Cost-Efficient Passive Houses in a Central European Climate

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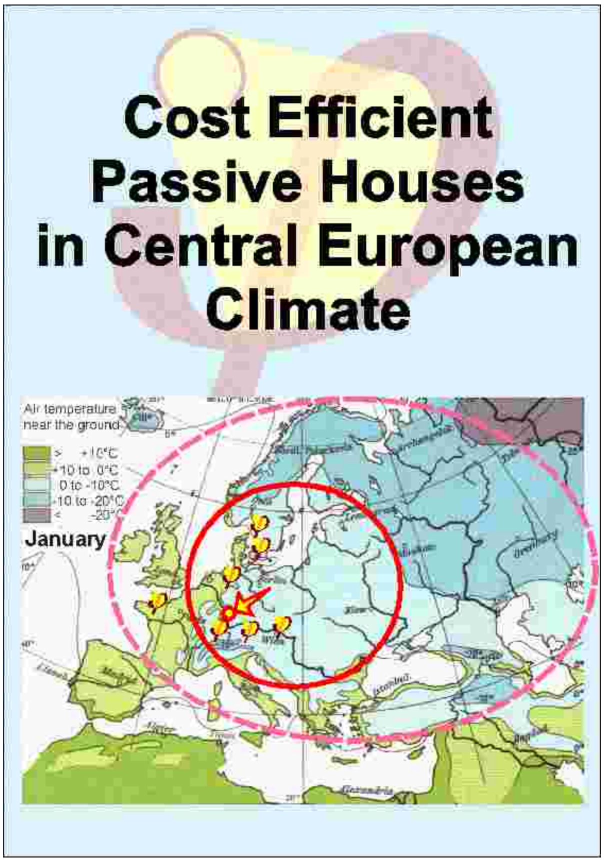
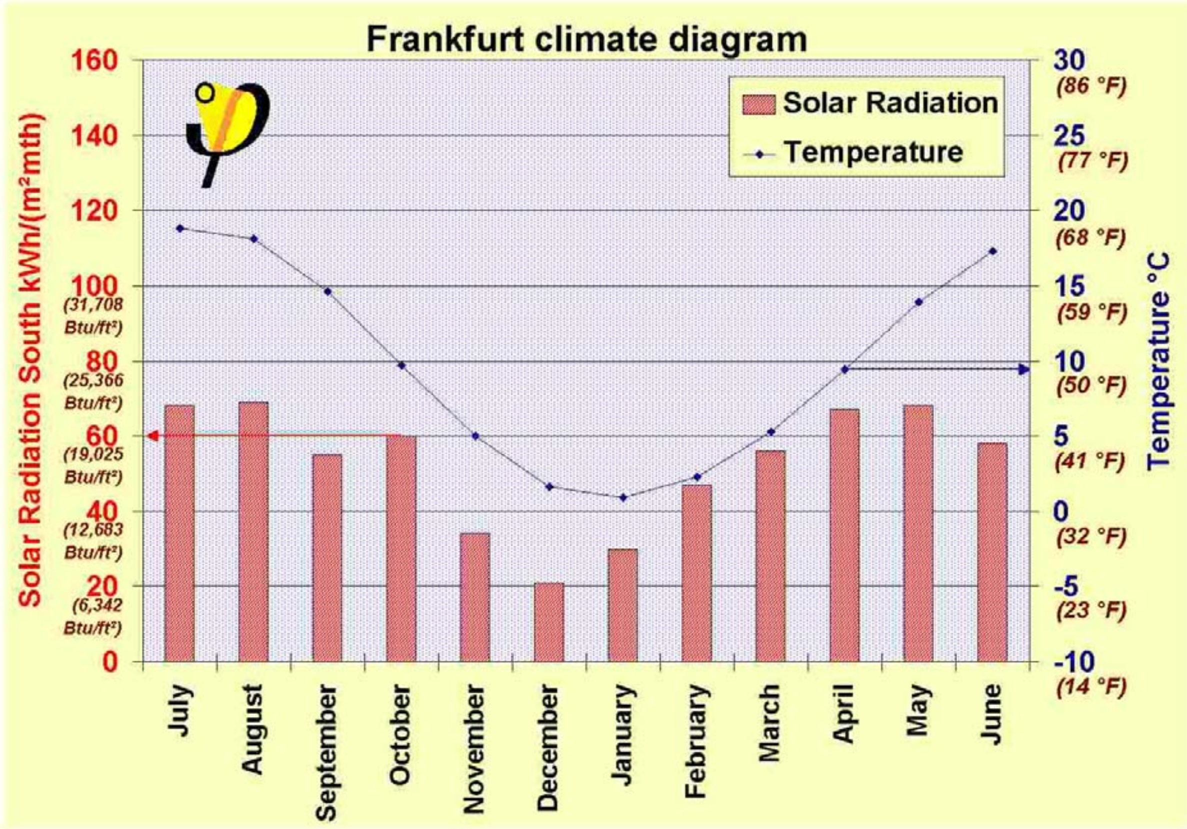


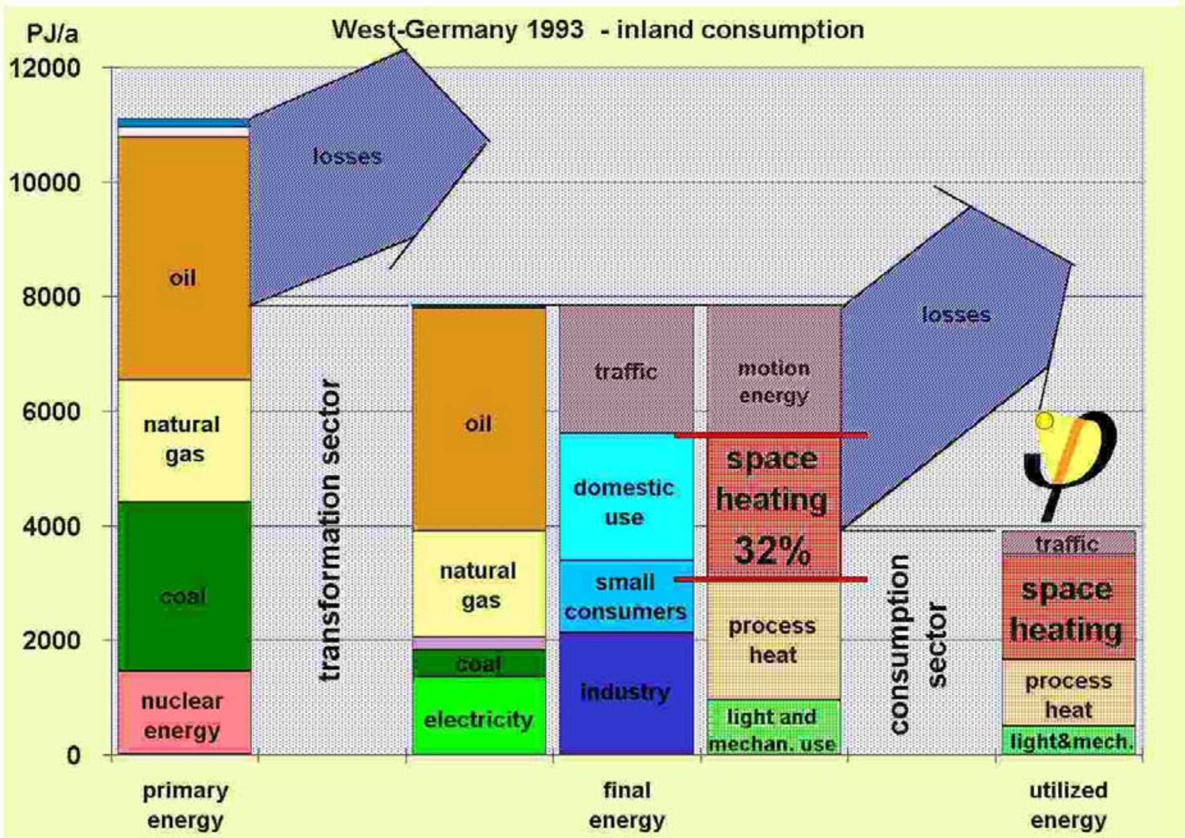
This paper contains a short explanation of **passive housing design in a Central European Climate.** The figures given were first presented at the 1998 ACEEE Summer Study on Energy Efficiency in Buildings at Asilomar, California.

The site of the first demonstration project, a building for four families constructed 1991, is located at Darmstadt near Frankfurt (arrow). Later, several building projects followed this approach, some of them within the European Union *Thermie* project called "CEPHEUS-Cost Efficient Passive Houses as EUropean Standard" (these sites are marked with a “φ“).

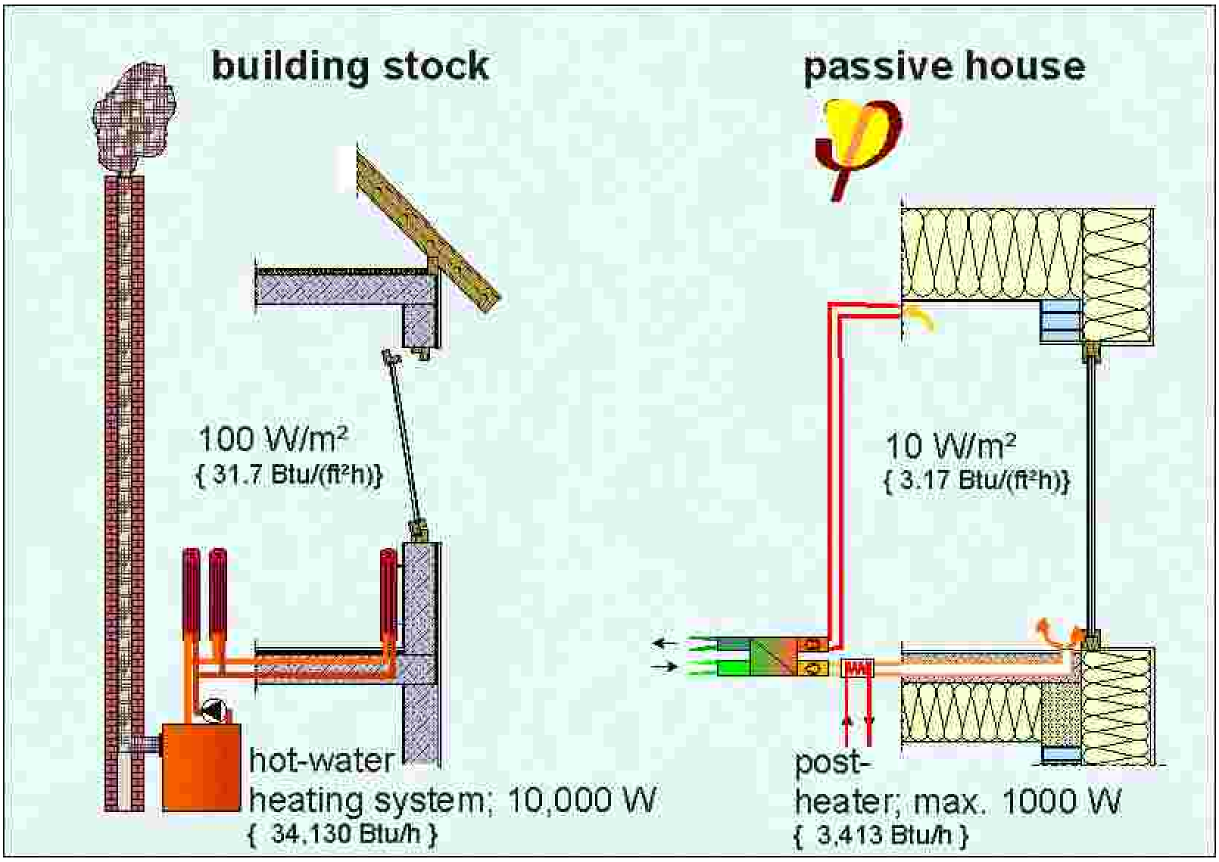
In Central European Climate the temperatures from December to February are around freezing. The results of our research hold at least for sites within the red circle. It may be extended to the larger area as well.



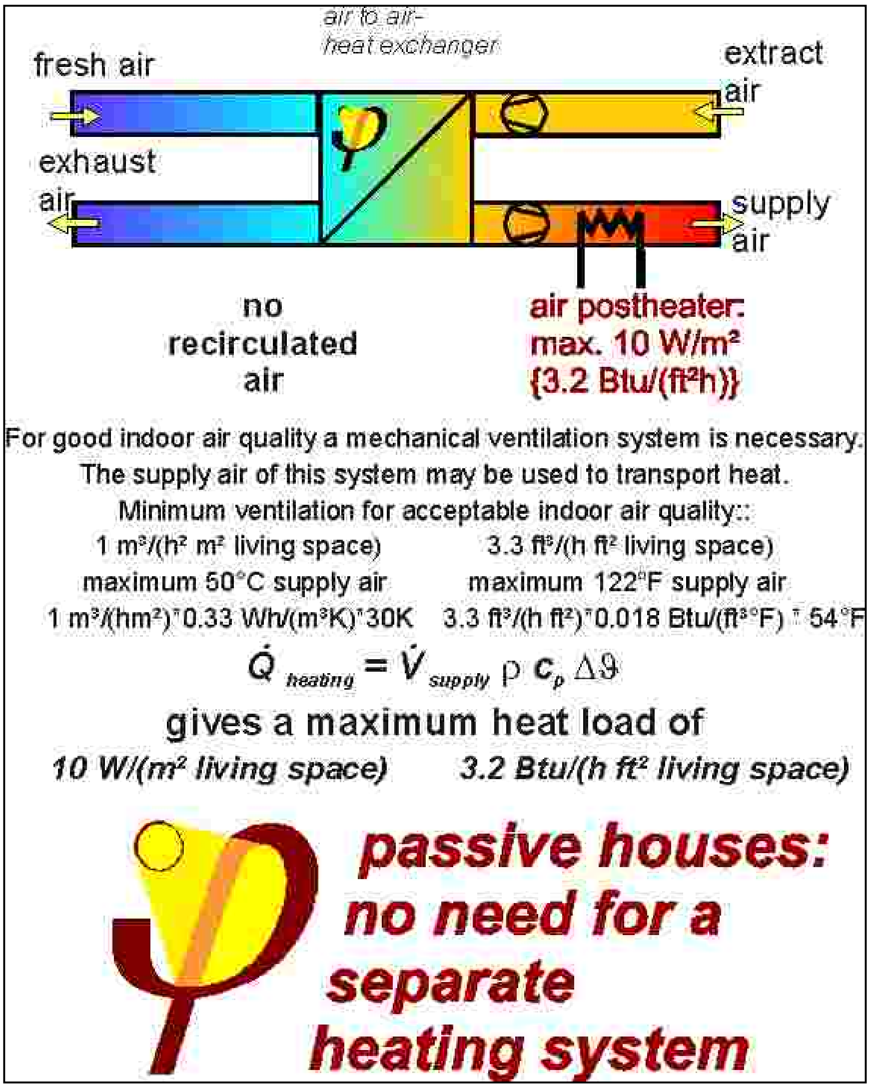
The Central European winters are quite cloudy and the sites are north of the 50th parallel. So there is just a small amount of solar radiation available in November, December and January; even with unshaded double pane windows, orientated exactly to the South, there is a net heat loss during these months.



Therefore it is not surprising that the energy demand for space heating is a large part of the total final energy used in Germany, amounting to about one third of total usage.

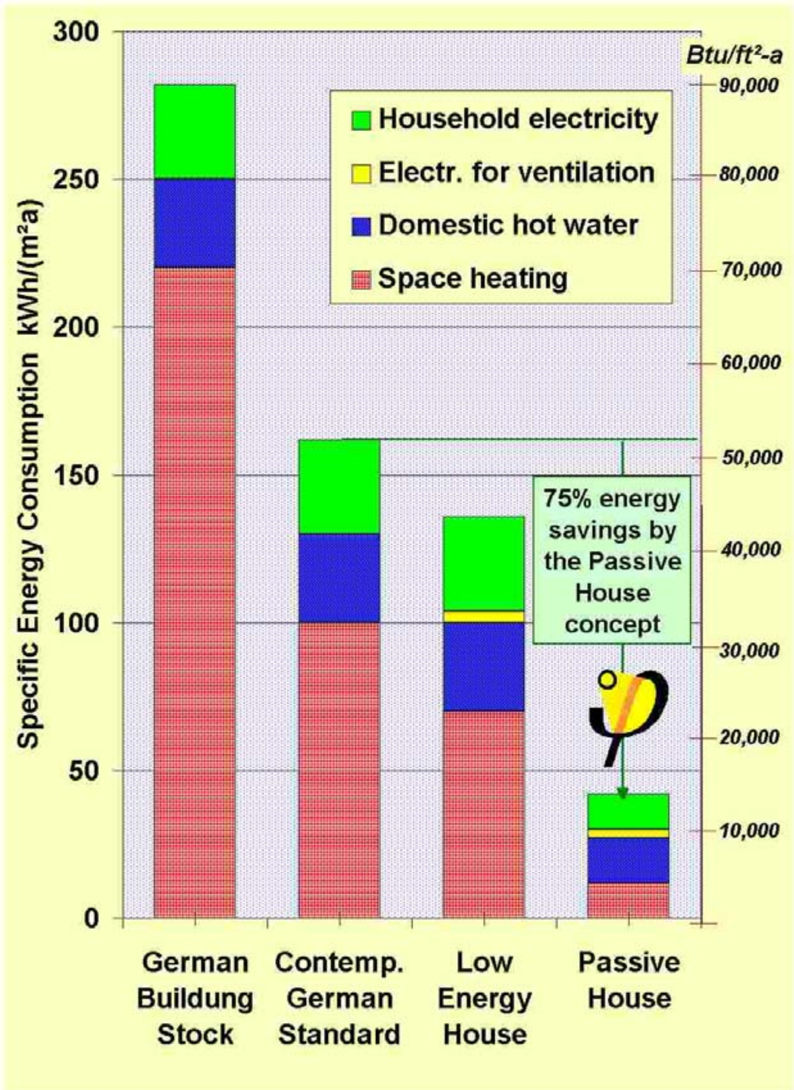


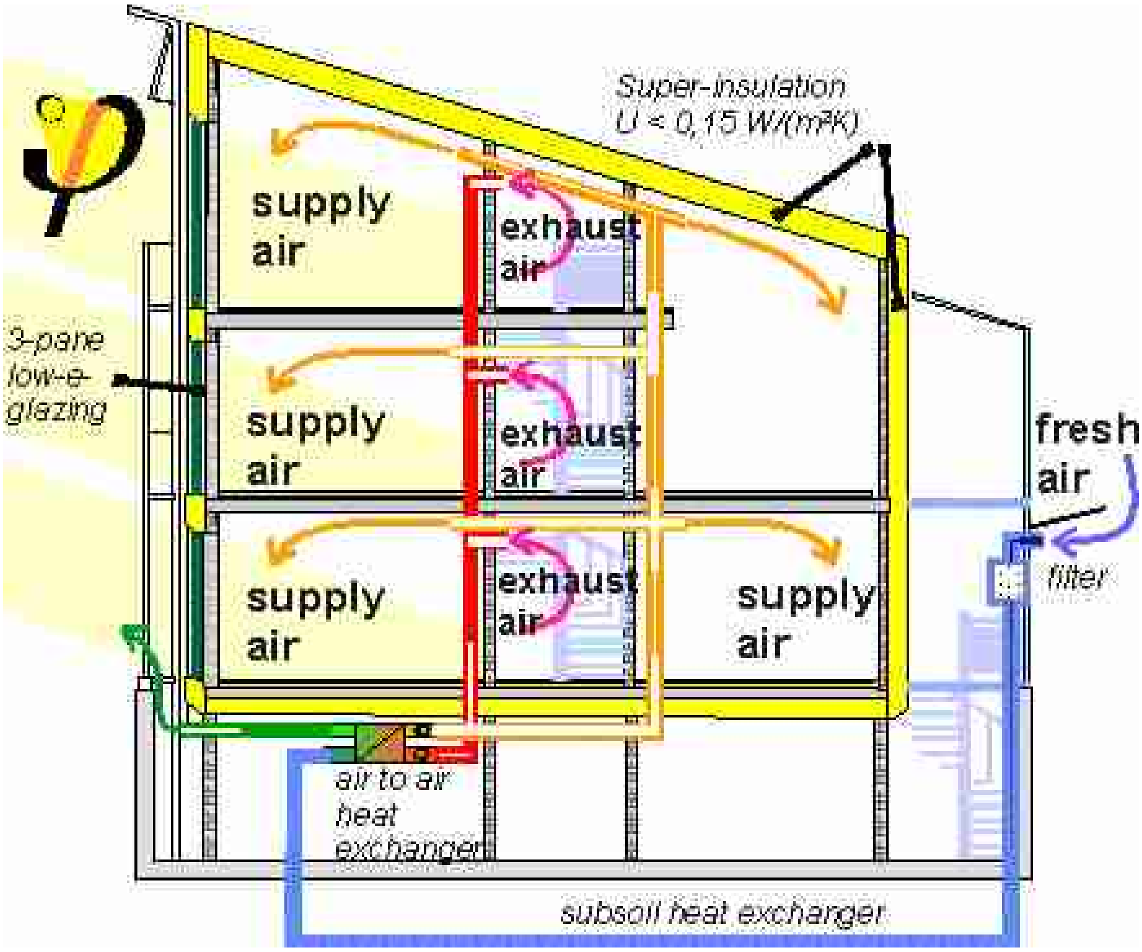
The standard system used in more than 80% of the Central European building stock is a hot-water heating system consisting of radiators, pipes and oil or gas boilers. Typically, we have a maximum heat load of about 100 W/m² {32 Btu/(h ft²)} or 10 kW {34.2 tons} for a 100 m² {1,080 ft²} dwelling. The essential idea of the passive house is to reduce the heat losses to such a small amount, that a separate heat system is not needed. It can easily been shown, that if the maximum heat load is less than 10 W/m² {3.2 Btu/(h ft²)}, the heat can easily be transmitted just by the supply air, which is distributed by the ventilation system (see the next figure for a proof). If it is sufficient to use just supply air (without any recirculated air) to meet the maximum heat load, the building is called a **passive house**.



A mechanical ventilation system is necessary to guarantee good indoor air quality. Recirculation of air should be avoided, however, and sufficient amounts of outside air provided. But the supply air of this system may be used to transport heat. If we assume a minimum ventilation rate of 0.4 ac/h, that gives at least 1 $m^3/(m^2h)$ {3.3 $ft^3/(ft^2h)$}. The maximum temperature at the postheater has to be limited to 50°C {122°F} to avoid dust pyrolysis. A simple calculation gives the maximum heat load of 10 W/m^2 {3.2 Btu/(h ft^2)}, which can be satisfied by simple postheating in the supply air. This result holds for all residential buildings; it dos **not** depend on climate.

Let's have a look on the specific energy consumption in the German residential sector. In buildings constructed before 1980, the consumption for space heating is 220 kWh/m² {70,000 Btu/ft²} in average. In addition, 28 kWh/m² {9,000 Btu/ft²} for domestic hot water and 32 kWh/m² {10,000 Btu/ft²} for domestic electricity is used each year. A new building, constructed according to the contemporary German building ordinances will use one half less energy for space heating than a 1980 vintage house. **Low energy houses**, which have been build in Germany since the 1980s and will be generally introduced in the building ordinance for the year 2000, save another 25 to 30%. In a **passive house**, the annual requirement for space heating is reduced to no more than 15 kWh/m² {4,800 Btu/ft²} or less than 7% of the heating energy used by the average house. But, in addition, the energy consumption for domestic hot water and electricity is reduced as well. In total, the objective is to reduce the total residential energy consumption **by about 75%** compared to present new building practice.



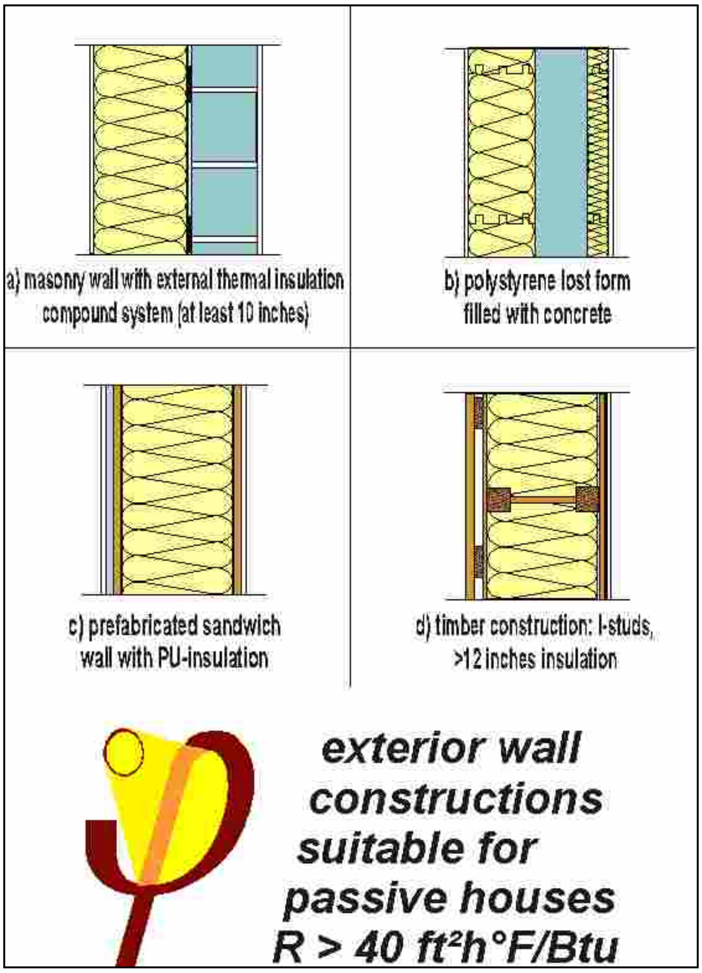


How can passive houses achieve the low 10 W/m² {3.2 Btu/(h ft²)} maximum heat load in a Central European Climate, where design temperatures are about -12°C {10°F}? The cross section of the first prototype building without heating system at Darmstadt shows the main characteristics:

- Passive houses are superinsulated using U~0.15 W/(m²K) {~R-40} ceilings, walls and slabs: insulation thickness 25-40 cm {10-16 inch}.
- Triple pane R-8 superglazings with two low-e coatings provide passive solar heat gains, which exceed the losses even during the winter months (U_w=0.7 to 0.8 W/(m²K)).
- A balanced mechanical ventilation system with a heat recovery of 80% to minimize ventilation losses.

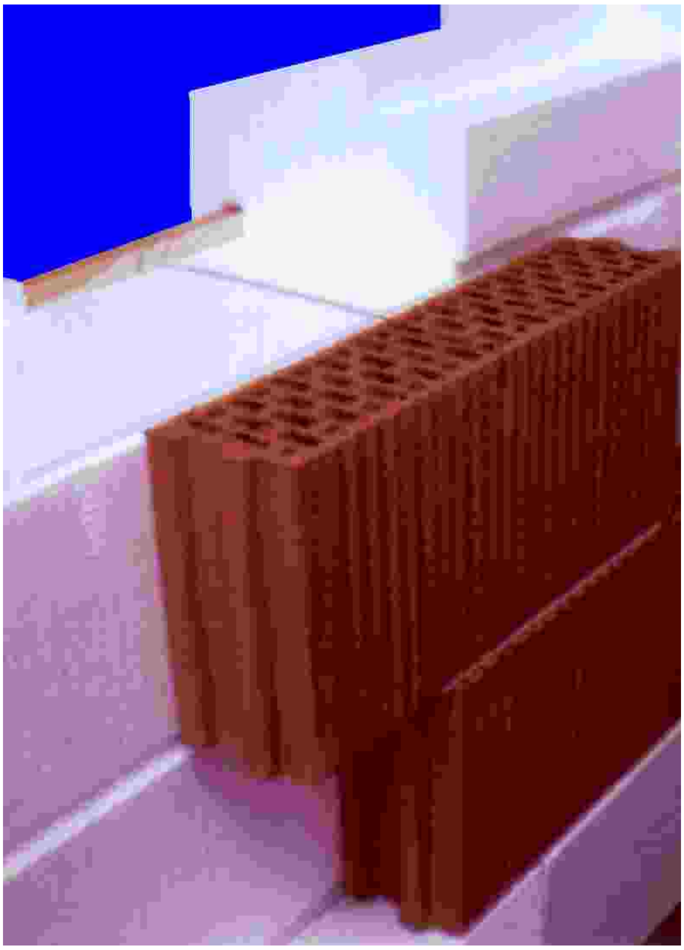
These properties are sufficient for passive houses in Central Europe.

During the last five years a lot of exterior wall designs suitable for passive houses have been used in Central Europe:



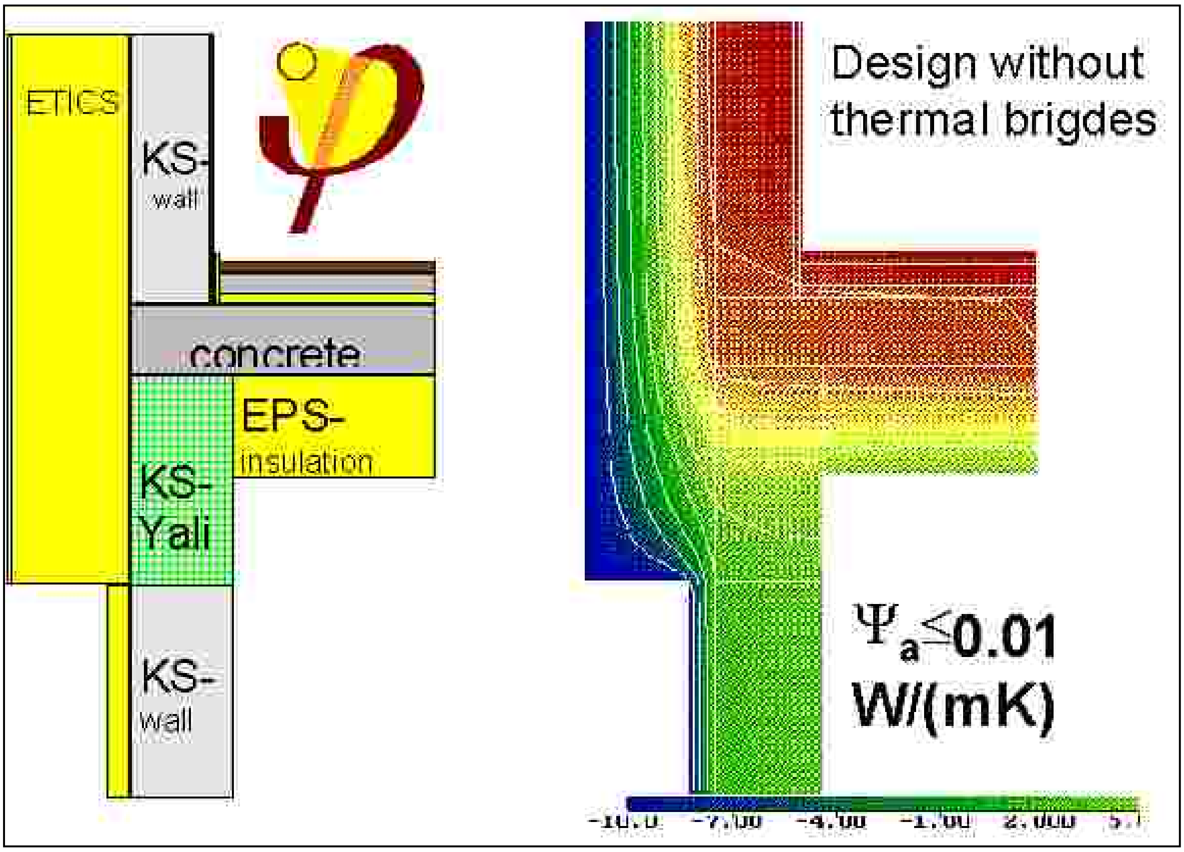
- Masonry walls with external thermal insulation compound system (at least 25 cm {10 in}).
- Lost forms, which will be filled on-site with concrete. The forms are made from expanded polystyrene and extra inches can be added externally.
- Prefabricated sandwich walls with polyurethane insulation.
- Timber construction with light-weight I-studs and more than 30 cm {12 in} insulation.

This figure shows the construction at the side with a new external thermal insulation system (ETICS), which has been developed especially for passive houses. The 30 cm {12 in} polystyrene blocks are set up first - the bricks later. Using this system, the wall with U=0.14 W/(m²K) {R-44} can be arranged faster and with lower costs compared to present practice (7.5 cm {3 inches} which just gives U~0.44 W/(m²K) {R~14}).

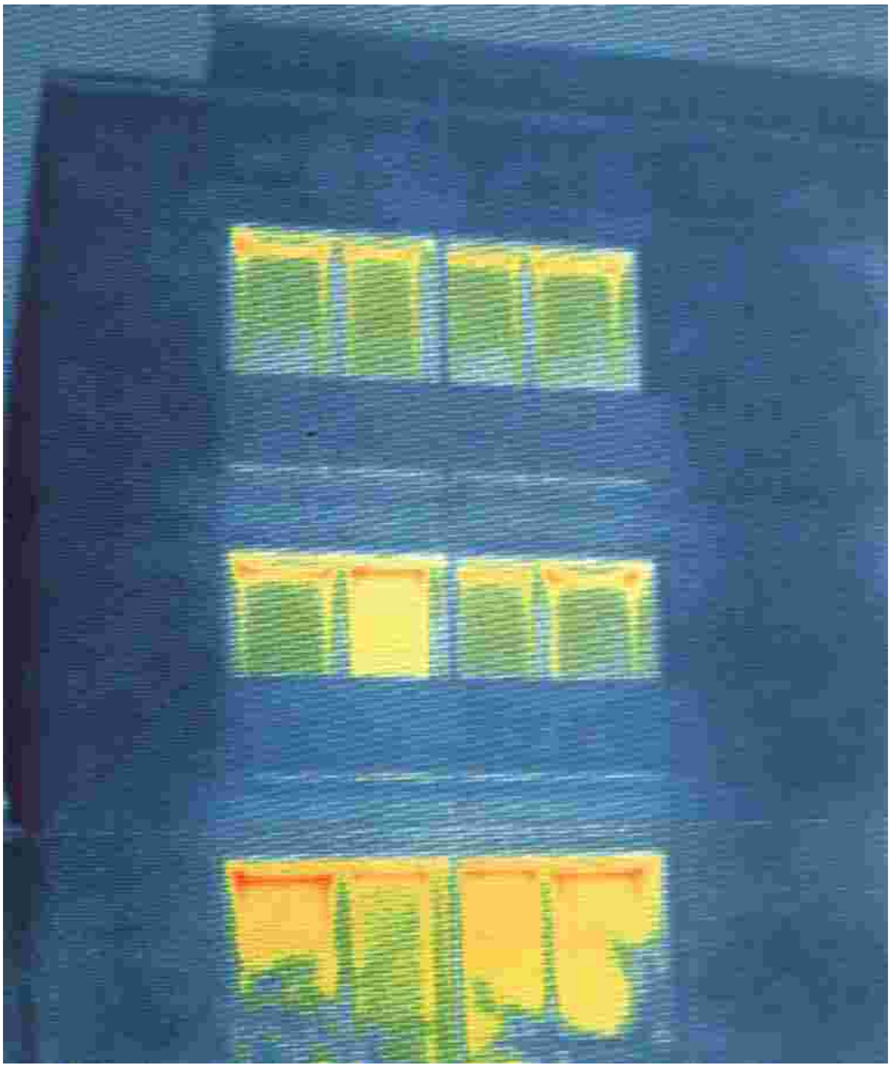


Airtightness

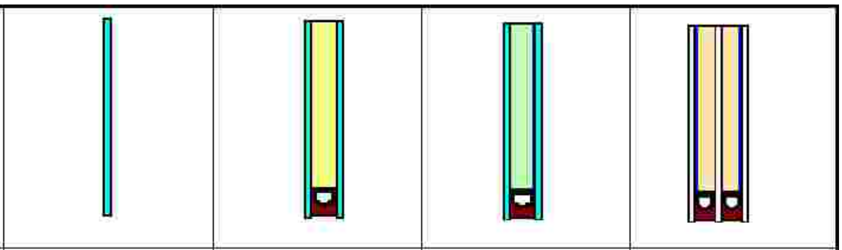
Passive houses have to be very tight. An airtight envelope is wrapped around the houses and joints are designed very accurately.



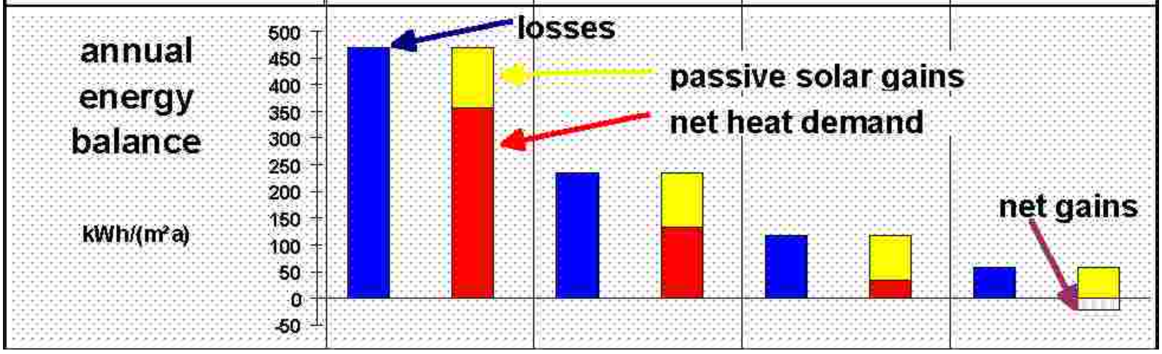
An interesting result of our research is that thermal bridges in super-insulated building envelopes can be reduced to about zero; this holds, if heat losses are calculated according to external measures of the shell. For the prototype buildings, all joints have been calculated by two-dimensional heat flow programs.



The reduction of thermal bridges was successful within the prototype buildings. This was proven by thermographic images of the building envelope. The facade looks uniformly deep blue; no thermal bridge effects could be detected. However, you can see that there are higher heat losses from the windows.

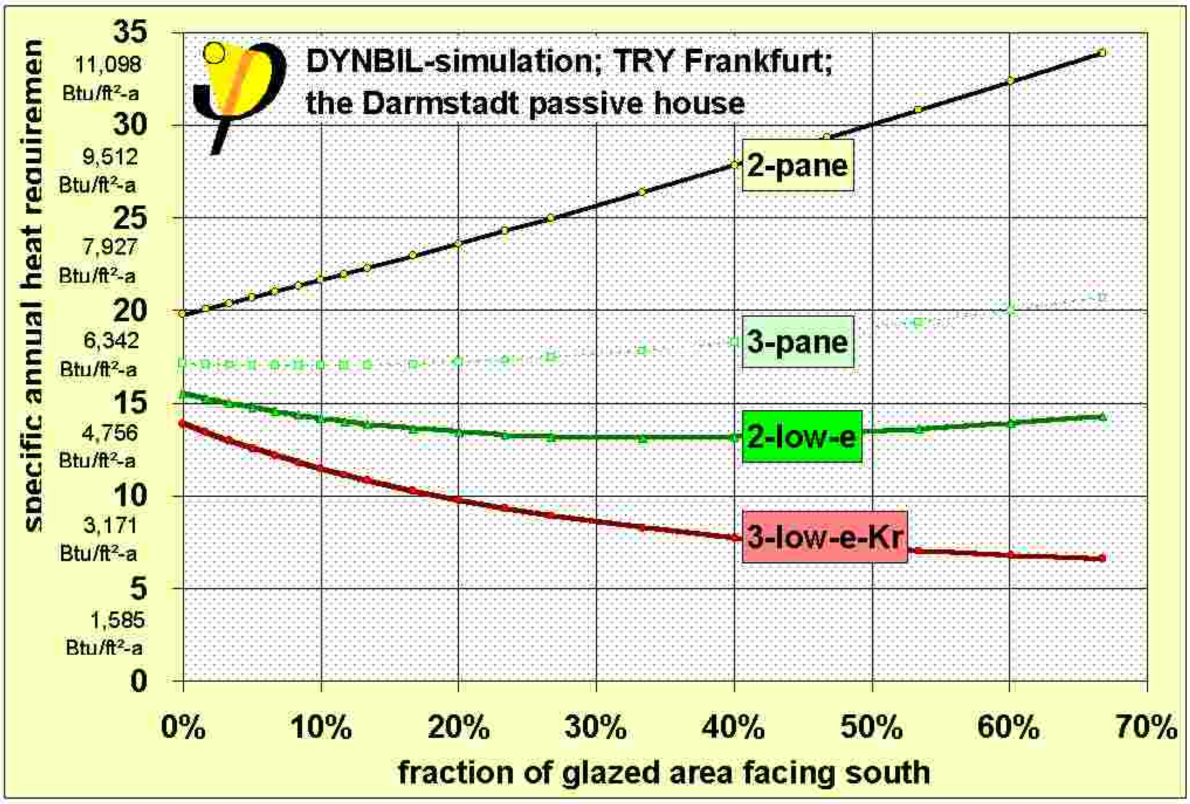


TYPE	single pane	double pane	double pane, low-e, Ar	triple pane, 2 low-e, Kr
R-value [ft²h°F/Btu]	1.0	2.0	4.0	8.1
Surface-Temp. (indoor: 68°F; outdoor 14°F)	28.7 °F	48.3 °F	58.2 °F	63.1 °F
Solar transmittance	85%	76%	63%	60%

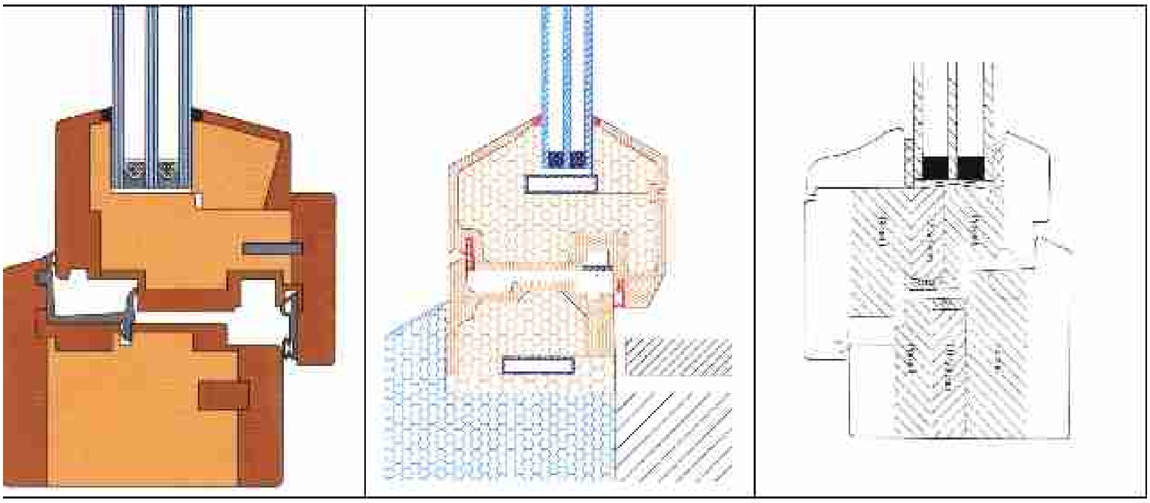


During recent decades there was a remarkable development in glazing quality:

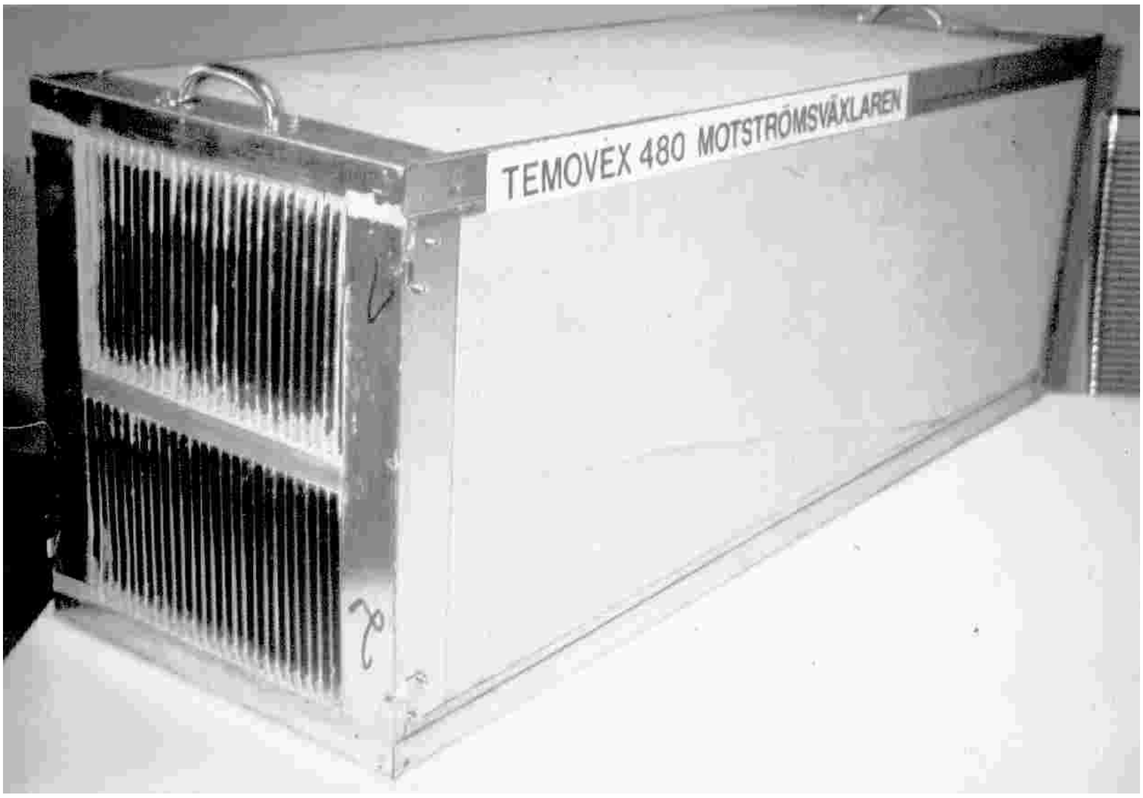
- Until 1980 in great parts of Central Europe single glazing has been used. These windows perform so badly that often frost forms on the inner surface!
- From 1984 to 1995 double pane windows with U=3 W/(m²K) {R-2} have been commonly used. Heat losses have been halved, but we still have condensation on the inner surfaces.
- Since 1990 there is a growing market for double-pane, low-e-glazing with U=1.5 W/(m²K) {~R-4}; with the 1995 ordinance these glazings have become mandatory. But the R-4 glazings are still not suitable for passive houses: The temperatures of the inner surface can be below 14.5 °C {58°F}; so there can be uncomfortable radiation.
- The glazings used in passive houses are triple pane with two low-e coatings (U=0.75 W/(m²K) {R-8}). Now the surface temperature is near to the indoor air temperature: therefore there is no need for a radiator. In the Central European climate the solar gains of these glazings, used in a south-orientated window with little shading, are higher than the heat losses even in December, January and February.



Simulation runs during the design of the prototype house showed that with a double pane window the annual heat requirement increases with increasing glazing fraction. However, with double pane low-e windows the annual heat requirement almost does not depend on the window size for south facing windows. But with the triple pane superglazed windows there are significant energy *savings* if window fraction is increased. These results have been proven for Central European climate; they may be extended to Northern and Eastern Europe as well.



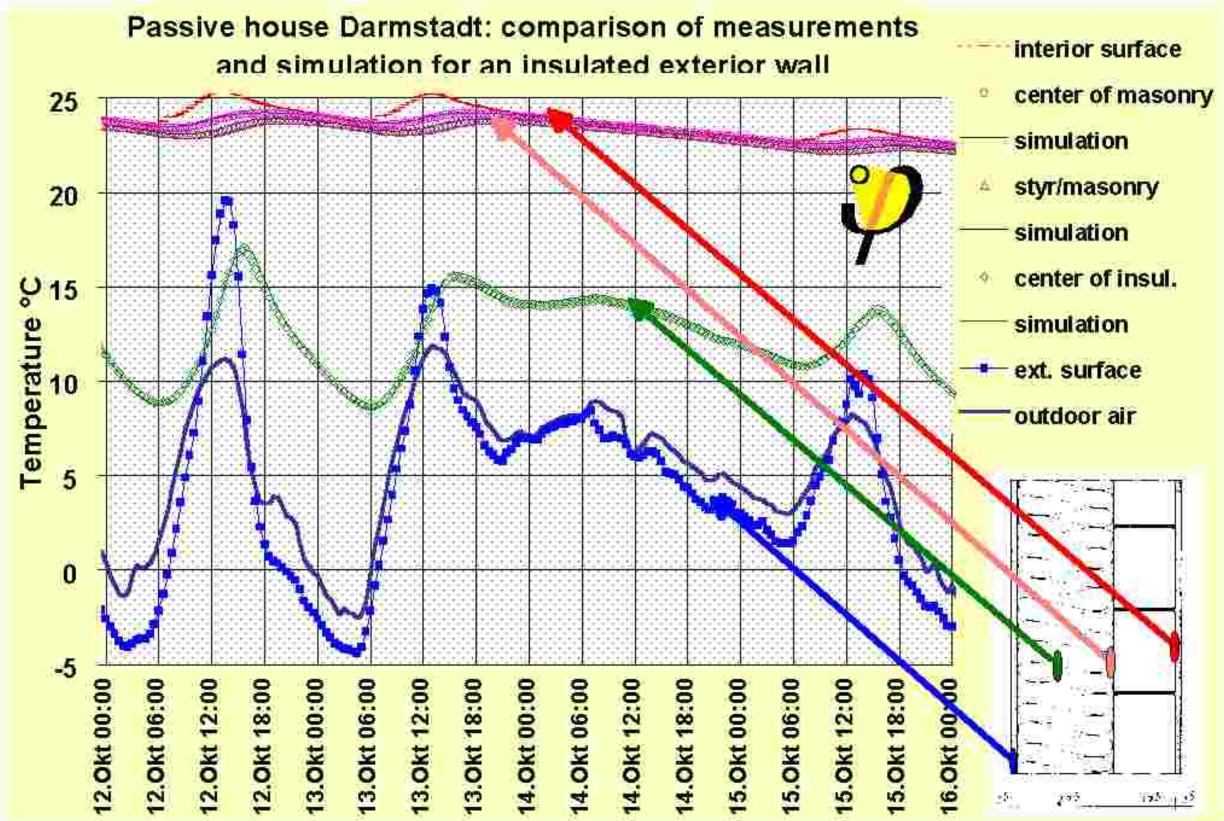
However, all the positive effects of solar gains can be negated if poor window frames and thermal bridges in the window area raise the heat loss excessively. Conventional window frames have R-values ranging between R 2.8 and 3.8. The heat loss of 1 ft² frame is thus more than twice that of superglazing. A further substantial thermal bridge is formed by the edge spacers. In order not to negate the solar gains by these additional losses, a window frame must be used that displays particularly high thermal performance. The figure gives a comparison of three superinsulated windows with "superframes" developed specially for passive houses.



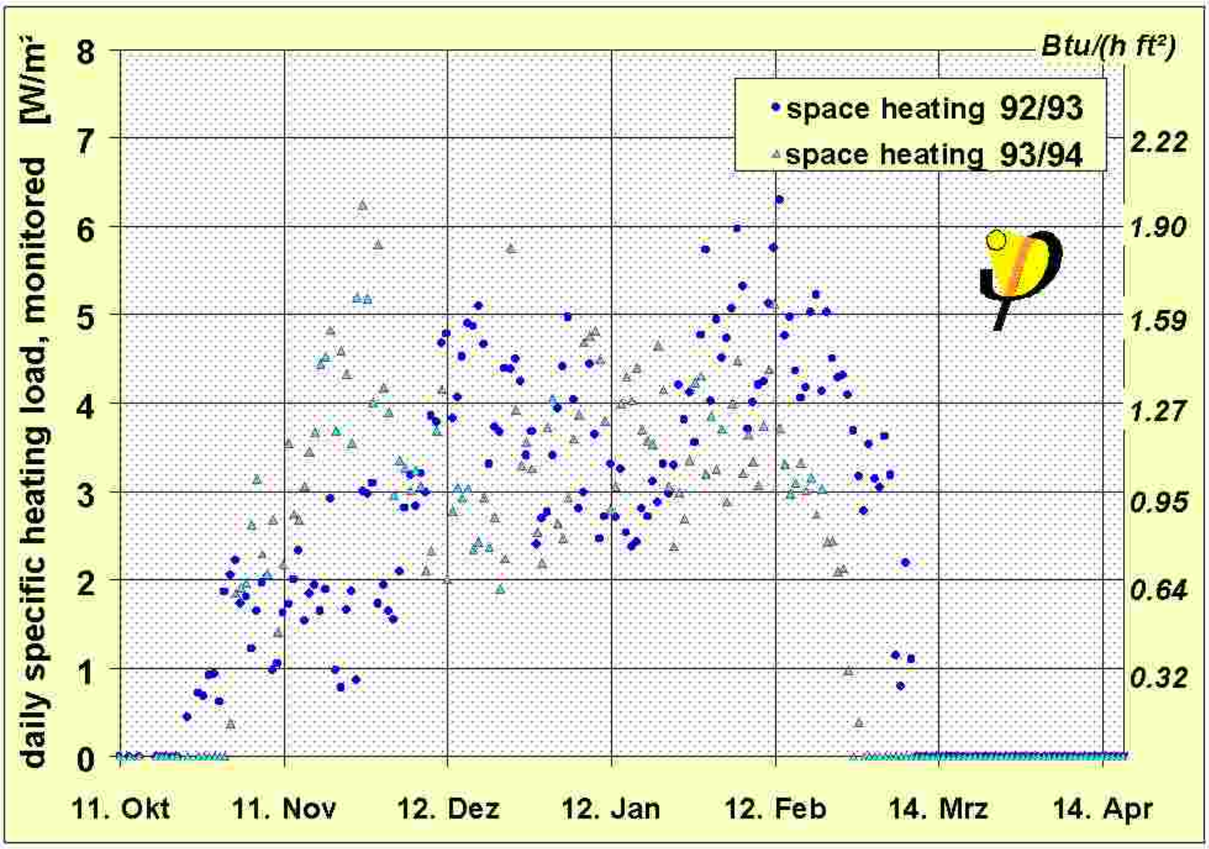
In the first passive house prototype in Darmstadt-Kranichstein, a high-efficiency counterflow air-to-air heat exchangers with measured heat recovery rate of more than 80% have proven themselves. The annual electricity consumption is 200 to 400 kWh/dwelling. There is, thus, no need to debate the issue of a „natural drive“ of the controlled ventilation, as the heat recovered by such an efficient system is, at 3,000 to 4,000 kWh/a, larger by about a factor of ten than the input power.

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

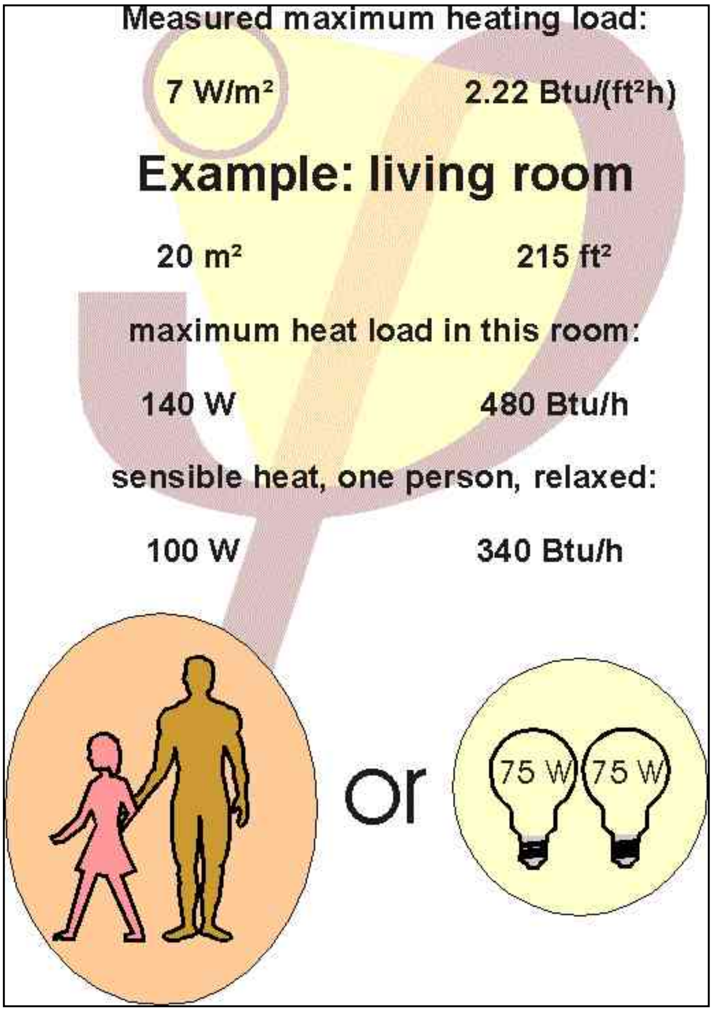
The construction of this house was financially supported by the Hessian Ministry of Environment and designed by the architects Prof. Bott/ Ridder/ Westermeyer. The building, with its four terrace-type dwellings, was completed in October 1991, and has been inhabited since that time by four families. The concept of the house is based on uncompromising conventional thermal insulation, optimized passive solar energy utilization, and highly efficient heat recovery from the exhaust air. The house is fitted with an extensive end use energy metering system.



In this figure, temperatures measured in the section of the superinsulated external wall are compared with the results obtained by the dynamical simulation model using the same boundary conditions. The difference between simulation and measurements in this field of dynamic heat transfer is very small: the calculations are within ±0.3°C {0.54°F}; this is about the accuracy of the measurements. Note that the temperature of the external surface is below outdoor air temperature most of the time; during the early afternoon it may be higher, if direct solar gains are absorbed.



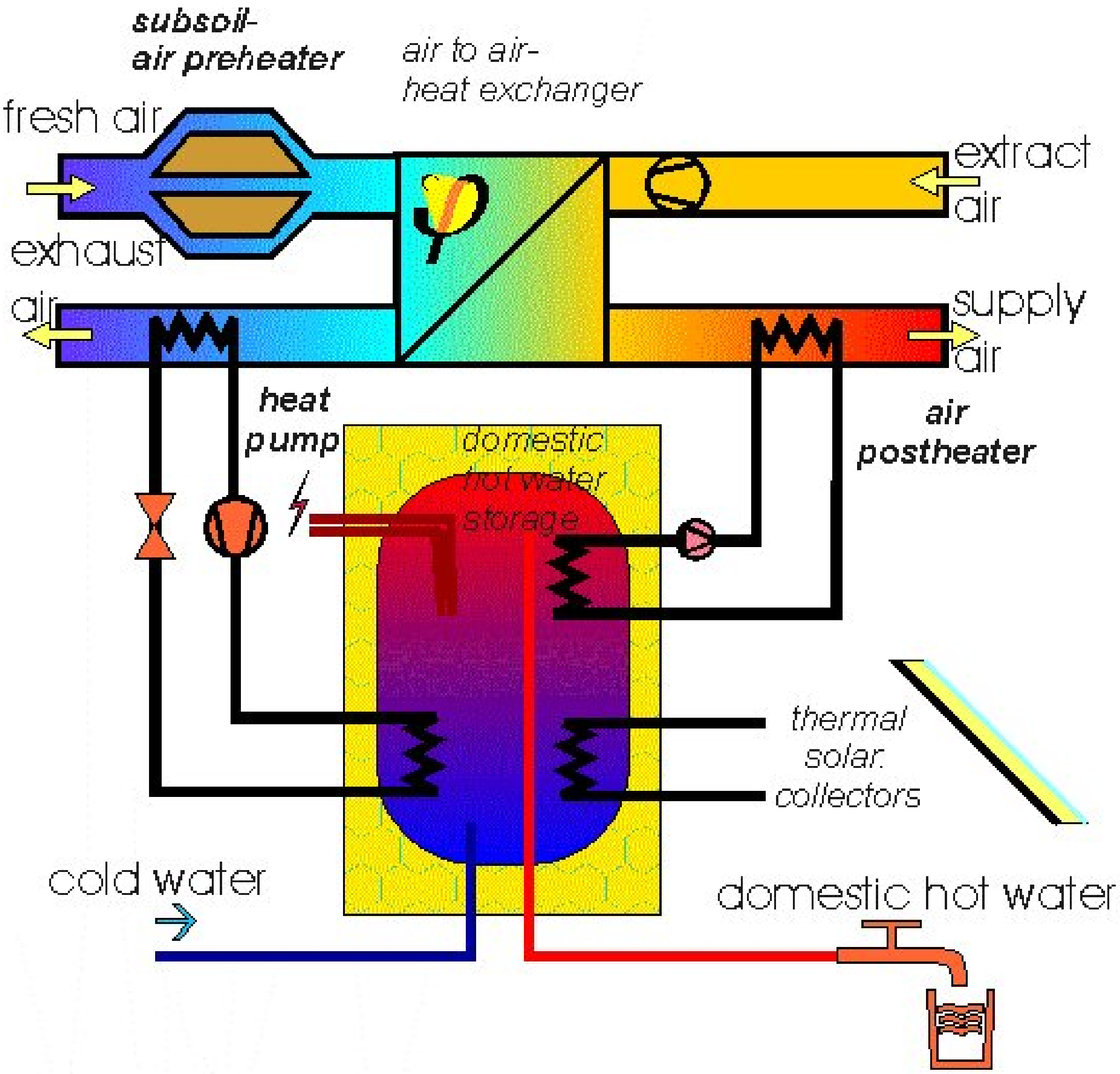
Each symbol in this figure represents the measured average specific heat load during one day. It´s the load of all four passive row houses; the load is divided by the total floor area, which is 156 m² {1,680 ft²} in each dwelling. Heating was never necessary before end of October and after end of February: It is concentrated in the center of the Central European winter, that is November to February. But the measured heating loads never exceeded 7 W/m² (2.2 Btu/ft²)). These are extremely low heating loads, adding up to 1.1 kW for the whole dwelling (3,700 Btu/hr).



This is exemplified by considering that, for the living room with 20 m² {215 ft²} living space, a resultant peak load of about 140 Watts could comfortably be "covered" with the free sensible heat of one adult person and one child, **or** with two conventional filament lamps. This exemplifies that in a passive house we are back to the human scale of energy flows!

The following cartoon I found in a book of my friend Jørgen Nørgård. A family is watching tv in a well-insulated low energy room. The weather forecaster says it will be "colder this weekend;“ therefore it is discussed, "Shall we ask some friends round to keep the room temperature up?"

Well, this should not be misunderstood. We do not want to force anybody to have guests all the time during winter. There are other ways to keep it warm, one is illustrated in the next figure.

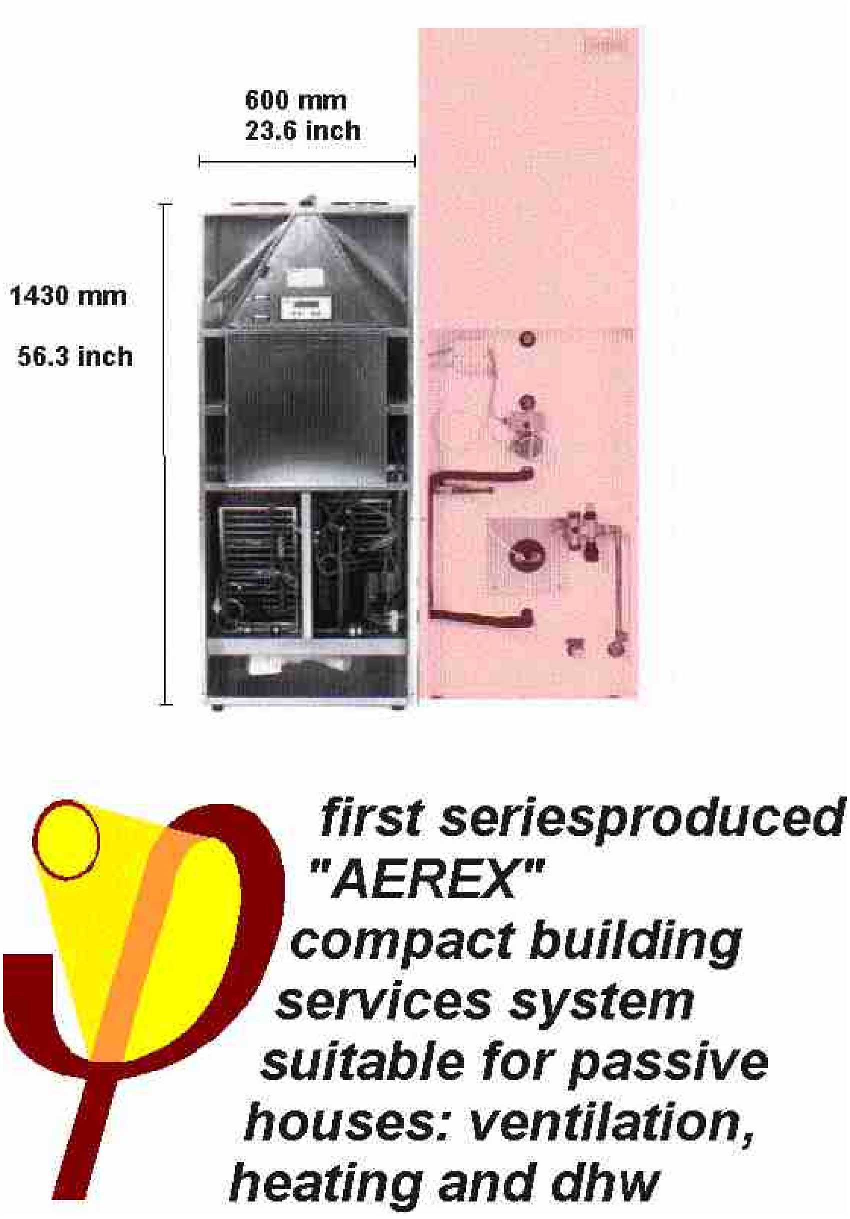


compact building services system suitable for passive houses: ventilation, heating and dhw

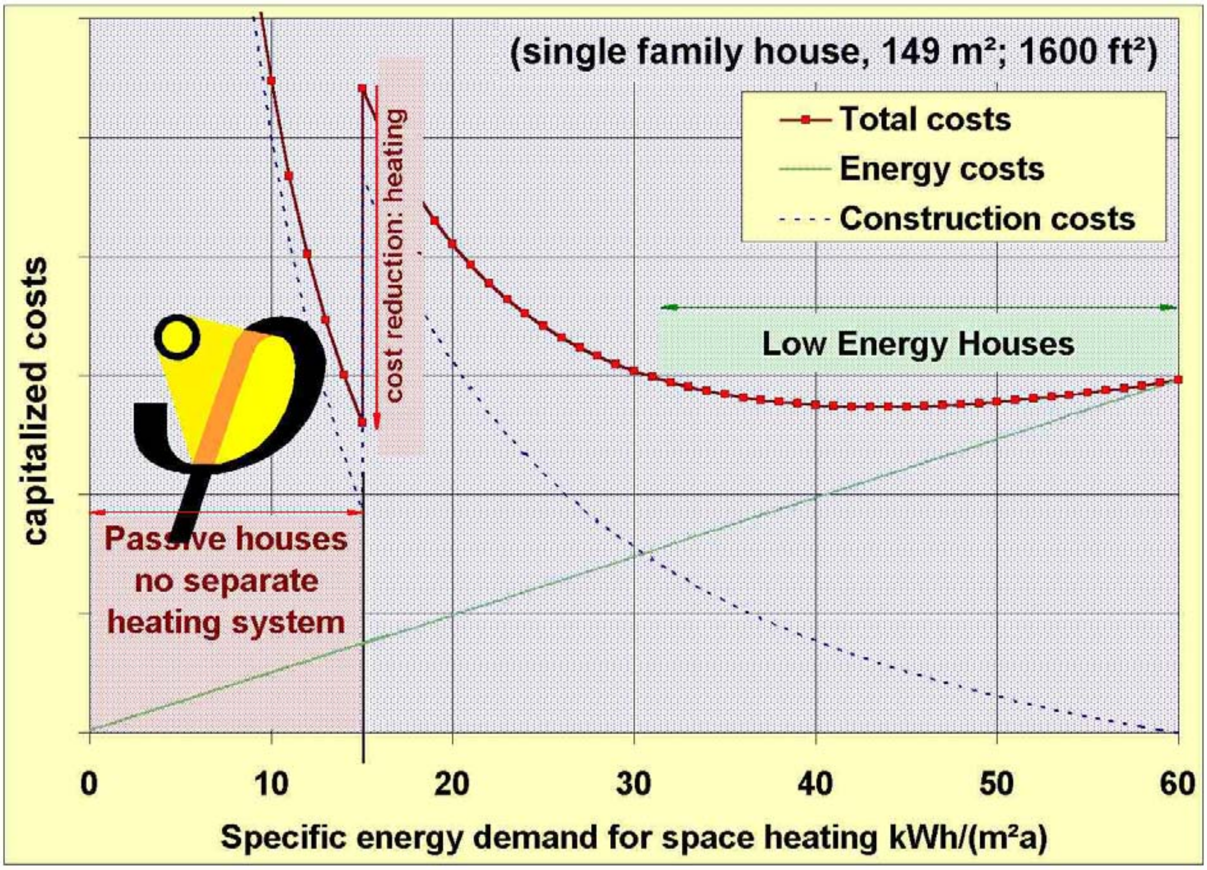
A ventilation system with heat recovery is indispensable in passive houses. As has been shown before, a small supplementary postheater situated in the supply air is sufficient to heat the whole dwelling. The heat required for the supply air postheater could for instance come from the domestic hot water system.

Another possibility is to provide the heat by means of a small, efficient heat pump. 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 {50°F}, even on the coldest days. Moreover, the exhaust air contains the entire latent heat of the water vapor released within the dwelling; if the exhaust air is cooled down to a temperature of 2°C{36°F}, then a total of 500 to 800 W {1,700-2,700 Btu/hr} heat output can be extracted from this source. A very simple, integrated system thus becomes possible for ventilating the dwelling and at the same time covering the supplementary heat requirement for space heating and domestic hot water 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.

First series produced "AEREX" for passive houses



The last figure shows it is thus possible to provide the entire hot water energy need, even for high demands, and the remaining space heating with an electric energy input between 1,000 and 2,200 kWh/a. A first series of such a system has been produced by an Austrian company and tested by the Freiburg Fraunhofer Institute. Using this type of equipment, heating, ventilation and hot water supply of a dwelling is reduced to a small system looking like an appliance just connected to the domestic electricity system and consuming no more electricity than an old refrigerator. It is not surprising that the costs of such a system can be very low compared with the hot water heating systems commonly used in Europe at present time.



If the efficiency of the building is increased by adding insulation, superwindows and heat recovery systems, the specific energy demand for space heating is reduced; but at the same time the construction costs (blue curve) are increased. It is hard to build extremely low energy houses because the slope of the added costs is increases greatly with lower energy use ("law of diminishing returns"). So there seems to be **not a chance** to reduce energy consumption to values lower than about 30 kWh/(m^2) {9,500 Btu/ft^2} with economically reasonable measures—indeed, is the widely held opinion of homebuilders in Europe that it makes no sense to increase thermal insulation more than that. But at the moment this paradigm is changing as knowledge about the passive house concept gets disseminated:

A key element of the economics of the passive house is that if the energy demand for space heating is reduced to a value below 15 kWh/(m²) {4,750 Btu/ft²} then a heating system is no longer needed. Therefore the costs of this system can be saved, which will pay at least for the "compact building services system" shown in the last figure and for most of the extra insulation. In addition, the operating costs for energy are extremely low in a passive house. If we add the capital and operating costs, the total costs of passive houses will not exceed those of present standard new buildings in Europe. Indeed, in a few years the passive house will be the most cost-efficient concept for new buildings.

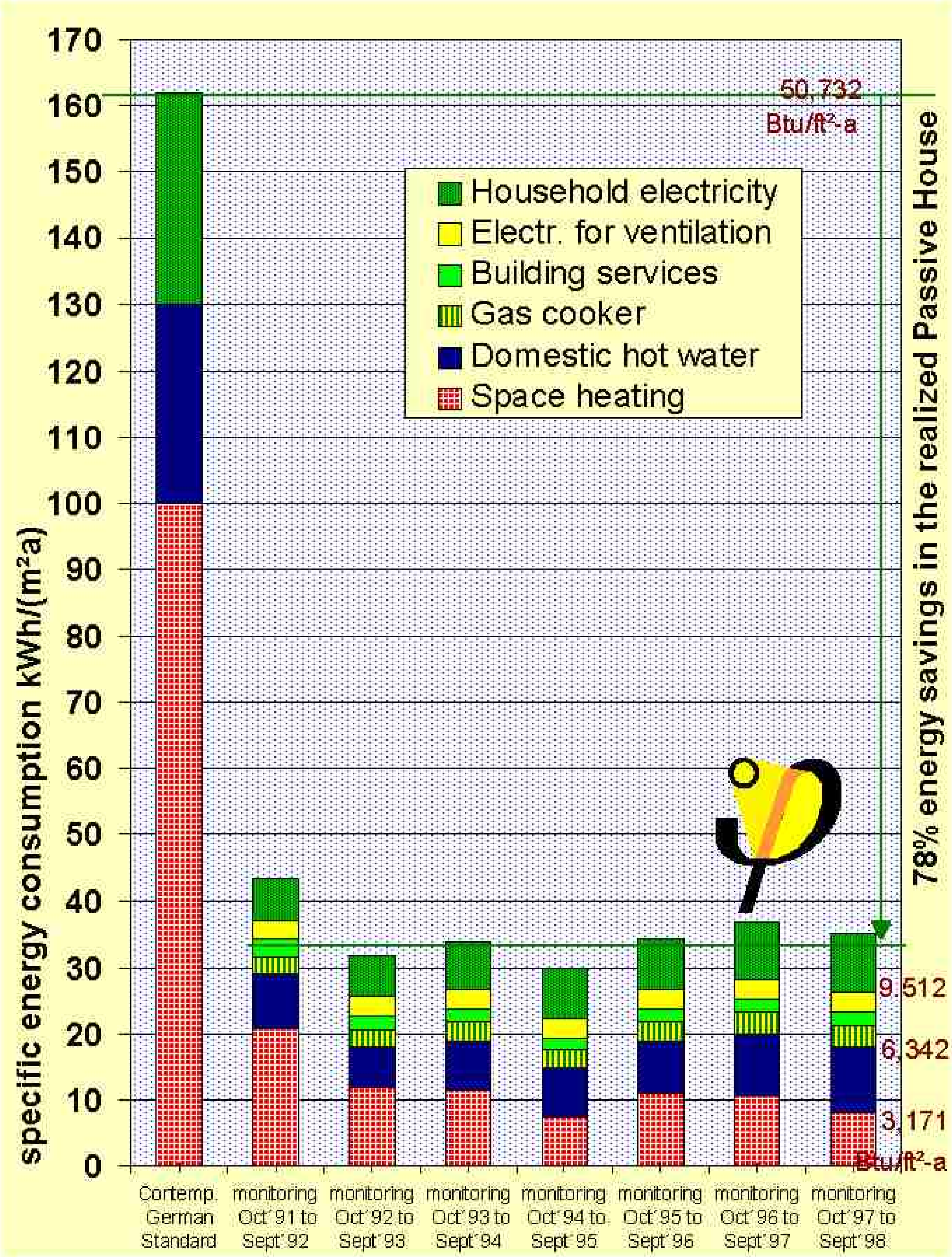
Efficiency of other appliances

In the prototype passive houses in Darmstadt all four households are equipped with all the large appliances commonly encountered today, but each with very high efficiency:

- connection of clothes washers and dish washers to the domestic hot water piping,
- compact fluorescent bulbs with electronic ballasts,
- refrigerators using less than 100 kWh/a,
- freezers using less than 117 kWh/a.

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

On average, a German household consumes about 32 kWh/m²/a) for household appliances (without space or water heating). In the passive houses in Darmstadt, the monitoring showed a reduction of this household electricity consumption to less than half.



These are the results of monitoring the total energy consumption of the four dwellings in the Darmstadt passive house:

- the final energy consumption for space heating was on the average 10 kWh/m²/a) {3,200 Btu/ft²/yr} of natural gas,

- in addition, 7.3 kWh/m²/a {2,320 Btu/ft²/yr} of natural gas was used for domestic hot water,
- the gas cooking stoves consumed 2.7 kWh/m²/a {850 Btu/ft²/yr)}
- and domestic electricity, ventilation and building services add another 14 kWh/m²/a {4500 Btu/ft²/yr)}.

Thus, the total final energy consumption for all purposes in this building is 31.8 kWh/m²/a {10,000 Btu/ft²/yr}, which has been stable over the last six years. Compared with a new building according to the contemporary German ordinance, the measured energy savings are more than 78%.

As a result, the objective of the passive house project was reached - see the figure "Stock - Cont. Standard - Low Energy House - Passive House" at the beginning of this paper.

Projects in succession: settlement of 22 row houses at Wiesbaden

The passive house prototype was so successful that a lot of projects followed some years later. This figure shows the building site of a small settlement of 22 passive houses in Wiesbaden. These houses have been built by Rasch&Partner and have been occupied since August 1997. These houses were built in the low cost segment of council flats with specific construction costs in the range of 1,000 Euro/m² { $83/ft²}.

★THERMIE★

EUROPEAN COMMISSION
DIRECTORATE-GENERAL XVII, ENERGY

THERMIE

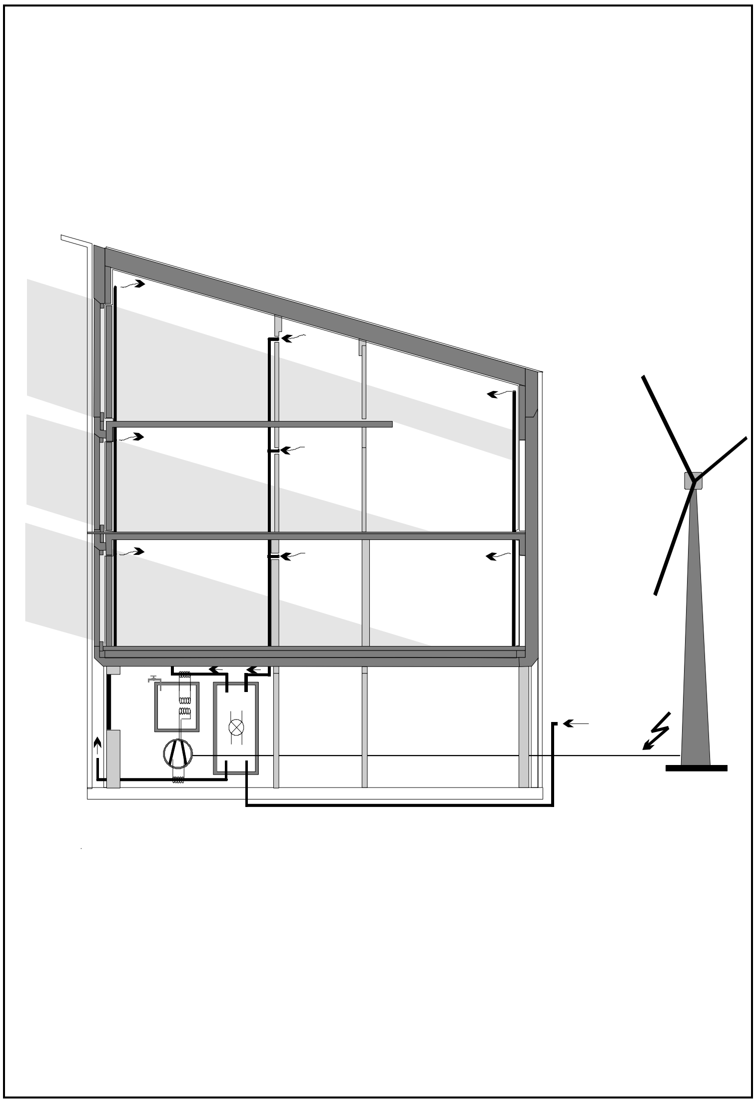
Project number:

BU/00127/97/ DE/SE/AT

CEPHEUS

Cost Efficient Passive Houses as European Standards

Passive Houses are buildings in which a comfortable interior climate can be achieved *without an active heating and air-conditioning system.* To permit this, the specific annual demand for space heating must be kept lower than 15 kWh/(m^2a), and the total final energy demand for space heating, demostic hot water, ventilation and household electricity must not exceed 42 kWh/(m^2a).
This forms the basis to cover the remaining energy requirement totally by renewables.



In 1998 the project "Cost Efficient Passive Houses as European Standards" started with support of the *Thermie* program of the European Union. The aim of this project is:

- the construction of 258 dwellings in cost-efficient passive houses in five European countries, including in Hannover in the immediate vicinity of the EXPO 2000 World Fair;
- Specific annual heat requirement of the passive houses lower than 15 kWh/m²/yr, so that a separate heating system is no longer necessary. The remaining heat requirement can be covered entirely through supplementary heating of the supply air that is required for indoor air quality, by means of recovering latent heat from the exhaust air.
- Total energy requirement of passive houses: $\leq$ 42 kWh/m²/a, i.e. by a factor of four lower than present average new buildings (space heating -80%, domestic hot water -60%, household electricity -60%)
- Cost-efficient passive houses after market introduction: i.e. the additional investments in passive technologies are not higher than the expected life cycle energy cost savings over a maximum 30 years.
- At the Hannover site: Completely renewable coverage of total energy requirement through integration with a wind turbine installation.
- Presentation of all projects at the EXPO 2000 World Fair in Hannover.

Passive houses at Hannover-Kronsberg

One of these CEPHEUS settlements will be erected at Hannover, at a building site near to the EXPO 2000. The city of Hannover has reserved an area for this in its development plan that directly adjoins the planned district centre. The land is owned by the city. The greater part of the area will be developed with two-story terraced buildings, and a smaller part with apartment buildings.

There will be some 3,000 dwellings in the final development stage. Not all of them will achieve the passive house standard. But, if we assume that all of them do, that would open an interesting opportunity:
Nearby the settlement, three sites for wind turbines in the 1.5 MW class have been reserved. The total electricity generated by these will be approx. 8.1 Million kWh/a. This is more than the 7.5 Million kWh of the total energy consumption of a passive house settlement with 3,000 houses at this site: the equivalent use of electricity will be

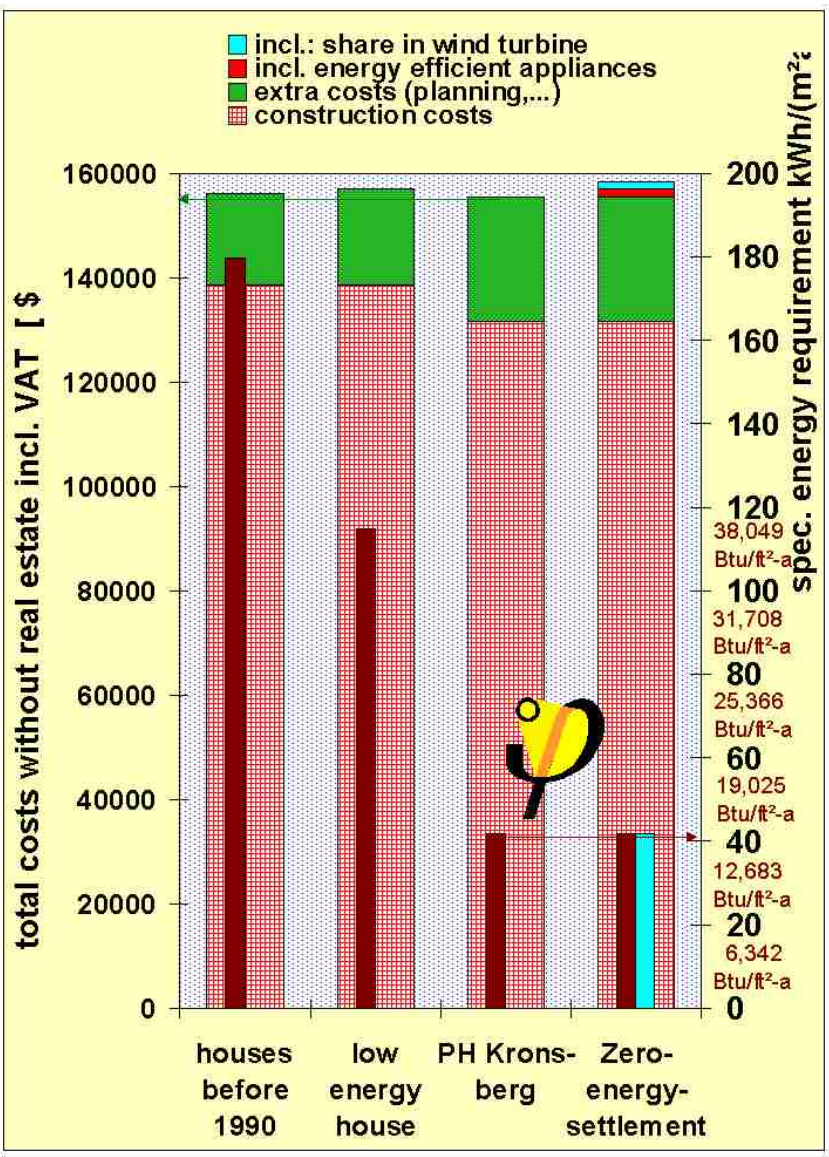
$$25 \text{ kWh/m}^2\text{/a} * 100 \text{ m}^2\text{/house} * 3{,}000 \text{ houses.}$$

This exemplifies that it is possible to supply passive houses on a completely renewable energy basis.
On the other hand, if the energy efficiency of the 3,000 dwellings is not better than the present average of new buildings, at least 14 wind turbines would be necessary to produce the same amount of energy consumed in the buildings. Not to speak about costs - but there is no space for so many turbines near to the site.

Cost-efficient passive houses at the Hannover Kronsberg-site

The total costs for a new row house in Germany including value added tax (but without real estate) were in the range of $ 156,000 before 1990 (117 m² living space {1,262 ft²}). These costs only changed a little bit looking at new low energy houses that have been build and sold in 1997 at the Hannover Kronsberg site. The interesting fact is, that the total costs of the passive houses, which have been sold at this site were not higher than that! But the price of these houses includes two extras:

- the extra costs of the highly efficient appliances, which are obligatory for this settlement ($1,500 per house) and
- the share in a wind turbine of a size, that is sufficient to offset the total energy consumption of the new built house ($1,400 per house).



The key conclusion of our experience is that:

Using passive house technology, it is possible to build new settlements with very low remaining energy consumption [less than 25 kWh/m²/a {8,000 Btu/ft²/yr}]. This is possible without increasing construction costs. In addition, the remaining energy consumption is so low that it is possible and economically justifiable to produce it completely with renewable energy sources.

Acknowlegdements:

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- the architects Prof. Helmut Bott, Karl Ridder and Hans-Jürgen Westermeyer who designed the first passive house at Darmstadt,
- Prof. Bo Adamson from Lund University for the general idea of the passive house and his help during the design period,
- the Hessian Ministry for the Environment for financing the mesurement and research program,
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- Karl-Heinz Fingerling (isofach, Kassel), who developed the first superefficient windows used in the passive house,
- Folkmer Rasch (Rasch&Partner, Darmstadt), who succeeded in building cost efficient passive houses of the second generation in 1997,
- Helmut Krapmeier (Energy Institute of Vorarlberg) and Manfred Görg (Stadtwerke Hannover) who took responsibilities in the definition and the ongoing work of the CEPHEUS project,
- the carriers of the "Cost efficient passive houses working group": Hessian Ministry of the Environment; Ministry of Housing Northrhine-Westfalia; PreussenElektra AG; Stadtwerke Hannover AG; VEBA; Landesentwicklungsgesellschaft Northrhine-Westfalia
- John Wilson (California Energy Commission) who looked through the english manuscript and made major corrections.

Find latest informations on the passive house development at the web: http://www.passiv.de .