LIFE-CYCLE ENERGY ANALYSIS: COMPARISON OF LOW-ENERGY HOUSE, PASSIVE HOUSE, SELF-SUFFICIENT HOUSE

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1 Abstract

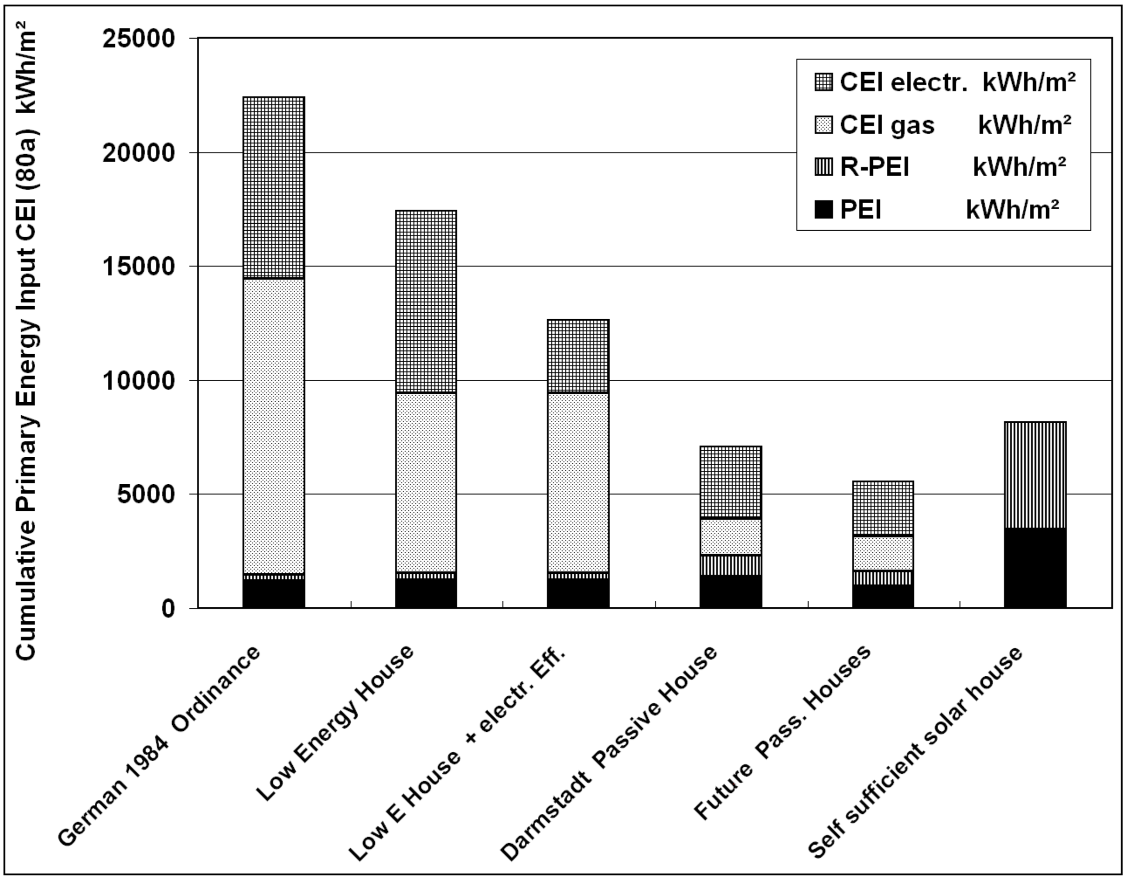

Fig. 1: Cumulative primary energy input compared

Abstract: The cumulative primary energy input (CEI) over a service life of 80 years has been compared for six construction standards (Fig. 1). For poorly insulated buildings (complying to the 1984 German Thermal Insulation Ordinance), the primary energy input for building production (PEI) only amounts to some 5% of the consumption of natural gas and primary energy for household electricity. With the low energy house (LEH standard), the volumes of electricity and natural gas consumption over the service life are brought to similar levels, amounting each to 45% of the total, so that further progress can above all be achieved by the efficient use of electricity (Low E House + electr. Eff.). Improving to the passive house standard, very good thermal protection reduces the heat requirement to such a low level that a separate heating system is not necessary any longer. The PEI of future passive houses can be even lower than that of conventional new-build houses. Projects with cost-effective passive

houses that cut the cumulative energy input by a factor of 4 are close to realisation. The approach to improve the building even more to a self-sufficient houses makes the cumulative energy input higher again than for a passive house, caused by the high primary energy input for production and replacement (R-PEI) of extensive technical systems.

2 Methodology

A complete inventory was drawn up for the passive houses built in Darmstadt, Germany, in 1990/91. The production inputs can be determined by linking the calculations of volume and mass quantities with material-specific primary energy and emission coefficients. The coefficients used in the literature vary substantially [1][2][3]; among these, the primary energy input values are the most reliable. Therefore a comparative life-cycle analysis of primary energy input is initially undertaken - given reliable raw data, the methodology for determination of other environmental impacts would be analogous. Energy figures are stated here in kWh (1 kWh = 3.6 MJ); for better comparability, values refer to living floor space. 80 a was selected as inventorisation period. The annual heat balances were determined with the procedure set out in the guideline for energy-conscious building design [4][14].

3 Reference House (1984 Ordinance) – Low Energy House (LEH) – Passive House (PH) – Self Sufficient House (SSH)

A mid-terrace house (156 m^2 floor space) complying to the ***1984 German Thermal Insulation Ordinance (WschVO 84)*** was taken as ***reference house***.

The German government intends to make low-energy design, which was already largely built reality in Sweden by the middle of the 1980s, the required standard by the 1999 new ordinance in Germany, too. ***The annual heat requirement of low-energy houses (LEH) is below 70 kWh/(m^2a).*** The heat consumption of low-energy houses is thus at least 50% lower than required by the 1984 German Ordinance. Good thermal insulation, reduced thermal bridges, air tightness, low-energy glazing and mechanical ventilation are decisive features. For the LEH standard cost-effective exhaust air ventilation systems are sufficient, using inlet vents for the (cold) fresh air flow into the building. In Germany low-energy houses are currently already offered on the market at the same costs as conventional dwellings [5].

A passive house (PH) is a building in which the heat requirement is so low that a separate heating system is not necessary and there is no loss of comfort; in Germany, this is the case if the annual heat requirement is below 15 kWh/(m^2a). Through efficient electricity usage, the total end-use energy requirement incl. household electricity and domestic hot water is lower than 33 kWh/(m^2a).

The decisive idea to develop cost efficient passive houses was, that to dispense with a heating system the heat requirement need not be zero: If the maximum heat load is less than 10 W/m^2, then the extremely low required heat load can be provided without additional effort via the supply air. The characteristic figures of Passive houses are: very good thermal insulation (U-values < 0.15 W/(m^2K)), avoidance of thermal bridges, high air tightness (n_{50}-values < 0.6 h^{-1}), super-glasing (U-values < 0.8 W/(m^2K) with solar transmittance factor g > 50 %) and ventilation systems with highly efficient heat recovery. The fundamentals of passive house design are to be found in the literature [6].

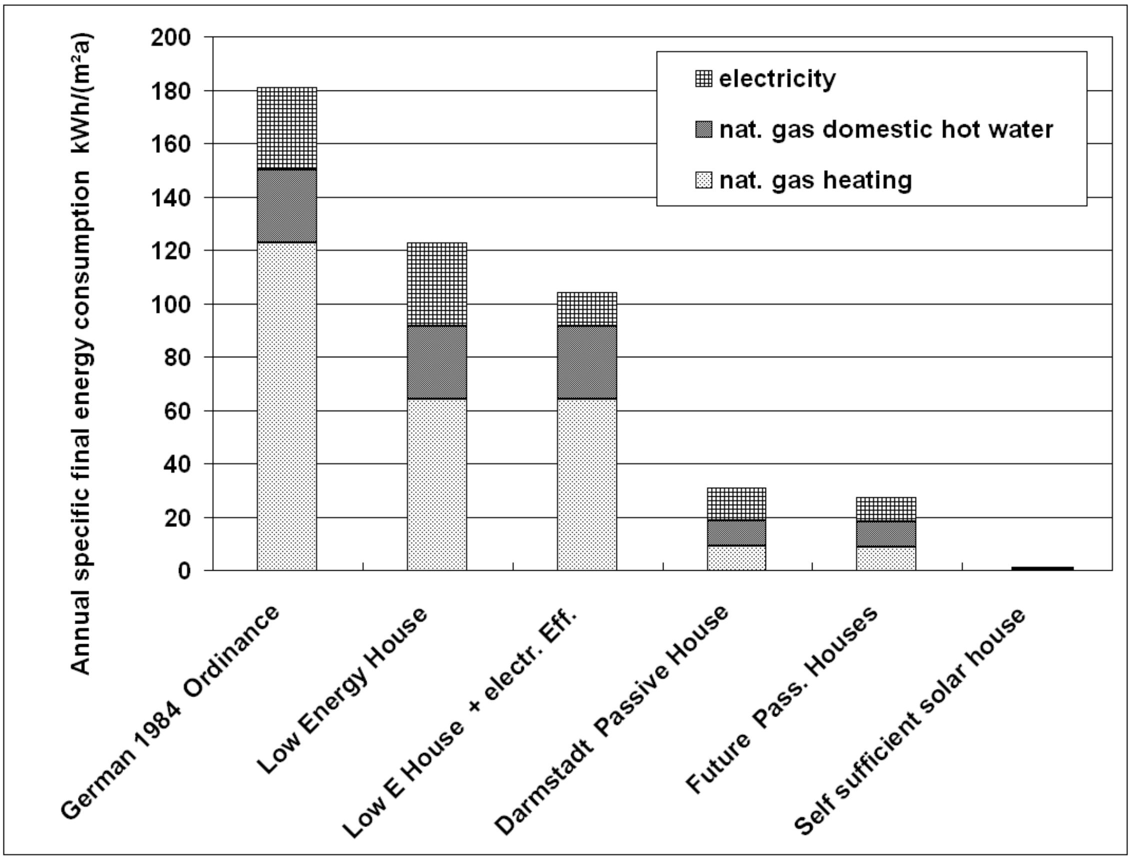

Fig. 2: Annual end-use energy consumption

A self-sufficient house (SSH) by definition needs no end-use energy deliveries - apart from the incident energy flows from natural sources (solar radiation, wind).

Energy self-sufficiency refers here not only to space heating, but also to domestic hot water heating, ventilation and household electricity: there are no grid connections and no fuel delivery. That such a building is technically realisable has been proven by the Self Sufficient Solar House (SSSH) of the Fraunhofer Institute for Solar Energy in Freiburg, Germany [7]. This house derives its residual thermal energy for domestic hot water from thermal solar collectors, its electricity from a photovoltaic array and in winter from fuel cells that burn the hydrogen produced by electrolysis during summer and stored in a H_2 - accumulator on site. The life-cycle primary energy balance for the SSSH has been reported in the literature [1].

4 First Passive Houses in Darmstadt-Kranichstein

The construction of the first passive house was supported by the Hessian Ministry of the Environment. The building was completed in October 1991 with four dwellings in a terrace-type layout, and has been occupied since then by four families. The basic concept of the house is based upon rigorous **conventional thermal insulation** (cf. Table 1), optimised **passive solar energy use** (triple-pane double-low-e glazing with Krypton in the spaces) and highly efficient **heat recovery (η>80%)**.

Table 1: Constructive details of the passive house (cf. also [8])

Element	Description (from external to internal surface)	U-value
Roof	Grass roof; filter medium; root protection foil; formaldehyde free chip-board; I-stud timber beams; battens; airtight polyethylene foil; gypsum plasterboard; wood-chip wallpaper, paint; cavity (445 mm) fully filled with mineral wool.	0.1 W/(m²K)
External wall	Mineral cast; 275 mm rigid expanded polystyrene foam; 175 mm sand lime blocks; 15 mm gypsum plaster covering all internal surfaces; wood-chip wallpaper, water paint	0.14 W/(m²K)
Cellar ceiling	Flat coat on fiberglass cloth; 250 mm rigid expanded polystyrene foam; 160 mm concrete; 40 mm polystyrene insulation against subsonic noise; 50 mm cement screed; 8-15 mm rod parquet, bonded; solvent-free seal	0.13 W/(m²K)
Windows	triple-pane double low-e glazing with Krypton filling. Wooden window frames with additional PU-foam insulation (CO_2-foamed, CFC-free)	0.7 W/(m²K)

The objective of the research project was above all to examine to what extent the energy consumption of dwellings can be reduced by exclusively passive measures. The evaluation of four measured years (Table 2) shows the house to meet the expectations with regard to energy efficiency. Compared to the average of German dwellings, the measured heating energy consumption was cut **down to** about **5%,** and the total final energy consumption for space and domestic hot water heating and household electricity is **down to** about **10%** [9].

Table 2: Measured consumption of passive house (average of four households).

Energy consumption (final energy) kWh/(m^2a) (floor space)	Energy carrier	Measured 91/92	Measured 92/93	Measured 93/94	Measured 94/95
Household electricity	ELEC-	6.27	6.17	7.11	7.48
Ventilation (electricity)	TRICITY	2.65	2.93	2.93	2.93
Joint electricity uses		2.85	2.10	1.87	1.82
Cooking gas	NATURAL	2.43	2.60	2.89	2.85
Domestic hot water	GAS	8.28	6.12	7.52	7.45
Heating		20.81	11.91	11.45	7.42
Total		**43.29**	**31.83**	**33.77**	**29.95**

5 The Primary Production Energy Input for the Passive House

On the basis of the working drawings and the bills for the material used, a complete inventory was compiled for the realised passive house in Darmstadt. Fig. 3 shows the production energy input (PEI) for individual types of work; the total for the mid-terrace house is 0.781 TJ or 1391 kWh/m². The structural core is dominant, with 51%. Thermal insulation (incl. windows) accounts for 14% (194 kWh/m²), the ventilation and heat recovery system for 2% (23 kWh/m²). Compared to the 1984 Ordinance, however, thermal insulation and ventilation save 123 kWh/(m²a) of running primary energy input every year. *The total primary energy investment for better energy efficiency thus pays back in primary energy in less than two years.*

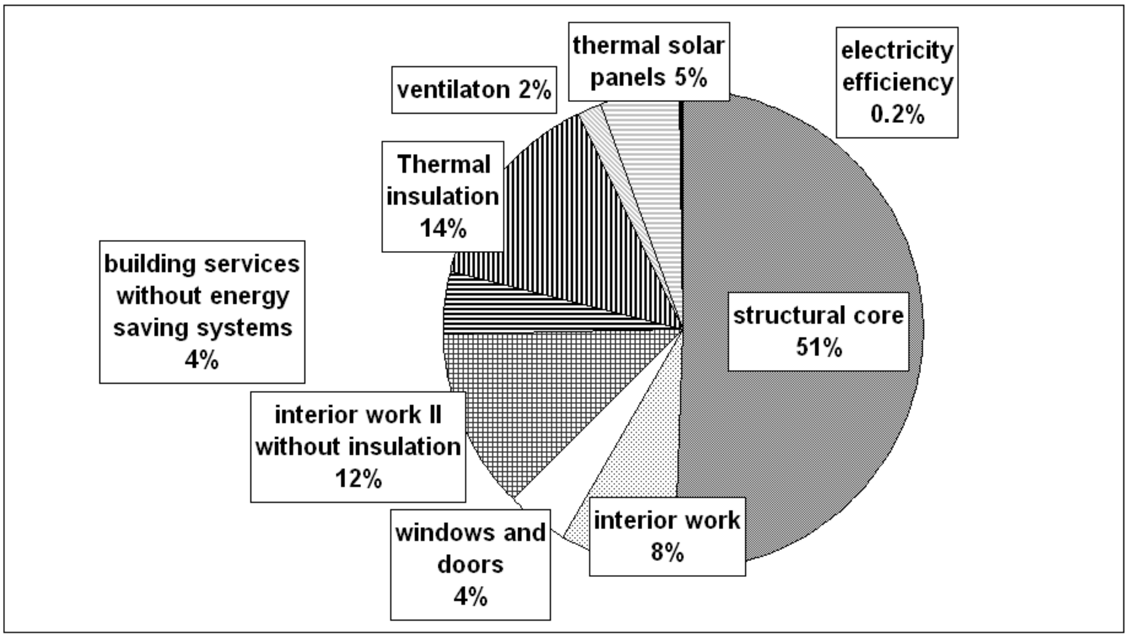

Fig. 3: Primary production energy input for the passive house at Darmstadt Kranichstein

The breakdown of PEI by materials is also interesting (Fig. 4). Here steel is dominant (29%; 407 kWh/m²), followed by concrete and stones (28%). Substantial PEI savings would be possible if these heavy materials were partly replaced by lightweight constructions. This is indeed the case with the 2nd generation passive house concepts, in which inter alia prefabricated timber elements are used.

The solar collector accounts for 5% (75 kWh/m²) of total PEI; the primary energy saved every year by the collector amounts to 19 kWh/(m²a). Measures taken in the passive house to efficiently use electric energy require by comparison only about 2 kWh/m² additional PEI, but save 60 kWh/(m²a) primary energy year by year [10].

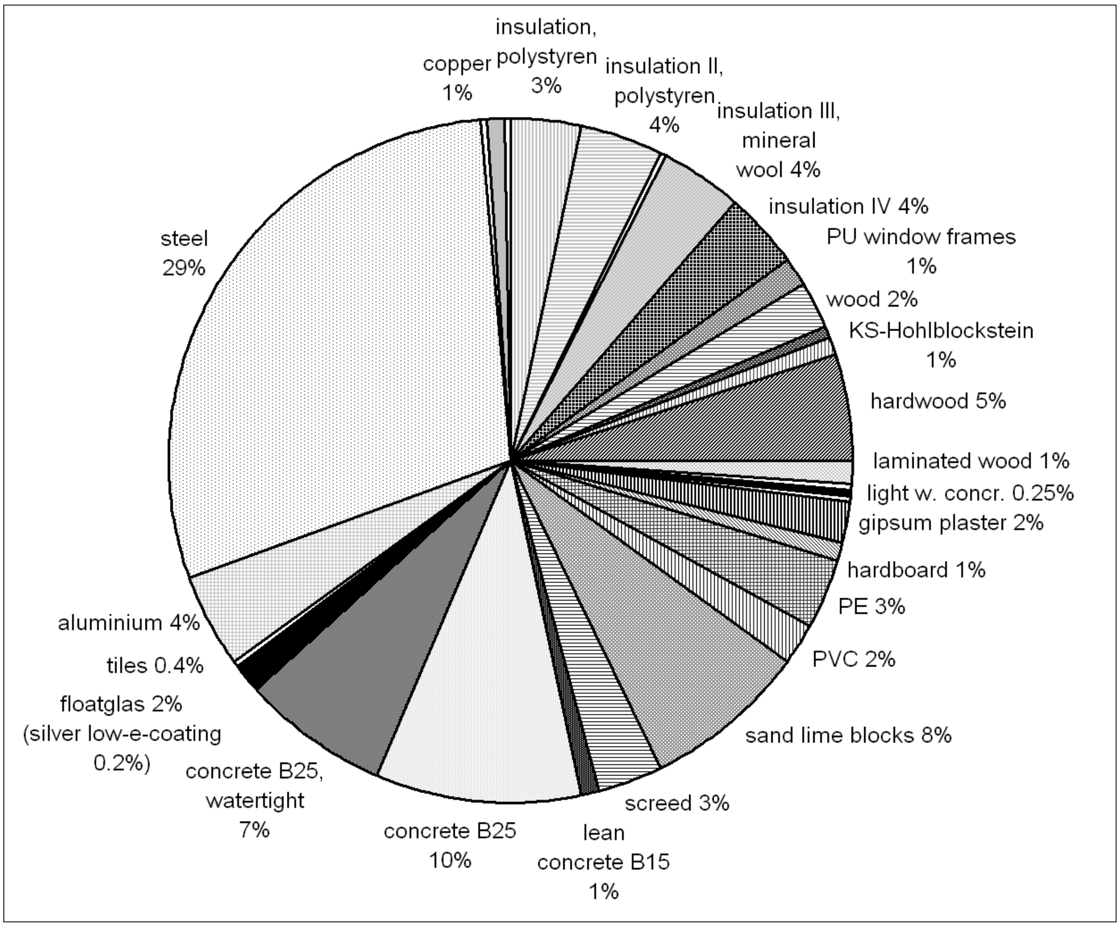

Fig. 4: Primary production energy input breakdown for different materials used in the passive house at Darmstadt Kranichstein

The additional PEI required for further measures that make the passive house into a "self-sufficient house" was taken from [1]: the translucent thermal insulation incl. blinds (23 kWh/m²), the enlarged solar collector (228 kWh/m²), the photovoltaic system (741 kWh/m²), the electricity storage (lead battery, 96 kWh/m²) and the H_2/O_2-system (274 kWh/m²). This PEI is evidently very high compared to the available savings potential (natural gas 20 kWh/(m²a); primary energy for electricity 40 kWh/(m²a)).

6 Life-Cycle Primary Energy Balance for Reference, Low Energy, Passive and Self Sufficient House

Fig. 5 shows the cumulative primary energy input (CEI) for 6 variants over a service life of 80a. The "starting points" of the 1984 Ordinance (PEI 1171 kWh/m²), low-energy house (1220 kWh/m²) and realised passive house (1391 kWh/m²) are very close together. After 2 years the CEI of the reference house (1984 Ordinance) is already higher than that of the low-energy house, which in turn is higher than the passive house. From then on the primary energy inputs develop largely proportionally to the differing consumption in use; the replacement inputs for the solar collectors in the passive house (every 30 years), however, are also perceptible.

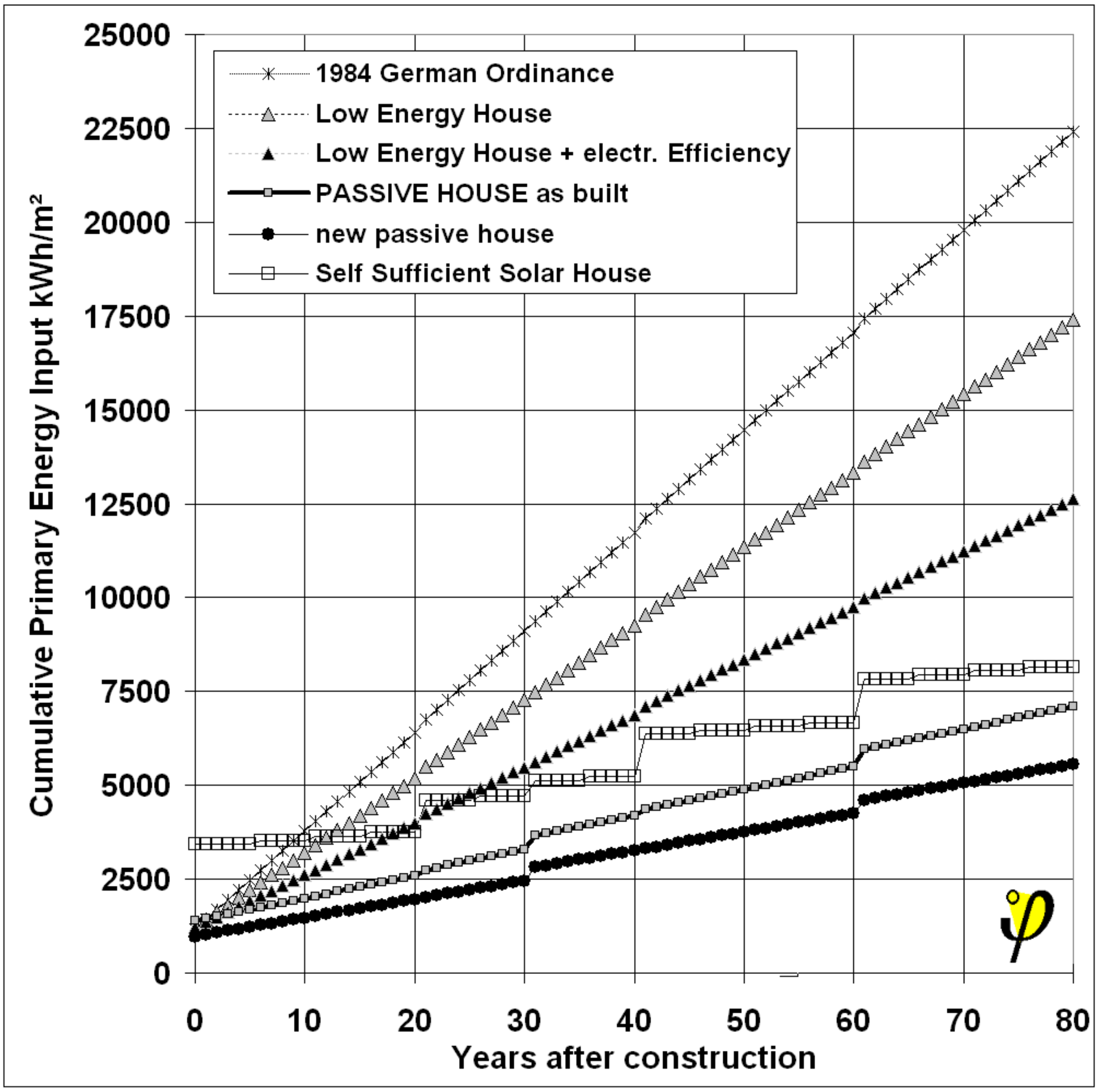

Fig. 5: Development of cumulative primary energy input over 80a service life for reference house (1984 Ordinance), low-energy house, passive house and self-sufficient house

The high PEI for the "self-sufficient house" is striking. As here furthermore every 10 a the lead battery, every 20 a the photovoltaic modules and every

30 a the thermal solar collectors have to be replaced, the PEI curve rises in discrete steps. At no point is the PEI lower than that of the passive house. It has been discussed in [1] how the high PEI of the self-sufficient house could be reduced. The technical input for an internal "infrastructure" as whole-year substitute for the grid is necessarily very large; seasonal storage systems with cycle rates close to 1 a^{-1} and systems for base, intermediate and peak load coverage are indispensable in the self-sufficient house.

While energy-saving systems of the building services are generally add-on devices that contribute additively to the investment costs and to the PEI, structural energy-saving measures are "substitutes". Thermally unfavourable, heavy building materials (such as concrete/bricks) are reduced and substituted by insulation materials - the PEI of a highly insulated house (such as the passive house) need therefore not necessarily be significantly higher than that of a conventional house.

Fig. 1 (on the first page of this paper) compares the cumulative energy input over 80 a for all 6 variants. Improved thermal insulation alone (LEH) leads to a reduction in CEI(80 a) of 22%: The field of household electricity then acquires particular importance. If the electric energy efficiency is improved as in the passive house, then the "Low E House + electr. Eff." case is already 44% below the reference case. With the further step to the passive house, the CEI(80 a) drops to less than 1/3 of the original value. With cost-effective 2nd generation passive houses (cf. Section 8) the balance can be further improved, whereby even the production energy input is reduced by using prefabricated timber elements - a total reduction by the factor 4 is achieved. The step to the self-sufficient house, however, leads to a rise in the CEI(80a) due to the necessary extensive technology.

7 The Influence of Insulation Thickness

As thermal insulation plays the decisive role for the LEH and PH standards, Fig. 6 shows how the production energy input for the mid-terrace house changes if exclusively the insulation thickness is varied (all other data as in the passive house case). Interestingly, the PEI initially drops until insulation thicknesses around 5 cm are reached, although the insulation material requires production energy: The reason lies in the reduction of the radiators (steel) caused by the reduction of the maximum heat load. At a thickness of approx. 23 cm this house finally reaches the passive house standard: Now the heat distribution system and the remaining radiators can be dispensed with, resulting in the drop in the curve. If in "new passive houses" the massive external wall is substituted by a timber construction with mineral wool insulation, then the bottom curve in Fig. 6 results for the PEI. At about 950 kWh/m², this is in fact 17% lower than for the reference house (1984 Ordinance).

To only consider the PEI is however misleading: Fig. 7 shows the cumulative energy input over 80 years CEI(80) for a "new passive house" as a function of insulation thickness. Here it becomes apparent that over the whole range the primary energy inputs during the operational phase are dominant, and that these drop greatly through thicker insulation (only from thickness in excess of 105 cm (!) onwards would the production input of the last cm exceed the savings provided by it).

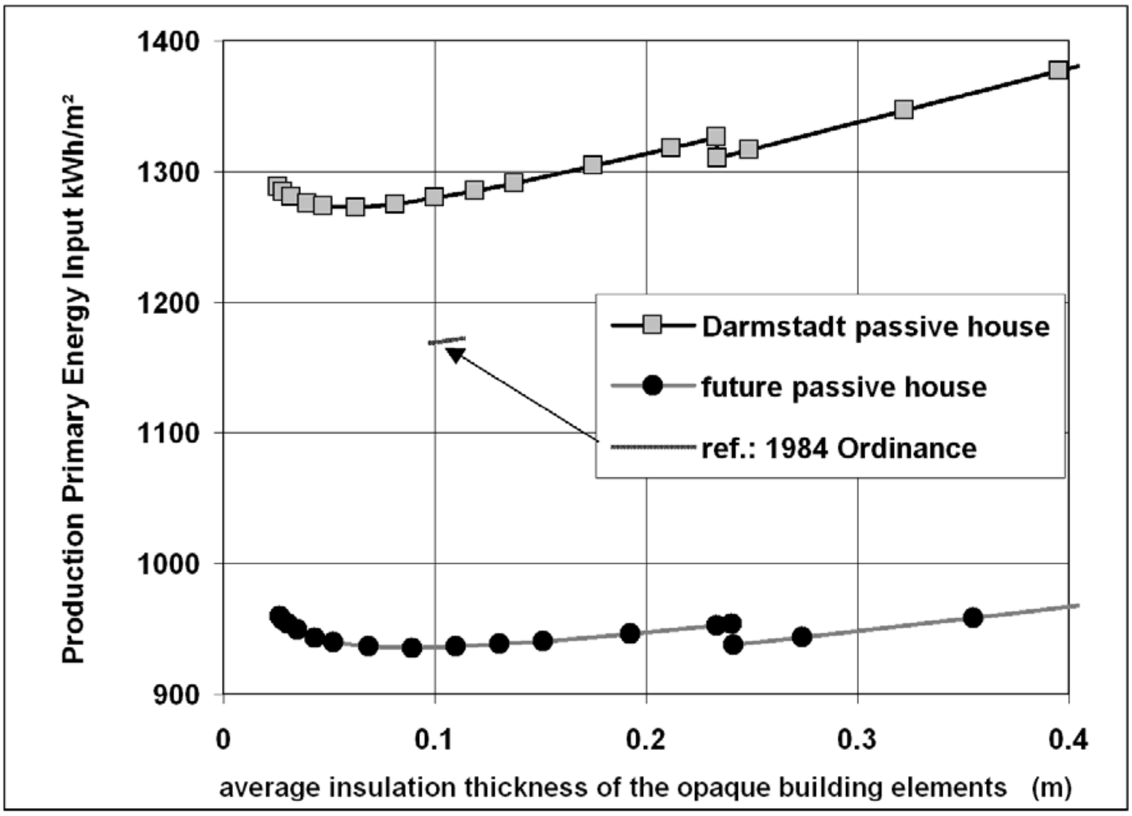

Fig. 6: Production energy input as function of insulation thickness (note: in this figure is the zero line suppressed)

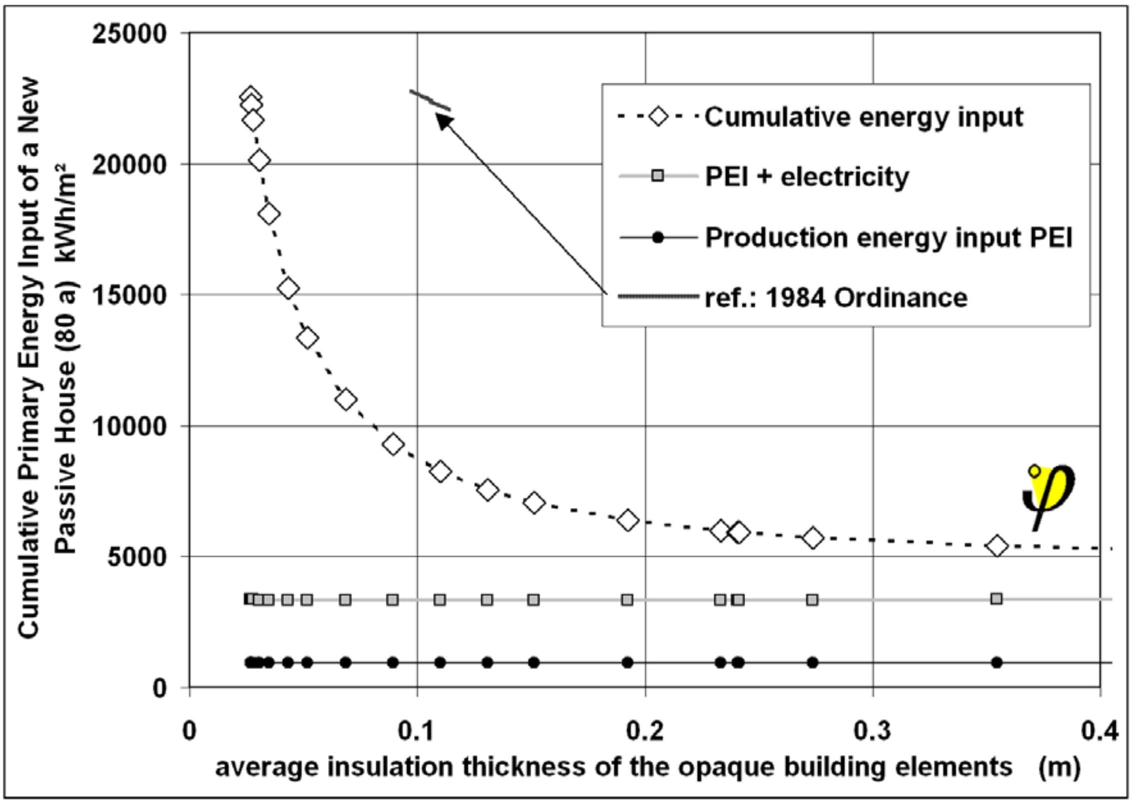

Fig. 7: Cumulative energy input (80 a) for a new passive house, as function of insulation thickness (note: in this figure the zero line is NOT suppressed)

8 Outlook: Cost Effective Passive Houses

The next step will be to develop and build cost effective passive houses. For these houses, prefabricated building products will be further developed:

- Highly insulating, thermal-bridge-free envelopes with various constructions, but all with U-values < 0.15 W/(m^{2}K).
- Further improved super-glazing with even lower heat losses (U-values lower than 0.7 W/(m^{2}K)) and yet high solar transmittance factors (more than 55%). [11]
- Window frames made of reinforced integrated PU foam elements, with U-values lower than 0.7 W/(m^{2}K).
- Compact building services systems with counter-flow heat exchanger for ventilation and the domestic hot water system, and simple, cost-effective back-up heating systems.[11]
- Highly efficient electric household appliances [12].

The "Cost-Efficient Passive Houses" working group [13] promotes these developments and accompanies the planning and realisation of the houses at seven sites, including Wiesbaden, Kassel and Hanover (Kronsberg development area in the vicinity of the EXPO 2000 site). With the new 2nd generation passive houses, the cumulative primary energy input over the life cycle will be lower by the factor 4 than that of a conventional reference house. It is intended that the capitalized total costs of these passive houses will also not exceed those of houses built according to the German 1984 Thermal Insulation Ordinance [11].

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This is an English translation of a Paper published in volume 8 of the publications of the working group of cost efficient passive houses (1997), to be cited:

Feist, W.: **Lebenszyklus Bilanzen im Vergleich: Niedrigenergiehaus, Passivhaus, Energieautarkes Haus**; in: Arbeitskreis kostengünstige Passivhäuser, Protokollband Nr. 8, Passive House Institute, 1997

Later added remarks from the author (2007):

1. All data given in this 1997 paper are still valid, for most of them have been measured in the demonstration building or are published data on the primary energy input PEI of materials. According to later publications these PEI so far did not change very much; nowadays there are systematic files available listing these data. In the future, however, the PEI will be significantly reduced by optimising the production methods. But that is not the contend of this paper.

2. The perspectives given in the Chapter 8 “Outlook: Cost Effective Passive Houses” have all been realized (with one exception – we did not succeed in getting a funding for the development of “Highly efficient electric household appliances”). The Cost-Efficient Passive Houses of the second generation have been built and monitored, the results have been published within the European CEPHEUS, see e.g.

   http://www.passivhaustagung.de/zehnte/englisch/texte/PEP-Info1_Passive_Houses_Kronsberg.pdf.

   The final energy consumption from the district heating system for space heating and hot water heating together were measured in the first year at 34,6 kWh/(m²a), this signifies savings of 75% compared to average new houses. See also

   http://www.passivhaustagung.de/Passive_House_E/Passivehouse_measured_consumption.html

3. In the year 2007 there have been some 10 000 Passive Houses built so far. An up-to-date information on that is going on in this development is always available at the main-page of the Passive House Conference: www.passivhaustagung.de