$^2$K) and the reduction of heat energy demand in the range of 300-400 kWh/a. This leads to the conclusion that the efficiency of the increase of the thermal insulation thickness has its economical and also ecological limits as it will be obvious from further diagrams. They can be quite well established using the computer simulation tools.

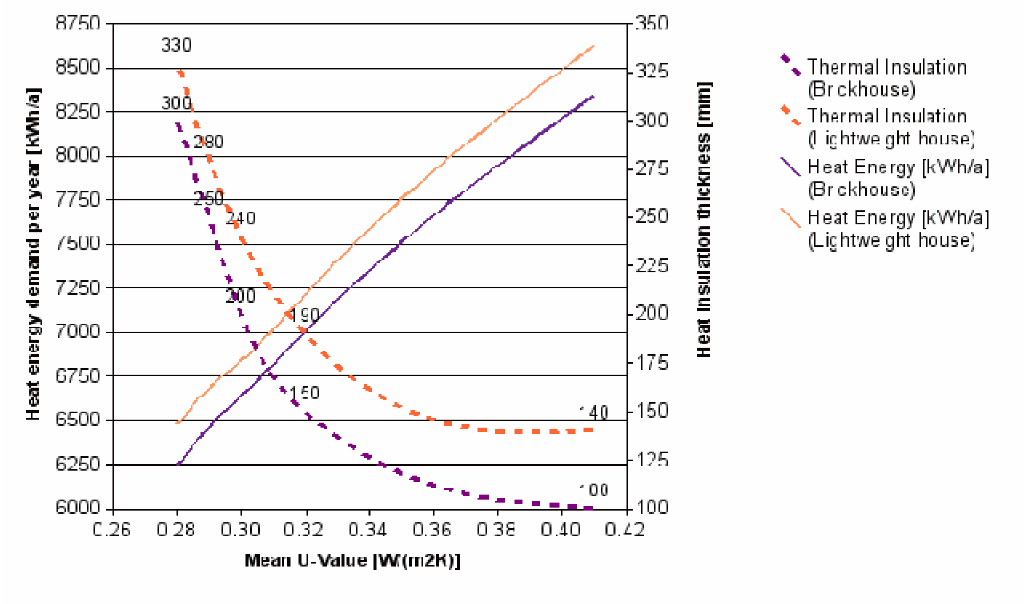


**Fig. 7** Diagram 2: The effect of the mean U-value improvement in dependence on heat insulation thickness upon the heat energy demand reduction.

Diagram 3 (**Fig. 8**) is a summary of the performed study and depicts the increase of the $CO_2$-emissions due to the building and operation of the case study house for both the heavy (B – brick house) and the lightweight (LW) variant as well. For each variant 5 modifications of the thermal insulation thickness (in diagram represented by the mean U-values) were examined. The starting values of the lines are the calculated GWP values due to the fabrication of the construction material and building products. The inclination of each line is then caused by the annual $CO_2$ output due to the building operation.
Looking at it two basic information can be deduced:

The improvement of the mean U-Value, and hence the thermal insulation thickness, under 0.32 W/(m$^2$K) does not have significant effect on $CO_2$ reduction within the first 25 years of operation. On the other side the GWP value due to the fabrication of construction material and building products can increase in case of heavy construction by up to 16 % and in case of lightweight construction by about 30 % for the U-Value of 0.28 W/(m$^2$K) against base variant. Provided that the building operation is based on renewable energy sources these lines would be shallower and closer to constant value. Therefore 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.

The lightweight variant seems to perform environmentally better than the heavy one. It is then purely the question of expected building service life and material durability that is to consider primarily when doing the decision between heavy and lightweight variant.

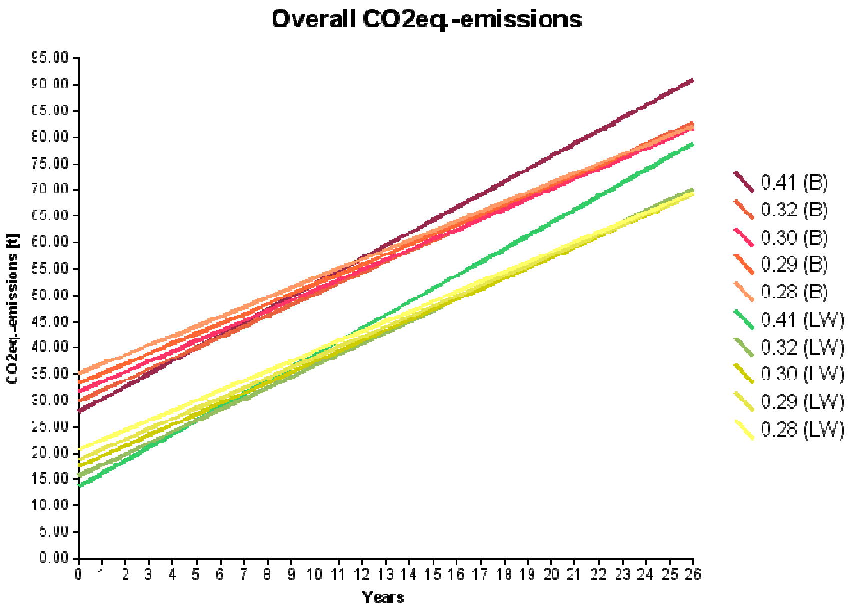


**Fig. 8** Diagram 3: The $CO_2$-emissions due to manufacturing and operation of the case study house calculated in dependence on time for both the heavy (B – brick house) and the lightweight (LW) modifications of the building envelope (represented by the mean U-values).

## 5 Conclusions

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 the increasing the thickness of thermal insulation and the improvement of the mean U-value are effective to certain extent only. Then it becomes a kind of useless overflow that just cost investment money. Providing that the building envelope is optimized and the use of renewable energy sources is made, the third way to improve the environmental harmlessness of the buildings is to use materials and products the production of which is as much $CO_2$ free as possible. In order to do this a kind of environmental product declaration for buildings (EPD) should be introduced as a complementary measure to energy passports of buildings that are being prepared at the present. In fact the work and first discussions on EPDs for buildings have already started, too [8]. As the energy passports are quite complex matter and a subject to strong criticism the author's opinion is that the EPD's should exclusively cover the period of the building's life cycle prior to its commissioning. The other option would be an EPD that would consist of the energy passport and of some other document that would describe the environmental quality of the building manufacturing before its commissioning. Whatever the decision will be, there is a lot of reliable information on the environmental quality of building products and materials already available. It can help progressive architects to assess and optimize the design quality from both points of view – the building operation and the building manufacturing as well. Perhaps, as a consequence, a new architectural style based on optimally insulated buildings supplied from central green power plants could originate.

*At this time I would like to express my warmest thanks to Professor Hanno Ertel from Institute of Building Products, Building Physics and Design (IBBTE) at Stuttgart University, who kindly provided me with all necessary information, working place and encouraged my efforts, and Ms. Anna Braune from Institute for Building Physics (IBP) of the same University, who gave me an established insight into GABI and explained many questions.*

*This work was supported by the Marie Curie Actions of the EC, the German Scientific Society and the Slovak Science and Technology Assistance Agency under the contract No. APVT-20-042202.*

## 6 References

[1] MÖTZL, H., MÜCK, W., TORGHELE, K., ZELGER, T. ET AL. *Ökologischer Bauteilkatalog. Bewertete gängige Konstruktionen.* IBO, Österr. Inst. f. Baubiologie u. -ökologie u. d. Zentrum f. Bauen u. Umwelt, Donau-Univ. Krems, Springer Verlag, Berlin, 1999 (in German)

[2] EYERER, P., REINHARDT, H.-W. *Ökologische Bilanzierung von Baustoffen und Gebäuden. Wege zu einer ganzheitlichen Bilanzierung.* Reihe: BauPraxis. Birkhäuser Verlag, 1999 (in German)

[3] Web page: *www.architektur.tu-darmstadt.de/buildingmaterials* (in German)

[4] *Esp-r - an integrated modelling tool for the simulation of the thermal, visual and acoustic performance of buildings.* Available at www.esru.strath.ac.uk.

[5] Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagen-technik vom 16.11.2001 (EnEV) (in German)

[6] FANTL, K., PANZHAUSER, E., WUNDERER, E. *Der österreichische Gebäude – Energieausweis. Energiepass.* TU Wien, 1996 (in German)

[7] *Radiance - a ray-tracing software system for UNIX computers available at http://radsite.lbl.gov/radiance.* Copyright: the Regents of the University of California.

[8] *Proceedings of the 13th LCA Case Study Symposium on Environmental Product Declarations with Focus on the Building and Construction Sector.* SETAC Europe, 7-8 December 2006, Stuttgart

**Dr.-techn. Ing. arch. R. Rabenseifer**

✉ KKPS SVF STU
Radlinského 11,
813 68 Bratislava 1, Slovakia

☎ +421 903 552 300

🗐 +421 2 52 920 482

☺ rabens@svf.stuba.sk

**URL** www.svf.stuba.sk