Cost Efficient Passive Houses in Central European Climate

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ABSTRACT

Passive houses are buildings in which a **high level of comfort can be achieved without a separate heating system** or air-conditioning system.

A prototype passive house has been occupied by four families since October 1991; it requires so little space heating (less than the equivalent of 160 m^3 natural gas per year for each dwelling with 156 m^2 living area), that it was indeed found possible to dispense with a dedicated heating system. The results of the research projects on the prototype passive house are presented, including comparison of measurement results with computer simulations.

In a passive house, largely passive techniques are employed to keep the interior climate comfortable: U-values of the buildung fabric $<0.15W/(m^2K)$; thermal brigdes reduced to almost 0; airtightness $n_{50}<0.6$ ac/h; air-to-air heat exchangers with $\eta>80\%$; insulated window frames and special 3-pane glazing give a total $U_w<0.8W/(m^2K)$ while energy-transmittance is kept >50%; latent heat recovery from exhaust air; highly efficient low energy household appliances.

The sum of space heating, domestic hot water heating and household electricity is extremely low, <42 kWh/(m^2a). This is about one quarter of the average consumption required by present building regulations for new buildings in Germany.

The passive house technology is suitable for use in cost efficient buildings; more than 50 passive houses were built in 1997 at low costs; in 1998, settlements of some 100 cost efficient passive houses in different designs will be built.

Passive Houses: No need for active heating and cooling

Passive houses are buildings in which a high level of comfort is achieved in winter and in summer without a separate heating system or air-conditioning system - the house 'heats' and 'cools' itself purely 'passively' [Adamson 1987] [Feist 1988]. In a passive house, largely passive techniques are employed to keep the interior climate comfortable: Good thermal insulation, passive use of solar energy by means of "superglazing", highly efficient recovery of heat from the exhaust air, and passive preheating of the supply air. This may be further supplemented by an active solar support of domestic hot water heating.

Theoretical feasibility of the passive house

A house cools to the extent to which it loses heat. In the passive house, this heat loss is reduced to such a low level that the free heat suffices to offset the losses. Computer simulations have shown that this indeed works in Central and Northern European latitudes (fig.1) [Feist 1993].

Practical feasibility of the passive house: Built prototype

The first house without need for a heating system in Germany was built in 1991 with the support of the state of Hessen in Darmstadt-Kranichstein [PHI 1997], which was designed by the architects Prof. Bott/Ridder and Westermeyer (fig. 2). The house has been occupied by four families since

October 1991 - it requires so little 'stand-by heat' for space heating (less than the equivalent of 160 m³ natural gas per year for a dwelling with 156 m² living area), that it was indeed found possible to dispense with a dedicated heating system. The results of the research projects on the prototype passive house are compiled below.

A low energy requirement for space heating can, however, also be achieved by 'consuming' large amounts of electric energy. This would not be in the interests of the objective of keeping the use of non-renewable energy as low as possible. Therefore a passive house is a building whose total specific energy consumption does not exceed 42 kWh/(m²a) under normal conditions of occupancy. A total energy performance ≤42 kWh/(m²a) means that a passive house can provide all the typical domestic energy services (space heating, domestic hot water, lighting, cooking, TV etc.) with a smaller energy usage than is currently used in an average household alone for electricity.

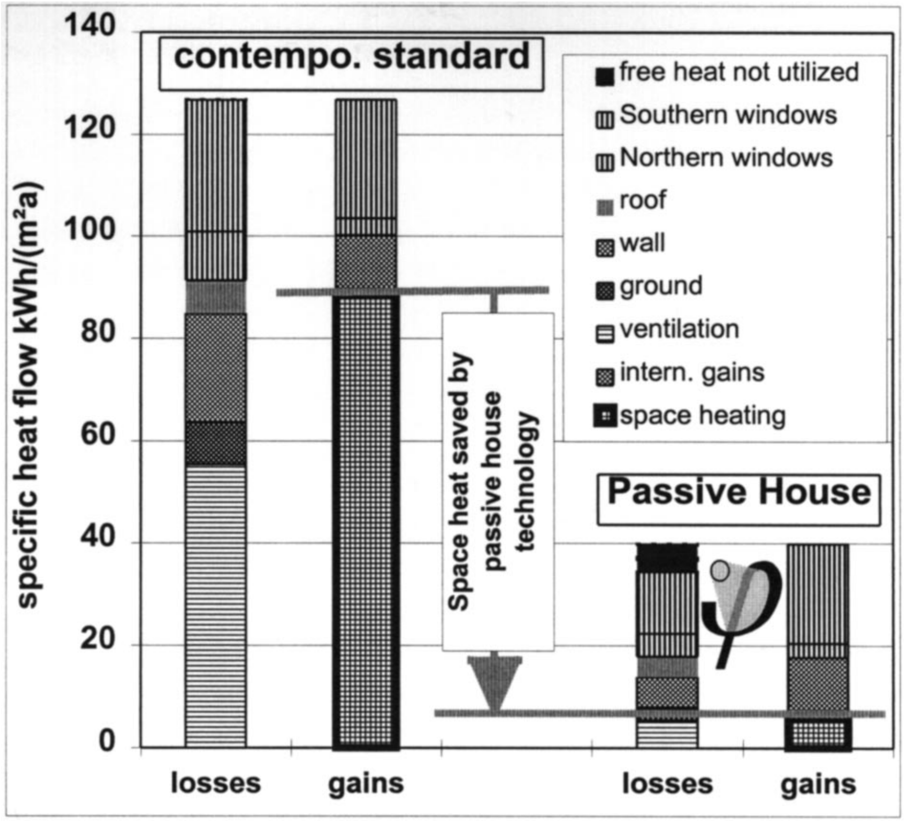

Fig.1: Energy balances of a standard house (left: 1991 German building code for new houses) and the passive house (right)

Passive House Technologies

Energy efficiency technologies have a decisive benefit: No further elements are required in addition to a conventional building: it is only necessary to construct the components that are used in any case (floors, outer walls, windows, roofs and ventilation) to high quality standards.

On the other hand, the ever greater reduction of heat losses does require increased investments. In-depth analysis has shown that the optimum thermal insulation of new buildings is achieved roughly at the level of the low-energy house standard (i.e. ~70 kWh/(m²a) specific annual heat requirement).

A passive house, however, requires substantially better thermal insulation - how can this then be justified? The decisive point is this: If efficiency is improved to such a degree that the ***remaining heat requirement*** of the house is not zero, but ***so low*** that a ***conventional separate heating system can be dispensed with*** without loss of comfort to the occupants, then the absence of the necessity to invest in heat distribution and radiative systems provides a downwards cost leap that finances the superinsulation measures inclusive of superglazing and high-efficiency heat recovery (fig. 3).

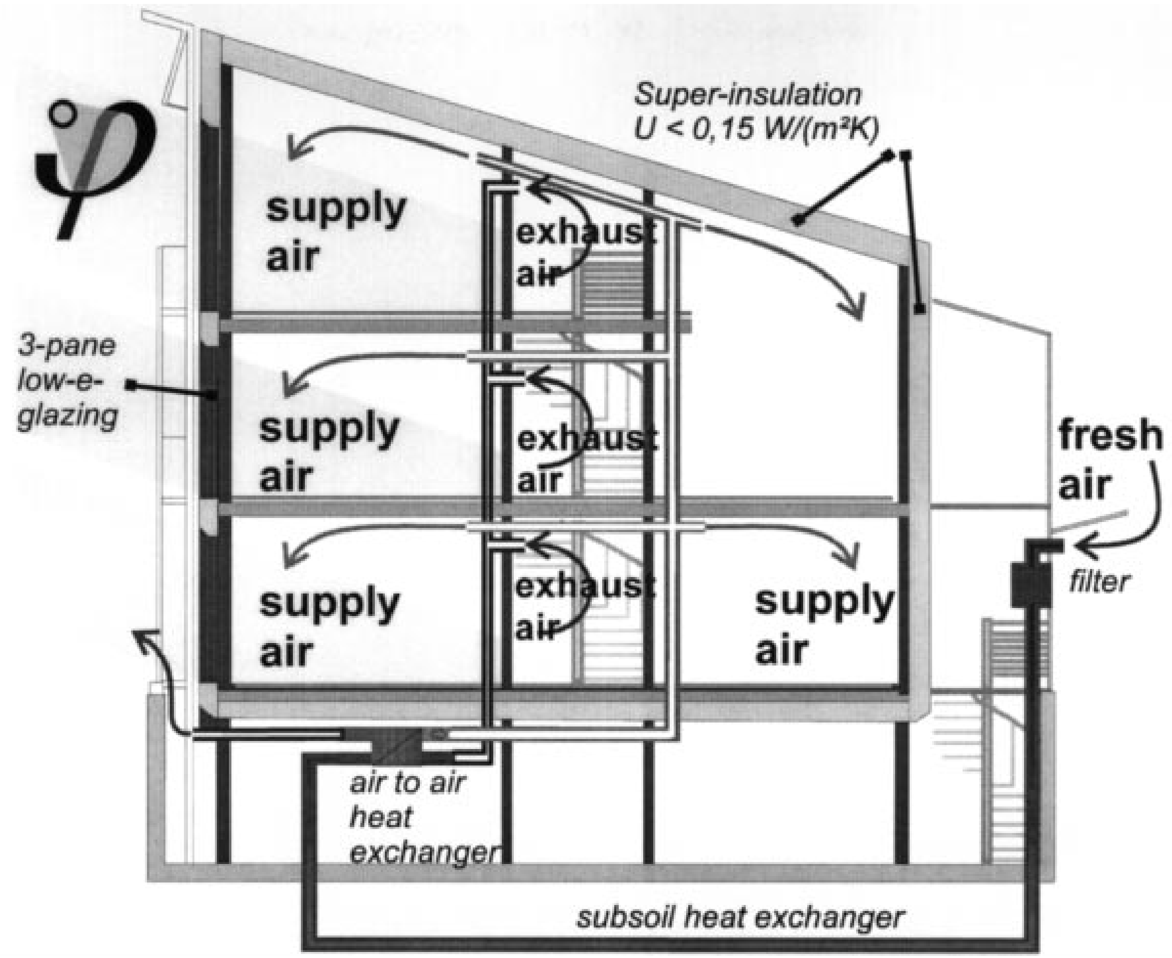

*Fig. 2: **Cross-section through the Darmstadt-Kranichstein passive house.** The closed thermal envelope has high insulating properties. The cross-section also shows how the ventilation system is channelled: Outside fresh air is drawn in via a filter box, then preheated in the subsoil heat exchanger and conveyed after flowing through the counterflow heat exchanger to the living rooms on the northern and southern sides of the house. Stale air is extracted centrally from the bathrooms, WC and kitchen, and exhausted outside after heat recovery.*

Without heat recovery from exhaust air houses do need a separate heating system in Central and Northern Europe. Heat recovery presupposes a channelling of the supply air and the exhaust air. If the supply air must be channelled, then it also offers itself as a heat transport medium. A certain amount of 'supplementary heat' can be distributed via the supply air if the following conditions are observed:

- Air must not be recirculated.
- The supply air must not be too warm at its outlet point (<33 °C).
- The supply air mass flow rates must not be raised above the amount necessary for satisfying indoor air quality, as otherwise the room air will become too dry. Under standard operating conditions, the volume flow will be about 30 $m^3/(h \cdot person)$ or about 140 m^3/h for a whole house. These values have proven themselves in the operation of the passive house prototype in Darmstadt-Kranichstein.

From these considerations follows the maximum heat load that can readily be transported with the supply air in a passive house. In Central European climate this heat load corresponds to a permissible annual heat requirement of 15 $kWh/(m^2a)$ - a value that is achievable with innovative technologies described in the following (the prototype in Darmstadt has achieved 10 $kWh/(m^2a)$ (measured)).

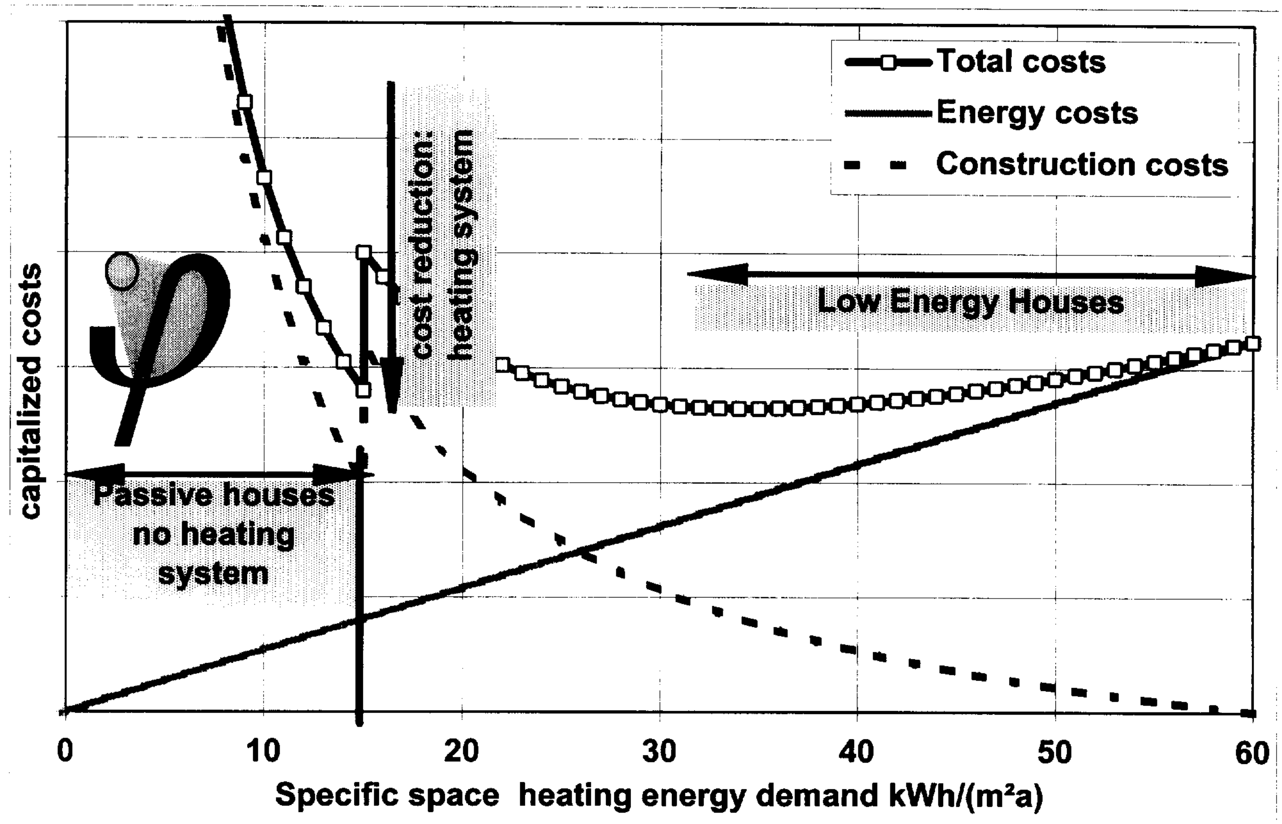

Fig 3: cost reduction by passive house technology

Superinsulation with U-values around 0.1 W/(m²K)

Experience has been available for some time with high-insulating building elements with U-values around 0.1 W/(m²K), in particular in Scandinavia and Canada. While the effectiveness of these elements is indubitable against the background of this experience, these thickly insulated building envelopes are generally customized products frequently involving a substantial design and craft workload. Innovative cost-effective serial production technologies are therefore decisive for the broad implementation of high-insulating building elements, and particularly for passive houses.

Construction without Thermal bridges

All connections in Passive Houses are optimised with the objective of minimising thermal bridges at economically acceptable cost. The goal of thermal bridge optimisation is to reduce the additional linear or point-shaped bridges nearly to the geometrically unavoidable level: with reference to outer surfaces, the thermal bridge loss coefficients are then close or equal to zero (Ψ<0.01 W/(mK)).

Airtightness

The importance of airtightness has already become apparent in low-energy house design [Carlsson 1980]. With a highly efficient heat recovery (η~80%), it is immediately clear that the uncontrolled infiltration of air through cracks in the building must be cut to insignificant levels. The n_{50} pressurization test ventilation rate must not exceed ***0.6*** $\boldsymbol{h^{-1}}$ in houses without heating systems. This is only about half the rate required in the corresponding Swiss standard.

Table 1: Overview – low-energy technologies used in passive houses (Central European climate)
The conventional reference house is a new construction according to 1991 German building code.

	Parameter	Conven-tional house	Passive house - without separate heating system
Superinsulation [IEA 1997] For the required reduction of fabric heat losses, insulation thicknesses of 25 – 40 cm are necessary; innovative load-bearing constructions, prefabrication	U-value [W/(m²K)]	0.2 to 0.5	< 0.15
Thermal bridge reduction All building element connections specially optimized	Ψ-value [W/(mK)]	0.1 to 0.5	< 0.01
Airtightness [Carlsson 1980] Compared to a conventional house, airtightness must be substantially improved in a passive house. This requires careful workmanship of details.	Pressurization test n_{50}-value [1/h]	2 - 4.5	< 0.60 (upper limit)
Subsoil heat exchanger The fresh air is preheated in tubes buried in the subsoil.	Preheating of air [°C]	-	Fresh air temperature > 8°C
Ventilation for indoor air quality Optimum concept for air flow through house, with incoming fresh air in living rooms and bedrooms, and exhaust air extracted from bathroom and kitchen.	Optimum indoor air quality [ppm CO_2]	-	< 1000 ppm CO_2
Heat recovery [Feist/Werner 1994] The energy content of the exhaust air is passed to the cold fresh air by means of counterflow heat exchangers with high-efficiency recovery.	Recovery rate of unit	-	> 80%
Passive solar energy utilization Southern (± 30°) orientation of principal facade with large glazed areas. As little as possible shading of the passive solar apertures (windows).	Optimized glazed area, minimized shading	-	passive solar > 33%
Windows [Feist 1993; 1998] Newly developed innovative 3-pane glazing with low U-value and high solar transmittance factor. Newly developed superinsulated window frames.	U-value Solar transmittance	1.4 57%	0.60 - 0.80 orientation of major parts ±30° South 50 to 60 %
Active solar energy utilization Newly developed cost-efficient flat plate collectors integrated in facade.	U-value ε-solar	-	2.5 W/(m²K) 90%
Innovative compact building services Latent heat recovery from exhaust air after subsoil heat exchanger by means of small heat pump as monovalent space heating and water heating system	COP compressor	-	> 3
Household appliances [Nørgård 1989] Careful selection of energy efficient household appliances such as dishwashers, refrigerators etc.	Electricity consumption of stationary appliances	-	more than 50% savings compared to standard appliances

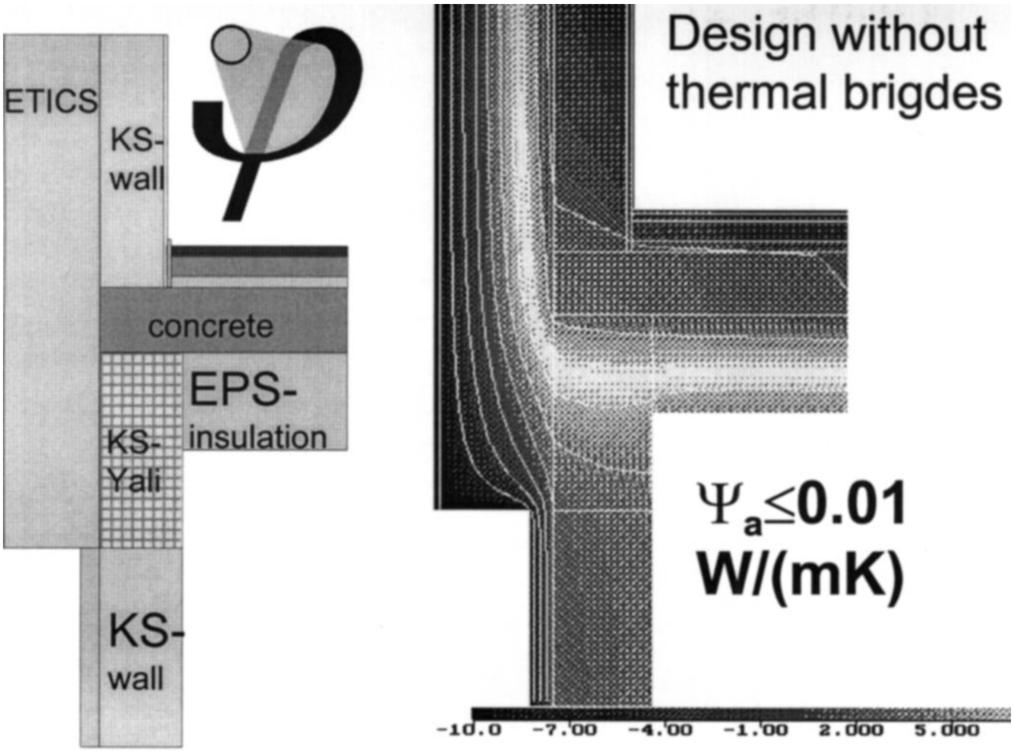

Fig. 4: Example of a thermal-bridge-reduced building element connection in the Darmstadt-Kranichstein passive house

Subsoil heat exchanger

On the basis of present energy prices and those to be expected in the future, seasonal energy storage can generally be seen as a very costly component if the annual storage must be built, insulated and technically linked up - unless a storage medium can be used that is available at the building site and which can be developed and utilized without substantial building efforts. ***The soil below the building*** is such a medium. It offers seasonal heat storage for thermal solar energy which is 'automatically' charged in summer through ambient heat and irradiation without any technical components, and which can be utilized in winter in a simple and cost-effective manner to ***preheat the fresh air***. To this purpose, sealed air ducts are laid in sufficient depth (more than 1 m) below the house, through which the fresh air is heated to roughly the temperature level of the subsoil prior to entry into the counterflow heat exchanger. This principle has already proven itself in the first passive house prototype in Darmstadt-Kranichstein; the measured fresh air temperatures after flowing through the subsoil heat exchanger were never below 8°C. This not only provides further energy gain, but also ensures that the counterflow air-to-air heat exchanger cannot freeze up at the exhaust air side. In addition, the temperature of the exhaust air is always above some 10°C, thus making it possible to employ the compact heating system for passive houses using a small heat pump described in the section “compact building service system” below.

Ventilation for indoor air quality

It is generally accepted today that controlled ventilation is essential to good indoor air quality [Feist 1995]. Experience in Sweden, Denmark, France, Germany and Switzerland indicates that a simple exhaust ventilation system generally suffices in **low-energy houses**. In a **passive house**, however, it is indispensable to have a system incorporating heat recovery. Such a ventilation system must establish a balance in the house between the incoming and outgoing air mass flow; any deviation from this balance leads to continuous in- or exfiltration through the building fabric. The untreated fresh air is conveyed to the inflow zone rooms, where the best air quality prevails: living room, children's room, bedroom. From there, the air passes through an overflow zone. The exhaust air is extracted in the damp rooms (kitchen, bathroom, WC), so that the directed air flow prevents odours and humidity from spreading in the dwelling.

High efficiency heat recovery

In the first passive house prototype in Darmstadt-Kranichstein, a high-efficiency counterflow air-to-air heat exchanger has proven itself [Feist, Werner 1994]. This has a measured heat recovery rate of more than 80%. Pilot projects have shown that an input power consumption of less than 0.4 Watt/(m^3/h) suffices to transport the supply and exhaust air in a properly-sized system. This corresponds to an annual electricity consumption of 200 to 400 kWh/dwelling. There is, thus, no need to debate the issue of a 'natural drive' of the controlled ventilation, as the heat recovered by such an efficient system is, at 3000 to 4000 kWh/a, larger by about the factor ten than the input power.

This high-efficiency heat recovery with minimized input power is made possible by using electronic commutated d.c. ventilators.

Passive solar energy utilization

The windows of the passive house are in effect solar collectors: The passively gained solar energy represents the main input-contribution in the energy balance (see fig.1).

If we have a building which (thanks to whatever principle it may apply) needs an extremely low level of active supplementary heating, then in Central and Northern Europe such a house will no longer have any heat consumption at all in any case during the summer and transitional seasons (i.e. from March through to November). The residual consumption is determined by the core months of winter: December, January and February. Unfortunately, the solar gains during this core period of Central European winter are small. A further climatic problem is that in the months with low irradiation the outside temperatures are also low. This makes the heat losses in this period the highest. Even the best translucent building elements (glazing) today still have substantially higher U-values than opaque elements; typical values for a superinsulated house are $U_{Wall} = 0.15$ and $U_{Glazing} = 0.7$ W/(m^2K). Glazed areas enlarged for the purpose of passive solar energy utilisation thus unavoidably also lead to larger losses. The above shows that what is decisive is solely the balance between the utilisable solar gains and the additional heat losses - in the core period of winter:

- The heat losses of the transparent areas, too, must be kept low: This calls for high-performance glazing with a high solar transmittance factor, **and** with a low U-value.
- The other losses associated with glazed areas must be kept low: Thermal bridges through the sealing around the panes and through the window frames etc..
- During winter months the solar gain through the relevant transparent areas must not be blocked.

The curve shown (fig. 5) here was calculated with the DYNBIL dynamic simulation model for the passive house in Darmstadt-Kranichstein. The validity of the simulation is ensured by the comparison with the measured values received later from the passive house. With conventional double glazing no net solar gain can be made in the passive house in Europe. At least a certain solar effect can be achieved with the 2-pane low-energy glazing predominantly used today in low-energy houses – gains occur, but lost back through the glass. Net passive solar gains occur during winter months, however, when high-performance 3-pane low-energy glazing (with krypton filling - also termed "superglazing") is used. With large, south facing and largely unshaded windows of this quality, the annual heat requirement can be halved again compared with the merely opaque superinsulated house. It has been shown by the author, that this result does almost not depend on the heat capacity of the building in Central and Northern European climate.

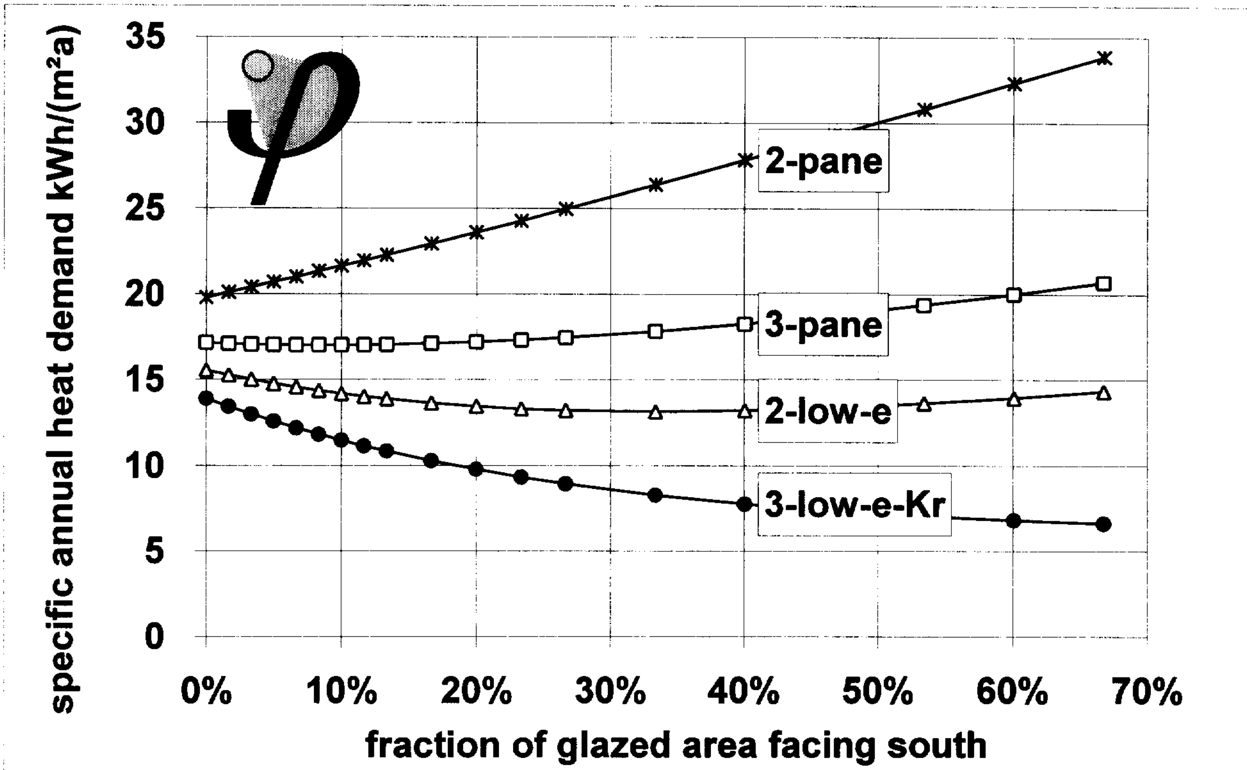

Fig.5: Dependence of residual heat requirement upon the proportion of glazing in the south facade (example: Darmstadt-Kranichstein passive house; Central European climate)

Innovative windows in the passive house: 3-pane low-energy glazing in superframes

The conclusion to be drawn from the last section is clear: The quality of glazing is in cold climates more important than its size [Feist 1993][IEA 1997]. Without pretending to be exhaustive, the following table gives an overview of types of glazing suitable for use in houses without heating systems in Central European climate.

Table 2: Types of Passive House Windows	**U-value of window [W/(m²K)]**	**Solar transmittance [%]**
2-pane low-e-glazing, wood frame **- generally unsuitable for passive houses, only as reference**	1.58	63
3-pane low-e-glazing/Krypton, wood frame	1.09	50
3-pane low-e-glazing/Krypton, "superframe"	0.70-0.80	50
innovative 3-pane glazing, "superframe", superspacer	***0.70-0.80***	***60***
3-pane low-e-glazing/Xenon, wood frame	0.88	41
3-pane low-e-glazing/Xenon, "superframe"	0.52	41
"Toptherm"	0.87	60
"HIT" window	0.60	40

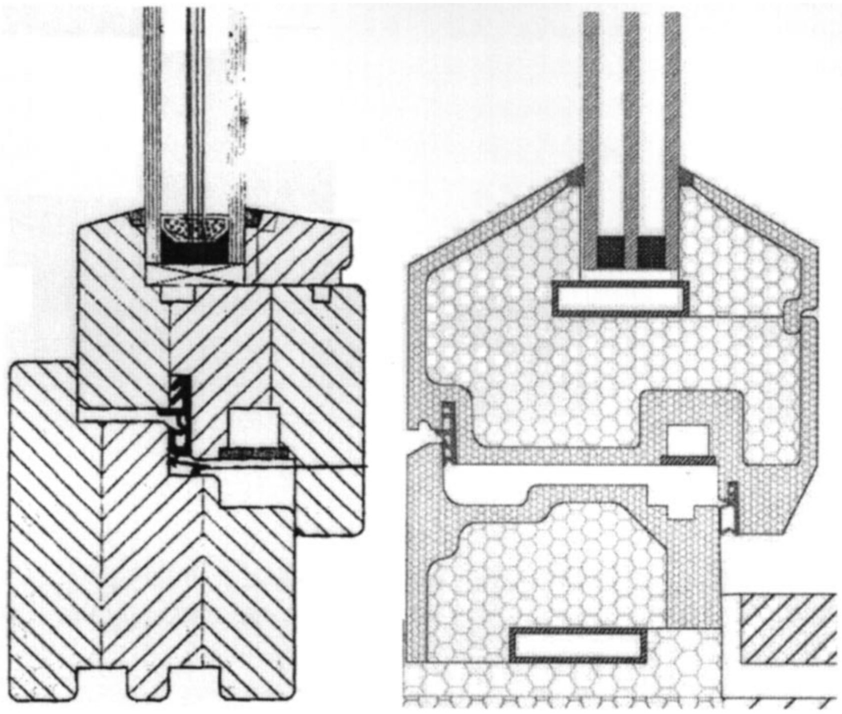

Fig. 6: Comparison: Superglazing in a standard wood frame (left) leads to a window U-value of 1.09 W/(m²K). With the special highly insulated "superframe" (right), a window U-value of 0.78 can be achieved [Feist 1998].

The comparison of glazing concepts lead to the development of a new 3-pane low-energy glazing with a particularly high solar transmittance, indicated in bold italics in the above table [Feist/Loga 1997].

All the positive effects of solar gains can be negated if poor window frames and thermal bridges in the window area raise the heat loss excessively. Conventional window frames have U-values ranging between 1.5 and 2 W/(m²K). The heat loss of 1 m² frame is thus more than twice that of superglazing. A further substantial thermal bridge is formed by the sealing around the panes. In order not to negate the solar gains by these additional losses, a window frame must be used that displays particularly high thermal performance. Fig. 6 gives a comparison between two windows - one with a conventional wood frame, and the other with the superinsulated "superframe" developed specially for passive houses.

Active solar energy utilization

In the Darmstadt-Kranichstein passive house prototype, a flat plate solar collector system supplies the four households with 60-70% of their domestic hot water demand. An active solar space heating contribution would only be possible in passive houses to any significant extent by means of a seasonal heat storage; a demand for supplementary heating only arises at all in passive houses in the months of November-February, in which in Central and Northern Europe the available solar gain is fairly small. The solar domestic hot water system in the passive house prototype is functioning according to plan. The active solar system displays the highest specific investment costs per saved kilowatt-hour of all components used in this building.

Compact Building Service System

The annual heat requirement in passive houses is indeed very low, but not zero. The heat consumption for space heating for a terraced house with 120 m² living area is at most 1800 kWh per year. Simulations and practical experience with built passive houses show that the maximum required heat load arising under these conditions on the coldest days is 10 watts per square metre living area. That means e.g. for a room with 20 m² a peak heat load of 200 watt - the output of two conventional filament lamps.

It is, thus, obvious that with the extremely low consumption levels and load a normal heating system would be completely over-sized and over-priced. It is precisely the possibility of dispensing with a conventional heating system that makes the standard of passive houses so interesting.

As the section "ventilation for indoor air quality" has shown, a ventilation system with heat recovery is indispensable in such a house without separate heating system. If we assume a supply air flow of 120 m^3/h under normal running conditions, then supply air volume suffices to transport the desired 1200 W if its temperature is raised by 30 K.

The heat input into the air takes place through a supplementary heating register (postheater) situated directly behind the air-to-air heat exchanger. After the register, the supply air duct must only run within the thermal envelope. A part of the heat is already emitted to the rooms through the supply air ductwork. The heat required for the supply air postheater could for instance come from the domestic hot water system.

A further possibility is to provide the heat by means of a small, efficient heat pump (annual COP >3; see fig. 7). The exhaust air after the air-to-air heat exchanger serves as heat source for the heat pump. If, as is recommended, a subsoil heat exchanger is used, then the temperature of this exhaust air never drops below 10°C, even on the coldest days. Moreover, the exhaust air contains the entire latent heat of the water vapour released within the house; if the exhaust air is cooled down to a temperature of 2 °C, then a total of 500 to 800 W heat output can be extracted from this source. A very simple, integrate system thus becomes possible for ventilating the dwelling and at the same time covering the supplementary heat requirement in a passive house: A small compact compressor as commonly used in refrigerators (electric rating: 300 W) extracts heat from the exhaust air, and this heat is passed to the supply air - there is no need for any further heat sources.

The described compact unit achieves a total electricity consumption level for space heating of less than 600 kWh/a. This is not substantially more than the auxiliary power consumption normally encountered in other heating systems.

In the passive house, the energy consumption for water heating is the largest individual item. Depending upon the demands of a family, the useful heat requirement for domestic hot water in a household ranges between 1,500 and 5,000 kWh/a. This is frequently increased by a further 1,000 to 3,000 kWh/a of heat losses from storage, supply and circulation lines and feeder lines.

An interesting hot water supply variant for the passive house is to install an efficient domestic water heat pump (annual COP > 3) that uses as its heat source the exhaust air after the air-to-air heat exchanger (Fig. 7). Over the greater part of the year, this exhaust air has temperatures above 15 °C, and provides a total source heat flow of 500 to 800 W. It is thus possible to provide the entire hot water, even for high demands, with an electric power input between 500 and 1500 kWh/a. A first series of such a system has been produced by an Austrian company and tested by the Freiburg Fraunhofer Institute [Bühring 1998].

The compact heat pump system described above is just one of many options available to meet the extreme low heat requirement of passive houses; others are e.g.: postheating of the supply air by a small gas furnace; use of heat from a district heating system; central heating with biomass-based fuels.

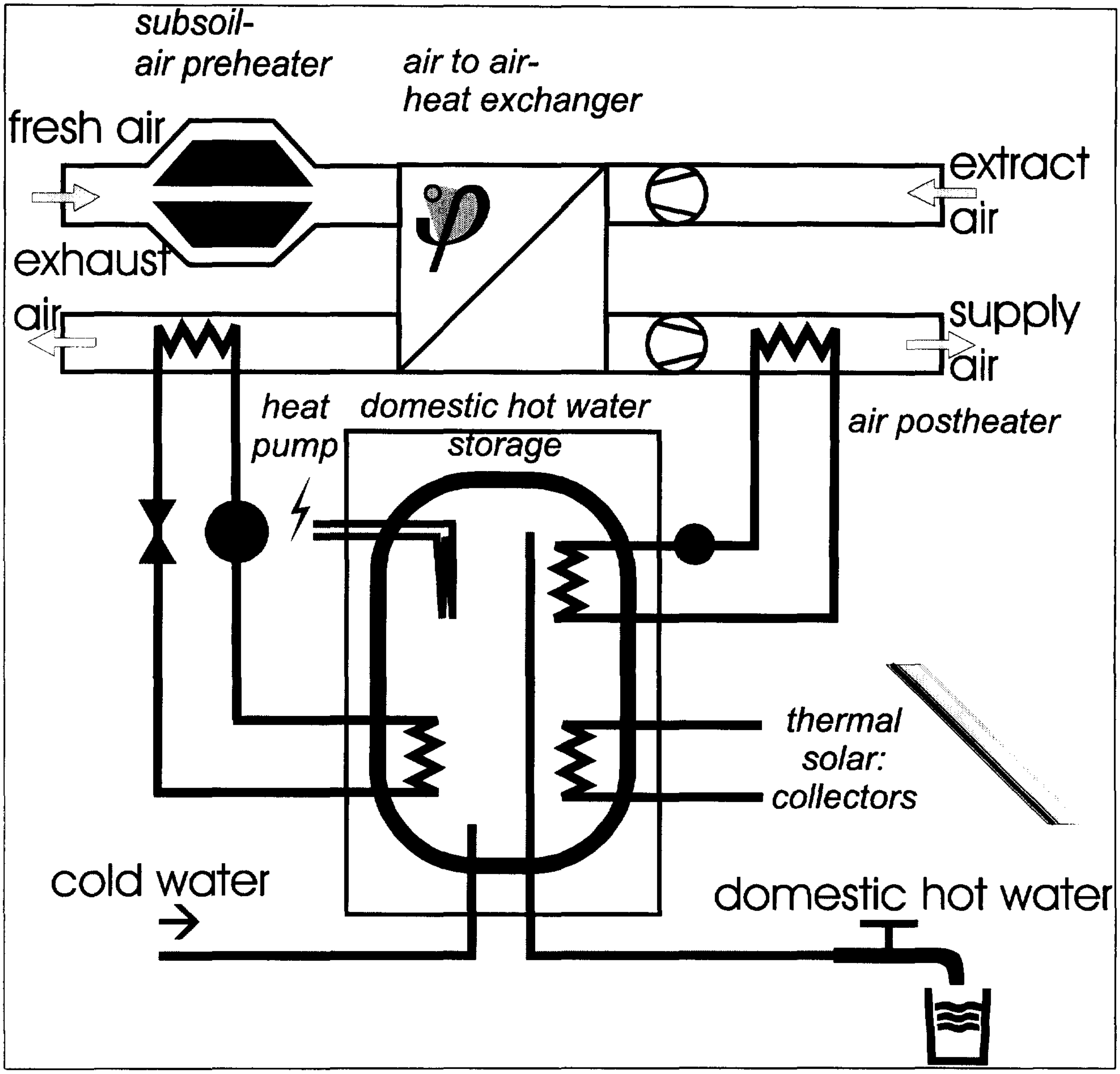

Fig. 7: Compact building services system for passive houses

High efficiency electric household appliances

If the energy consumption for space heating and domestic hot water is so reduced as is the case in passive houses, then the electricity bill becomes the dominant part of the consumption costs. As with space heating, the energy consumption of residential electricity end-uses can be greatly reduced by means of efficient appliances [Nørgård 1989].

On average, a German household consumes about 32 kWh/(m^2a) household electricity (totally, without space heating). In the first built passive houses in Darmstadt-Kranichstein, the monitoring showed a reduction of this household electricity consumption to less than half, although the four households are equipped with all the large appliances commonly encountered today [Ebel 1996].

- refrigerator with less than 100 kWh/a
- comprehensive daylighting concept,

- compact fluorescent bulbs with electronic ballast,
- power packs with minimized standby consumption,
- connection of washing machines and dishwashers to the hot water piping.

A high efficiency of electric appliances in the passive house is also desirable because of the associated avoidance of high internal heat load in summer: it is then easier to keep the interior climate comfortable during very hot weather.

The Darmstadt-Kranichstein passive house research and demonstration project

Design, construction and occupation

The average total final energy consumption for four dwellings in the passive house for household electricity, fan operation, domestic hot water and back-up heating amounts to less than 32 kWh/(m²a)(measured), and is thus lower by about a factor of ten than the German average (Fig. 8).

The construction of this house was financially supported by the Hessian Ministry of Environment. The building, with its four terrace-type dwellings (Fig. 2), was completed in October 1991, and has been inhabited since that time by four families. The basic concept of the house is based on uncompromising conventional thermal insulation (cf. Table 3), optimized passive solar energy utilization and highly efficient heat recovery from the exhaust air. The house is fitted with an EDP-based measurement data registration system. The „ebök" engineering consultancy (Tübingen) was commissioned by the Wüstenrot Stiftung Deutscher Eigenheimverein e.V. foundation and the Hessian Ministry of Environment to perform the measurement programme. The evaluation of five years of measured data (cf. table 4) shows the house to fulfill the expectations with regard to energy efficiency. Compared to **the average of German dwellings**, the measured consumption for heating is down to about **one twentieth**, and the total final energy consumption for space and water heating and household electricity is down to about 10%.

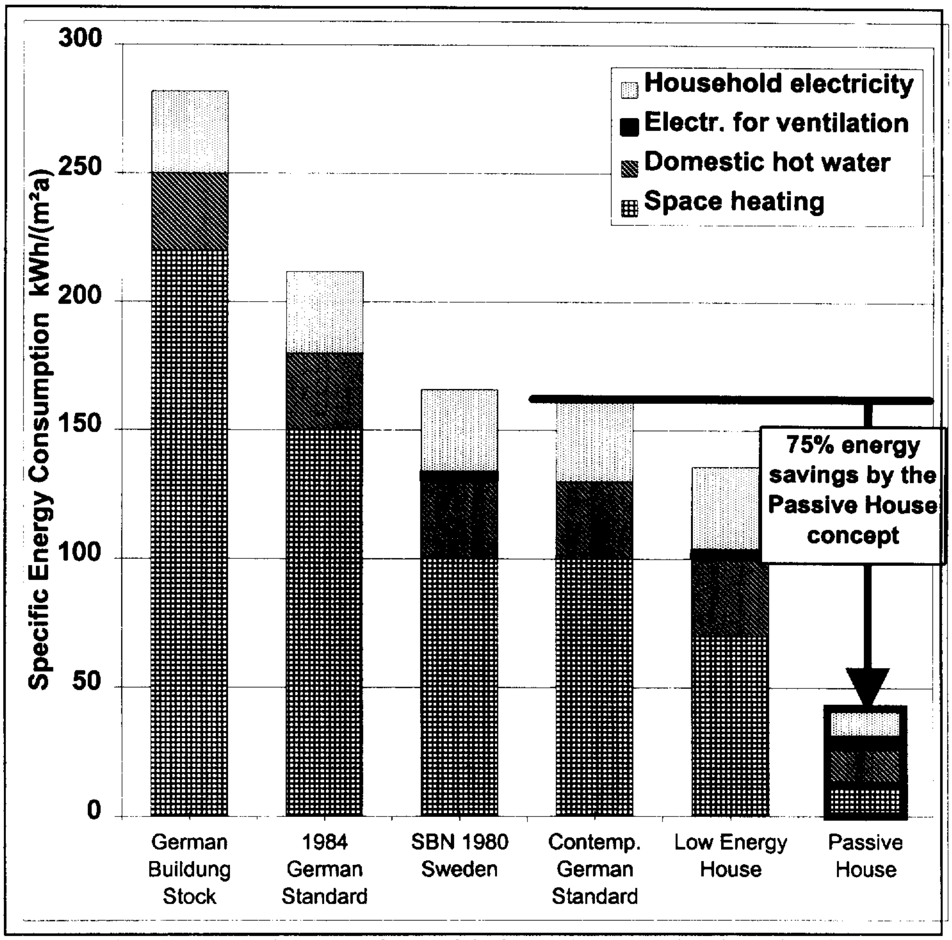

Fig. 8 Comparison of energy demand indexes (measured values for the passive house)

Table 3 Construction of the Darmstadt-Kranichstein passive house

Element	Description	U-value
Roof	Grass roof; filter medium; root-protectant foil; formaldehyde-free chipboard; I-section timber beams (hardboard web); battens; **seamless airtight polyethylene foil**; gypsum plasterboard; wood-chip wallpaper, water paint; cavity (445 mm) fully filled with **mineral wool**	0.1 W/(m²K)
External walls	Mineral cast; 275 mm rigid expanded polystyrene; 175 mm sand-lime blocks; 15 mm interior gypsum plaster throughout; wood-chip wallpaper, water paint	0.14 W/(m²K)
Basement ceiling	Flat coat on glass cloth; 250 mm rigid expanded polystyrene board; 160 mm normal concrete; 40 mm polystyrene footstep insulation; 50 mm cement screed; 8-15 mm rod parquet, bonded; solvent-free seal	0.13 W/(m²K)
Windows	3-pane low-emissivity glazing with krypton filling. Timber frames with insulating PU mouldings (CO_2-foamed, CFC-free)	0.7 W/(m²K)

A look at the cross-section (Fig. 2) shows the good thermal insulation wrapped around the building without any penetration or other disturbance. The southern facade has large windows with excellent glazing quality, which effectively serve as passive solar collectors. A highly efficient heat recovery ventilation system is used, which conveys supply air to the living rooms and extracts spent air from the kitchen and bathrooms. This description already names all of the decisive components of the passive house: There are no other mysterious or complicated elements.

The goal of the **"Electricity Saving in the Passive House"** demonstration project was to prove with the technology already available today that the electricity consumption for household energy uses can be cut to a third of the values encountered in comparable households, and the additional gas consumption for heat substitutes to less than 15%. The measured electricity consumption as a function of living floor space figures **11.65 kWh/(m²a).** With a reference value of 32 kWh/(m²a) for the German average we find **electricity savings of 63%.**

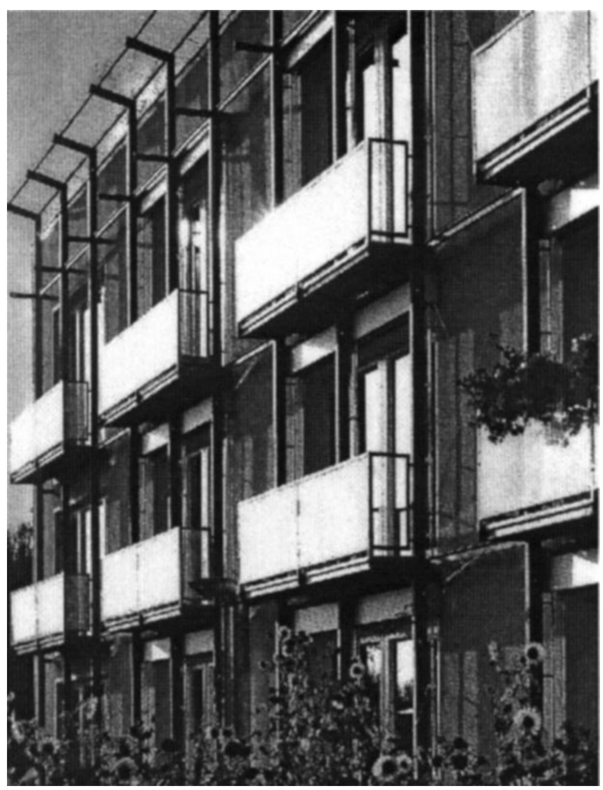

Fig. 9 Southern elevation of Darmstadt-Kranichstein passive house; designed by architects Prof. Bott/ Ridder/ Westermeyer

Results of measurements in the inhabited house

A comprehensive continuous registration of measured data was performed in the passive house. More than 200 quantities were continuously surveyed, including climate, indoor air temperatures and humidity, radiator temperatures, temperature profile and heat flow in one wall, temperature profile and heat flow in the roof, surface temperatures of windows, status of insulating sliding shutters, air flow rates of ventilation system, flow rates and temperatures of cold water, rainwater and hot water, heat metering of heating, hot water, circulation and solar collector.

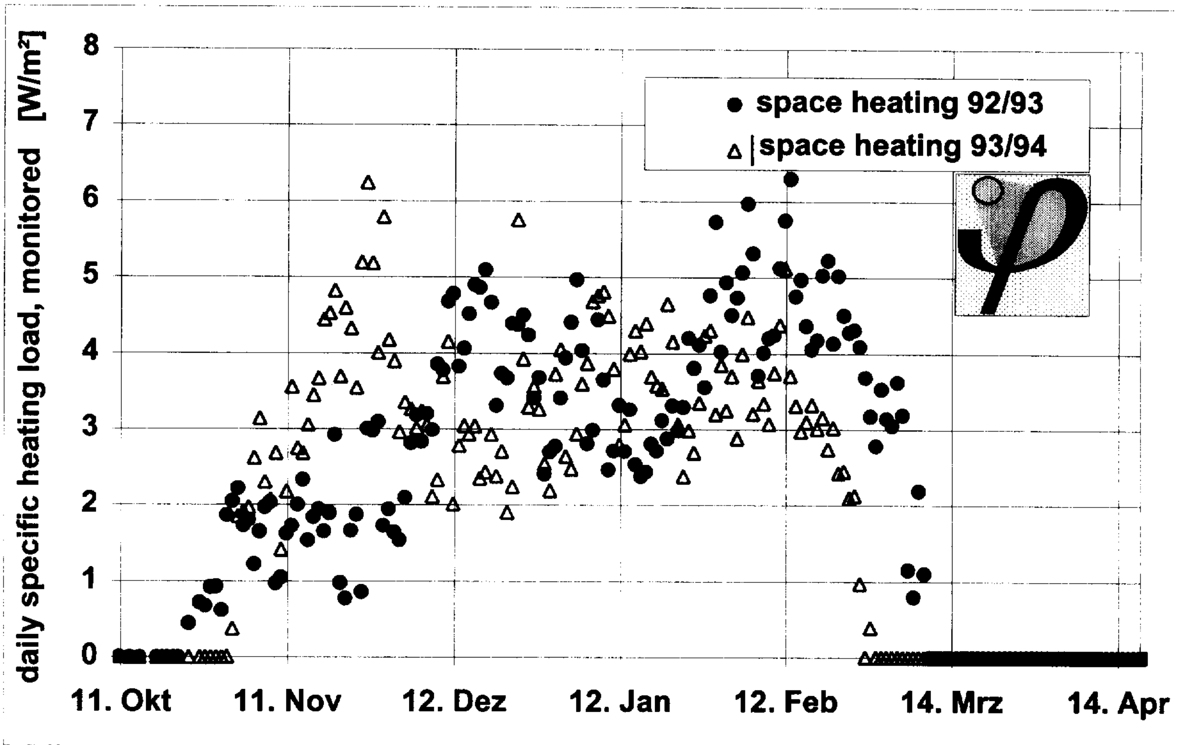

*Fig. 10 Daily specific heating load, measured over two heating periods in the building (all four dwellings; 4 * 156 m² living space in total; each symbol represents the average load of one day).*

In individual measuring operations, the following were also determined:

- With thermography: Any inhomogenity of the thermal insulation
- With pressurization tests: Airtightness of envelope
- With tracer gas measurements: Air change rate, ventilation efficiency

As had been aimed at, the specific total energy consumption (as a function of living space) in the passive house is **lower** than the household electricity consumption alone of average German buildings. The total final energy demand of the passive house is thus almost 90% lower than that of comparable single-family buildings (of the same living space) in the stock.

Fig. 10 shows the measured daily average heating loads of the four dwellings (devided by living space). In the second year (full circles) and the third year (triangles), the measured maximum heating loads never exceeded 7 W/m². These are extremely low heating loads: This is exemplified by considering that, e.g. for the living room with 22 m² living space, a resultant peak load of about 150 Watts could comfortably be "covered" with two conventional filament lamps.

Table 4: Measured final energy demand in the Kranichstein passive house **Energy demand index** (final energy in kWh/a kWh/(m²a) dived by living space in m²)	Energy carrier	Reference: average of the German building stock	Measured in passive house 92/93	Measured in passive house 93/94	Measured in passive house 94/95
Household electricity	ELECTR.	32	6.17	7.11	7.48
Ventilation (electricity)			2.93	2.93	2.93
Joint electricity uses (e.g. pumps of the heating system)			2.10	1.87	1.82
Cooking (in the passive house with nat. gas)	NAT.		2.60	2.89	2.85
Domestic hot water (in the passive house with nat. gas)	GAS	30	6.12	7.52	7.45
Space heating (in the passive house with nat. gas)	or OIL	220	11.91	11.45	7.42
Total (4 dwellings with 156 m² living space each)		**282**	**31.83**	**33.77**	**29.95**

The CEPHEUS-Project: Cost Efficient Passive Houses as EUropean Standards; Example: EXPO 2000 at Hannover - Kronsberg

Integrated concept with global impact through EXPO-2000

The city of Hannover is the venue for the EXPO 2000 World Fair, due to take place in the year 2000 under the ambitious motto of "Man-Nature-Technology". For half a year, the world will be the guest of Hannover and will have an opportunity to collect information and exchange experience on perspectives and concrete pathways towards sustainable development for humanity. A key topic will be the environmentally and socially acceptable solution of the world's energy problems. Energy consumption in buildings is particularly important here. Both in the planned EXPO Theme Park and at a multitude of decentral sites, innovative solutions revolving around Building-Energy-Environment will be demonstrated. The Hannover-Kronsberg passive house project has already been proposed by the EXPO Jury for registration as an official EXPO project. It is expected that all realized building projects will be presented together in a special EXPO 2000 Architectural Exhibition, flanked by, among other things, a Global Architecture Congress. Within this context, the CEPHEUS project creates a particular focus at the Hannover site.

A new "Kronsberg" district is planned (building work commenced in 1997) next to the EXPO fair grounds, in which some 3,000 dwellings are to be created by the year 2000, and some 6,000 dwellings in the final development stage. For this new district, the city and the municipally owned utility (Stadtwerke) of Hannover have developed an energy concept that aims at very high environmental and energy conservation standards for the whole district. As a basic concept, the whole development is to have a very good low-energy house standard with quality assurance and an electricity-saving concept, and is to be supplied with district heat from decentral cogeneration. This shall secure primary energy savings and CO_2 emission reductions of 50-60% for the overall area compared to conventional building. In certain areas of the district, more far-reaching, innovative concepts are to be demonstrated that are presently not viable on the market, but could become so in the near future. This will offer an opportunity to compare, at one site, different innovative approaches in their built form.

The Kronsberg passive house project is an integral component of the overall energy concept for the new Kronsberg district. The city of Hannover has reserved an area for this in its development plan hat directly adjoins the planned district centre. The land is owned by the city. The greater part of the area (106 dwelling units, DUs) shall be developed with 2-storey terraced buildings, and a smaller part with apartment buildings (72 DUs).

The Kronsberg project will be realized by a Partnership between the Stadtwerke Hannover, Rasch & Partner and the Deutsche Bau und Boden Bank AG.

The draft designs were submitted by Rasch, Rudolf, Such (Fig. 11) and Naumann & Stahr. With the realization of 6 different designs with different forms of construction and building materials, the great bandbreadth of the passive house approach will be illustrated at one site.

Fig. 11 Passive houses, design by M. Such, to be built at the Hannover Kronsberg expo 2000

For the coverage of the remaining heat demand (for space heating and domestic hot water), too, different solutions are to be demonstrated in Hannover. The houses located on the western rim of the development area, particularly the apartment buildings, are to be connected to the nearby local district heating system. Here very economical solutions shall be found for heat transfer and distribution. The terraced housing located uphill eastwards shall, by contrast, only be supplied with electricity. Heat generation here shall be by means of a combination of solar thermal collectors and small monovalent heat pumps using the exhaust air as their heat source (see 3.10).

It is intended that the clients/purchasers of the passive houses (without separate heating system), in a package with the purchase of the passive house, will share in a wind turbine that suffices to cover their remaining energy requirement. The turbine will be installed by a private operating society on a hilltop in the immediate vicinity of the residential development. Sites for this have already been allocated in the official land-use (zoning) plan. For the block with 114 passive houses, a share of only 11-14% of the planned 1.5 MW turbine is necessary. This means that the three 1.5 MW turbines projected on the Kronsberg hilltop could satisfy the entire remaining energy requirement of more than 3,500 passive houses - fully CO_2-free.

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