CEPHEUS – measurement results from more than 100 dwelling units in passive houses

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Abstract

Passive houses offer extended living comfort with only 15 to 20% of the space heating demand of conventional new buildings. This is achieved by improving the efficiency of building components, such as walls, windows or ventilation system, which are necessary in every building anyway. Thus, the extra costs of this standard are only about 10% of the total building costs. Within the EU-funded demonstration project CEPHEUS (Cost Efficient Passive Houses as EUropean Standards), 14 passive houses with 221 dwelling units have been built at different building sites, with different planners and users and of different construction types. In this paper, detailed measurements for 11 passive house projects are presented.

All projects show extraordinarily low space heat consumption with an average during the first heating season of 20 kWh per square metre *living area*. Compared with newly erected buildings that obey local legal standards, 80% of the space heat consumption could be saved. In addition, the total primary energy consumption (including household electricity) was less than 50% of that of conventional new buildings.

The mean room temperature in the heating period was 21.4 °C. Even at very low outdoor temperatures the room temperatures did not go down significantly. The measurements show that the buildings also offer comfortable summer conditions. Indoor temperatures rarely rose above 25 °C.

Users were well pleased with the simple techniques used. Even with tenants in low-income housing the projected energy savings could be reached. A social research project showed a high degree of user satisfaction.

The Passive House Idea

WHY BUILD PASSIVE HOUSES?

The Passive House standard offers a cost-efficient way of minimizing the energy demand of new buildings in accordance with the global principle of sustainability, while at the same time improving the comfort experienced by building occupants. It thus creates the basis on which it is possible to meet the remaining energy demand of new buildings completely from renewable sources – while keeping within the bounds set by the limited availability of renewables and the affordability of extra costs.

What makes the approach so cost-efficient is that, following the principle of simplicity, it relies on optimizing those components of a building which are necessary in any case: The building envelope, the windows and the automatic ventilation system (which is expedient anyway for hygienic reasons). Improving the efficiency of these components to the point at which a separate heat distribution system is no longer needed yields savings which contribute to financing the extra costs of improvement.

DEFINITION OF THE PASSIVE HOUSE STANDARD

The term “Passive House” refers to a construction standard that can be met using a variety of technologies, designs and materials. It is basically a refinement of the low energy

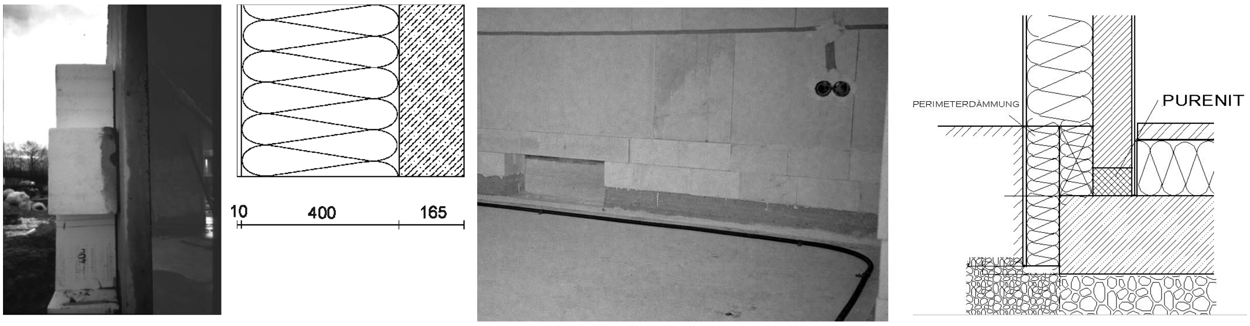

Figure 1. *Left : Wall insulation at the gable wall in the CEPHEUS sub-project 01-Hannover. Right: Thermal bridge reduction at the base point in 02-Kassel.*

house standard. Passive Houses are buildings which assure a comfortable indoor climate in summer and in winter without needing a conventional heat distribution system. To permit this, it is essential that the building's heating load does not exceed 10 W/m^2.

The small heating load is roughly equivalent with an annual space heat requirement of 15 kWh/(m^2a). Passive Houses thus need about 80% less space heat than new buildings designed to the various national building codes valid in 1999 when the CEPHEUS projects were planned and built. The small space heat requirement can be met by heating the supply air in the ventilation system.

The standard has been named "Passive House" because the 'passive' use of incidental heat gains – delivered externally by solar irradiation through the windows and provided internally by the heat emissions of appliances and occupants – essentially suffices to keep the building at comfortable indoor temperatures throughout the heating period.

It is a part of the Passive House philosophy that efficient technologies are also used to minimize the other sources of energy consumption in the building, notably electricity for household appliances. The target of the CEPHEUS project was to keep the total primary energy requirement for space heating, domestic hot water *and household appliances* below 120 kWh/(m^2a). This is lower by a factor of 2 to 4 than the specific consumption levels of new buildings designed to the standards presently applicable across Europe.

WHAT MAKES A BUILDING A PASSIVE HOUSE?

The various components of the Passive House approach can be classified under the following basic elements. The first three (superinsulation, heat recovery and passive solar gain) are crucial to the Passive House concept. To fully minimize environmental impacts, however, the other two are necessary (electrical efficiency) or expedient (meeting remaining energy demand with renewables).

1. Superinsulation

The basic idea of the Passive House – to reduce heat losses to the point at which internal and solar gains render a separate heating system superfluous – requires as a first step an excellent thermal insulation of exterior building elements. The U-values of the exterior building elements generally range between 0.1 and 0.15 W/(m^2K). The types of construction that can be used are highly diverse: Massive, lightweight and mixed constructions were used in the CEPHEUS sub-projects.

Transmission heat losses include not only the heat flows through the regular building elements, they also occur at corners, edges, junctions and penetrations. Excessive losses at such 'thermal bridges' must be avoided. Fortunately, this is possible solely through geometrical analysis without costly multidimensional heat flow computations. The method is explained in [Feist 1999, Feist 1999a].

Growing importance attaches to the airtightness of building envelopes. Leaking envelopes lead to a great number of problems that need to be prevented: Condensation water damage, draughts, layers of cold air right above the floor level, elevated energy consumption. A Passive House has a maximum n_{50}-value (air changes per hour at a pressure difference of 50 Pa between inside and outside) of 0.6 h^{-1}. The principles for achieving this excellent airtightness were set out in a special CEPHEUS building physics guideline [Peper 1999a]. Essentially, detailed planning is the main prerequisite for good airtightness: a rigorous concept for a single airtight envelope that encloses the interior space, detailed plans for airtight building element junctions and a reduced number of penetrations enable tradesmen to implement an airtight building.

2. Combining efficient heat recovery with supplementary supply air heating

Passive houses have a continuous supply of fresh air, optimized to ensure occupant comfort. The flow is regulated to deliver precisely the quantity required for excellent indoor air quality. Typical air change rates are about 0.25 to 0.4 h^{-1}. Higher air change rates would result in uncomfortably dry indoor air. It is permissible to heat the supply air to ca. 55 °C when required by means of a heating element downstream from the heat recovery unit. Higher temperatures could lead to dust carbonization in the supply air and possibly in or on the supply air ducts, i.e. dust particles would smoulder on hot surfaces and produce undesired smells. A simple calculation shows that this approach limits the heating loads in Passive Houses to 10 W/m^2.

To bring the space heat requirement down below 15 kWh/(m^2a), structural measures alone do not suffice in central Europe. It is only by means of high-efficiency Passive House heat recovery systems that the target can be achieved with acceptable structural measures given the current state of the art. Heat recovery effectiveness ratios of at

Figure 2: *Airtight and thermal-bridge-free junction at the eaves in 11-Horn; high-efficiency heat recovery unit in 01-Hannover; insulated window frame made from aluminium – polyurethane foam – wood.*

least 75% are required; as field measurements conducted within CEPHEUS have shown, these ratios can indeed be achieved and even exceeded by means of counterflow heat exchangers. Additional fresh air preheating in a subsoil heat exchanger is possible, which further reduces the need for supplementary air heating.

However, high overall efficiency is only achieved if the reduction of ventilation heat losses is not at the price of high electric power input. Electricity-saving fans and low pressure losses in the system are essential. The ventilation systems are generally driven by highly efficient direct current motors and consume 0.4 W/(m^3/h) or less. They can achieve annual performance factors (ratio between heat saved and electricity consumed) of 10 to 15.

3. Passive solar gain

Efficiency potentials having been exploited, the passive gain of incoming solar energy through glazing dimensioned to provide sufficient daylight covers about one third of the minimized heat demand of the house. In a Passive House, windows need to permit net solar gains, above and beyond their normal lighting and (in summer) ventilation functions. The preconditions for this are: low heat losses through the window, suitable glazing; and, if possible, southward orientation and low degree of shading. Nevertheless, Passive Houses do not depend on building sites which permit large solar gains.

Because the Passive House no longer needs a separate heating system, a further requirement is that occupant comfort directly in front of the window must be ensured despite there being no radiator. From this, the need for a window U-value of less than 0.8 W/(m^{2}K) can be derived for Middle European climate (cf. on this e.g. [Schnieders 1999]). This value can only be achieved with triple low-emissivity glazing filled with heavy noble gases. Such glazing achieves, depending upon the fill gas and the coating, U-values down to 0.5 W/(m^{2}K) and a total solar energy transmittance (g-value) of 50 to 60%. Even in the short heating season of the Passive House, from November to March, the energy balance of such glazing is positive. In contrast, double low-e glazing has net losses in the core winter period.

Window frames for Passive Houses need good thermal insulation. The thermal bridge at the edge seal is minimized by using stainless-steel or plastic spacers and by means of increasing the depth to which the glazing is inserted within the sash/frame. Today, a lot of manufacturers, mainly in Germany and Austria, supply thermally-insulated frames with U-values below 0.8 W/(m^{2}K).

Correct installation is necessary, too. If the windows are positioned within the insulation plane of the thermal envelope and that insulation overlaps the window frame as far as possible, the thermal bridge loss coefficient of installation can be 0. Otherwise, the overall U-value may increase by up to 50%.

4. Electric efficiency means efficient appliances

In Passive Houses, the heat requirement for space heating is reduced massively; the requirement for domestic hot water is also reduced by efficient technologies. Under these circumstances, the household electricity requirement is the largest element of final energy demand for the dwelling; if it remains at the levels commonplace today, it is about twice as high as the energy demand for heating. The task within CEPHEUS was therefore to trial tools by which households can be equipped with high-efficiency electric appliances.

Through fitting the Passive Houses with efficient household appliances, hot water connections for washing machines and dishwashers, airing cabinets and compact fluorescent lamps, electricity consumption is reduced greatly compared to the average housing stock, without any loss of comfort or convenience. All building services are designed to operate with maximum efficiency. High-efficiency appliances are often no more expensive than average ones, or pay themselves back through electricity savings.

5. Meeting the remaining energy demand with renewables

Cost-optimized solar thermal systems can meet about 40-60% of the entire low-temperature heat demand of a Passive

Table 1. Measured volume-adjusted n_{50} building leakage indexes for the CEPHEUS projects as built.

Project	01-Hannover	02-Kassel	03-Gothenburg	04-Egg	05-Hörbranz	06-Wolfurt	07-Dornbirn	08-Gnigl	09-Kuchl	10-Hallein	11-Horn	12-Steyr	13-Luzern	14-Rennes
Construction type	mixed	solid	timber	solid	solid	mixed	timber	timber	mixed	mixed	mixed	solid	timber	mixed
Mean n_{50} / h^{-1}	0,30	0,35	0,31	0,51	0,47	0,33	1,1	0,97	2,2*	0,58	0,61	1,6**	0,57	11**

* In 09-Kuchl, a large internal leakage is probably the reason for the high n_{50}-value.

** For these projects, only values from preliminary airtightness measurements were available at the time of analysis. In the meantime, remedial work has been carried out; however, new measurement results are not available.

House. The low remaining energy demand moreover makes something possible which would otherwise be unaffordable, and for which available supply would not suffice: over the annual balance, the remaining energy consumption (for space heating, domestic hot water and household electricity) is offset completely by renewable sources, making the Passive House fully primary-energy- and climate-neutral. Within CEPHEUS, this has been realized in the 01-Hannover sub-project – at prices within the normal market range.

The CEPHEUS project

Within the CEPHEUS project, 221 housing units were built to Passive House standards in five European countries. The scientific evaluation of the operation should demonstrate technical feasibility (in terms of achieving the targeted energy performance indexes) at low extra cost (target: compensation of extra investment cost by cost savings in operation) for a variety of different buildings, constructions and designs implemented by architects and developers in several European countries. Investor-purchaser acceptance and user behaviour under real-world conditions should be studied. The opportunity for both the lay and expert public to experience the Passive House standard hands-on at several sites in Europe was to be created. Finally, CEPHEUS should create the preconditions for broad market introduction of cost-efficient Passive Houses. Figure 3 gives an impression of the building sites and the types of Passive Houses that have been constructed there.

Measurement results

Part of CEPHEUS was a comprehensive measurement project for the determination of energy performance indexes and thermal comfort. Unfortunately, some projects were not yet occupied during the measurement phase. Consequently, results from the continuous measurements are not available for a sufficiently long period in all projects. Nonetheless, measurements from more than 100 dwelling units in 11 sub-projects in Germany, Austria and Switzerland were evaluated. In the following, the most important results from the common evaluation are presented.

AIRTIGHTNESS TESTING

In all CEPHEUS building projects, the remaining air leakage rates were measured by means of building airtightness tests in accordance with EN 13829.

The results documented here show that the remaining air leakage rates ranged between 0.30 and 0.61 h^{-1} in 9 CEPHEUS projects. In most of the other projects, a better result would be possible by means of carrying out remedial work on the junctions where air infiltration was identified. Wherever no rigorous airtightness design was presented, the results were far poorer. In Rennes, for example, a systematic airtight plane within the lightweight external walls to the north of the building had initially been dispensed with (the manufacturer of the natural fibre insulation material had stated the view that an airtight layer would not be necessary for such a construction); this led initially to disastrously poor pressurization test results ($n_{50} = 11\ h^{-1}$). Airtight foils were then retrofitted, but it was no longer possible to implement systematically airtight junctions at their edges.

CEPHEUS has thus proven in practice that the high levels of airtightness requisite for the Passive House standard can be achieved in practice in all construction types in a reproducible manner, that the recommendations made in [Peper 1999] provide an excellent basis for airtightness, and that rigorous planning of airtightness details is the key to success.

ENERGY PERFORMANCE INDEXES

In order to render the energy indexes of the projects comparable, a uniform procedure for calculating treated floor area (TFA) was defined. The TFA essentially comprises the sum of the floor areas of all residential rooms within the thermal envelope; it includes half of the floor areas of ancillary rooms within the thermal envelope. The TFA is about half the size of the gross floor area that is frequently used as a reference. As a result, energy indexes are about twice as high as if they were based on the gross floor area. A precise definition of TFA calculation is given in [Schnieders 2001]. That publication also presents and discusses the measurement results in more detail than is possible here.

ENERGY CONSUMPTION FOR SPACE HEATING

Measured space heating consumption

Space heating consumption is the most important criterion for assessing the CEPHEUS Passive Houses, and depends primarily upon the thermal quality of the building envelope, which is the decisive factor for energy consumption over the entire service life of the building (50-100 years). In contrast, building services components and household appliances are generally replaced after about 20 years; their impact upon the total energy balance across the whole service life of the building is therefore smaller.

Figure 4 shows the measured space heat consumption levels for the CEPHEUS projects. The graph shows the space heat consumption per square metre (TFA) and year for each dwelling unit. Within each project, consumption levels are sorted by size. For each project, a horizontal bar indicates the TFA-weighted mean.

The figure shows major differences in space heat consumption levels, both among the projects and among individual dwelling units within projects. Some projects achieve roughly the envisaged space heat consumption levels of ca. 15 kWh/(m²a), while others are significantly above this.

The differences within individual projects are even larger than those between the projects. Such degrees of variance in space heat consumption are also known from measurements in the building stock. In addition to differences in the constructions of dwelling units, they are due above all to different indoor temperatures, the impact of which is particularly strong in multifamily apartment buildings (02-Kassel, 09-Kuchl and 06-Wolfurt).

Figure 3. *Location of the CEPHEUS projects.*

Normalized annual consumption levels

It is known from simulation computations and from measurements that indoor temperatures have a great influence on space heat consumption in Passive Houses. It is therefore not purposeful to compare directly the measurement results shown in Figure 4 with previously calculated values, particularly as measurement data extending over a whole year are not available for all projects. In order to allow for comparisons, the measured values were extrapolated to a

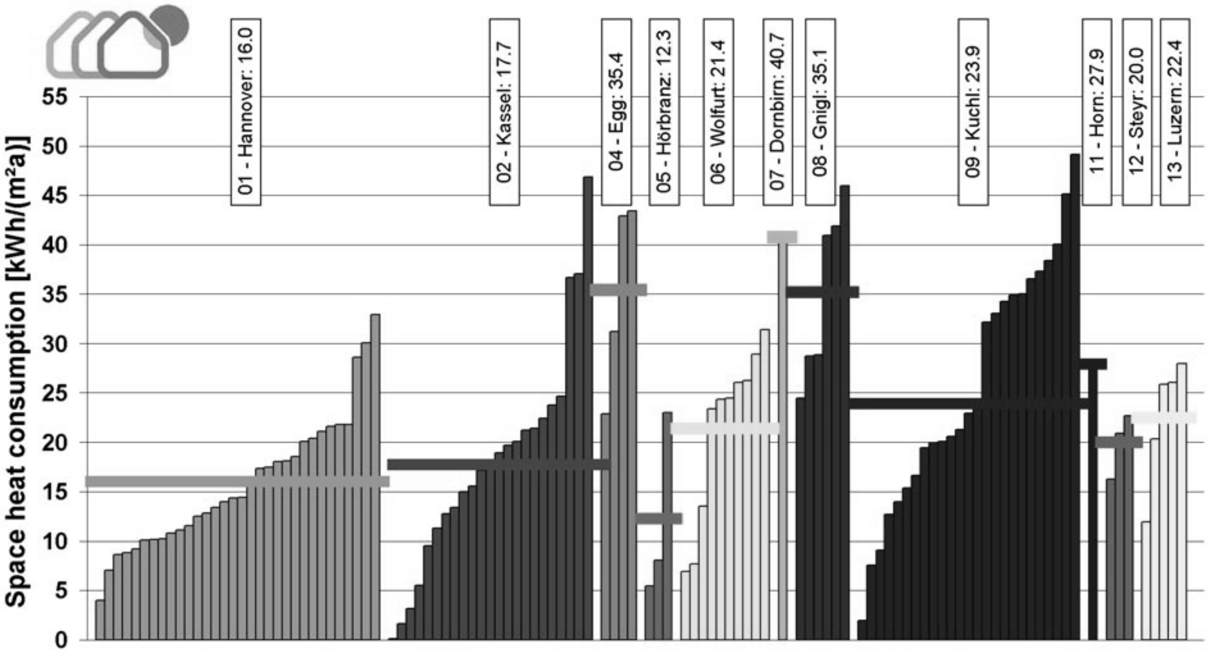

Figure 4. *Measured space heat consumption of CEPHEUS buildings per square metre TFA (partially extrapolated). For every project the TFA-weighted mean is displayed as a horizontal bar.*

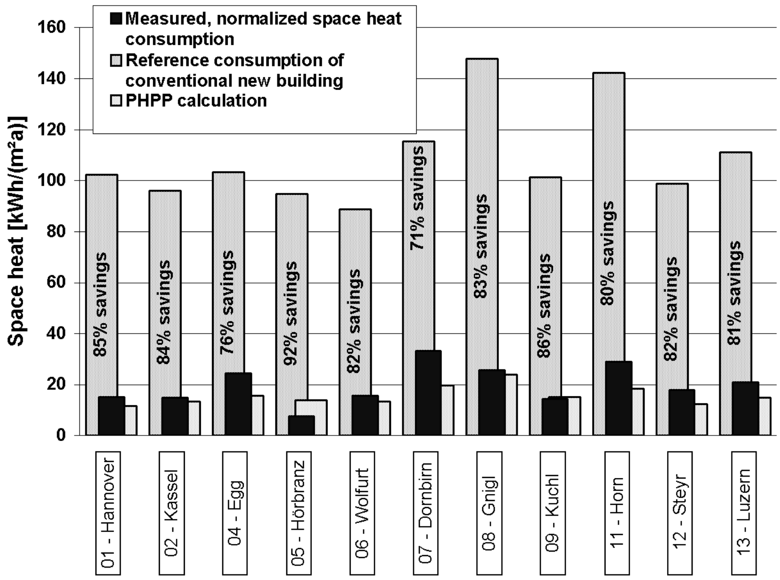

Figure 5. *Space heat consumption levels determined by measurements, extrapolated for a whole year and normalized to 20 °C indoor temperature ('normalized space heat consumption') compared to the consumption of conventional new buildings and to the values calculated in advance using the PHPP Passive House Planning Package.*

full year using the monthly procedure pursuant to EN 832, and normalized to an indoor temperature of 20 °C. In the present instance, this type of extrapolation can be considered conservative (for a reasoning of this cf. [Schnieders 2001]).

Figure 5 compares the normalized space heat consumption levels to reference consumption levels of conventional new buildings that have the same geometry and are built in accordance with locally applicable construction law, and with the space heat requirement values calculated in advance (using the PHPP Passive House Planning Package [PHPP 2002]). The PHPP consists of a number of Excel tables and performs a steady-state energy analysis of a passive house based on the European standard EN 832. It has proved to be an excellent, relatively easy-to-use tool for properly designing Passive Houses.

Compared to the reference consumption of conventional new buildings, analysis of the normalized space heat consumption shows that the buildings saved 84% space heat over the area-weighted mean. Savings were lowest in those projects which were not yet fully completed or where the occupants moved in only during or shortly before the measurement period. In all houses that were already occupied for a longer period, savings are more than 80%.

It is generally known in the construction sector that energy consumption levels, particularly those for space heat, in the first heating season can be higher than those that develop later during continuous operation – this is due to structural drying, final building work that is still in progress, suboptimal settings of the building services systems, and, finally, the habituation phase of occupants. If occupation starts in winter; heating up the cooled-down building components for the first time can consume up to ca. 3 kWh/m^2 alone. Consequently, the original CEPHEUS proposal provided for a measurement phase for all houses extending over two years; this, however, was not approved by the European Commission.

ENERGY CONSUMPTION FOR DOMESTIC HOT WATER

The measured useful heat consumption levels for domestic hot water heating exhibit considerable variance, as does the space heat consumption. On average, the consumption levels correspond roughly to the reference values, i.e. the typical consumption (25 litres per person per day at 60 °C) of dwelling units with comparable occupancy ratios. As hot water consumption is also a characteristic of the comfort demands of occupants, the study shows that the demands of the occupants of the CEPHEUS projects do not deviate significantly from the general average.

HOUSEHOLD ELECTRICITY CONSUMPTION

Given the extremely reduced space heat consumption of Passive Houses, the share of electricity consumption in the overall energy consumption is higher. This applies particularly in terms of primary energy. Consequently, the CEPHEUS projects also made efforts to reduce household electricity consumption.

Some projects exhibit major savings. In other projects, consumption levels are only slightly below the reference values; in some projects they are even higher. This can be explained by the circumstance that in some projects electricity consumption was not given the same priority in implementation as space heating consumption. In the 01-Hannover and 06–Wolfurt projects, however, implementation of the electricity conservation approach was demonstrated convincingly – although, in Germany and Austria, it is generally up to the occupants to purchase equipment.

In 01-Hannover, house buyers had the incentive of a rebate of 2 000 Euro on the buying price of their Passive House if an annual household electricity demand of less than 18 kWh/(m^{2}a) could be proven in a free electricity efficiency advice session. This led to savings of 38% compared to the reference value of average German households (cf. [Peper 2001]). It should be noted in this context that the

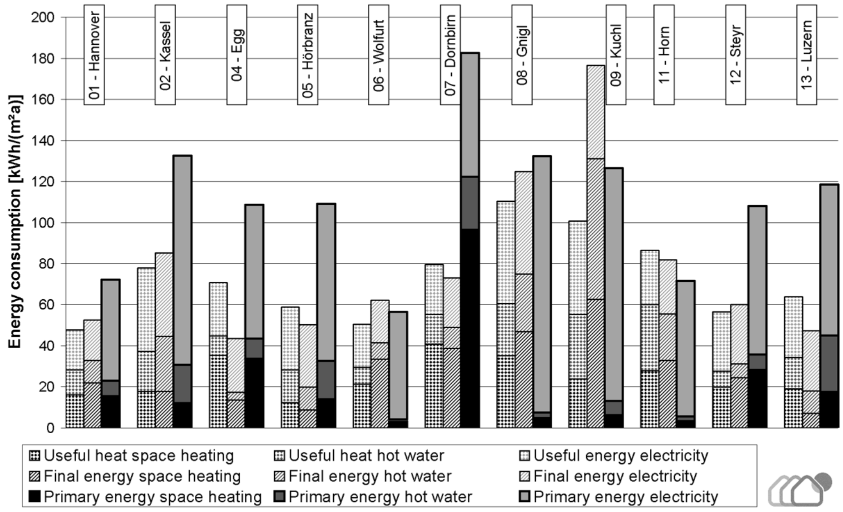

Figure 6. *Comparison of useful, final and primary energy consumption for space heat, domestic hot water and all electricity applications in the houses. For each project, the cumulative bar at the left represents useful energy consumption, that in the middle final energy and that on the right primary energy consumption. The primary energy factors were determined from GEMIS 4.0 [GEMIS]: Gas 1.15, electricity 2.5, district heat: 0.7, wood pellets: 0.1.*

measured value includes the electricity consumption of building services systems, including the ventilation system.

FINAL AND PRIMARY ENERGY CONSUMPTION

This section is concerned with the non-renewable proportions of final and primary energy consumption. Thus, for instance, energy consumption for hot water heating provided directly by a solar thermal installation is not included in the final energy consumption figures. In contrast, consumption for household, fan and building services electricity, and electricity for joint uses across several dwelling units are included in full in the consumption figures stated. The final energy consumption figures already contain any distribution losses and losses at heat producers.

Figure 6 provides an overview of the mean useful, final and primary energy consumption levels of the projects (sites). Where no data were available for a complete year, the available measured data were extrapolated. In Figure 7 there is given a comparison of the consumptions of the CEPHEUS projects and buildings with the same geometry that might have been erected at the same location obeying only the local legal restrictions.

The figures illustrate that in all projects exceedingly low primary energy consumption levels were achieved. Compared to conventional new buildings, useful, final and primary energy savings of more than 50% were achieved, space heat consumption was even reduced by 80%.

Two factors emerged as being particularly important for the ratio between final and useful energy consumption: Very low final energy consumption levels can be achieved using heat pump systems such as packaged units. These systems deliver more thermal energy than the electrical energy they consume. However, the coefficient of performance (COP) of the heat pumps corresponds roughly to the primary energy factor of the household electricity. Because of the low consumption levels achieved in the Passive House, the heat distribution losses gain importance particularly in cases where there is centralized heat production in larger buildings. Reduced distribution losses alone have the potential to yield further final energy savings of 20–30%.

Heat production from wood pellets has a particularly positive impact upon primary energy consumption: In all projects using pellet boilers, the share of space heat and hot water in total primary energy consumption figured less than 15%. In these cases, household electricity consumption dominated the overall primary energy balance of the building. In all projects, household electricity consumption turns out to have particular importance for primary energy usage. Here major savings potentials are still untapped.

HEAT LOADS

The downward leap in costs when the Passive House standard is reached occurs because the separate heating system can be dispensed with: The heat load conveyable by means of the supply air, which is required in any case, suffices to keep the house warm. The measured mean daily heat loads are therefore of particular interest. If we enter these in a graph against outdoor temperature, we can compare them with the theoretical heat loads computed from the specific heat losses and internal gains of the building for each day. This presentation provides information on the energy balance of the building and the quality of workmanship.

Figure 8 shows four such diagrams for selected projects. In 06-Wolfurt and 13-Lucerne the measured heat loads are on average slightly below the theoretical line. This is due to the solar gains, which can compensate for a part of the heat losses. Downward deviations from the theoretical heat load line occur particularly when outdoor temperatures are higher (in spring and autumn, with correspondingly longer periods of solar irradiation) and when outdoor temperatures are very low (which is always associated with a clear sky).

In 11–Horn, the measured heat loads fluctuate greatly around the theoretical heat load line. This is because this project is a single-family house. Due to the great thermal inertia of the Passive House, random fluctuations in heat loads

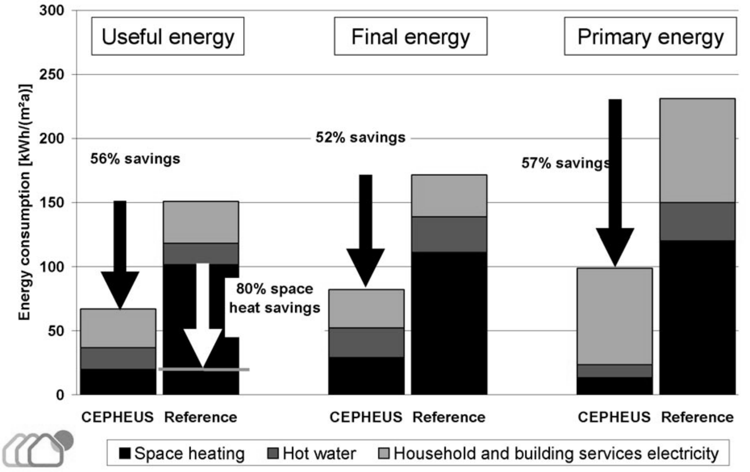

Figure 7. *Comparison of the measured energy consumptions of all CEPHEUS projects (TFA-weighted mean) with the corresponding values of ordinary, newly erected buildings. In the values for electricity and total consumption, household electricity is included. This must be taken into account when comparing with data from other projects where only heating and DHW are given.*

can occur from one day to the next that only average out over a group of several dwelling units.

08-Gnigl is in a very shaded site: In the core winter period no direct sunlight reaches the house. In autumn and spring, in contrast, there are solar gains that correlate in the diagram with higher outdoor temperatures. This model explains why, compared to the theoretical values, the curve of measured heat loads against outdoor temperature is steeper.

USER COMFORT

Indoor temperatures in winter

Figure 9 shows the mean values of the measured indoor temperatures in winter. The values generally refer to the months of November to February. 07-Dornbirn was only occupied in late December 2000; here the temperature data are for January and February.

The figure shows that in all CEPHEUS buildings the mean indoor temperature over all occupied zones and the whole measurement period was above 20 °C. Occupants typically set temperatures between 21 and 22 °C; the range of the occupied houses is, however, from 17 to 25 °C (the mean temperatures below 17 °C measured in 01-Hannover belong to unoccupied houses). When the insulation standard of a building is improved, a trend towards higher indoor temperatures can generally be observed: If the improved comfort is technically realizable at low cost, it is evidently also desired.

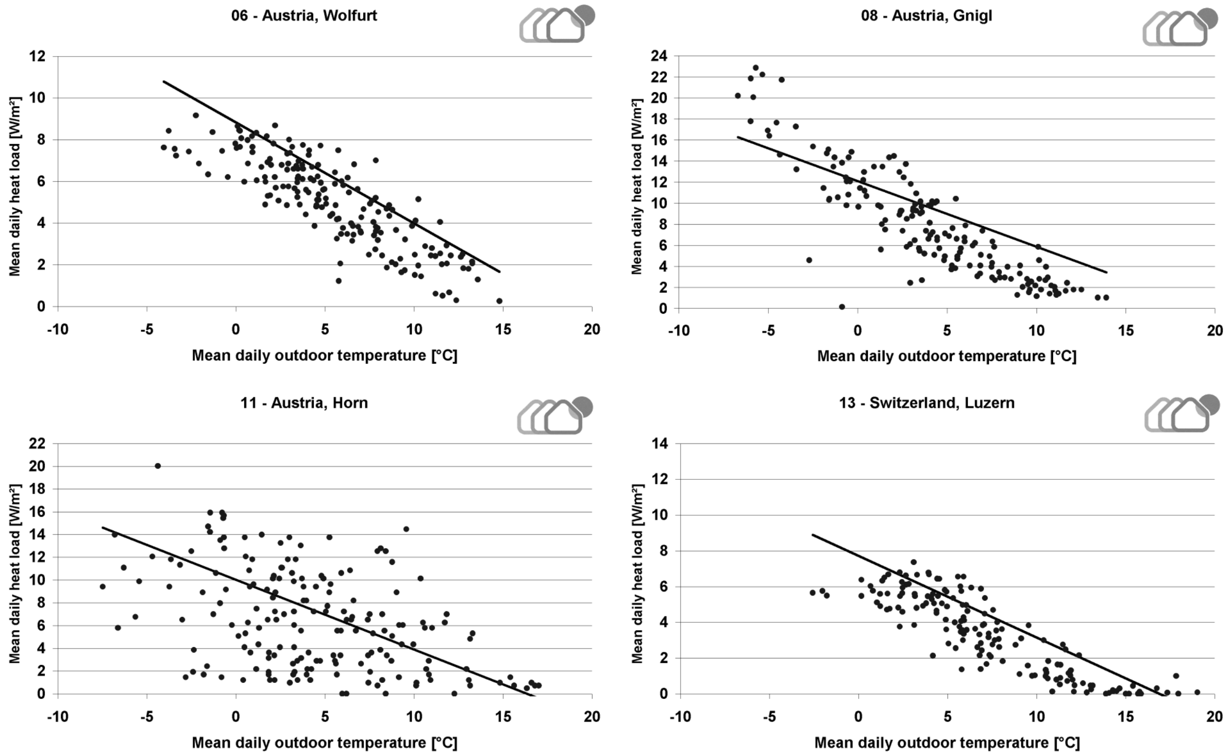

Figure 8. *Correlation between mean daily heat load and outdoor temperature. The straight line is the theoretical heat load on the basis of building-specific heat losses, internal gains and measured mean indoor temperatures.*

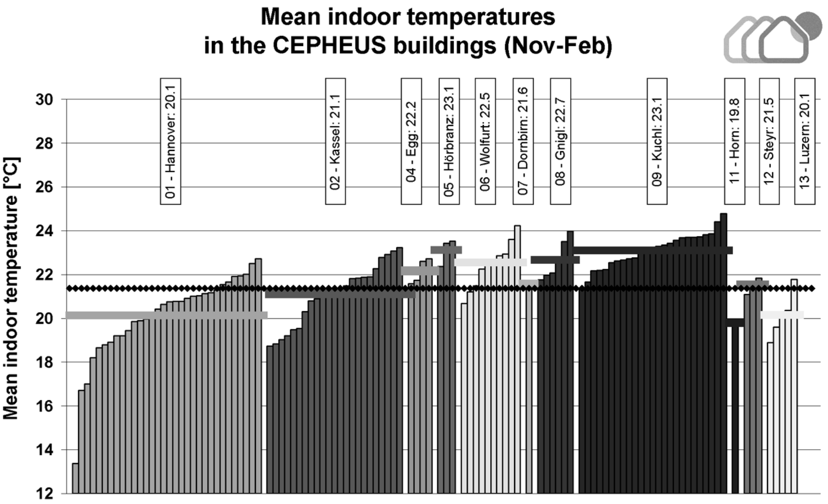

Figure 9. *Mean indoor temperatures in winter (generally from 1 November to 28 February).*

Indoor temperatures in summer

Due to the truncated measurement period, data for the summer were only available for few projects. For 01-Hannover, it should be noted that 8 of the 32 houses were unoccupied during the measurement period or were not used for residential purposes.

Summer indoor temperatures are of particular interest: Would the excellent thermal insulation and optimized passive solar energy use perhaps lead to overheating in summer? Figure 10 presents the mean indoor temperatures between 1 May and 31 August. The figure further shows for each house the temperature that was not exceeded for 95% of the time in the stated months. This latter value is a better measure of summer-time comfort than the maximum temperature reached, as individual temperature peaks can occur in the absence of occupants or in exceptional situations and are thus not representative.

The results show that the summer-time indoor climate in 01-Hannover and 02-Kassel is acceptable. Mean temperatures are far below 25 °C in most of the dwelling units; a temperature of 27 °C is only exceeded in exceptional cases. The peak values in Hannover were even subject to conditions that explain the relatively high temperatures. E.g., the house with the highest 95th percentile was heated during the studied summer period due to a control system malfunction; in the four months, 9.2 kWh/m^2 were consumed for space heating.

09-Kuchl has about 1 K higher temperatures. In some dwelling units even the mean summer temperatures range significantly above 25 °C. On the other hand, room temperatures in Kuchl are relatively high in winter, too: the mean temperatures in summer are only 1.8 K higher than those in winter.

The measurement results show clearly that summer temperatures in Passive Houses can be kept in a comfortable range. On closer examination of the temperature curves it was found that the users can attain highly comfortable summer-time temperatures through appropriate ventilation behaviour. Occupancy ratios and shading elements are important, but are secondary to ventilation behaviour. These issues are discussed in greater detail in [Peper 2001].

USER ACCEPTANCE

The high level of user acceptance among Passive House occupants is illustrated very clearly by the findings of the social science evaluations conducted in 01-Hannover and 02-Kassel.

The results reported in [Danner 2001] and [von Oesen 2001] show the high degree of acceptance in the Hannover-Kronsberg Passive Houses. Satisfaction with the indoor climate in winter is stated by a substantial majority of occupants as good to very good. Not a single occupant gave a negative rating. Moreover, the higher surface temperatures and the even temperature distribution throughout the space (no temperature stratification) compared to 'normal' houses are experienced as highly pleasant. For summer, too, the occupants confirm the measurement results – 88% of those surveyed state that they are satisfied or very satisfied with the indoor climate in summer. Air quality is rated by 95% of occupants as good to very good. Not a single occupant gave a negative rating. When asked about their satisfaction with their ventilation system, there was not a single negative assessment of the ventilation system with heat recovery.

In Kassel-02, the question was posed before and after the first heating season whether the users would recommend Passive Houses to others. Figure 11 illustrates very well the exceedingly high level of user acceptance in rental housing, too. Importantly, the substantially more positive assessment after the first heating season shows that initial scepticism has been dispelled by the experience made in the first winter with the pleasant and comfortable indoor climate.

PROOF OF COST-EFFECTIVENESS

The improved construction quality of the building envelope and the highly efficient ventilation systems in Passive Houses require extra investment. If the approach is pursued rigorously, this is counterbalanced by investment cost savings for the no longer necessary conventional heating system. However, in most sub-projects of CEPHEUS it was not possible to reduce the overall costs of building services. In total, the extra construction and engineering system investment was found to be between 0 and 17% of the pure construction

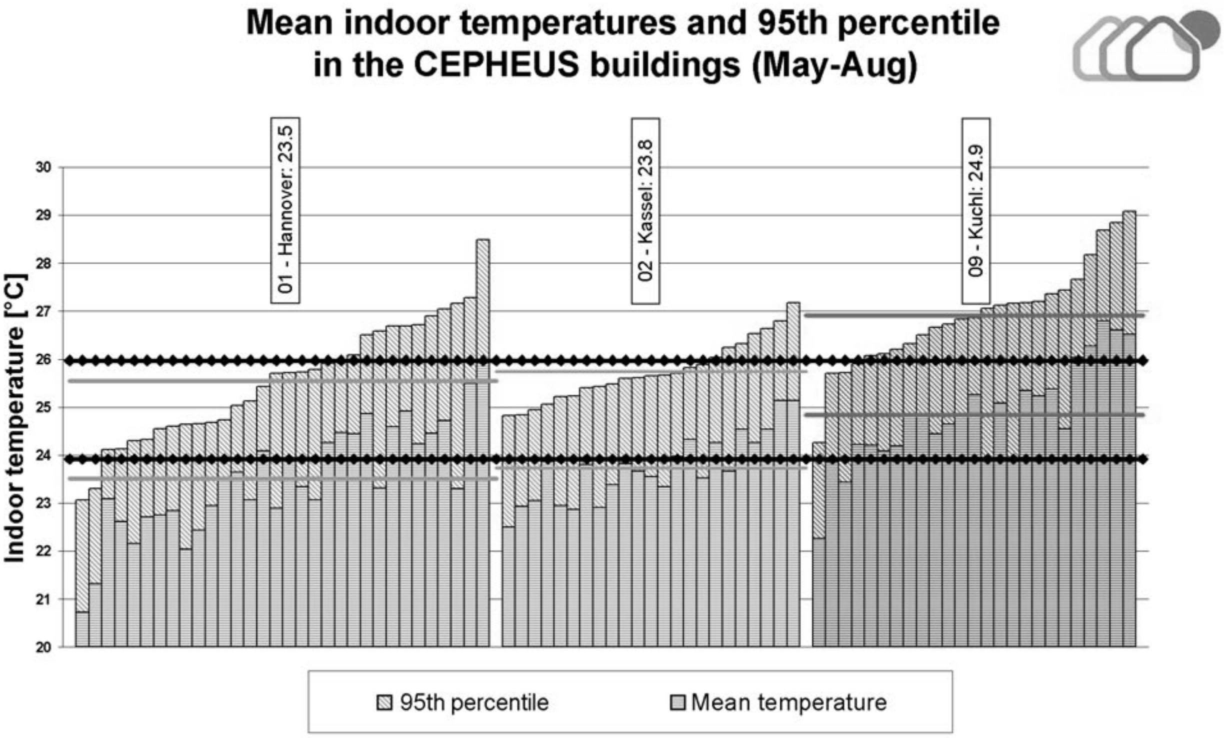

Figure 10. Mean indoor temperatures from May to August and 95th percentile of hourly mean values of average house-specific indoor temperatures for the 01-Hannover, 02-Kassel and 09-Kuchl projects. The black lines cutting across the projects represent the overall mean values of the three sites.

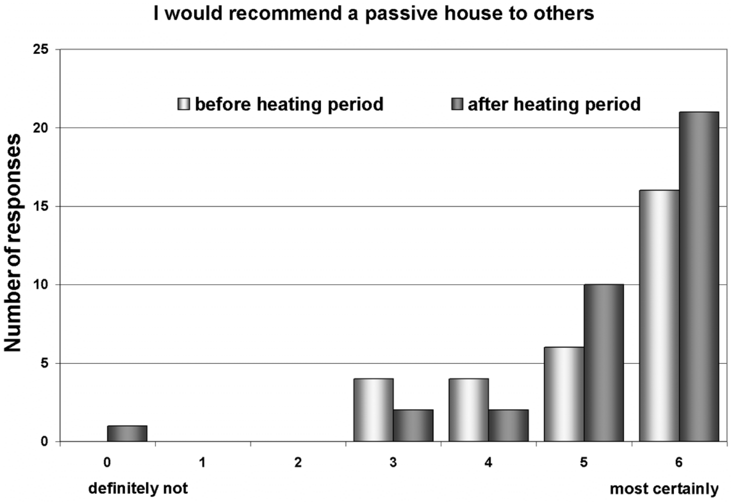

Figure 11. Results of a social science evaluation in the publicly-assisted rental housing construction sub-project in Kassel/Germany. Figure from [Hübner 2001].

costs. On average over 12 projects, the specific extra investment cost is 91 Euro/m² or 8% of total building cost.

A good measure for economic appraisal is provided by determining the costs of the energy conserved. For this, the extra investment for the efficiency technology and the solar thermal installations is levellized across 25 years of service life at 4% real interest; to this is added the additional operating cost of the Passive House components. By dividing the annual costs thus determined by the annual fuel savings, we receive a sum per kilowatt-hour saved. This ratio is well suited for comparisons with the present or potential future costs of energy supply.

The cost of the heat saved in Passive Houses determined in this way averages across the 12 projects at 6.2 Cent/kWh. This compares with present reference costs of final energy averaging 5.1 Cent/kWh. Compared to the typical cost of solar thermal heat, which is currently 10 to 15 Cent/kWh, this is a very favourable value – and all the more so with regard to potential energy price increases across the long service life of buildings.

By analysing the development of investment costs it is expected that within a few years building passive houses will be economical even at present energy prices.

Conclusions

Passive Houses are buildings in which the space heat requirement is reduced by means of passive measures to the point at which there is no longer any need for a conventional heating system; the air supply system essentially suffices to distribute the remaining heat requirement. The space heat requirement of the houses as built averages about 15 kWh/(m²a).

This is less than 20% of the energy requirement mandated by the building regulations currently in force in the participating countries.

CEPHEUS has tested and proven the viability of the Passive House concept at the European level. In Germany, Sweden, Austria, Switzerland and France, a total of 221 housing units in 14 building projects have been built to Passive House standards and are now occupied. The project demonstrated the functional viability of the Passive House concept at all sites, the actual achievement of the space heat savings target, practical implementability of Passive Houses in a broad variety of building styles and constructions, project-level economic viability and a high degree of satisfaction of building occupants.

The Passive House technology has triggered a fresh burst of innovation in the construction industry. Passive house components are available from an increasing number of manufacturers. CEPHEUS has made publicly accessible all experience gained and the key planning tools for the Passive House concept. Today, every architect in Europe can implement Passive Houses.

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The majority of the numerous reports on the CEPHEUS project are in German. By the date of publication of this paper, the English version of the final report, on which part of this paper is based, should be available as a PDF-file from www.enercity.de.

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