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Energy-efficient terrace houses in Sweden Simulations and measurements

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Abstract

Reducing energy use in buildings is essential to decrease the environmental impact. Outside Gothenburg in Sweden, 20 terrace houses were built according to the passive house standard and completed in 2001. The goal was to show that it is possible to build passive houses in a Scandinavian climate with very low energy use and to normal costs. The houses are the result of a project including research, design, construction, monitoring and evaluation. The passive house standard means that the space heating peak load should not exceed 10 W/m^2 living area in order to use supply air heating. This requires low transmission and ventilation losses and the building envelope is therefore highly insulated and very airtight. A mechanical ventilation system with approximately 80% heat recovery is used. The electric resistance heating in the supply air is 900 W per living unit. Solar collectors on the roof provide 40% of the energy needed for the domestic hot water. The monitored delivered energy demand is 68 kWh/m^2 a. Energy simulations show that main differences between predicted and monitored energy performance concern the household electricity and the space heating demand. Total delivered energy is approximately 40% compared with normal standard in Sweden.

Keywords: Energy-efficient; Passive houses; Measurements; Simulations; Scandinavian climate

1. Introduction

Reducing the energy use in buildings is an important means to decrease the environmental impact of the building sector that stands for 40% of the energy use in society. There is a growing movement especially in Germany, Austria and Switzerland to build passive houses that are based on energy conservation measures and an efficient mechanical ventilation system with heat recovery. In Germany more than 4000 passive houses have been constructed [1,2]. The first project was built in 1991 in Darmstadt, Germany. By now, a large documentation is available on design, construction, measurements and evaluation for different passive house projects.

The passive house standard means that the space heating peak load should not exceed 10 W/m^2 living area in order to use supply air heating. The resulting space heating demand will approximately be 15 kWh/m^2 a but will vary depending on climate. Solar collectors are often used for domestic hot water (DHW) and energy-efficient household appliances are recommended.

Lindås, outside Gothenburg, is the first passive house project in Sweden. The houses are the result of a project extending over four years, carried out by EFEM Arkitektkontor, Energy and Building Design at Lund University, Chalmers University of Technology, and the Swedish National Testing and Research Institute (SP). This paper describes the buildings, presents simulation results of key design parameters, presents monitored energy performance and finally discusses the differences in early design stage assumptions and goals with the actual performance of the buildings.

2. Description of the buildings

2.1. The building envelope

The strategy when designing the houses was to minimise transmission and ventilation losses and use solar energy for domestic hot water and at the same time achieve high comfort for the occupants. Four rows with in total 20 units were built and completed in 2001 (Figs. 1 and 2). Each unit has a living area of 120 m^2 (mid unit) or 124 m^2 (end unit) in two storeys.

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Fig. 1. Twenty terrace houses in four rows (Hans Eek).

The building envelope is highly insulated with 40–50 cm insulation in walls and roof, see Fig. 3. Special care was taken to minimise thermal bridges and to ensure an airtight building envelope. The mean *U*-value of the building envelope including windows is 0.16 W/m^2 K (Table 1). The average airtightness at 50 Pa was measured as 0.3 l/s m^2 which is much better than required by the Swedish Building Code, i.e. 0.8 l/s m^2.

Two types of three pane windows were used. The operable type has two low-emissivity coatings, one gap with argon and one with air. The other window type is fixed and includes two low-emissivity coatings and krypton gas in both gaps. The energy transmittance is ca. 50% and the visual transmittance is 64% for the operable window and 68% for the fixed. The mean *U*-value of the windows for a house unit is 0.85 W/m^2 K.

2.2. Ventilation and space heating

Each house is equipped with a mechanical ventilation system with heat recovery. The exhaust air in a counter flow heat exchanger heats supply air. It provides approximately 80% heat recovery. The space heating demand is covered by electric resistance heating in the supply air, 900 W per unit (approximately 8 W/m^2).

During summer the heat exchanger can be turned off (automatic bypass) and the house ventilated without preheating of the supply air and by opening windows. Balconies and roof overhang provide protection against excessive solar radiation. The roof window above the staircase gives light in the mid part of the house, and is also used for ventilation in the summer.

Fig. 2. View from the south (Maria Wall).

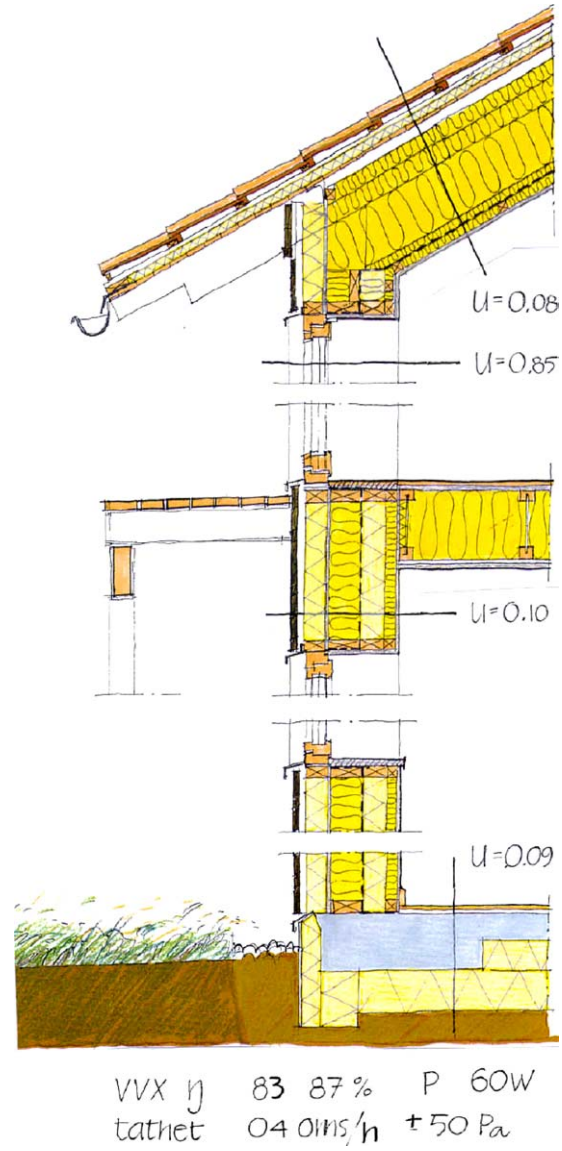

Fig. 3. Section (EFEM Arkitektkontor).

2.3. Domestic hot water supply

Solar collectors of 5 m^2 per unit provide the energy for approximately 40% of the hot water demand. The 500 l storage tank is equipped with an electric immersion heater to cover the rest of the demand [3,4].

Table 1
U-values of the building envelope

Building envelope	*U*-value (W/m^2 K)
Exterior walls	0.10
Roof	0.08
Ground floor	0.11
Windows, average	0.85
Door	0.80
Average, building envelope	0.16

3. Methods

3.1. Simulations with DEROB-LTH

Simulations were carried out during the design stage as a basis for decisions. In addition, simulations were done after the buildings were completed to analyse the final design and changes during the design stage. The program DEROB-LTH was used. DEROB is an acronym for Dynamic Energy Response of Buildings. The program, originally developed at the Numerical Simulation Laboratory, the School of Architecture, University of Texas, Austin, was further developed at the Division of Energy and Building Design, Lund University, under the name DEROB-LTH [5,6]. The Lund version was used in this study. The program is a research tool and is continuously developed at the Division [7–9].

Climate data from Gothenburg 1988 were used in the simulations. The mean outdoor temperature was 8.4 °C in 1988. Maximum temperature was 29.6 °C and occurred in June. Minimum temperature was −12.6 °C and occurred in January. This year is considered as a typical year [10].

The geometrical simulation model of the mid unit is shown in Fig. 4. The parametric studies shown in this paper were carried out for a mid unit. A family with two adults and two children were assumed in the simulations for the base case. In most cases, the setpoint for heating was 20 °C and the occupants were assumed to use shadings or increased ventilation to limit overheating above 26 °C. A theoretical setpoint for ‘‘cooling’’ was therefore used in order to reflect this strategy and to ensure that the energy stored in the building was not overestimated. The potential heating season studied was from 1st of October to 30th of April.

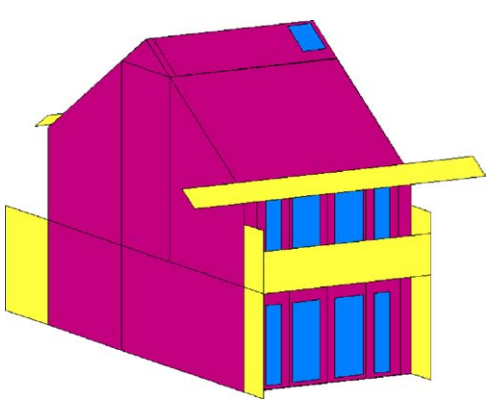

Fig. 4. The geometrical model of a mid unit in DEROB-LTH. The walls towards other units are assumed adiabatic.

3.2. Monitoring

The energy performance of the buildings was monitored by SP. As participant of the research project, Energy and Building Design received monitoring data which were the base for results presented in this paper. For further details on the monitoring data, see Ref. [3].

4. Parametric studies

Following are parametric studies that illustrate the type of studies carried out during the design stage and that show the importance of some of the design parameters on space heating demand and peak load.

4.1. Setpoints for indoor temperature

The preferred indoor temperature will obviously influence the space heating demand and the peak load for heating. In addition, if temperature fluctuations are allowed, it will enable energy to be stored in the thermal mass of the building.

The peak load for heating and the annual space heating demand for the mid unit are shown in Fig. 5. The heating setpoint is always 20 °C but the allowed highest indoor temperature is varying between 20 and 26 °C in the different simulation cases. Above 26 °C the occupants are assumed to increase ventilation and/or use shading devices.

If the temperature is allowed to vary between 20 and 26 °C, the space heating demand will be 7.5 kWh/m^2 a. However, if the indoor temperature should be kept constant at 20 °C the space heating demand will be 12.9 kWh/m^2 a since the thermal mass could not be used to store excessive energy from day to night. To allow a temperature fluctuation between 20 and 23 °C in the house is sufficient to make use of solar and internal gains. The peak load for heating will only be slightly influenced.

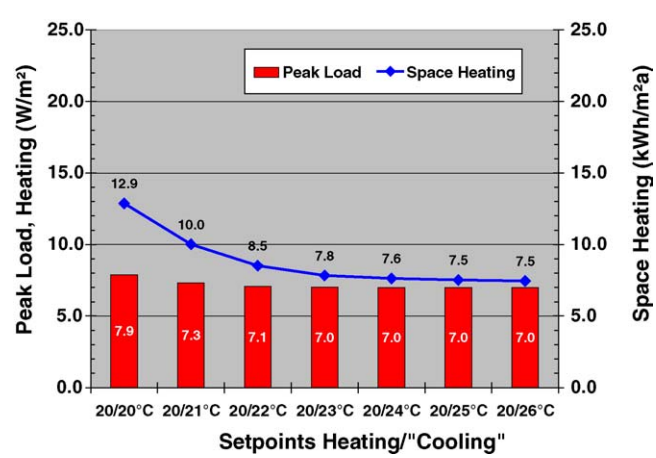

Fig. 5. Heating peak load and space heating demand for a mid unit with different setpoints for ‘‘cooling’’. The setpoint for heating is fixed to 20 °C.

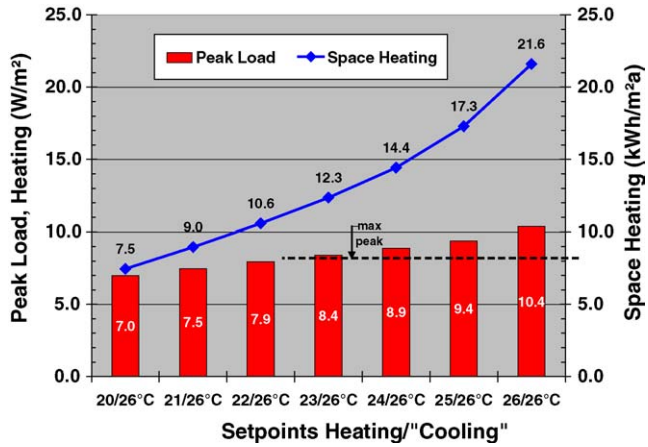

Fig. 6. Heating peak load and space heating demand for a mid unit with different setpoints for heating. The setpoint for ‘‘cooling’’ is fixed to 26 °C.

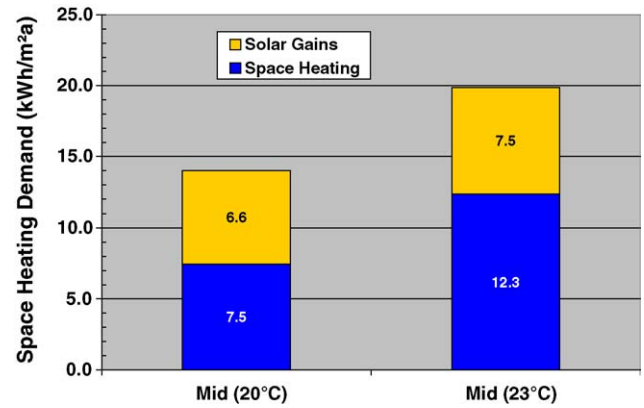

Fig. 7. Space heating demand and solar gains for a mid unit heated to 20 and 23 °C.

Quite a few people prefer a higher indoor temperature than 20 °C which was also seen in the measurements. In Fig. 6, the consequence of higher indoor temperature on peak load and space heating demand is shown with different setpoints for heating, between 20 and 26 °C. The setpoint for ‘‘cooling’’ is set to 26 °C in all cases.

The space heating demand is three times higher if the house is heated to 26 °C instead of 20 °C (Fig. 6). At the same time the peak load will go from 7.0 to 10.4 W/m^2. Note that the installed electric resistance heater in the supply air is limited to approximately 8 W/m^2. Thus, with the assumed user behaviour and climate, the house can be heated to approximately 23 °C.

The Passive House concept using supply air heating recommends that the peak load should not be higher than approximately 10 W/m^2 (floor area). The actual installed power (8 W/m^2) could thus be increased to 10 W/m^2 if needed. If the supply air heater would give 10 W/m^2, the mid unit could be heated to around 26 °C. However this is depending on, e.g. the number of occupants living in the house, and their habits.

In the base case for the following simulations, the setpoints are 20 °C for heating and 26 °C for ‘‘cooling’’. This is often accepted as normal temperature fluctuations in houses for a Scandinavian climate.

4.2. Solar gains

In an energy-efficient house, the heating season is shorter than in a standard house with larger thermal losses. As a result the available solar gains will be reduced when the heating season is shorter, since solar radiation is very limited during the winter in Sweden.

In Fig. 7, the space heating demand is shown for the mid unit when heated to 20 and 23 °C, respectively, for the heating season 1st of October to 30th of April. The bottom part of the bars show the space heating demand and on top are the usable solar gains. The solar gains are calculated by two simulations; one without solar radiation in the climate file, and the other one with the real climate data for solar radiation. The mid unit requires 7.5 kWh/m^2 a for space heating but if there would be no solar radiation at all, the mid unit would have needed 7.5 + 6.6 = 14.1 kWh/m^2 a.

For the setpoint of 20 °C the solar gains cover approximately half of the heating demand. When the house is heated to a higher indoor temperature, the solar gains increase, but can only to a minor degree cover a higher indoor temperature setpoint. Therefore, the space heating demand will also increase.

The peak load is almost not influenced by solar gains; see Fig. 8 that shows the corresponding peak load for different heating setpoints. The reduction of the peak load due to solar gains is only 1 W/m^2; equal to the heat from one or two light bulbs in a house unit. The peak occurs usually in early morning after a cold night when potential solar gains stored in the building mass already have been used.

4.3. Airtightness

The airtightness of the building envelope has a very high influence on the space heating demand and the peak load. The average airtightness of the houses was measured as 0.3 l/s m^2 at 50 Pa. Totally eight units were measured by SP [3]. Estimated infiltration rate based on the measurements were calculated as

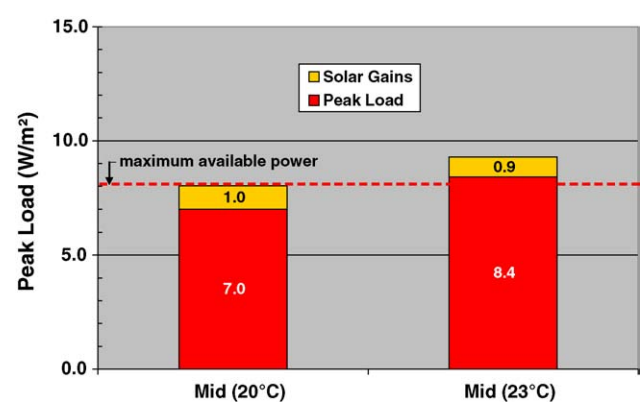

Fig. 8. Peak load and solar gains for a mid unit heated to 20 and 23 °C. The line represents the maximum available power for the electric resistance heating in the supply air.

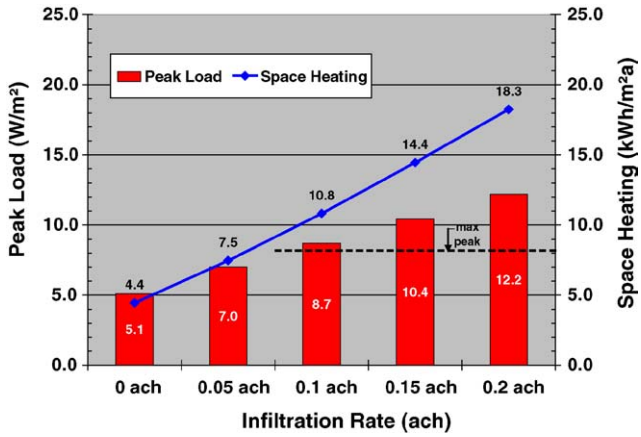

Fig. 9. Peak load and space heating demand (setpoint 20 °C) for a mid unit with different infiltration rates.

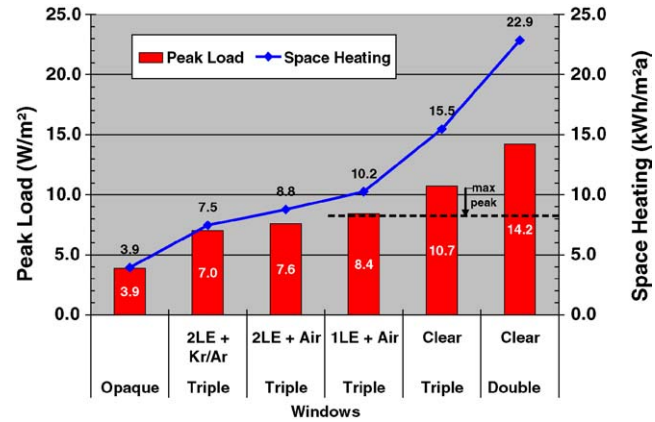

Fig. 10. Peak load and space heating demand (setpoint 20 °C) for a mid unit with different window types. The first "opaque" case means that all windows are changed to the wall or roof construction.

0.05 ach, according to Ref. [11]. If the requirements according to the Swedish Building Code were exactly fulfilled, the infiltration rate would be approximately 0.1 ach. However, the airtightness is normally not measured to check if the requirements are fulfilled. Therefore, the average air leakage in ordinary buildings could be higher than 0.1 ach.

A leaky envelope would jeopardize the Passive House concept and radically worsen the quality of the highly insulated building envelope, as can be seen in Fig. 9 where the peak load and space heating demand are shown for different infiltration rates. The second case (0.05 ach) represents the estimated airtightness of the buildings. How to achieve an airtight building envelope was one of the most important factors discussed during the design stage.

4.4. Window type

Modern energy-efficient windows for housing include one or two low-emissivity coatings and noble gas such as krypton or argon in the air gaps. In order to see the importance of the glazing parts the number of low-emissivity coatings, the type of gas in the gaps and the number of panes were studied.

In Fig. 10, the peak load and space heating demand are shown for different window types. The frame has not been changed. In addition a case is shown when all windows (glass + frame) have been changed to the well insulated wall or roof. This first "opaque" case means that the house is completely without windows. The second case "Triple 2LE + Kr/Ar" is the windows installed in the houses. For each additional case one component has been changed at a time, to see the influence of every single part.

Comparing the opaque case with the (real) second case; i.e. the triple glazing with two low-*e* coatings and krypton/argon in the sealed gaps, shows that having windows in the house will increase the energy demand and peak load. The solar gains through the windows will not fully compensate for the larger transmission losses through the windows than through a well insulated wall. However, the increase is not so large and of course the benefit of having windows is undisputed. A study regarding window area was made in [12].

To use windows with air (2LE + Air) instead of noble gas (2LE + Kr/Ar) in the sealed gaps is of minor importance. If the cost differs considerable, this is good to know. However, if the triple glazed window only has one of the low-emissivity coatings (1LE + Air) and especially if no coating at all is used (Clear Triple), the influence on the space heating demand and peak load is much larger.

The change from triple clear to double glazing has the largest single impact. Furthermore, if a double clear glazing is used instead of the actual windows the space heating demand will increase from 7.5 to 14.2 kWh/m^2 and the peak load will increase from 7.0 W/m^2 to 14.2 W/m^2, which disables using the Passive House concept and in particular will cause discomfort.

4.5. Occupancy

It is very difficult to predict the number of occupants and their behaviour, the amount of household appliances and how energy-efficient they will be. Therefore it is necessary to study different scenarios during the design stage. It is especially important for low-energy houses, e.g. passive houses in which internal gains have a higher relative influence.

In Fig. 11, the peak load and space heating demand is shown for four occupants (two adults + two children), two occupants (adults) and no occupants. The case with no occupants illustrates if the house would be empty for the whole heating season. Only the refrigerator, freezer and DHW boiler will still give rise to some internal gains. To see the relative importance of the internal gains compared to solar gains, the first case with four occupants and no solar radiation is included. The yearly mean available gains from the four occupants are 4.3 W/m^2, for two occupants 3.4 W/m^2 and for no occupants 1.7 W/m^2. Part of these gains will be useful.

A family with four occupants has more influence on the space heating demand and peak load than the solar gains have,

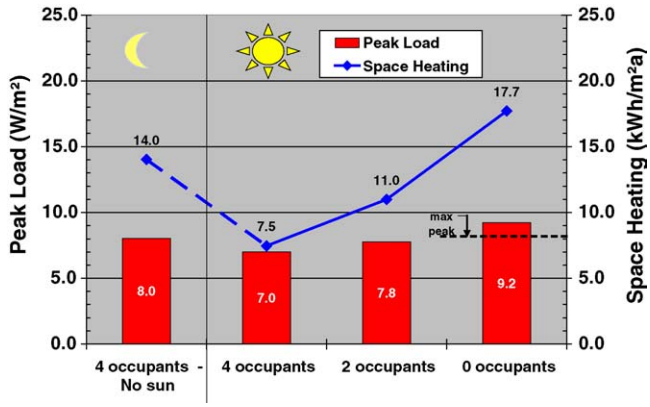

Fig. 11. Peak load and space heating demand (setpoint 20 °C) for a mid unit with different number of occupants. The first case is for the base case of four occupants, but without solar radiation.

see Fig. 11. The installed heating power of approximately 8 W/m^2 indicates that without occupants, the indoor temperature could go below 20 °C during cold periods.

5. Monitored energy performance

5.1. Annual energy demand

The variation in monitored energy use for the 20 house units is large but not exceptional, see Fig. 12. The total delivered energy (''bought energy'') varies between 45 and 97 kWh/m^2 a for different households. The average delivered energy demand is 68 kWh/m^2 a. The total monitored energy demand for space heating, domestic hot water and household electricity during a year is shown in Table 2. The monitoring year is considered very close to a normal year.

5.2. Changes in design and assumptions from design stage to the final buildings

5.2.1. Studied changes influencing the space heating demand and peak load

During the design stage, assumptions and different solutions were defined and analysed in order to estimate the influence on,

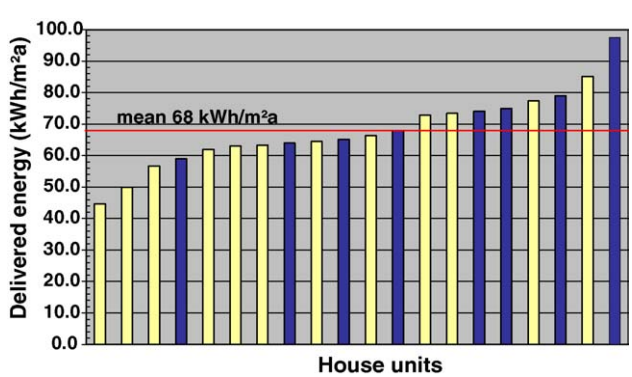

Fig. 12. Monitored delivered energy per house unit during a year. DHW heating, space heating, electricity for mechanical systems and household electricity. The dark bars are end units. Based on data from Ref. [3].

Table 2
Monitored average energy use for the 20 units

Monitored energy use (kWh/m^2 a)	
Heating of space and ventilation air (electricity)	14.3
Domestic hot water heating; electricity	15.2
Fans and pumps	6.7
Lighting and household appliances	31.8
Delivered energy demand	68.0
Domestic hot water heating; solar energy	8.9
Total monitored energy demand	76.9

Based on data from Ref. [3].

e.g. the space heating demand and peak load. During the process some building parts changed from what were originally planned. Furthermore, early assumptions could be more accurately specified after tests and monitoring. Changes were made for the window type, estimated infiltration rate, the efficiency of the ventilation heat recovery and the setpoint for heating (preferred indoor temperature).

In order to study the influence of these changes on the space heating demand and the peak load, simulations were carried out. For each change a new simulation was done, as a stepwise procedure. Below is a description of the changes made for each simulation step for the four parameters studied.

5.2.1.1. Step 1: design stage assumptions.

Window type: During the design stage, both types of windows (fixed and operable) were planned to have krypton gas in the sealed glass units. In this simulation step, the operable window type therefore has two low-emissivity coatings and one krypton and one air gap. The fixed window type included two low-emissivity coatings and krypton gas in both gaps.

Infiltration rate: An infiltration rate of approximately 0.02 ach was estimated as possible to achieve. This value was used as an average air leakage for the house.

Heat recovery of ventilation: At an early design stage, hopes were to find a heat exchanger with 85% heat recovery or more. The chosen heat exchanger was tested at SP. After some developments the heat recovery was measured as 83% during standardized conditions. Therefore, 83% heat recovery of the ventilation was assumed as input for the simulation in this step.

Setpoint for heating: For the parametric studies during the design stage, different indoor temperatures were assumed in order to estimate the influence on the energy demand and peak load. As a base case, 20 °C was used, which also is the setpoint for heating in this simulation step.

5.2.1.2. Step 2: changed window type. During the construction stage, the operable window type was changed from one with krypton filling to one with argon in the sealed glass unit. Thus, the operable window type has two low-emissivity coatings with one argon and one air gap. All other parameters were the same as in Step 1.

5.2.1.3. Step 3: increased infiltration rate. The average air tightness of the houses was measured as 0.3 l/s m^2 at 50 Pa. Estimated infiltration rate based on the measurements was calculated as 0.05 ach. This infiltration rate was used in the simulation for Step 3. All other parameters were the same as in Step 2.

5.2.1.4. Step 4: reduced ventilation heat recovery. The ventilation heat recovery was in practice lower than measured at standardized conditions in laboratory during the design stage [3]. The average heat recovery was therefore reduced to 80% for this simulation. All other parameters were the same as in Step 3.

5.2.1.5. Step 5: higher indoor temperature. Results from monitoring showed that the indoor temperature of course varied between the different households. The temperature was in general higher than expected, during the heating season approximately 23 °C, which was used as setpoint in Step 5. All other parameters were the same as in Step 4.

5.2.2. Influence on the space heating demand and peak load

In Fig. 13, the space heating demand and peak load for each simulation step is shown. As expected the space heating demand is not influenced much by the change of window (gas) type (Step 2). The higher infiltration rate gives rise to an increase of 1.8 kWh/m^2 a in space heating demand (Step 3). A 3% reduced ventilation heat recovery is not crucial (Step 4). The choice of 23 °C as indoor temperature, instead of 20 °C has the highest impact; an increase of 4.9 kWh/m^2 a (Step 5). From Steps 1 to 5, the space heating demand increases from 4.7 to 12.3 kWh/m^2 a.

Correspondingly, the change in peak load for space heating gives similar results. However, the peak is less influenced than the energy demand. Note that the last simulation, Step 5, will lead to a peak load that is approximately the same as the maximum available for the house.

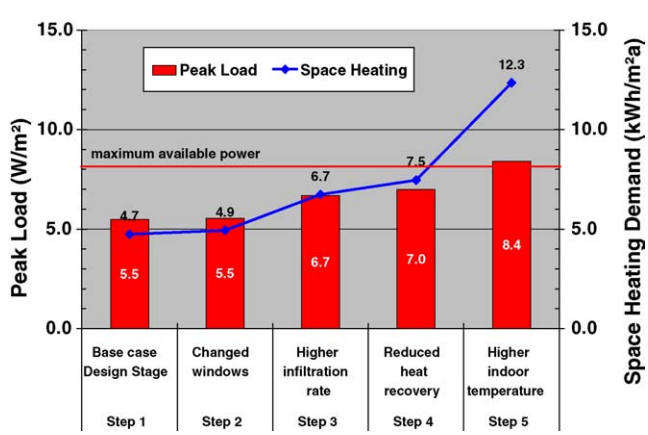

Fig. 13. The change in peak load and space heating demand for a mid unit from design stage to the final design.

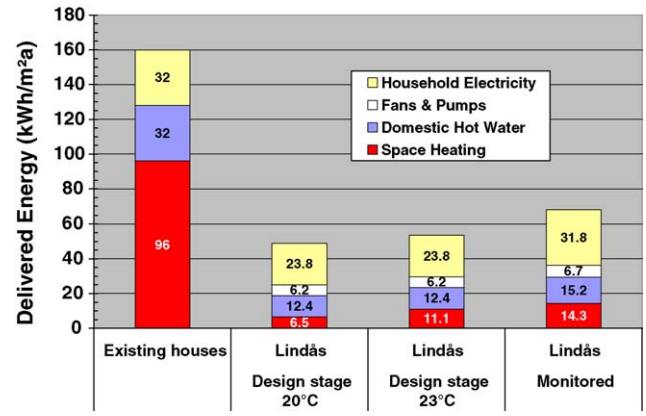

Fig. 14. Delivered energy use as predicted during the design stage (20 or 23 °C, average unit), compared to the monitored energy and compared to the average delivered energy in the existing Swedish residential building stock year 2000 [13].

5.2.3. Predicted and monitored DHW demand

During the design stage, the DHW demand was assumed to be 3000 kWh/a per unit or 24.7 kWh/m^2 a. The goal was that 50% should be supplied by the solar collectors. The monitored DHW demand was 24.1 kWh/m^2 a of which 8.9 kWh/m^2 a (37%) was supplied by the solar collectors and 15.2 kWh/m^2 a by electricity.

5.2.4. Predicted and monitored household electricity

The household electricity was assumed to be 2900 kWh/a per unit or 23.8 kWh/m^2 a. The intention was to install energy-efficient household appliances, which however was not done. The monitored household electricity demand was 31.8 kWh/m^2 a. This is at the same level as the average household electricity demand in Sweden, see Fig. 14 that shows the monitored total delivered energy compared to the average in Sweden.

5.2.5. Predicted and monitored delivered energy

Energy savings is approximately 60% compared to houses built according to the Swedish Building Code and practice, see Fig. 14 that compares monitored delivered energy in the terrace houses with normal standard in Sweden. The predicted energy demand is also shown for the heating setpoint 20 and 23 °C respectively, and compared with the monitored delivered energy. As can be seen, the main differences between predicted and monitored values concern the household electricity and the space heating demand.

6. Conclusions

Simulations during the design stage show that the air-tightness of the building envelope is essential in order to reach the targets of maximum peak load of 10 W/m^2 and a low space heating demand, around 15 kWh/m^2 a. Pressurisation tests showed that the airtightness at 50 Pa was 0.3 l/s m^2 which was only slightly higher than the goal set, and much better than required by the Swedish Building Code.

The efficiency of the heat exchanger is slightly less than expected due to that the defrosting system was changed to bypass the heat exchanger a few minutes each hour when the outdoor temperature was less than −2 °C. The ventilation heat exchanger, the control system and the function of the defrosting system could be further improved.

Simulations show that energy-efficient windows are essential to reduce thermal losses. Low-emissivity coatings are an important part of these windows. In addition, such windows ensure high thermal comfort and give daylight to the rooms. Modern low-energy windows with low-emissivity coatings do not give rise to large thermal losses since solar gains are partly compensating. However, they still loose more energy than a well insulated wall in a Swedish climate.

Occupancy behaviour is highly influencing the space heating demand and peak load. Hence, different occupancy profiles should be studied by simulations during the design stage. Also different indoor temperatures and how these affect the energy demand and peak load should be studied. Traditionally the setpoint for heating is 20 °C for simulations of the energy balance of buildings. However, it is often the case that occupants prefer higher indoor temperatures.

Simulations show that for a mid unit, the combination of changes made from the design stage to the final design resulted in an increased space heating demand from ca. 4.7 to 12.3 kWh/m^2 a and an increased peak load from ca. 5 to 8 W/m^2. The single most influencing factor is the higher indoor temperature.

The use of household electricity is higher than expected, since the occupants have more electric equipment than assumed and the household appliances were not as energy-efficient as proposed during the design stage. However, the use of household electricity is not higher than for an average Swedish household.

The efficiency of the solar DHW system was only 37% instead of the expected 50%, partly due to that the storage tank was poorly insulated and larger than needed for the installed DHW system, which give rise to high tank losses.

The total delivered energy estimated during the design stage for an average unit was 49 kWh/m^2 a. This was based on estimations of the project group and the simulated space heating demand for the indoor temperature of 20 °C. With an indoor temperature of 23 °C the calculated energy demand was 54 kWh/m^2 a. These values should be compared with the monitored energy demand of 65 kWh/m^2 a as average for the mid units, 72 kWh/m^2 a for the end units and 68 kWh/m^2 a as average for all units. The difference between the calculations made during the design stage and the measurements was mainly due to higher indoor temperature, higher household electricity use and lower solar fraction for the solar collectors than predicted. The reduction of total delivered (bought) energy in the houses compared with normal standard in Sweden is approximately 60%. In future projects, it should be able to reduce the electricity use even further.

The design process was carried out in collaboration with client, builder, architect, consultants and researchers. A series of seminars with different main topics were carried out in which all the parties participated. In this way different alternatives were discussed and everyone was informed about final decisions and why it was important. Furthermore, the architect visited the building site to explain the importance of airtightness and how to make the construction details in a correct way. The houses have proved to be a good way to demonstrate the possibilities in achieving affordable housing with very low energy use and high comfort. New passive house projects are now in planning and constructed in Sweden.

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