EVALUATION OF THE COST EFFICIENCY OF AN ENERGY EFFICIENT BUILDING

U.D.J. Gieseler, F.D. Heidt[1], W. Bier

University of Siegen, Department of Building Physics and Solar Energy
Walter-Flex-Str. 3, D-57068 Siegen, Germany
http://nesa1.uni-siegen.de , e-mail: heidt@physik.uni-siegen.de

ABSTRACT

This paper presents quantitative results about the economics of different levels of thermal insulation for a building envelope. Results are calculated on the basis of an example building in Germany, which is a recently built single family house with materials commonly used in light-weight constructions. Defining the cost efficiency of energy efficient building allows to identify solutions which are already economically viable as well as to determine specific costs of the investment into advanced sustainable building.

INTRODUCTION

For cold and moderate climates the first important step towards a reduction of the heating demand of buildings is an improvement of thermal insulation. This not only saves energy but also allows to install low-temperature heating systems, which is a pre-requisite for the usage of renewable energy sources like solar radiation. Moreover, such buildings exhibit a much better thermal comfort. However, energy saving measures which preserve this comfort (= better energy efficiency) usually are combined with corresponding higher costs. Best cost efficiency means that the same energy saving is achieved at lowest costs. Results of this paper show, up to which level of thermal insulation for each component of building envelope (wall, roof, bottom floor, windows) the investment is cost efficient at today's energy prices. Any further investment to reduce the energy demand is merely into sustainability and/or comfort improvement. Therefore, the value for cost efficiency indicates for which building solutions investments are paying back. It further allows to calculate the specific costs of a non-economic investment and thus establishes a ranking of most favourable options.

METHOD

For this contribution a single family house with low energy consumption in Hünsborn (Germany) is taken as a reference building. It was completed in 1997 as wooden framework construction with two upper floors and without basement. Figure 1 presents a view from the south-east and a summary of building parameters. The house is equipped with a balanced ventilation system with heat recovery by an efficient counter-flow heat-exchanger. The floor heating system is supplied by district heat.

This building has been intensively monitored during two years from 1997 to 1999 [1]. Data were used to establish and to evaluate a detailed simulation model with TRNSYS [2]. The model is based on TRNSYS type 56 and considers the house as separated into 7 zones. It even includes the treatment of self-shading and the time-dependent reduction of solar radiation due to the landscape and obstructions in the neighbourhood of the house [3]. As a first result, this model yields excellent agreement between measured and simulated room temperatures in all zones for a period of four months, with a standard deviation of 0.3 °C. Also, measured and simulated annual heating demand are very close together (within 2%). This, of course, happens only if simulations are run under identical conditions for weather, internal gains and ventilation rates as they occurred during the measurements. The observed coincidence between simulation results and meas-

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[1] Author, to whom correspondence should be addressed.

Location (Hünsborn): 50.95°, 7.85° east, 260 m	
$A_{NHFA^*} = 200\ m^2$, $V_{air} = 600\ m^3$	
$A_{window} = 65.0\ m^2$	$U_{window} = 1.3\ W/(m^2\cdot K)$
$A_{floor} = 114.5\ m^2$	$U_{floor} = 0.32\ W/(m^2\cdot K)$
$A_{wall} = 193.1\ m^2$	$U_{wall} = 0.23\ W/(m^2\cdot K)$
$A_{roof} = 189.3\ m^2$	$U_{roof} = 0.21\ W/(m^2\cdot K)$

*NHFA = net heated floor area.

Figure 1. Reference building in Hünsborn, Germany. South-east view and key parameters.

ured values proves the validity of the developed simulation model. Therefore, it was used in the following to determine the amount of savings in heat energy due to various measures for that purpose. These measures comprise better thermal insulation, changing the orientation of the house as well as changing the size and quality of glazing. For the simulations a typical weather data set representing a locally and long-term averaged German climate has been chosen (Trier, METEONORM [4]) in order to avoid results which are dependent on the micro-meteorology of the site or on particular characteristics of individual years.

Basically, the demand of heat energy for buildings can be calculated by different methods. Besides time dependent simulations as e.g. under TRNSYS, quasi-stationary (monthly) energy balances can be used, as they are described in the European code EN 832 [5]. For calculations according to the latter method, the software tool NESA [6] was applied. In this given case, results for the annual heating demand from TRNSYS simulations and calculations according to EN 832/NESA agree very well (64.2 kWh/(m²a) and 64.5 kWh/(m²a), respectively). This degree of coincidence may be exceptional. Nevertheless, as a matter of fact, for common buildings the values for the annual heating demand from quasi-stationary calculations and simulation results do not differ by much more than 5%. A comparative study of time dependent and quasi-stationary methods displayed, that for the determination of transmission losses through opaque components results from a steady state model like that used for Eq. 6 are quite sufficient. The same is true for ventilation-induced heat flows. Any transfer of heat or radiation through windows, however, may need a more detailed consideration. Therefore, for investigations of building orientation, window size and quality of glazing, the TRNSYS model has been used in order to determine potential energy savings in the most accurate way.

From the additional investment costs for a better building envelope and corresponding saved energy a cost efficiency can be defined. Yearly investment costs normalised to yearly energy savings E_{save} are given by

$$C_{inv} = \frac{I_{tot} \cdot A}{E_{save}}, \quad [C_{inv}] = \frac{€}{kWh} \ , \tag{1}$$

where I_{tot} is the total initial investment and A is the annuity. The annuity factor A depends on the interest rate p and is assumed to be constant. With n the considered period of time in years the annuity factor is:

$$A = \frac{p \cdot (1+p)^n}{(1+p)^n - 1}, \quad [A] = \frac{1}{a} \ . \tag{2}$$

The annuity represents that fraction of an investment, which must be raised yearly (here: by energy savings) to balance the capital value of the investment after the time period n. This amortisation time n must be less or equal the lifetime of the system. It is chosen equal to the expected lifetime of the considered elements, which implies the lowest constraints on the cost efficiency of the considered technologies.

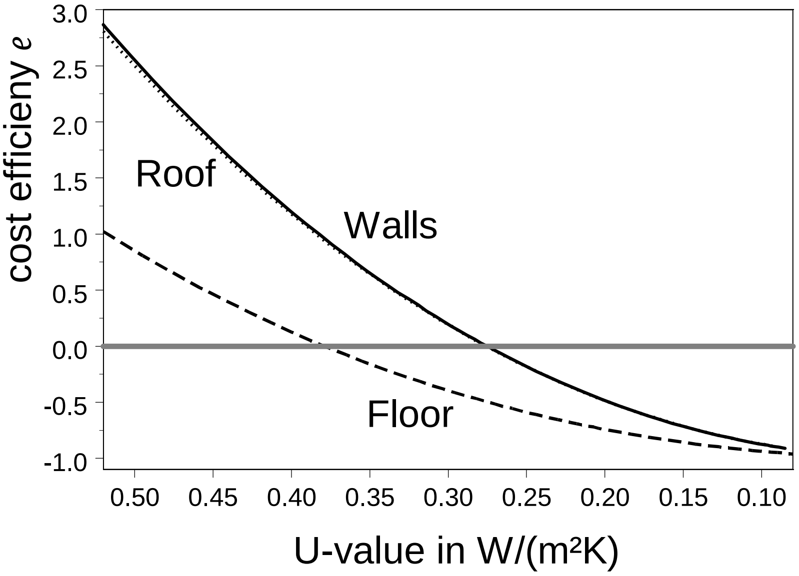

Figure 2. Cost efficiency e_{inv} (Eq. 3) vs. *U*-value from analytical approximations using Eq. 6.

For a financial evaluation of the energy savings, the energy costs C_E in €/kWh must also taken into account. The cost efficiency e_{inv} of an initial investment can be defined as the difference between energy costs C_E and investment costs for energy savings C_{inv}, normalised to these investment costs according to:

$$e_{\text{inv}} = \frac{C_E - C_{\text{inv}}}{C_{\text{inv}}} = \frac{C_E}{C_{\text{inv}}} - 1 \; . \tag{3}$$

This definition of cost efficiency implies values of e_{inv} between –1 and positive infinity. $e_{\text{inv}} \approx -1$ corresponds to vanishing energy costs $C_E = 0$ or to a very big capital investment with almost no energy savings $E_{\text{save}} \approx 0$, and, therefore, $C_{\text{inv}} \approx \infty$. Almost positive infinity is achieved for very low or vanishing capital investment $C_{\text{inv}} \approx 0$.

If C_{inv} is smaller than or equal to the energy costs C_E, the investment pays back within the considered time period and e_{inv} is = 0. This investment is economically sound and everybody who is able to provide the required capital saves energy *and* money. Present time (spring 2002) energy prices for amounts of energy which are consumed in small to medium size residential buildings and which include the base rates are at about $C_E \approx 0.05$ €/kWh.

A cost efficiency of $e_{\text{inv}} < 0$, however, indicates a financially not rewarding investment. This investment is merely to save energy, which includes savings of resources, the reduction of CO_2-emissions and environmental pollution and which is simultaneously a measure for climate protection. In other words, this investment spends money in order to improve the sustainability of housing. For all cases with $e_{\text{inv}} < 0$ the *absolute* specific costs to save energy C_{inv} ($e_{\text{inv}} < 0$) are calculated according to:

$$C_{\text{inv}} (e_{\text{inv}} < 0) = C_E / (1 - |e_{\text{inv}}|). \tag{4}$$

To determine the absolute specific costs for saved CO_2 instead of saved energy, C_E must be inserted with the unit €/(kg CO_2) instead of €/kWh. For natural gas with 0.21 (kg CO_2)/kWh, for example, and an energy price of C_E = 0.05 €/kWh the costs corresponding to one kilogram CO_2 are C_E = (0.05 €/kWh) / (0.21 (kg CO_2)/kWh) = 0.238 €/(kg CO_2). For a case with efficiency $e_{\text{inv}} = 0$ this results in investment costs to save CO_2-emissions of $C_{\text{inv}} = C_E$ = 0.238 €/(kg CO_2). These, however, are rewarded during the considered time period due to corresponding savings in fuel. For cases with $e_{\text{inv}} < 0$ this means that the *additional* specific costs ΔC_{add} to save energy and/or emissions come to the difference between C_{inv} ($e_{\text{inv}} < 0$) and C_E:

$$\Delta C_{\text{add}} = C_{\text{inv}} (e_{\text{inv}} < 0) - C_E = C_E \, |e_{\text{inv}}| / (1 - |e_{\text{inv}}|). \tag{5}$$

Thus $e_{\text{inv}} = -0.10$ results in *additional* specific costs of ΔC_{add} = 0.026 €/(kg CO_2) which is equivalent to ΔC_{add} = 0.006 €/kWh, and $e_{\text{inv}} = -0.90$ yields ΔC_{add} = 2.142 €/(kg CO_2) or ΔC_{add} = 0.450 €/kWh, respectively.

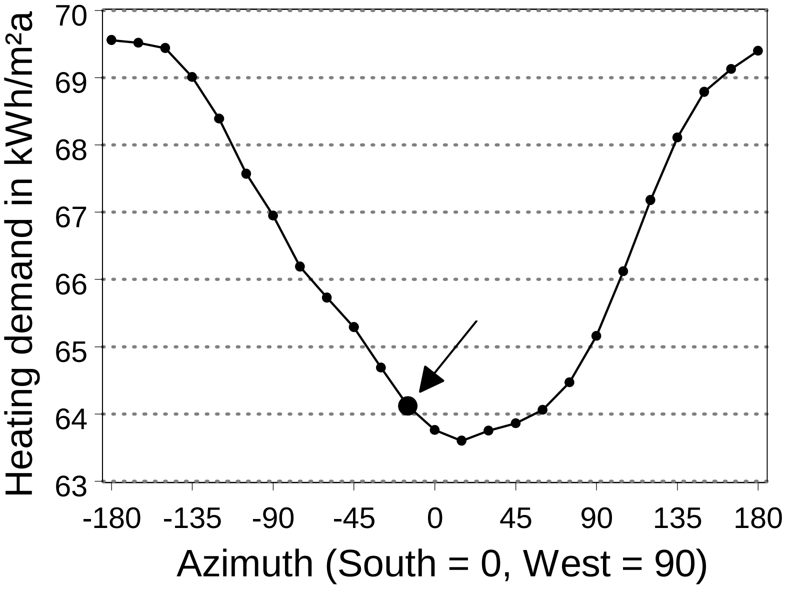

Figure 3. Dependence of the heating demand on orientation. Discrete symbols show results of the simulations. The orientation vector is perpendicular to the large roof area, which is visible in Fig. 1. An azimuth angle of 0° means, this roof area faces south. The arrow designates

DISCUSSION OF RESULTS

Results are obtained from the analysis of different options (better thermal insulation, orientation of the house, size and quality of glazing) to modify the envelope of the given reference building. For each option, the corresponding procedure consists of three steps: calculation of annual energy savings, estimation of accompanying (additional) costs, as well as determination and evaluation of cost efficiency.

For steady state analysis the annually saved energy E_{save} due to an improvement ΔU of the air-to-air heat transmission coefficient through opaque building components like wall, roof and floor is:

$$E_{\mathrm{save}} = HDD \cdot 24\ \mathrm{h/d} \cdot \Delta U \tag{6}$$

where $\Delta U = U(d - 0.01\ \mathrm{m}) - U(d)$ is the improvement of U-value due to one additional cm of thermal insulation, leading to the thickness d of the thermal insulation. HDD are the heating degree days on the basis 20°C/12°C in units of Kd. For the bottom floor, HDD has to be calculated on the basis of ground temperatures (instead of outdoor temperatures), which are assumed to be constant at 9 °C for the given location and weather data. If floor heating is installed (as is the case for the reference building), additionally a bigger heat loss to the ground has to be considered (by increasing the indoor floor temperature).

TABLE 1. MEAN SPECIFIC COSTS OF ADDED THERMAL INSULATION [7].

Thermal Insulation of	Material	Thermal conductivity in W/(mK)	Costs in €/(cm·m²)	Lifetime in years (a)	Interest rate	Annuity factor in 1/a
Wall	Mineral wool	0.040	1.00 ± 20%	50	8 %	0.082
Roof	Mineral wool	0.035	1.15 ± 20%	50	8 %	0.082
Floor	PUR	0.025	2.20 ± 20%	50	8 %	0.082

TABLE 2. TYPICAL PRICES FOR CONSTRUCTION ELEMENTS OF THE BUILDING ENVELOPE.

Building element	U-value in W/(m²K)	g-value	Costs in €/m²	Lifetime in years (a)	Interest rate	Annuity factor in 1/a
Wall	0.23	NA	210 ± 40	50	8 %	0.082
Window	Glass: 1.1, Frame: 1.8	0.60	500 ± 100	30	8 %	0.089
Window	Glass: 0.7, Frame: 0.7	0.54	800 ± 150	30	8 %	0.089

Specific costs of added thermal insulation products (per m² area and cm thickness) are compiled in Table 1, whereas Table 2 presents typical prices for walls and windows. Prices include paintings, coatings, installation and tax. Windows are with plastic frames and outside shutter. Prices of windows refer to a mean size of 1.5×1.0 m² and are based on German market conditions.

Figure 2 displays cost efficiencies (Eq. 3) of thermal insulation on walls, roof and floor as function of the obtained U-values. The underlying energy savings are calculated according to Eq. 6 for steps of 1 cm for the insulation thickness. Efficiencies become zero for $U_{\mathrm{roof}} = U_{\mathrm{wall}} = 0.28$ W/(m²K) and $U_{\mathrm{floor}} = 0.38$ W/(m²K). The corresponding thickness of insulation is 11 cm (wall and roof) and 6 cm (bottom floor). The different results for the elements originate from higher costs of insulation material as well as from smaller potentials to save energy for the bottom floor.

Figure 3 shows the dependence of annual specific heating demand on the orientation of the house. Here, an angle of 0° means, that the (normal vector of the) large roof area, which can be seen in Fig. 1, points exactly south. The maximum variation of annual heating demand due to the orientation is less than about 6 kWh/(m²a) for a complete rotation of the reference building. The cost efficiency of this measure, however, is very high, as almost no costs arise for that purpose.

In order to investigate the influence of quality and size of glazing, always the optimum orientation of the reference house has been chosen. Exchanging all windows of the reference building (65 m², $U_{\mathrm{glass}} = 1.1$ W/m²·K, $U_{\mathrm{frame}} = 1.8$ W/m²·K) by triple pane windows ($U_{\mathrm{glass}} = U_{\mathrm{frame}} = 0.7$ W/m²·K) results in energy savings E_{save} of 55.2 kWh per m² window area and year. This leads to a cost efficiency e_{inv} of –0.897. According to Eq. 5 the improvement of window quality gives rise to additional costs ΔC_{add} of 0.435 €/(kWh saved energy), totally about 1,561 € per year.

The overall size of windows in the living area (33.5 m²) is by far larger than the required window area for sufficient daylight. Therefore, this situation has been compared with a case where this window area is 14.1 m². No significant change of the annual specific heating demand was observed for increasing the window area from 14.1 m² to 33.5 m² in the predominantly south facing living area. The investment goes into the substitution of walls by windows (additional costs 290 €/m², see Table 2), but for the reference building, energy savings due to increased solar gains are almost zero, if not negative. This results in a cost efficiency close to –1, and specific additional costs, if applicable, tend to infinity.

SUMMARY AND CONCLUSIONS

Based on a reference building, parametric calculations have been performed in order to investigate the cost efficiency of various energy saving measures for the outer envelope. These calculations were performed for a single family house in wooden framework construction with low energy consumption in Germany. The results achieved are therefore limited to buildings of comparable type in mid-Europe. However, the method of calculation can be easily applied to other buildings or building types, respectively. It is also straightforward to update the cost calculation to local system and energy prices as well as effective interest rates.

Results show, that for the considered opaque elements, depending on the insulation material used and for today's energy costs (in Germany), thermal insulation levels at walls and roof of $U = (0.28 \pm 0.03)$ W/(m²K) and at bottom floor of $U = (0.38 \pm 0.04)$ W/(m²K) describe values (with estimated bands due to material cost variations) up to which the investment costs will be paid back by energy savings. Additional thermal insulation would not be cost efficient but improves the thermal comfort and is an investment into saving of resources and reduction of CO_2-emissions. Increasing the window size over the necessary amount for daylight and/or improving the U-value of windows beyond current technological standards is not cost efficient. Here, again, higher levels of thermal insulation enhance the indoor comfort. However, the costs for such investments into better comfort and sustainability with values for e_{inv} of about –0.90 or less are rather high and correspond to additional costs of 0.45 €/(kWh saved thermal energy) or more.

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