Passive houses in Sweden

From design to evaluation of four demonstration projects

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Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2010
Report EBD-T--10/12

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 110 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 46 000 students attending 274 degree programmes and 2 000 subject courses offered by 63 departments.

Division of Energy and Building Design

Reducing environmental effects of construction and facility management is a central aim of society. Minimising the energy use is an important aspect of this aim. The recently established division of Energy and Building Design belongs to the department of Architecture and Built Environment at the Lund University, Faculty of Engineering LTH in Sweden. The division has a focus on research in the fields of energy use, passive and active solar design, daylight utilisation and shading of buildings. Effects and requirements of occupants on thermal and visual comfort are an essential part of this work. Energy and Building Design also develops guidelines and methods for the planning process.

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Doctoral Thesis

Keywords

Passive house, Energy efficiency, Residential buildings, Building construction, Planning process, Ventilation

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Abstract

The use of energy is a major global issue both according to climate changes but also in the aspect of national safety tied to the trade with energy sources. Of the total energy use in the member states of the European Union, about 40% is used in residential and commercial buildings. Passive houses are one way to reduce the energy use in buildings and at the same time keep a good indoor comfort. The basic idea of the passive house concept is to have well insulated and air tight climate shell together with a mechanical ventilation system. Within this research, four Swedish passive house projects have been followed from the early planning stage to evaluation of the actual buildings; three apartment building projects in Värnamo, Frillesås and Alingsås and one single-family house in Lidköping. Three of the projects were new built and the fourth, in Alingsås, was a renovation project. The research was funded by the Swedish Energy Agency and has been a five year project. The main purpose with the study was to see how energy efficient residential buildings, mainly passive houses, can be built in Sweden and on a more widespread scale than before.

The total measured energy use for space heating, domestic hot water and common electricity was in Värnamo 36 kWh/m^{2}a, in Frillesås 50.5 kWh/m^{2}a, in Alingsås 65.7 kWh/m^{2}a and in Lidköping 51 kWh/m^{2}a, revised to a normal year. The peak load for space heating is measured to be somewhat higher than the required 10 W/m^2 (12 W/m^2 required in the single family house).

Previous research shows that a ventilation air change rate of 0.5 ach seems to be necessary in order to achieve a good indoor air quality. Simulations made in this research shows that not much energy is saved by decreasing the ventilation rate below 0.5 ach and should be avoided to assure a good indoor comfort.

Some products have been detected to be in need of development to ease the building of passive houses in the future, e.g. easier used ventilation units, supply air devices suitable for space heating distribution and woodburning stoves with a power to the room of 1 – 3 kW.

There were some additional costs in these demonstration projects for e.g. education, air-tight solutions and more expensive products which can

be decreased in future projects when more suitable products are available on the market and when the knowledge and experience of how to build energy efficient buildings is natural and well spread. The three clients of the apartment buildings have all continued with building new passive houses or renovating according to the passive house principles after their demonstration project was finished.

Contents

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Finally, I would like to thank you who are about to read my thesis. Remember – with great knowledge comes great responsibility!

Lund, October 2010

Ulla Janson

Nomenclature

A	heated area (m^2)
A_{temp}	the area of the building inside to inside of the building envelope, which is heated above 10°C.
$A_{temp + garage}$	the area of the building inside to inside of the building envelope, including the heated area of the garage if it is placed inside the climate shell, which is heated above 10°C
c_p	Specific heat capacity (J/kg K)
e_{bp}	energy correction factor bio fuels (-)
e_{dh}	energy correction factor district heating (-)
e_{el}	energy correction factor electricity (-)
$e_{s,w}$	energy correction factor by solar systems or wind power plants (-)
G	Total living area (m^2)
L	length (m)
L_{2D}	thermal coupling coefficient from two-dimensional calculation W/(mK)
P	Power (W)
P_{max}	Peak load for space heating (W/m^2)
P_{SFP}	specific fan power (W/m^3s)
P_t	Transmission losses (W)
P_{tot}	Overall heat loss coefficient for space heating (W)
P_v	Ventilation losses (W)
ΔP	Pressure difference (Pa)
Q	Energy (kWh)
Q_{bp}	Delivered energy bio fuels (kWh/m^2a)
Q_{dh}	Delivered energy district heating (kWh/m^2a)
Q_{el}	Delivered energy electricity (kWh/m^2a)
Q_{fan}	Energy use for the fan (kWh/m^2a)
Q_H	Additional heat from the space heating system (kWh)
Q_I	Internal gains (kWh)
$Q_{requirement}$	Required maximum total delivered energy ($kWh_{weighted}/m^2a$)

Q_s	Solar gains (kWh)
$Q_{s,w}$	Delivered energy by solar systems or wind power plants (kWh/m^{2}a)
Q_T	Transmission losses (kWh)
Q_{tot}	Total energy demand for space heating (kWh)
Q_v	Ventilation losses (kWh)
$Q_{weighted}$	Bought energy, weighted (kWh$_{weighted}$/m^{2}a)
q	Ventilation air flow rate (l/s m^2 or m^3/h or m^3/m^{2}h or ach)
$q_{infiltration}$	Ventilation losses due to air infiltration/ exfiltration (m^3/h)
$q_{mechanical}$	Mechanical ventilation rate (m^3/h)
R	Thermal resistance (m^{2}K/W)
R_{tot}	Total thermal resistance (m^{2}K/W)
t	Time (h)
$T_{exhaust}$	Exhaust air temperature (°C)
$T_{extract}$	Extract air temperature (°C)
T_{indoor}	Indoor air temperature (°C)
$T_{outdoor}$	Outdoor air temperature (°C)
$T_{outdoor,dim}$	Coldest outdoor temperature at the specific location (°C)
T_{w1}	Water supply temperature (°C)
T_{w2}	Water return temperature (°C)
T_{supply}	Temperature of the supply air after the heat exchanger (°C)
$T_{supply,\ heated}$	Temperature of the supply air after the heating coil (° C)
T_0	Ambient temperature (°C)
ΔT	Temperature difference (°C)
ΔT_{tot}	Total temperature difference (°C)
U	Thermal transmittance (W/m^{2}K)
V	Volume (m^3)
$\dot{V}$	Volume flow (m^3/s)
ρ	Density (kg/m^3)
η	Efficiency (%)
$\eta_{exhaust\ air}$	Efficiency of the heat exchanger according to exhaust air (%)
$\eta_{supply\ air}$	Efficiency of the heat exchanger according to supply air (%)
η_u	Utilization factor (-)
Ψ	Linear thermal transmittance (W/mK)

1 Introduction

The use of energy has become a major global issue in recent years. It is mostly the environmental aspects of high energy consumption that are discussed but there is also a growing awareness of national safety aspects tied to the trade with energy sources, connected to the increasing scarcity of energy supplies. Climate change due to global warming is no longer something that is expected to happen in the future; it has already started to affect many countries with melting glaciers, tropical storms and rising sea levels and is now seen as one of the biggest challenges that are facing mankind in the coming years (European parliament, 2010 a). The use of energy and consequently the greenhouse gas emissions need to decrease dramatically in the following years. In this chapter, the background to the need of reduced energy use and thereby energy efficient buildings are discussed.

1.1 Global energy use

The decrease in greenhouse gas emissions is in most countries regulated by the Kyoto Protocol. The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change and was adopted in Kyoto, Japan, in December 1997 and entered into force on February 16, 2005 (UNFCCC, 2010). In the protocol, 37 industrialized countries and the European community have undertaken binding targets on reduction of their greenhouse gas (GHG) emissions, in order to try to fight global warming. The reduction in the participating countries amounts, on average, to 5% of GHG emissions compared to the levels in 1990, during the period 2008-2012 and 8% for the countries within the European Union (countries included before May 1, 2004). The Kyoto protocol may be seen as an important first step towards a global emission reduction with stabilized GHG emission levels. It is most important to have a new ratified international framework for future GHG emission levels when the Kyoto protocol ends in 2012. The work with a new framework is proceeding with negotiations and discussions. Unfortunately, the meeting in Copenhagen in 2009 did not result in a new binding protocol.

The use of energy varies a lot between countries and also the energy use per person within their populations. The OECD countries account for the largest current world energy use. Many other countries are however increasing their living standards and consequently their need of energy supply, and in the IEO2009 projections the total world use of marketed energy is projected to increase by 44% from 2006 to 2030, with its largest increase in non-OECD countries (EIA, 2010). China and India are the fastest-growing non-OECD economies. Together they accounted for about 10 percent of the world's total energy use in 1990 but in 2006 their combined share was 19 percent, indicating that they will be key world energy users in the future. Also other non-OECD countries, like the Middle East, Central and South America, Non-OECD Asia and Africa, show robust growth in energy use.

Energy use in the residential sector (energy used by households excluding transportation uses) accounted for about 15 per cent of world delivered energy use in 2006 (EIA, 2010). The energy use in residential buildings varies according to income levels, availability of natural resources and differences in climate. Generally, typical households in OECD countries use more energy than those in non-OECD countries, and many non-OECD countries remains unconnected to the power grids and rely heavily on wood and charcoal for cooking. In both China and India, the rural population mostly uses biomass for cooking. With a higher income this might be replaced by marketed fuels such as propane and electricity. The IEO2009 projections only account for marketed energy and the change of energy source will therefore make the energy use visible in the statistics.

More than 60 percent of global electricity supply is currently extracted from natural gas and coal (European parliament, 2010b). It is difficult for renewable technologies to compete economically with fossil fuels. The use of renewable energy facilities for electricity generation is encouraged by government policies in many OECD countries, particularly those in Europe with e.g. feed-in tariffs, tax incentives and market-share quotas. In non-OECD countries, hydroelectric power is expected to be the predominant source of renewable energy.

1.2 Energy use in the European Union

In 1998, the European Union signed up to the Kyoto Protocol, which has since then been used as a base for the energy saving measures taken within the EU. Energy use varies a lot in the European Union, both between the countries and between different sectors (European parliament, 2010c). The European parliament considered that, in order to decrease the greenhouse gas emissions and at the same time decrease the amount of imported energy supply, energy use within the Union has to be reduced. It is difficult for the European Union to have full control on the imported energy supply. Instead, by encouraging energy efficiency measures within the Union, it has been seen possible to decrease the total energy demand and in this way decrease the need of imported energy supply. With three focus topics; Climate change, Secure the energy supply within the union and Strengthen the Union's competitiveness, the European Commission has the goal to create a highly energy-efficient, low carbon economy (European Parliament, 2010d). The security of supply follows the Green paper (European parliament, 2010e).

The three major targets regarding energy efficiency measures set up by the Commission, to be met by the Union by 2020, are often known as the 20-20-20 targets. The first 20-target is to reduce the greenhouse gas emissions in the EU by at least 20% by 2020 compared to the levels in 1990. The second target is that 20% of the total energy use within the EU should by 2020 come from renewable energy sources. Within the second target, there are different binding targets for the percentage of renewable energy sources for different countries in the union, where Sweden should have the highest share of 49% renewable energy sources by 2020. The third 20-target is to reduce the total primary energy use in the union by 20% compared to the energy consumption forecast for 2020; this should be achieved by energy efficiency measures. This objective corresponds to achieving an approximately 1.5% saving per year up to 2020. (European Parliament, 2010d). The 20-20-20 targets were enacted by the European Parliament and Council in June 2009. By these actions, the Union hopes among other things to prevent the global temperature from increasing to more than 2°C above pre-industrial levels, which correlates to the Kyoto protocol (European parliament, 2010a).

1.2.1 Energy use in buildings

Of the total energy use in the member states of the European Union, about 40% is used in residential and commercial buildings, which makes the building sector responsible for approximately 36% of the Union's total carbon dioxide emissions (European parliament, 2010a). There is, according to the Commission, a great potential for reducing the total energy use in the EU if the energy use in buildings is decreased; 27% of estimated energy saving potential is said to be in residential buildings and 30% in commercial buildings. This could be compared to the energy saving potential of 25% in the manufacturing industry and a 26% potential reduction in the transport sector. It is however explicitly stated by the Commission that it is important to maintain the same quality of life for the tenants when energy use in buildings is reduced.

Improving the energy performance of buildings is considered by the Commission to be a cost effective way to reach the 20-20-20 targets and also a way to create job opportunities, particularly in the building sector when energy efficient techniques, products and services must be developed. Within the impact assessment made in the proposal for the Directive of the European Parliament and of the Council on the energy performance of buildings, later adopted in May 2010, the explicit target set up for reduced energy use in the building sector is 60 – 80 Megatonne of oil equivalent (Mtoe)/year by 2020, i.e. a reduction of 5-6% of the EU final energy in 2020; – 160 to 210 Mt/year CO_2 savings by 2020, i.e. 4-5% of EU total CO_2 emissions in 2020 (European parliament, 2010f).

1.2.2 Energy performance of Building Directive (EPBD)

To be able to reduce the energy use in buildings, the EU has introduced a legal framework to work within all member states; Directive 2002/91/EC on the energy performance of buildings (European parliament, 2010g), which is the main legislative instrument at EU level regarding the energy performance in buildings. The directive covers energy demand for space heating, domestic hot water, cooling, ventilation and lighting. It includes regulations regarding new buildings and major renovation of existing buildings; both residential and non-residential buildings. Exceptions can however be made e.g. for historic buildings. The directive should be fully implemented in all member states before January 31, 2012 and in public buildings by December 31, 2010. Both a primary energy indicator and a carbon dioxide emission indicator shall be used in order to clarify the building's total impact on the environment.

According to the directive, the energy performance of a building is to be determined by either calculation or measured annual values of energy use. The energy demand for heating and cooling should be related to actual indoor temperature. If a calculation is made, European standards need to be used together with the actual thermal characteristics of the building, such as thermal capacity, insulation, passive heating, cooling elements and thermal bridges. The technical installations and internal loads, and also the air- tightness of the building, should be included in the total energy performance. The specific design, orientation and outdoor climate of each building should be considered.

Within this Directive 2002/91/EC on the energy performance of buildings, four key points are set with concrete actions to be taken by all member states (European parliament, 2010h);

1) To set minimum standards in all member states on the energy performance of both new buildings and buildings that are renovated;

According to this directive, all member states are obliged to enhance their building regulations and to introduce energy certification schemes for buildings. There are no fixed EU-wide energy levels in the directive; each member state is responsible to set national minimum standards on energy use in buildings, to be able to consider differences in e.g. outdoor climate and local building traditions. The set up levels of energy performance of buildings may differ between new and existing buildings and also between different categories of buildings.

In each member state, there should be set up levels regarding energy performance in buildings that undergo major renovations. The concept of major renovation is satisfied if the total cost of the renovation related to the building envelope or the technical building systems is higher than 25% of the value of the building, excluding the value of the land upon which the building is situated. A renovation could also be considered major if more than 25% of the surface of the building envelope undergoes renovation (European parliament, 2010h).

The directive states that the requirements on energy levels are to be updated at least every five years in order to reflect technical progress in the building sector. All national standards must, according to the directive, consider indoor climate conditions in order to avoid possible negative effects such as inadequate ventilation.

2) To use a common methodology for calculating the integrated energy performance of buildings

The energy performance of buildings should be calculated for the annual energy demand and not be limited to the heating season. It should include heating and air-conditioning installations, application of renewable energy sources, passive heating and cooling elements, shading, indoor air quality, adequate natural light and design of the building. It should be possible for the energy performance requirements for both new buildings and buildings under major renovation to be reached in an economic way, so that the house owner gets lower energy bills in future. Therefore, a calculation method with both financial aspects and energy measures taken into consideration should be used, as established by the Commission by December 31 2010.

3) If public buildings; to have a system of energy certification of buildings on both new and existing buildings with the information displayed for the public

Within the energy certification made of buildings, the house owner should be informed through the energy performance certificate about the energy performance of the building, together with practical advice on how to improve it.

4) To have regular inspections of boilers and air-conditioning systems and to perform energy declarations

There are other Directives dealing with energy use in buildings that need to be considered when national policies are made e.g. Eco-design of Energy-using Products Directive (2005/32/EC), Directive on the Promotion of Cogeneration (2004/8/EC), Energy End-use Efficiency and Energy Services Directive (2006/32/EC) and the proposed Directive on the Promotion of the Use of Energy from Renewable Sources. Relevant provisions on buildings can also be found in the Construction Products Directive (89/106/EEC); and in the Sustainable Production and Consumption and Sustainable Industrial Policy Action Plan.

1.2.3 Recast of the Directive

In 2008, a recast of the Directive 2002/91/EC on the Energy Performance of Buildings (EPBD) was presented by the Commission in order to strengthen the energy performance requirements and to clarify and streamline some of its provisions (European parliament, 2010h). A political agreement on the substance of the recast was reached on November 17, 2009, and the directive was formally adopted on May 19, 2010.

In the revised directive, all member states are required to actively promote buildings in which both carbon dioxide emissions and primary energy use are very low or equal to zero. National plans should be made with clear definitions of these types of buildings and targets for their uptake. It is allowed to have separate definitions for new and refurbished residential buildings, new and refurbished non-residential buildings and buildings occupied by public authorities. All member states should give feedback to the Commission on the work with these buildings, and according to the directive public authorities should take a leading part with buildings occupied by them. Targets should be set for the minimum percentage of these almost zero energy buildings by 2015 in each member state and national plans should be made on how the number of these houses should be increased. By December 31, 2018, all publicly used buildings within the

European Union should be nearly-zero energy buildings and by December 31, 2020, all new buildings within the Union should be nearly-zero energy buildings. Also, national political decisions should be taken to stimulate that when buildings are renovated, this should include increasing the energy performance of the building to nearly-zero energy buildings.

To be financially able to reach the targets, grants can be applied for by the member countries from the European regional development fund, to be used in building projects to increase energy efficiency and the use of renewable energy sources in the building sector. Products used in buildings that do not use energy but indirectly have a determining impact on the building's energy demand, must now use the energy label system as previously used in e.g. household appliances. Examples of products that now need to be labelled are windows, window frames and entrance doors (European parliament, 2010i).

1.3 The Swedish building stock – residential buildings

The total number of residential buildings in Sweden in 2008 was almost 4.5 million, which is an increase of 40% compared to 1970. In 2009, the number of new build residential buildings in Sweden was 22 900, where 8373 were single family houses and 14 427 apartments in multifamily houses (Statistiska Centralbyrån, 2010a).

Looking at the statistics of new build residential buildings in Sweden since 1964; the overall production of both apartment buildings and single family houses is currently at a moderate level, as can be seen in Figure 1.1.

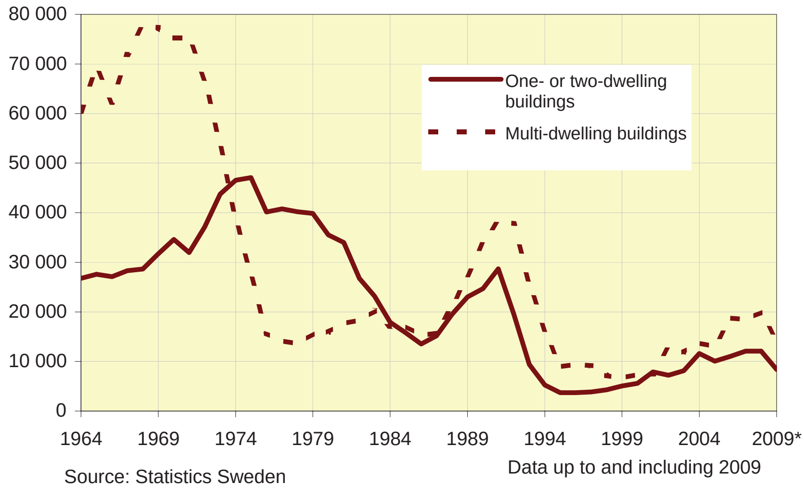


Figure 1.1 *New build residential buildings 1964 – 2009 (Statistiska Centralbyrån, 2010b).*

1.3.1 Multi family houses

The final years of construction of the existing multi family houses in the Swedish building stock are presented in Figure 1.2, where it is shown that the major part of the existing multi-family buildings in Sweden were finished during the time period 1941 – 1970. Many of these buildings were built as a result of the building programme set in Sweden in the early 1960s. This programme is popularly called "Miljonprogrammet" where the target was to build one million apartments during a period of 10 years. The apartments had a high standard and the main purpose of the programme was to decrease the overcrowding and bad living conditions which were by then very common in Sweden.

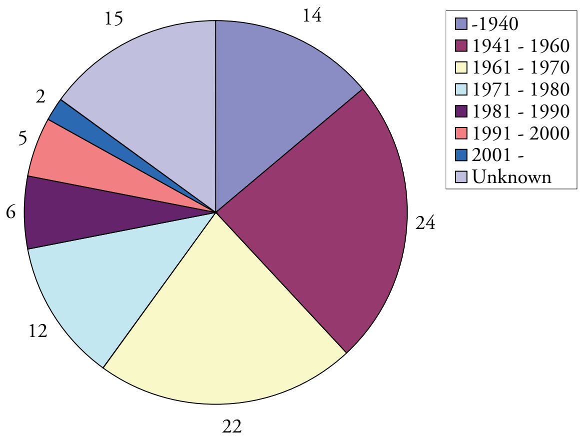


Figure 1.2 *The Swedish multi family houses building stock presented as a percentage of the final year of construction (Statistiska Centralbyrån, 2010b).*

1.3.2 Single family houses

The final years of construction of the single family houses in the Swedish building stock are presented in Figure 1.3. Most single family houses in the Swedish building stock were built before 1940 and during 1960 – 1975, where many were built as a part of "Miljonprogrammet".

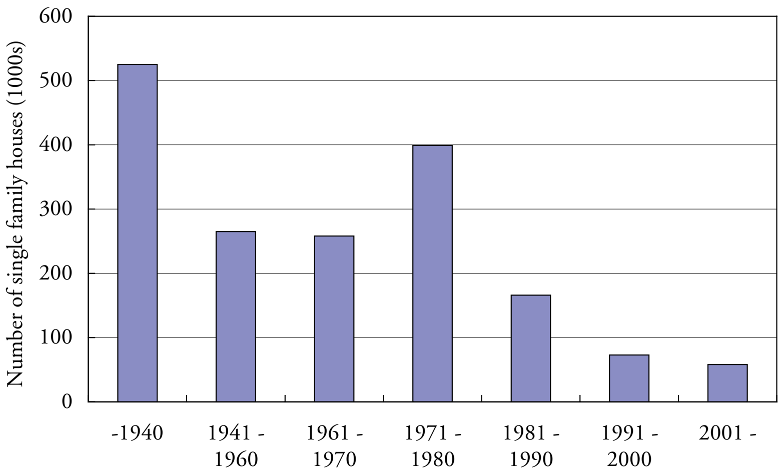


Figure 1.3 *Final year of construction of the single family houses in the Swedish building stock, 1000s (Statistiska Centralbyrån, 2010b).*

As earlier shown in Figure 1.1 and here also seen in Figure 1.3, the number of new built single family houses in Sweden has been at a moderate level since 1990.

1.4 Energy use in the Swedish building sector

The total energy use in Sweden in 2008 was 614 TWh (Statens Energimyndighet, 2009a). The energy use in the building sector was in 2008 measured to 141 TWh (149 TWh revised according to degree days), where 71 TWh were energy use from electricity, 43 TWh energy from district heating, 12 TWh energy from oil products, 1.8 TWh energy from gas and 14 TWh from bio fuels. The percentage of the energy use in the Swedish building stock, according to the total energy use in Sweden, was in 2008 35.5%.

Energy use for space heating and domestic hot water represents 61% of the energy use in the buildings. The use of oil as the energy source for space heating and domestic hot water has decreased by 90% since 1970 in the total building and services sector.

The total use of electricity in the building sector has been on the level of approximately 70 TWh per year since 1990 in figures revised according to degree days. Most of the electricity is used as common electricity in non-residential buildings; annually approximately 30 TWh since 1999. In 2008, the household electricity in single family houses was approximately 6000 kWh per household and year (Statens Energimyndighet, 2009a). Using a living area of 120 m^2 in single family houses (Johansson & Storm, 2001); the annual use of household electricity in single family houses is calculated to 50 kWh/m^2a. In multi family houses, the use of household electricity was approximately 40 kWh/m^2a in 2008 (Statens Energimyndighet, 2009c). The energy use for space heating, domestic hot water and household electricity (only included if electricity is the major energy source) in the existing building stock, broken down by final year of construction of the building, is presented in Figure 1.4.

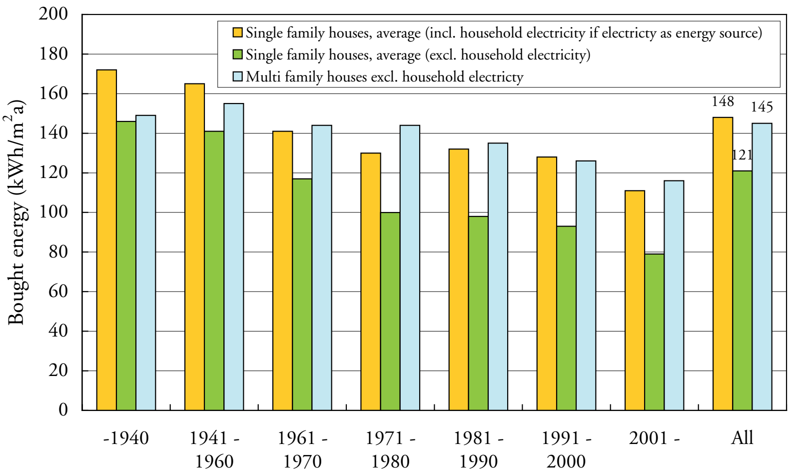


Figure 1.4: *Bought energy for space heating, DHW heating and electricity according to final year of construction of the building (Statens Energimyndighet, 2009b and c).*

1.4.1 Swedish political targets regarding energy use in buildings

Since Sweden is part of the European Union, the Swedish building regulations regarding energy use should be based on the European Energy Performance of Buildings Directive (EPBD). The legislative level of carbon dioxide emissions set for Sweden by the European Union, during 2008 – 2012, should not exceed 104% of the measured levels in 1990. The Swedish government has decided to sharpen the level to be at the most 96% of the measured levels in 1990, which is a decrease by 4% (Statens Energimyndighet, 2009a).

There are 16 environmental targets decided by the Swedish government that must be fulfilled by 2020 (goals regarding the climate are due in 2050) (*Prop 2009/10:155*). A new structure for the work with the targets was proposed in 2009 (*Prop 2009/10:155*). One of the 16 targets is “A good built environment”, where the target is to decrease energy use per heated area of dwellings and premises by 20% by 2020 and 50% by 2050 with reference to the energy use in 1995. The decrease should be made possible by energy efficiency measures to decrease the need of delivered energy to the buildings but also by the use of renewable energy sources. Also, after 2020, fossil fuels should no longer be used in the building sector. The 16 targets are continuously monitored and verified according to their consequences for the environment, financial increase, competitiveness and costs; both for the public sector and for individuals (*Prop. 2005/06:145*).

According to this government climate bill 2008/09:162, 50% of the total energy use in Sweden should be renewable in the year 2020. In 1990, the share of renewable energy in Sweden was 33.9% and has increased to 44.1% in 2008. The reason for such a high percentage of renewable energy sources is not only the high access to water power and biomass, it is also due to Swedish energy policies with e.g. the tax on carbon dioxide emissions that was legislated in 1991. Subsidies have been given to house owners when the energy source for the building is changed from an oil burner to bio-fuel or when electric resistance heating is changed to another energy source e.g. district heating or bio fuels. However, to reach the target of 49% renewable energy sources by 2020, set by the European Union and the target of 50% set by the Swedish government, further measures need to be taken.

1.4.2 Energy use – single family houses

Electricity use as a source of space heating in single family houses has decreased since 1990 but it is still the most common energy source for space heating. Approximately 40% of the single family houses in Sweden are using electricity as their energy source for space heating and domestic hot water. The use of heat pumps for distribution of space heating has increased in recent years and in 2007 there was a heat pump in 37% of all single family houses in Sweden (Statens Energimyndighet, 2009a). The total energy use in 2008 in single family houses for space heating and domestic hot water was 31.5 TWh where 12.7 TWh was distributed by electricity (excl. household electricity), 11.4 TWh was distributed by biofuel, 5.1 TWh by district heating, 2.0 TWh by oil and 0.2 TWh by gas.

20% of the single family houses have a solution with a combination of bio fuel and electricity as the energy source for space heating and domestic hot water.

Electrical under floor heating and fan heaters contribute to warming up the building, but in the statistics are measured as household electricity, not space heating. Since 2001, the use of household electricity in single family houses has been on a relatively even level with lighting as the major item, followed by fridge/freezer and electricity for entertainment as the third item (Statens Energimyndighet, 2009b). The total use of electricity for space heating and domestic hot water in single family houses in 2007 including electricity for heat pumps was 13.7 TWh (14.8 TWh revised according to degree days).

The statistics show a decrease in delivered energy for space heating and domestic hot water in single family houses ended after 2000. This might be a result of a better energy performance in these buildings. It could also be a result of high use of heat pumps for space heating in these buildings, which is more or less the standard solution in single family houses built during this period. Depending on the COP-factor of the pump, the heat pump may contribute to the building three times more energy than the energy needed for the pump. The total use of energy in the building decreases but not necessarily due to a building with a higher energy performance. In the statistics, only the bought electricity for the pump shows, not the actual energy demand for space heating of the building and domestic hot water.

1.4.3 Energy use – multi family houses

In multi family houses, district heating is the most common energy source for space heating and domestic hot water. Of a total of 25.2 TWh used, 22.8 TWh was supplied by district heating, 1.2 TWh came from electricity, 0.7 TWh from oil, 0.3 TWh from gas and 0.2 TWh from biofuel. In 2006, the average energy use for domestic hot water and space heating in multi family houses using district heating was 153 kWh/m^2a which had decreased to 148 kWh/m^2a in the statistics presented in 2008 (Statens Energimyndighet, 2009c; Statistiska Centralbyrån, 2007).

1.4.4 Current Swedish building regulations regarding energy use in buildings

The Swedish building regulations regarding energy use in residential buildings and non-residential buildings were updated in February 2009 (Boverket, 2009a; Plan- och bygglagen, 1987). In these updated regulations, maximum limits for energy use for space heating, domestic hot water heating and common electricity are set. In the building regulations Sweden is divided into three climate zones as shown in Figure 1.5.

Figure 1.5 *Swedish climate zones*

The allowed total energy use in residential buildings varies according to the three climate zones. There are also different levels of the allowed total energy use in buildings if the energy source for space heating and domestic hot water is electricity or if another energy source is used. The maximum allowed total energy use is presented in Table 1.1 (Boverket, 2009a).

Table 1.1 Maximum allowed total energy use in residential buildings.

Energy source	Climate zone 1 (kWh/m^2a)	Climate zone 2 (kWh/m^2a)	Climate zone 3 (kWh/m^2a)
Electricity	95	75	55
Other	150	130	110

In non-residential buildings, the limitations on maximum energy use can vary if the ventilation rate is higher than the hygienic flow of 0.5 ach. If the ventilation rate is kept at normal levels, the maximum level of energy use for space heating, domestic hot water and common electricity may not exceed the values presented in Table 1.2.

Table 1.2 Maximum allowed total energy use in non-residential buildings.

Energy source	Climate zone 1	Climate zone 2	Climate zone 3
Electricity (kWh/m^2a)	95	75	55
Other (kWh/m^2a)	140	120	100

In March 2010, the Swedish Government presented a bill to the Swedish Riksdag regarding an update of the current Plan och Bygglag (Prop 2009:10/170). Regulations regarding sustainable buildings are included in the bill presented.

1.4.5 Regulations regarding energy performance in renovation projects

A renovation of a building need to comply with some basic laws and regulations set up by Boverket. Several regulations; Byggnadsverkslagen paragraph 2, Byggnadsverks-förordningen paragraph 8, Plan och Bygglagen chapter 2 and Boverkets Ändringsregler (BÄR), all mention that the use of energy in the renovated building should be low, but unfortunately no explicit figures are set as for new build buildings. The lack of figures can be a limitation when a renovation of a building is performed, since the level of "low" energy use after renovation is set according to the ambition of the owner of the building.

As presented in Section 1.3 Figure 1.3, the number of new build residential buildings in Sweden is at a moderate level compared to the number of dwellings in the existing building stock. It is naturally important to have effective regulations on maximum allowed energy use in new buildings to ensure that new buildings are as energy efficient as possible, but it is also important to take energy efficiency measures in the existing building stock, to be able to reach the energy targets set up by both the European Union and the Swedish Government. According to EPBD, maximum levels of energy use in renovated buildings should be set by each member country in the European Union. To reach the required major decrease in national energy use and the energy use in buildings, house owners of the existing building stock need to be encouraged by the government to carry out energy efficiency measures. There is in any case a great opportunity to increase the energy performance of buildings when they are renovated. Many of the multi-family houses finished during the period 1961 – 1970 are now in need of renovation. By including energy efficiency measures in these renovation processes, the energy use in these buildings may be drastically reduced.

1.5 Object, method and limitations

The main purpose of this research was to see how energy efficient residential buildings, mainly passive houses, can be built in Sweden and on a more widespread scale than before. The research has been a five year project and included four demonstration projects, which have been the base for the study.

The initially expected result was to find guiding principles and tools needed for planning passive houses, not only describing project specific solutions but making the system solutions usable for planning in more general terms, and also to study the possibilities and limitations of energy efficient buildings in a Swedish perspective and climate. The goals set up regarding energy use in the demonstration buildings for space heating and domestic hot water were 25 – 50 % of the energy used in similar buildings built according to the current Swedish building code.

Other questions raised in the study were what are the keyfactors for a successful, energy efficient building project? Was it at all possible to renovate existing buildings into passive houses or to build a single family passive house in a Swedish climate? Is there a lack of products needed for passive houses on the market, are there issues in the building production phase that need to be solved and – most important – how is the comfort for a person living in a passive house?

1.5.1 Method

Within this research the four demonstration projects have been followed from the early planning stage to evaluation of the actual buildings. Joining as part of the planning group, advice and help has been given to architects, consultants and the clients. In the planning process, general advice and conceptual solutions were investigated and developed by e.g. making sensitivity analyses to compare different building constructions, making energy simulations of the buildings at different stages of the planning process and inspecting drawings of systems. Information about the basic idea of passive houses has been spread during the first days of education in each project. Lack of components, systems and planning aids were identified.

The building process and the buildings were analyzed and evaluated to facilitate the multiplication of demonstration projects. During the construction of the building projects, the work on the building site was closely followed and participants in the building process were interviewed about their work. By using a phenomenological approach with participant observations, the experiences of the different groups within the case studies have been observed.

Feedback gathered about the projects is presented in this study; both regarding positive and negative experiences, so that the concept of energy efficient buildings can be spread and further developed.

One of the major questions raised within the study was what energy levels were possible to reach in these demonstration projects; figures that could be used as a base for clients to demand in other energy efficient buildings in Sweden. To answer this question, simulations were made during the planning process of the suggested constructions and measurements were made when the tenants had moved in regarding actual energy use, use of domestic hot water and indoor temperatures.

1.5.2 Simulations

To estimate the annual energy demand and peak load for space heating in the four demonstration projects, simulations were made using DEROB – LTH v 1.0 (Kvist, 2006). Indoor temperatures were also calculated during both the cold and warm seasons, to ensure a good indoor climate. DEROB-LTH is a dynamic simulation program for calculation of energy demands, peak load for space heating, indoor temperatures and indoor comfort etc. All simulations made in DEROB – LTH presented in this thesis were made within this research.

The specific thermal bridges in the constructions were calculated using Heat 2 v 7.1. Heat 2 is a simulation program for two-dimensional transient and steady-state heat transfer validated against the standards EN ISO 10211 and EN ISO 10077-2 (Blocon, Sweden). This dynamic program can be used to calculate U-values for building components, estimations of surface temperatures and analyses of window frames, but in this study it is used for calculations of the thermal coupling coefficient (L_{2D}) and thermal transmittance (ψ) according to EN ISO 10211.

1.5.3 Measurements

After the buildings were finished, the performance of the finished buildings was studied in detail. Measurements were made in all four projects of actual energy use for space heating, domestic hot water use, household electricity and electricity for common areas. Indoor and outdoor temperatures were also measured. In some cases, relative humidity and moisture ratio were measured in the building constructions. In one case study measurements were made of operative indoor temperature and solar radiation.

The measurements of energy use within the building were closely analyzed using quantitative methods with data collection and data analysis. To put the results in a context, they were compared with statistics. The energy use for space heating varies with the outdoor climate during the measuring period. To be able to compare the energy use for space heating between the projects and with statistics, the energy use for space heating was revised according to degree days, using climate data from Swedish Meteorological and Hydrological Institute (SMHI). The calculation of the SMHI degree days is based on the assumption that the building should be warmed up by the heating system to an indoor temperature of 17°C (SMHI, 2009). The rest of the space heating needed is assumed to be gained from solar radiation and internal heat loads. For every day, the difference between the average outdoor temperature and +17°C is calculated. Since the solar radiation is of major importance in the sunny part of the year, the degree days are only calculated when the daily mean temperature drops below a certain temperature; in April this temperature is +12°C, in May-July +10°C, in August +11°C, in September +12°C and in October +13°C.

1.5.4 Interviews

The observations and measurements were complemented by interviews performed using a qualitative method with clients, project leaders, craftsmen and the tenants. The interviews with the tenants were made in a semi-structured way. The semi-structured interview method was also used in the interviews with the project leaders and with some of the carpenters. The information gathered on the building sites was mostly received by open interviews.

In a semi structured interview, the questions are determined before the interview starts, but the interviewee is allowed to talk freely. This type of interview also gives the interviewer an opportunity to develop the interview step by step and ask the interviewee attendant questions.

The answers from the interviews and the measured results of energy use and indoor temperature are compared using triangulation. If the answers received from the tenants concerning e.g. indoor comfort verify the measured results, the validity of the measured results increases. It is important for the results to have a high validity to be able to use them in a more general way. This combination of information can also give a larger and more developed view of the measured results, and improves the possibilities to make a correct analysis and suggestions of improvements (Holme & Solvang, 1997).

1.5.5 Limitations

The focus in this project is the total energy use in buildings and indoor comfort. There are no deeper studies of moisture problems, only a brief overview when problems have occurred in the projects. The indoor air quality was not measured. The energy use and environmental strain due to the choice of material used within the buildings are not considered.

The method used in this study has been to be a participant in all steps in the building process. Because of this, it might sometimes be difficult to evaluate my work and the way my participation has influenced the final result. However, it was not the purpose to study the behaviour of different actors without interference during the process of building a low-energy building. The work has instead been focused on technical possibilities and limitations to find out which developments are still needed and to see how far we can reach at the moment in designing and constructing energy-efficient buildings.

1.6 Structure of the thesis

Chapter 2 gives an introduction to the concept of passive houses and their development until the current status. The German and Swedish passive house criteria are presented together with basic design principles of passive houses.

The demonstration projects are presented each in a separate chapter, starting with the apartment buildings in Värnamo in Chapter 3, the apartment buildings in Frillesås in Chapter 4, the single family house in Lidköping in Chapter 5 and finally the renovation project in Alingsås in Chapter 6. In these chapters, a close evaluation of each project is presented from the early planning stage to measurements and experiences of the finished buildings.

In Chapter 7, the results from the four demonstration projects are compared, both regarding the annual energy use and also the tenants' opinions received in interviews. The questions used in the interviews are presented in Appendix A at the end of the thesis.

The impact of solar radiation on a passive house built in a Swedish climate is presented in Chapter 8. The influence of different outdoor climates on the annual energy demand for space heating is also discussed in this chapter.

Different ventilation rates and their influence on health, on energy demand for space heating and bought electricity for fans in ventilation units are presented in Chapter 9. The heating power that can be distributed with the supply air at different air change rates is calculated based on national regulations on ventilation air change rates.

In Chapter 10, discussions and conclusions are made based on the results from the study. Good experiences and innovative ideas are presented together with not very successful solutions and suggestions of improvements. The lack of products needed for passive houses is described and suggestions are made on how passive houses can be introduced on a broad market in Sweden.

2 Passive houses

The passive solar building design has been used for thousands of years, where heat gain from large window areas facing south has covered the energy demand for space heating (U.S Department of Energy, 2010). Thermal mass in the building construction has then been an important parameter to be able to store the solar energy within the building from day to night. This type of buildings, where solar heat gain is used as the main source for space heating, are common in climates with a high amount of solar radiation, e.g. in Arizona and New Mexico in the United States.

The passive house concept presented in this chapter still uses the solar thermal gains but also has a major focus on decreasing the thermal losses through the building envelope and on maintaining a good indoor climate all year round. The initial idea of this passive house concept was to make it possible to create a building with a high indoor thermal comfort built at a low investment cost. When the building envelope is so well insulated that the indoor surface temperatures get close to the indoor air temperature, thermal indoor comfort is achieved without the need to place radiators on external walls and below windows. The cost for the radiator system is then saved and the overall cost for the passive house can be lowered (Feist, 2006a).

Another important parameter for a high indoor comfort is an airtight climate shell. To achieve a comfortable indoor climate in an airtight building it is necessary to use mechanical ventilation. In passive houses, an air-to-air heat exchanger is used in the mechanical ventilation system to extract the energy from the exhaust air and use it to heat the supply air; however recirculation of air is not used. The combination of a well insulated and airtight climate shell and the heat recovery in the ventilation system makes it possible to provide space heating by the ventilation system alone, distributed with the hygienic air flow rates, needed in any case for a good indoor air quality. This yields savings to the building costs when a separate heating system is no longer required (Schnieders & Hermelink, 2006).

This is the basic thought of the "modern" passive house; that the building envelope should be so well insulated and airtight that it should be possible to distribute the required space heating with the supply air that is needed in any case, at normal ventilation rates. In colder climates additional space heating might be needed on cold days with almost no solar radiation. The extreme low energy use in passive houses provides financial security for the house owner if the energy prices increase (Smeds & Wall, 2007).

Internal heat gains are received by passive solar gain, from persons and from waste heat from household appliances. The use of household electricity should be at a low level, both to decrease the total use of electricity, but also to avoid excessive indoor temperatures and consequently a cooling demand.

2.1 Development of passive houses

The first idea of the passive houses known today was developed by Professor Bo Adamson in the Department of Building Science at Lund University, Sweden. During the 1980s and the beginning of the 1990s, he had cooperated with The Ministry of Construction concerning "Design of energy efficient houses in People's Republic of China including utilization of passive solar energy". In the project a feasibility study of Passive houses in Beijing was carried out (Adamson, 1989). Within this study, the use of passive solar space heating was developed further with the idea to remove the space heating system in a multi storey residential building. The money saved on the removed heating system was put on improving the building envelope by additional insulation, better windows and improved airtightness. These measures were proposed to increase the thermal comfort in the building and to limit the energy demand. The local climate in this project has cold winters but lots of solar radiation. The solar heat gain was used for space heating with large glazed areas facing south. The result showed that a good "passive design" was a good basis even for a house in cold climates with no auxiliary heating or cooling.

After this study, Professor Bo Adamson continued the work with passive houses together with his research colleague Wolfgang Feist, who was a visiting PhD student at Lund University in Sweden at the end of the 1980s (Feist, 2006a).

2.1.1 First passive house in Darmstadt Kranichstein, Germany

In May 1988 the full passive house concept was developed and in 1990 the first passive house was realized in a four unit terrace house built in Darmstadt Kranichstein, Germany. The first passive house tenants moved into their apartments in 1991. The building envelope was very airtight, with an air leakage of only 0.22 ach at a pressure of 50 Pa. The mechanical ventilation system had a highly efficient heat exchanger with an efficiency of 87%.

To be able to evaluate the performance of the building, the house in Darmstadt was equipped with monitoring devices (Feist, 1992; Feist, 1994). The goals of the project were reached not only in terms of energy efficiency; in a sociological study the measured good indoor air quality was confirmed and also showed a high degree of user satisfaction (Schnieders et al, 2006). The measurements of this building have continued since 1991 to see how a passive house is working over time with e.g. measurements of the airtightness of the building envelope (Peper, Kah & Feist, 2005). The development of passive houses continued in Germany with the good measured results from the passive house in Darmstadt as a base, learning that the key factors to a well functioning passive house are a combination of a highly insulated climate shell and a high efficiency heat exchanger in the ventilation system (Peper et al, 2005).

2.1.2 CEPHEUS

To create the conditions for a broad market introduction of passive houses, the European Passive House project CEPHEUS, "Cost efficient Passive Houses as European Standards", was funded in 1998, as a project within the THERMIE Programme of the European Commission (CEPHEUS.DE). The CEPHEUS project was running during 1998-2001 and within this project buildings complying with the German Passive House standard were tried out in 221 housing units built in five European countries. The building projects participating were closely evaluated regarding technical issues and total energy use. Also user behaviour was studied.

The results from the CEPHEUS projects showed low levels of final and primary energy use; up to 50% less energy use compared to conventional new buildings was achieved. Household electricity use turned out to have particular importance for primary energy use and could, even though the primary energy use was measured to be extremely low, be further reduced (Feist, Schneiders, Dorer & Haas, 2005). The passive solar gains were also studied. The average use of domestic hot water was 25 litres per person per day in the CEPHEUS projects (Schnieders et al, 2006). Interviews with the tenants in the buildings showed that thermal comfort was good to very good, both in single family houses and in apartment buildings.

2.1.3 First passive houses in Sweden

The first passive houses in Sweden were built in Lindås outside Gothenburg in 2001, ten years after the first Passive house was finished in Germany and was a part of the CEPHEUS project. The Lindås project contains 20 terrace houses built as co-operative flats and were a result of a demonstration project extending over four years, carried out within cooperation by Efem Architects in Gothenburg, Energy and Building Design at Lund University, Chalmers University of Technology in Gothenburg and the Swedish National Testing and Research institute SP in Borås.

The 20 units are divided into four buildings placed in rows where each unit has a living area of 120 m^2 or 124 m^2 in two storeys. Like all CEPHEUS projects the houses in Lindås were closely evaluated both regarding technical issues and with interviews with the tenants. The average airtightness at 50 Pa was measured as 0.3 l/s, m^2. The average measured delivered energy demand was 68 kWh/m^2a (Wall, 2006). Experiences from Lindås have later been used in several subsequent Swedish passive house projects and lots of people have been to educational visits to the project.

The second passive house project in Sweden is located in Glumslöv, Landskrona in the south of Sweden. 35 rental apartments were built in 2003-2004. No overall evaluation of the project has yet been published.

2.1.4 IEA SHC Task 28

The CEPHEUS project was followed by e.g. the IEA SHC Task 28 that started in April 2000. The core of this task was to help participating countries to achieve significant market penetration of sustainable solar housing by the year 2010. There were 18 participating countries within the task, all working with new residential buildings. One major outcome from the task was two books where the first volume includes strategies and solutions for designing low energy buildings and in volume two, examples of low energy buildings from participating countries are presented together with construction details e.g. thermal bridges and ventilation solutions (Hastings & Wall (Eds), 2007).

2.1.5 PEP: Promotion of European Passive Houses

Another important project for the development of passive houses was PEP: Promotion of European Passive Houses that was finished in May 2006. Eight European countries participated in this project. The aim of the project was to document practical solutions for passive houses in different regions and climates and to document the energy saving potential of the passive house concept throughout Europe. Also a preparation for an international scheme for passive house certification was compiled; this was done in relation to national energy performance certification schemes and the European Performance Building Directive (EPBD). Local building traditions and lack of building components suitable for passive houses were barriers discovered in the project. Also limited construction skills and limited know-how were barriers for passive houses. It was seen in this study that local building traditions can also be a barrier against new constructions and façade materials (Intelligent Energy Europe, 2007).

2.1.6 IEA SHC Task 37

In June 2006 a new IEA SHC project started; Task 37 Advanced Housing Renovation with Solar and Conservation (International Energy Agency Solar Heating and Cooling Programme, 2006). Within this IEA Task, the focus was on energy efficient retrofitting solutions and solar applications added to existing buildings, and on strategies for a broad market penetration for these solutions. The 12 participating countries were mainly European but also experts from New Zeeland and Canada were engaged in the project. The task was running from July 2006 to June 2010.

2.1.7 North Pass

In 2009 the European NorthPass project started in order to promote the implementation of very low energy buildings such as passive houses in northern climates. The outcome of the project should be documentation of local criteria for low-energy buildings, guidelines for design, marketing approaches and dissemination of the results to designers, builders, decision-makers, etc. The work plan is reaching to 2012 (VTT, 2009).

2.1.8 Present status

Passive houses are now built in many countries all over the world. In December 2008, the number of passive houses was estimated at 15 000 dwellings world wide (Rosenthal, E. 2008-12-26) Many of them use the passive house definition set up by the German Passivhaus Institute, but also national requirements are set up in e.g. Norway and Austria (Thullner, 2010). Most of the passive houses are found in Germany, Austria and Switzerland. The concept has extended from dwellings to other building categories like office buildings and school buildings and is increasingly applied in building rehabilitation.

There are also other concepts apart from passive houses for energy efficient buildings, like the Swiss standards "Minergie", "Minenergie –P" and "Minenergie-Eco", where Minergie –P is similar to a passive house. There are some other German standards like "RAL Low-energy ", "Niedrigenergie", "7-liter haus", "4-liter-haus etc" and in Austria the "3 litres house" can be found (Thullner, 2010).

2.2 The German passive house criteria

In 1996, Dr Wolfgang Feist founded the German Passive Haus Institute. The staff at the Passive Haus Institute works as consultants in passive house projects and evaluate both passive house projects and solutions of constructions. They have developed the Passive Haus Planning Package, PHPP, a calculation program to use in the planning process of passive houses. The German Passivhaus Institute has also set up a passive house definition based on requirements for the building that need to be fulfilled in order that the building can be heated with the supply air at normal ventilation rates.

"A Passive house is a building for which thermal comfort (ISO 7730) can be achieved solely by postheating or postcooling of the fresh air mass, which is required to fulfil sufficient indoor air quality conditions (DIN 1946) – without a need for recirculated air" (Passivhaus Institute, 2010 a).

2.2.1 Energy demand and peak load for space heating

The German passive house standard requires that the building must be designed to have an annual space heating demand, as calculated with the Passiv Haus Planning Package (PHPP), of not more than 15 kWh/m² per year or to have a peak load for space heating of 10 W/m², at an indoor temperature of 20°C (Passivhaus Institute, 2010b). When calculating the peak load, the internal gains from household appliances etc are set to 1.6

W/m^2 (FEBY, 2009). When calculating the space heating demand, the internal gains for household appliances etc are set to 2.1 W/m^2 (Passivhaus Institute, 2010b). In addition, passive solar heat gains are taken into account when calculating the space heating demand.

The total primary energy use (space heating, domestic hot water and both common and household electricity) must not exceed 120 kWh/m^2 per year based on primary energy conversion factors set up by the Passivhaus Institute. The requirement for a maximum primary energy demand prevents the reduction of the space heating demand at the expense of large internal gains from electric appliances. This also discourages using electricity as energy source for space heating (Feist et al, 2005).

2.2.2 Building envelope

In the German passive house standard, requirements are also set up for the building envelope. The building envelope should be well insulated and no component of the opaque climate shell is allowed to have a U-value that exceeds 0.15 W/m^{2}K. The U-value of the windows is limited to a maximum 0.8 W/m^{2}K including frame, with solar heat gain coefficients around 50%. The air leakage through the building envelope should be below 0.6 air changes per hour (ach) (n_{50} 0.6 / hour) by a pressurisation of 50 Pa using a blower door test, resulting in approximately 0.05 ach infiltration rate under normal pressure conditions.

2.2.3 Other requirements

Domestic hot water should be provided by solar thermal systems or a heat pump.

2.3 The Swedish passive house criteria

The passive house criteria made by the German Passivhaus Institute have been adjusted in Sweden by the working group FEBY, Forum för Energieffektiva Byggnader, to be suitable for the Swedish climate conditions and the Swedish building code. The first version of this voluntary standard was published in 2007. The work with the standard was funded by the Swedish Energy Agency and in the working group representatives from Aton teknikkonsult, IVL Swedish Environmental Research Institute, SP the Swedish National Testing and Research institute and Energy and Building Design at Lund University participated. The standard has been further developed and the second version was published in June 2009, later updated in October 2009 (FEBY, 2009). The standard is available for residential buildings and non-residential buildings such as schools. In addition to this voluntary standard the Swedish regulations BBR 16 should of course be followed (Boverket, 2009a) when planning and building passive houses, as for any other building.

2.3.1 Energy demand and peak load for space heating

The levels of the peak load for space heating in the Swedish passive house criteria are set for the three climate zones according to the Swedish building code see Figure 2.1.

Figure 2.1 Swedish climate zones.

The peak load for space heating, P_{max}, for residential buildings and non-residential buildings varies from 10 W/m^2 in climate zone 3, to 12 W/m^2 in climate zone 1. For detached houses of less than 200 m^2, P_{max} should not exceed 12 W/m^2 in climate zone 3 and 14 W/m^2 in climate zone 1 as presented in Table 2.1.

Table 2.1 Limits for peak load for space heating in Swedish passive houses.

Climate Zone	P_{max} residential buildings and non-residential buildings (W/m²)	P_{max} detached houses < 200 m^2 (W/m²)
3	10	12
2	11	13
1	12	14

The peak load for space heating is calculated at an indoor temperature of 20°C. Heat gained from household appliances and persons included in the calculations should be maximum 4 W/m^2.

As in the German passive house definition, the requirements regarding the peak load for space heating in buildings are set to make it possible to use the ventilation system as the heating system at normal air supply rate. The P_{max} levels possible for residential buildings at normal ventilation rates can be calculated according to Equation 2.1, 2.2 and 2.3.

$$T_{supply,heated} = T_{outdoor,dim} + \eta \cdot (T_{indoor} - T_{outdoor,dim}) \qquad \text{Equation 2.1}$$

$$P = q \cdot \rho \cdot c_p \cdot (52 - T_{supply,heated}) \qquad \text{Equation 2.2}$$

$$P = q \cdot \rho \cdot c_p \cdot (52 - (T_{outdoor,dim} + \eta \cdot (T_{indoor} - T_{outdoor,dim}))) \qquad \text{Equation 2.3}$$

Where:

$T_{supply,heated}$ = temperature of the supply air after the heat exchanger (°C)
$T_{outdoor,dim}$ = the coldest outdoor temperature at the specific location (°C)
T_{indoor} = the indoor temperature (°C)
η = efficiency of the heat exchanger (%)
P = Peak load for space heating (W)
q = Ventilation airflow rate (l/s, m^2)
ρ = Density of air (kg/m^3)
c_p = Heat capacity of air (J/kg,K)

According to the Swedish building regulations, the minimum ventilation air rate per person for comfort ventilation is 0.35 l/s, m^2, i.e 1.26 $m^3/h,m^2$ (Boverket, 2009a). The indoor temperature is set to 20°C. The efficiency of the heat exchanger is here set to 80%. The density of air is 1.2 kg/m^3 at 20°C and 1 atm. The heat capacity of air is 1000 J/kg,K.

The maximum supply air temperature is here set to 52°C and the design outdoor temperature to -16°C. The maximum heating power available in the supply air is then calculated as shown in equation 2.4.

$$P = 0.35 \cdot 10^{-3} \cdot 1.2 \cdot 1000 \cdot (52 - (-16 + 0.8 \cdot (20 - (-16)))) = 16.4\ W/m^2$$

Equation 2.4

This maximum power calculated to 16.4 W/m^2 is the limit of using the ventilation system to heat the building at the given input values. This calculation assumes a heat recovery of 80% which probably is too optimistic at the given outdoor temperature of -16°C. However, a lower heat recovery would result in a somewhat higher possible heating power without reaching the temperature limit of 52°C. Thus the criteria are on the "safe side". The limit specified for a single-family house in climate zone 1 (14 W/m^2) has, according to this calculation, some margins to the maximum available power distributed in the supply air.

The levels of the energy demand for space heating are only recommendations in the Swedish criteria document, not a requirement. The reason is that the levels of bought energy for space heating can vary a lot between buildings with the same construction, depending on energy source and distribution system. Even though the amount of bought energy for space heating is low, it will not guarantee an energy efficient building construction and a good indoor climate. For instance, a heat pump with a COP factor of 3 will only use a third of the energy that the building actually needs for space heating. The recommended levels of bought energy are presented in Table 2.2. The energy use includes energy for space heating, domestic hot water and common electricity (such as fans and pumps). Thus, household electricity is excluded as in the Swedish building regulations. There are two values for each climate zone; the criteria are different for electrically heated buildings and other heating sources. The energy use is calculated using an indoor temperature of 22°C.

Table 2.2 Recommended levels of total bought energy for Swedish passive houses (FEBY, 2009).

Climate Zone	Q_{max} non-residential and residential buildings (kWh/m^{2}a)	Q_{max} non-residential and residential buildings (electricity) (kWh/m^{2}a)
3	≤50	≤30
2	≤54	≤32
1	≤58	≤34

To verify the energy use in the building, it should be possible for the use of household electricity, common electricity and energy used for domestic hot water and space heating to be read off separately every month. Also, the amount of water used for domestic hot water should be measured. At the same time, the number of persons living in the building must be noted and taken into consideration, to be able to compare different projects.

The heated area referred to in the Swedish passive house requirements is $A_{temp + garage}$. This area is used for calculating both the peak load and energy demand for space heating per square meter in Swedish passive houses. The term A_{temp} is defined in the Swedish building regulations BBR 16 (Boverket, 2009a) as the area of the building inside to inside of the building envelope, which is heated above 10°C. The area $A_{temp + garage}$ include the heated area of the garage if it is placed inside the climate shell; this is different from the Swedish building code.

2.3.2 Building envelope

According to the Swedish passive house criteria, the U-values of windows including frame may not exceed 0.90 W/m^{2}K. The U-values should be measured according to SS-EN ISO 12567-1. The air leakage through the building envelope should be maximum 0.30 l/s,m^2 at +/- 50 Pa, measured according to the Swedish standard SS-EN 13829 (SIS, 2000).

2.3.3 Other requirements

In the Swedish passive house criteria, it is recommended to have a ventilation system with overall system efficiency of at least 70%. The SFP value of the ventilation unit is recommended to be maximum 1.5 kW/(m^3/s).

The sound level from the ventilation system should conform to sound class B according to SS 025267 (SIS, 2004), with an allowed sound level in rooms of 26 dB(A) and 35 dB(A) in kitchens. The supply air temperature may not exceed 52°C in the supply air terminals.

2.4 Passive house design principle

Are Rødsjø at the Norwegian Housing Bank and Tor Helge Dokka at SINTEF Byggforsk have drawn up a passive house design principle, which includes five steps as presented below. This design principle is also described in SHC – IEA Task 37 (International Energy Agency Solar Heating and Cooling Programme, 2006). The basic thought of this passive house design is that, in the first place, the building construction must be designed to ensure that the peak load for space heating is as low as possible. Building components which are necessary in any case in the building envelope, the windows and the ventilation system, are optimized to reduce the need of energy for space heating to the lowest possible level. Thermal bridges must be avoided, as must infiltration through the building envelope. Detailed planning in all steps of the building process is necessary to achieve a well functioning passive house with sufficient airtightness. Not until then should the energy supply and choice of energy source be discussed and decided.

Step 1: Reducing thermal losses through the building envelope. Use windows with U-values below 0.8 W/m^2K, use a continuous airtight layer in the building constructions to achieve an airtight building envelope and install a balanced ventilation system with a high system heat recovery efficiency ($\eta > 75$ %).

Step 2: Minimize the need of electricity by installing energy efficient fans, pumps, appliances and lighting systems. This reduces the use of electricity but also decreases the risk of excessive indoor temperatures in summer due to lower emitted internal gains.

Step 3: Utilize solar energy, both for passive solar gains in the heating season through windows by an optimal placement of the windows but also as a source for domestic hot water production and possible installation of photovoltaics for local production of electricity.

Step 4: Measure the total energy use and energy behaviour and at the same time visualize for the tenant its use of energy for space heating, domestic hot water and electricity use in a user friendly and transparent way.

Step 5: Choose energy source as the last step, when all other measures are taken. This enables the energy system to fit each specific project and its low space heating demand. Here an optimization between the energy source and the energy distribution system within the building is also of great importance.

The five steps can be illustrated in the “Kyoto pyramid”, see Figure 2.2.

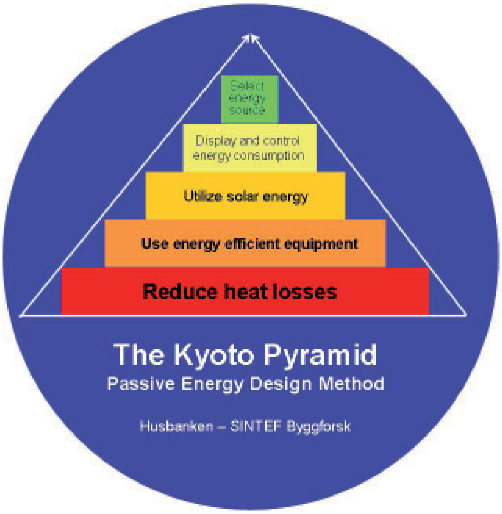


Figure 2.2 *The "Kyoto pyramid" showing schematically the passive design principles (Husbanken/SINTEF Byggforsk, Are Rødsjø/Tor Helge Dokka).*

2.5 Important parameters in the design of passive houses

If the construction of the building ensures a very low peak load needed for space heating and enables space heating to be distributed with the supply air at normal ventilation rates, the basic passive house concept is fulfilled; the passive house concept is not an energy performance standard. However, to reach these very low values of peak load for space heating and to get a well functioning passive house, it is necessary to put a major focus on some parameters in the planning and construction process for the passive house.

Passive house constructions used in for instance Central Europe can not be assumed to work unconditionally in other parts of the world. It is important to develop passive house solutions for each location, suitable for the actual climate and geographic conditions. Local building traditions as well as national/local building regulations must also be considered as discussed in the European Building Directive.

2.5.1 Building envelope

The overall U-values of the building construction should be kept at a low level using highly insulating materials. The mean value of opaque parts of the building envelope (walls, roof and floor) in Swedish passive houses is usually about 0.1 W/m^2K. In Mid-European passive houses, the U-value of the opaque parts of the building envelope usually needs to be below 0.15 W/m^2K. The temperature fluctuates slowly in passive houses because of the high insulation levels.

The thermal bridges need to be reduced to a minimum for instance around windows and the foundation construction, to ensure a good indoor comfort and decrease thermal losses.

2.5.2 Windows and solar shadings

It is important that the window area is optimized to avoid excessive indoor temperatures in the summer, to avoid discomfort due to low surface temperatures and cold down draughts and to avoid a high space heating demand during the heating season. By placing windows in an optimal orientation of the dwelling (windows facing south) maximal advantage can be achieved from passive solar gains. However, for Swedish climates the solar gains are limited during the very short heating season of passive houses in combination with low solar gains during winter. Well dimensioned south window overhangs let the winter sun enter the building while the sun during the summer is shaded to avoid overheating. During spring and autumn vertical shadings outside south windows are more efficient and for windows facing east or west, vertical shading devices are always essential since horizontal overhangs do not cut off the radiation at lower angles. An overhang such as a roof could also decrease potential external condensation on the window pane.

The advantages of windows with low U-values are not only reduced thermal losses. The windows used in passive houses have a more comfortable interior surface temperature compared to regular windows, even in cold outdoor conditions. This improves the comfort experienced by occupants. A window with a U-value of less than 0.8 W/m^2K has, in Mid European climate, proved to ensure occupancy comfort directly in front of the window, necessary when no radiator is mounted (Schnieders, 2003).

2.5.3 Airtightness

Airtightness is very important in a passive house for several reasons. The high level of airtightness is important to get a uniform indoor temperature without draughts. Also, a higher level of air leakage through the external building envelope may cause damage through penetration of warm, humid air into the building construction, which might cause condensation. Furthermore, high infiltration rates will lead to an increase in air that does not pass through the heat exchanger of the ventilation system, increasing the need for space heating.

2.5.4 Ventilation system

Installation of a mechanical ventilation system is necessary in a passive house to achieve a good indoor climate. The balanced mechanical ventilation system supplies air according to national requirements for a good indoor air quality, in Mid-European countries typically 0.3 – 0.4 ach (Schnieders et al, 2006; Thullner, 2010). In Swedish passive houses typical air flow rates are about 0.5 ach due to Swedish building regulations.

The ventilation system needs to have a high overall efficiency in order to save as much energy as possible in the exhaust air. The unit also needs to be very quiet and it should be easy to change filters. The energy use for the fans in the unit must be low. Furthermore, the ventilation system has to be equipped with a bypass for the heat exchanger to keep the indoor temperature low in the summer.

Depending on what is most suitable for each specific building project, the ventilation unit in an apartment building can be placed as small separate units in each apartment or as one central unit, placed for instance in the attic, which supplies the whole building. To make sure that thermal losses from the ventilation system are low, it might be necessary to insulate the ducts. Uninsulated ducts could also cause a thermal bridge carrying cold outdoor air through the heated living area on its way to or from the heat exchanger.

2.5.5 Space heating

The additional energy needed for space heating could be distributed by the ventilation system or by a traditional heating system. If the ventilation system is used, the space heating can be supplied by a heating coil or electrical heating battery in the supply air system. The heat in the waterborne heating system can be supplied in many different ways; via the condenser of an exhaust air heat pump, by district heating, by a pellets system or a solar system. Electric resistance heating is also possible; however this is often associated with a high primary energy demand. The maximum temperature of the supply air in the ventilation system should not exceed 52°C, to avoid pyrolysis of dust. If the supply air temperature is more than 52°C it could lead to dust carbonization in the supply air and possibly in or on the supply air ducts, i.e. dust particles would smoulder on hot surfaces and produce undesired smells (Schnieders et al, 2006). If the peak load for space heating in the room exceeds the limit of heating by air, an additional heating system is needed for peak power supply, for instance a small radiator mounted on an interior wall of a room (Feist et al, 2005).

People are often used to having a radiant heat source in each room, in most cases a heating radiator. Of course a passive house could be heated with radiators, but if the client wants to make the most of the passive house concept and utilize the possibility to heat the building with air, some tenants might miss the radiated heat. A woodburning stove could compensate for this need of radiant heating in a building heated by air. Standard solutions for the integration of woodburning stoves into passive houses do not yet exist and an installation of a woodburning stove needs to be carefully planned in each project. If a woodburning stove is desired, it is important to balance the ventilation system correctly to avoid an underpressure in the room where flue gases are discharged. The woodburning stove must have an adequate air supply according to fire regulations and the heat should preferably be extracted from the stove via a heat exchanger. The exchanged heat can be used for heating other rooms or for heating domestic hot water (Haas, 2007). There is a risk that the heat radiated and convected from the stove quickly causes overheating of the room where it is located, when the heat gained from the stove exceeds the heating demand of the room or even the entire building. To avoid excessive indoor temperatures, the heating power in the stove needs to be low, i.e. 1 – 3 kW. Only a few stoves with this required low heating power are available on the market (Feist et al, 2005).

2.5.6 Education

The concept of building passive houses implies knowledge and education of everyone involved in the project, which may cause an additional cost for the first projects. Experience shows that it is important that the architect is aware of space needed for ventilation pipes, solar shadings, placement for the air supply unit and sizes and placement of windows early in the project (Feist et al, 2005).

3 Apartment buildings in Värnamo, Oxtorget

Finnvedsbostäder, the public housing company in the town Värnamo in the south of Sweden (latitude 57°12'12 N), has built 40 rental apartments according to the passive house principles at a place called Oxtorget in the very centre of Värnamo (Figure 3.1). The project was finished in June 2006. Värnamo is a small town that is slowly growing. The apartments are a part of the local municipality's plan of expansion. In this chapter, the building process of these passive houses is described together with measurements of the energy performance of the buildings.

Figure 3.1: Passive house apartments in Värnamo.

3.1 Basic requirements

The apartments at Oxtorget were at first planned to be regular apartments but the building permit was appealed against by the neighbours. During the time for appeal, the general manager of Finnvedsbostäder had time to closely study the passive house principles and gained good knowledge of what requirements to specify for e.g. the building constructions. At the time when it was decided that it was allowed to build new apartments at Oxtorget, the general manager of Finnvedsbostäder had convinced people that Oxtorget should be a passive house project. In the beginning of the planning process, the architect, the structural engineer and the HVAC consultant went to the existing passive houses in Lindås on a study visit. Since the planning process of the apartments started before the Swedish passive house criteria were set up, the planning group instead made a list of requirements for the project that used together would make the building work as a passive house. These requirements were also used in the application to the Swedish Energy Agency for a demonstration project. As a demonstration project, funding could be granted for extra costs regarding quality assurance during the building process, measurements, evaluation and dissemination but not for any construction costs. In the application, the following requirements regarding the buildings were specified;

U-values:	Windows: 0.85 W/m^{2}K Exterior walls: 0.10 W/m^{2}K Roof: 0.08 W/m^{2}K Floor facing ground: 0.09 W/m^{2}K (excluding foundation) Entrance door: 0.6 W/m^{2}K
Airtightness:	0.2 l/s, m^2 (leaking area) at 50 Pa
Acoustics:	Swedish Class B, including walls between apartments and floors, which means a highest allowed sound level from interior installations in bedrooms of 26 dB(A) and in kitchens 35 dB(A) (SIS, 2004)
Household appliances:	Energy class A++
Air heat exchanger efficiency:	85%
Solar collectors:	Yes, for domestic hot water
Drainage heat exchanger:	Yes

3.2 Building construction

The work from the architect and the structural engineer resulted in a total of 40 apartments located in five separate buildings. Two of the buildings have two floors and three have 2.5 floors. The apartments have two, three, four or five rooms with either a balcony or with a patio on the ground floor (Figure 3.2). The ceiling height in the apartments is 2.50 m, except for the top floor in the buildings with 2.5 storeys, where the ceiling follows the roof slope. To distribute the daylight within the apartments, fanlights are placed over the interior doors, between rooms.

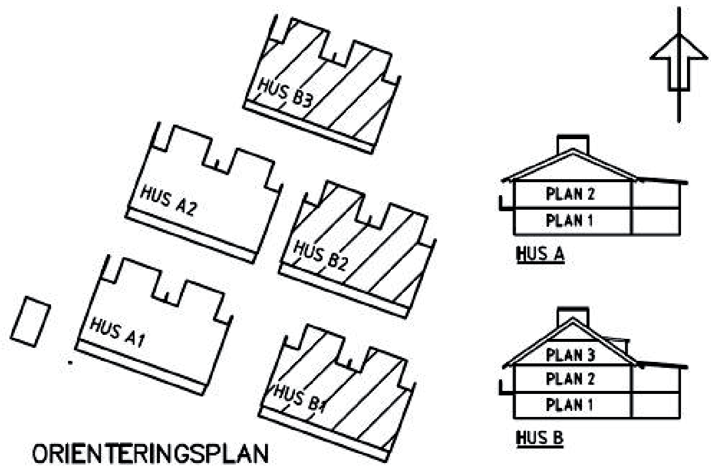


Figure 3.2 Plan of the Oxtorget area and sections of the buildings (Drawing: bsv arkitekter).

U-values for the building envelope are shown in Table 3.1. The part of the floor facing ground right under the apartment walls has a total U-value of 0.15 W/m^2K excluding foundation.

Table 3.1 U-values of the building envelope parts.

Building envelope	U-value [W/m^{2}K]
Ground floor (excl. foundation)	0.09
Exterior walls	0.095
Roof	0.07
Windows, average	0.94
Door	0.60

On the bathroom floor there is plastic matting. In the hallway there is rubber matting and the rest of the apartment is parquetted. The indoor walls are painted; the tenants can choose wallpaper at their own cost. The white goods used are in energy class A++.

3.2.1 HVAC system

Every apartment has its own mechanical ventilation system; a small ventilation unit with air-to-air heat recovery, placed in a walk-in closet to minimize internally generated sound. The apartments are heated by the supply air. On cold days, when the heat recovery is not enough to heat the apartments, the supply air is additionally heated by an electric heating battery placed in the ventilation unit. The rating of the supply air heating battery was 0.9 kW or 1.8 kW depending on the size of the apartment (14.5 W/m^2 – 16.8 W/m^2). The peak load demand for space heating was calculated in the planning process as lower than the installed size of the heating battery. However, due to the availability of heaters (900 or 1800 W), the actual <u>installed</u> capacity was higher than stated for the passive house concept.

According to the producer of the ventilation unit, the heat exchanger has a temperature efficiency of 85%. The heat exchanger unit is automatically defrosted. The exhaust air filter is an EU3 and the outdoor filter EU7.

To make sure that no noise will be generated in the apartments from the fans in the ventilation units, two silencers are mounted on the supply air system, right after the heat exchanger unit. On the exhaust air duct, one silencer is mounted.

The ventilation air flow at normal settings is around 30 l/s in the two and three room apartments and 40 l/s and 45 l/s in the four and five room apartments. This ventilation corresponds to air flow rates of 0.38 l/s,m^2 to 0.48 l/s,m^2; higher than the 0.35 l/s,m^2 as specified in the Swedish building code. The exhaust fan in the kitchen is separated from the rest of the ventilation system and is equipped with a timer.

The ventilation unit is running continuously 24 h per day, with five different possible air flow levels for the fans. The supply air temperature is adjusted by a sensor in the exhaust air placed in the exhaust air duct. When the tenants leave their apartment, they can press a button for a reduced airflow. If the indoor temperature becomes too low with this reduced flow, the sensor gives a signal to turn up the air flow until the indoor temperature reaches the required level. In the summer, an automatic by-pass function in the ventilation unit supplies the outdoor air into the apartment without passing the heat exchanger. The by-pass function can be blocked. This will be needed if the indoor temperature becomes higher than normal because of e.g. a party in the house when the outdoor temperature is low.

3.2.2 Domestic hot water system

All five apartment buildings have solar collectors on the roof connected to a central room for domestic hot water production, one in each building, see Figure 3.3. There are 25 m^2 of solar collectors on each building. The solar fraction was assumed in the planning process to be 50%. Additional heat for domestic hot water is supplied from an electric battery in the accumulator tank.

Figure 3.3 Solar collectors.

The cold water in Värnamo holds a temperature of 5 – 9°C. The cold water pipes installed in the buildings are additionally insulated, to prevent them from cooling floors and walls. There is no hot water circulation in the buildings, something usually installed in apartment buildings in Sweden to avoid Legionnaires' disease and also to minimize the waiting time for domestic hot water in the apartments. Instead, to prevent the domestic hot water temperature from falling in the distribution system, the domestic hot water pipes are highly insulated. The insulation of both cold and hot water pipes also prevents a rise in the temperature of the cold water due to the heat from the hot water when water runs. The client is very well aware of the problem with Legionnaires' disease and has been thinking closely about it when designing this solution.

3.3 Simulations

In order to make an estimate of the annual space heating demand and peak load for space heating with the planned constructions, one of the five buildings in the project was simulated using DEROB-LTH v 1.0 (Kvist, 2006). In the program, the building was built up by coordinates into a 3-D volume as shown in Figure 3.4. The building used in the simulation has a ceiling height of 2.50 m (building type A). The balconies and the unheated storage rooms that are located outside the entrances of the apartments are here modelled as solar shadings.

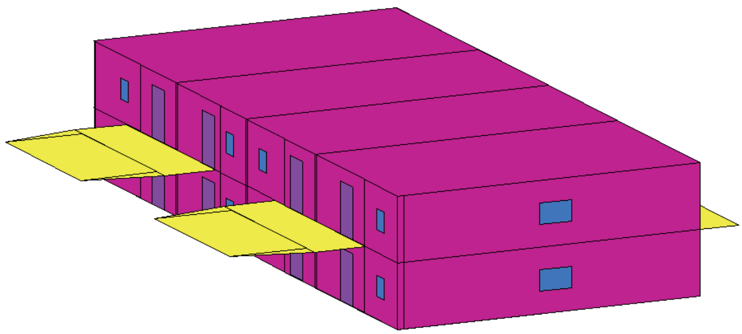


Figure 3.4 The apartment building at Oxtorget as simulated in DEROB – LTH v 1.0

In the simulation, the following input data were used:

Heated area:	598 m^2
U-values:	Floor facing ground: 0.09 W/m^2K Outer wall: 0.095 W/m^2K Inner wall: 3.3 W/m^2K Roof: 0.07 W/m^2K Outer door: 0.06 W/m^2K Windows: 0.94 W/m^2K
Ventilation:	Air leakage: 0.05 ach Mechanical ventilation: 0.5 ach Efficiency of heat exchanger: 80% Ventilated volume: 85%
Orientation:	The facades with the balconies and patios are almost facing south; they are rotated 20° clockwise from south
Soil resistance:	2.64 m^2K/W
Ground reflection:	20%
Internal gains:	4 W/m^2

Indoor temperatures: The indoor temperature is set to 20°C and 22°C respectively. For the studies of energy demand and peak load for space heating, the maximum allowed indoor temperature was set to 25°C. Above this temperature, the occupants are assumed to reduce the temperature by using shading devices and/or opening windows.

Climate data: The simulation is made with climate data for Jönköping, with a maximum outdoor temperature of 27.2°C, minimum outdoor temperature of -18.9 °C and an average outdoor temperature of 5.4°C over the year used in the simulation (Meteotest, 2004).

3.3.1 Calculated results

With an indoor temperature of 20°C the peak load for space heating was calculated to 8.3 W/m^2. The annual space heating demand was calculated to 9.8 kWh/m^2a.

If the indoor temperature in the simulation was set to 22°C the peak load for space heating was calculated to 9.1 W/m^2 and the space heating demand was calculated to 12.8 kWh/m^2a. The constructions were designed to avoid thermal bridges. Small thermal bridges might anyway occur in the junctions between parts of the construction. Energy demand caused by these thermal bridges was not included in the calculated result.

3.4 Tendering

The client took a lot of time to learn about passive houses before he invited tenders for the project according to the law on public tendering as described earlier. It was important for the client to have much knowledge about passive houses to be able to know what to order and what demands to set up to be reached by the contractor, in order to get a passive house that would work perfectly. Since the specification of requirements was much stricter than in a normal project, many contractors desisted from making an offer. They did not know if they were going to be able to reach the demands aimed for. The required level for airtightness seemed especially hard to achieve. Finally, only two contractors tendered for the contract.

The large contractor NCC was awarded the general contract and NCC was responsible for engaging the subcontractors. The subcontractors chosen for the project were experienced and had been working in projects with NCC before, with good results. The law of public purchasing was used for all the subcontractors.

3.5 Planning deviations

Before the general contractor started with the constructional work, they had a discussion with the client, Finnvedsbostäder, about the specification of requirements. This resulted in a few deviations from the original requirements.

Dreh-Kipp windows with the required U–value of 0.85 W/m^2K were at the time of purchasing in 2005 not produced by any Swedish window producer. It was important for the client to get Dreh-Kipp windows so the tenants could air the apartments in a good way and also for the tenants to be able to safely leave their apartment with the window in airing position. Due to the impossibility to purchase Dreh-Kipp windows with the required U-value in Sweden, the set up U-value was adjusted by the client. To still ensure a good total U-value for the windows, the number of fixed windows was increased where the U-value could be lower than the U-value for the operable windows. The mean U-value of the windows purchased in this project was 0.94 W/m^2K.

The airtightness of 0.2 l/s m^2 specified by the client for the buildings seemed hard to achieve for the contractor. Together with the client they decided a new requirement of 0.4 l/s m^2 with the goal to reach 0.2 l/s m^2 if possible.

3.6 Education

In September 2005, before the major work started on site, everyone involved with the project attended an afternoon of education. The requirements for passive houses and the importance of airtightness were discussed. Full scale models of the wall and roof constructions were placed at the working area and discussed by the contractors. Inspiration and solutions from the contractors in the earlier passive house project in Glumslöv were passed on. This afternoon of education was much appreciated by the contractor and the carpenters said it made them aware of things of special importance when building passive houses. The information from this day of education was later passed on to the subcontractors.

The full scale models of the roof, outer wall and foundation construction used on this day of education were kept on site, see Figure 3.5. The carpenters looked at these together with the drawings before working. These models were much appreciated by the contractors.

Figure 3.5 *Model of wall and ground construction with the eps-insulation at bottom, the double concrete ground construction and the long side wooden wall.*

3.7 The construction stage

3.7.1 Foundation construction

The work on the foundations of the five houses started in August 2005. After excavation, crushed aggregate was spread on the ground. Insulation to stabilize the construction was put on the crushed aggregate under the load bearing plinth. To avoid thermal bridges, two L-units were put outside the plinth for thermal insulation (Figure 3.6). This construction is chosen to achieve high indoor comfort with no risk of cold floors or cold inner walls. The L-units are standard products on the market; no new material was needed, only new thinking.

On the inside of the plinths, 350 mm of insulation was placed and on top of the insulation a concrete slab of 100 mm was cast on site. The sliding surface between the foundation and the walls separating the apartments was made airtight. The work with the foundation was performed during the warm season. Everyone at the construction site agreed that this was very good and made the work run easily.

Figure 3.6 *Insulation of foundation construction with the double eps foundation insulation to the left and to the right; the eps insulation filled with the load bearing concrete construction.*

3.7.2 Load bearing structure

The walls in the load bearing structure were made of concrete and cast on site. To reduce the moisture content in the load bearing concrete construction, the apartments were ventilated until the required moisture content of maximum 85% was reached. The concrete used for all constructions had a w/c ratio of 0.6.

After the hardening process of the walls, the work continued with the ceiling/ floor also cast on site, then the walls on the next floor were made and so on. Finally the concrete skeleton was made, see Figure 3.7. All walls and floors were made to comply with the Swedish sound class B.

To cast concrete walls on site was more common about ten years ago and the contractor said to prefer using prefabricated concrete constructions, which was more commonly used by the contractor. The client insisted on casting the load bearing structure on site and in the planning process additional time was reserved to cover for uncertainties in this casting process. However, the work went very smoothly and the casting took much less time than assumed, saving not only time but money.

Figure 3.7 *Concrete construction cast on site.*

3.7.3 Exterior walls

The exterior walls were made of a timber frame construction and erected on site. From the outside, the walls consist of a façade material, wood studs with mineral wool, expanded polystyrene, plastic foil and on the inside wood studs with mineral wool and gypsum board (Figure 3.8). Building the outer wooden walls on site makes it easy to adjust the height of the walls if necessary.

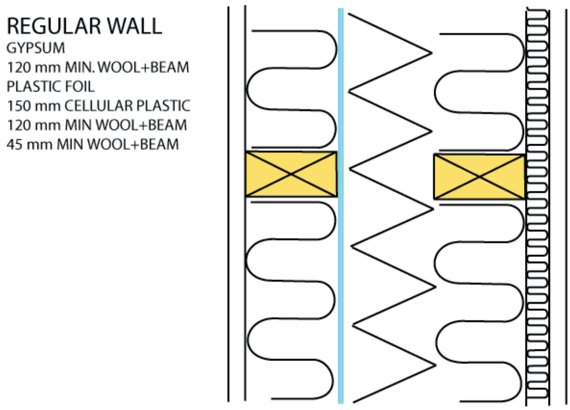


Figure 3.8 *Exterior wall.*

The placing of the plastic foil in the wall construction creates an installation layer of 120 mm that makes it easy to avoid damage to the plastic foil when mounting pipes and electrical equipment, see Figure 3.9.

Figure 3.9 *Installation layer.*

Additional measurements of RH in the concrete load bearing construction were performed before the walls were erected, to ensure that the moisture content was low enough. Even though the measurements showed that the moisture content was low, a metal sheet was placed on the concrete slab to break capillary suction and to protect the timber construction from the moisture in the concrete slab. A small spacer block made of plastic was also put under the wooden beam for additional moisture reduction. The steel strip construction was tested to ensure that it did not constitute a thermal bridge (Figure 3.10).

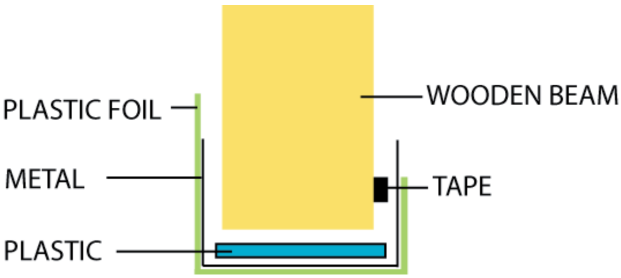


Figure 3.10 *Protection of wooden construction.*

When the outer walls were erected, first the internal wooden frame construction was made from the inside, then the plastic foil was mounted on the outside, followed by the polystyrene and the external wooden frame construction. On the initiative of the structural engineer, the moisture content in the wooden beams in the wall construction was checked before the walls were closed up. This was not a specified demand set by the client, but it was done to guarantee the durability of the construction over a long period of time.

To mount the wooden walls from the outside was something the carpenters said was irrational. They thought it was especially inconvenient to work from the outside when pulling the plastic foil in front and behind the sills. The carpenters suggested a revised wall construction, as presented in Figure 4.11, where construction of the wall started outside and then work continued from the inside.

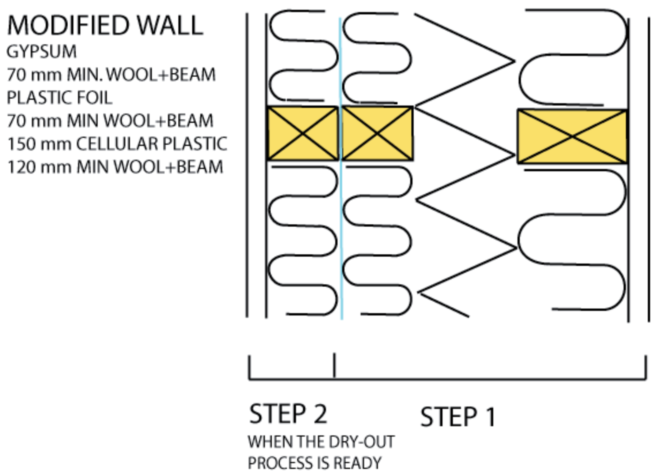


Figure 3.11 Suggested outer wall construction.

The projection of the roof in the construction protected the carpenters and the building from bad weather. To protect the walls from snow during the cold months, a tarpaulin was suspended from the roof towards the ground as additional weather protection.

The thick walls and the position of the windows close to the outside allow the flaring of the deep window cross-section into the room. This construction allows more daylight into the room and is often seen in old castles. To build this window construction took time to finish and the carpenters said that to make the building process shorter, the window bays should be straight.

3.7.4 Roof construction

The wooden roof construction was erected on site. Two different solutions for insulating the roof were used, depending on the number of storeys of the building. Three of the buildings that had a 2.5 storey construction had a loose wool roof insulation following the roof slope, see Figure 3.12. The construction is properly ventilated by a sheet of particle board, creating an air gap. On the inside of the insulation, facing the room, a plastic foil is mounted. To secure the impenetrability of the plastic foil it is closely sealed with double sided adhesive tape.

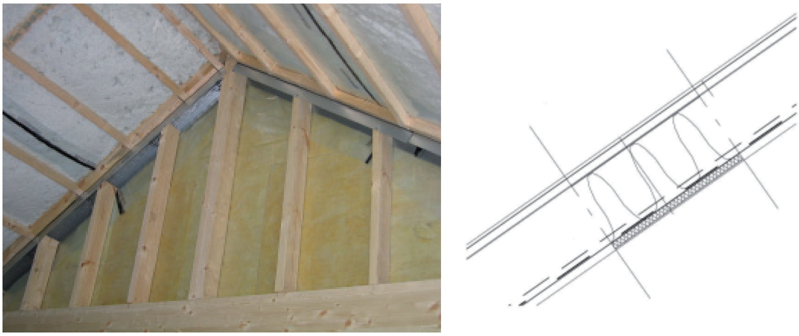


Figure 3.12 Roof in building with 2.5 storeys (Drawing: bsv arkitekter).

The remaining two buildings built in two storeys had a horizontal ceiling where the loose wool insulation was placed in the attic in a ventilated construction, see Figure 3.13.

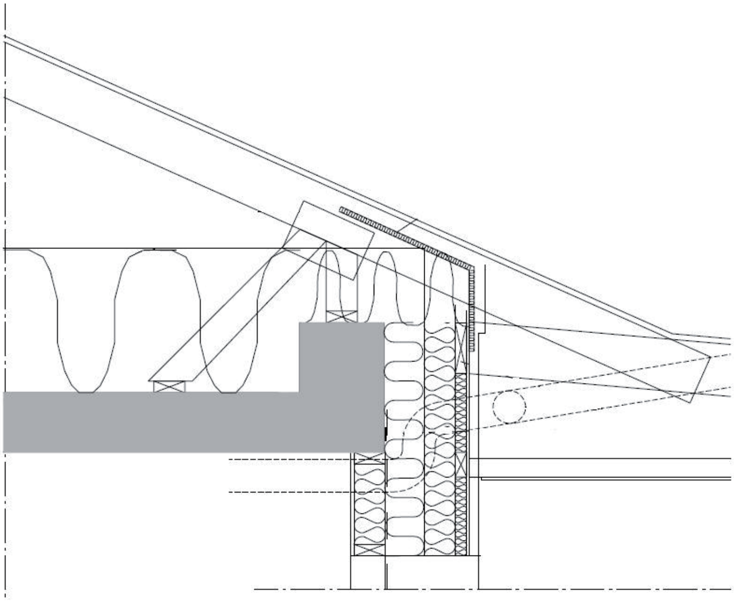


Figure 3.13 Roof in building with two storeys (Drawing: bsv arkitekter).

3.7.5 Windows and entrance doors

It was very difficult to find an entrance door on the Swedish market that had the requested U-value of 0.6 W/m^{2}K. There were entrance doors with a sufficiently low U-value available on e.g. the German market, but German doors open inward and Swedish entrance doors must open outward. Therefore, the general manager of Finnvedsbostäder made his own door design and produced it at one of the largest Swedish door companies (Figure 3.14). The windows used in the project had a mean U-value of 0.94 W/m^{2}K.

Figure 3.14 *Per-Magnus Rylander working at Finnvedsbostäder and the entrance door.*

3.7.6 HVAC-system

As planned, all apartments have their own air-to-air heat exchanger placed in a walk-in closet next to the bathroom. The drainage pipe from the heat exchanger discharges in the bathroom. Space heating is supplied by an electric heating battery on the supply air side in the heat exchanger unit. To ensure low carbon dioxide emissions, the electricity is supplied from a wind power plant. The two fans in the ventilation unit used in the smaller apartment each have a rated output of 58 W.

The indoor temperature is planned to be 20°C but can be set higher if required by the tenants. To help the tenants to know if their indoor temperature is at 20°C and therefore their energy bill will be low, there is a display mounted on the wall, one in each apartment, showing the indoor temperature, see Figure 3.15. For higher temperature in the bathrooms, there is an electrically heated towel rail in each bathroom. The towel rail has a timer, to make sure it is only switched on for maximum one hour.

Figure 3.15 Display showing the temperature in each apartment.

3.8 Additional experiences

To keep a good feeling of teamwork among the contractors, every Friday a meeting was held on site by the general contractor. The work done during the week was then discussed and also if new solutions had been found or if problems had occurred. The interviewed contractors said that these meetings gave a great feeling that each carpenter's achievements really counted; a feeling of importance. It also made the people involved in the project proud of their achieved results. They all delivered the project to the client with really straight backs.

Representatives from the general contractor thought that it was fun participating in the project and that many new solutions and ideas used at the project at Oxtorget could be passed on and used in future projects.

The client has, after a close evaluation of the project at Oxtorget, decided to continue adding more passive houses to their building stock, starting with 50 apartments that will be ready in the summer of 2010.

3.9 Economy

The calculated total cost for the client when the project was finished in 2006 was SEK 50 243 000. The purchased total cost was SEK 52 300 000. The final cost for the client was SEK 55 700 000. The gross amount per square metre, subsidies not subtracted, ended up at SEK 17 898 /m^2. The total cost for the contractor was SEK 36 700 000, VAT not included; approximately SEK 11 800 /m^2. In these prices, the cost of the piece of land is included as well as costs for electricity and water connections. The client estimates that for building a regular house just meeting the building code requirements, the cost in 2006 would probably be around SEK 15 000 /m^2. In 2003, the client built similar apartments, but not according to passive house requirements. The cost of building these apartments was approximately SEK 13 000 /m^2.

The difference between the cost for the client and the cost for the contractor shows that there is a large cost for the design stage. Since the planning first started with regular houses and then had to be modified to passive houses, the first documents used in the process for building permission had to be drawn up twice.

More time was used by the contractors than was expected, even though the general contractor added 1000 h when they made the tender, compared to a usual apartment project. Especially it took more time than expected to meet the requirements for airtightness. It was however experienced by the general contractor that the additional time needed to achieve the required airtightness decreased when the carpenters became used to its routine, and much less time was needed to build house number five than the first building. Making the concrete frame took less time than expected. The general contractor estimated the extra hours not allowed for to total around 1000 h, which makes the additional time needed for the contractor to total 2000 h, compared to regular apartment projects.

The application for subsidies was for SEK 1 650 000. The project received two financial contributions from the Government. One was for using solar collectors for domestic hot water and the other was a contribution from the Swedish Energy Agency for making this a demonstration project. To manage the extra costs in the project, the board of Finnvedsbostäder has decided to extend the depreciation from 40 to 50 years.

The companies in Sweden included in SABO; Swedish Public Housing Companies, have calculated the mean values of their rents (including heating). In Sweden this level in 2004 was SEK 754 /m^{2}a. The client Finnvedsbostäder, which is included in SABO, had a mean value of SEK 718 /m^{2}a for their rental cost in 2004. The mean value of the rent in these new passive house apartments is approximately SEK 888 /m^{2}a, excluding heating. The rents for the apartments were in 2006:

2 rooms, 62 m^2; SEK 5 100 (984 SEK/m^{2}a)
3 rooms, 80 m^2; SEK 5 700 (852 SEK/m^{2}a)
4 rooms, 105 m^2; SEK 7 600 (862 SEK/m^{2}a)
5 rooms, 107 m^2; SEK 7800 (876 SEK/m^{2}a)

In the above rents, heating, household electricity and domestic hot water are not included.

3.10 Measurements

Measurements of actual energy use in the buildings started the day the tenants moved in to their apartments and are made by the client. These measurements are not specially made because this is a demonstration project. The client Finnvedsbostäder uses measurement when charging the rent for the apartments in many of their buildings, where the tenants pay for their actual energy use. The tenants can follow their energy use on the internet and specified on the rental notification and their actual use of energy for space heating, household electricity and domestic hot water heating is paid for every month. This makes it easy for the tenants to have an influence on both the use and the energy costs.

The measurements made during the period 070201 to 080201 are here closely evaluated.

In each apartment, the amount of total bought electricity is measured, which includes space heating and household electricity.

The energy use for space heating is measured separately in four apartments; one apartment of each size. The percentage between the total electricity use and the measured electricity used for space heating was calculated in the eight apartments, getting one percentage value for each size of apartment. The calculated percentage was then multiplied by the total electricity use in corresponding apartment sizes in the rest of the four buildings, getting an approximation of the energy use for space heating in all five buildings.

The fan electricity use in the ventilation units is measured in four apartments, one of each size and is used for all apartments in the following combinations of apartment sizes.

The energy use for household electricity for each apartment is calculated using the measured total electricity use in the apartments, less the use of electricity for space heating and the fans.

The volume of domestic hot water use is measured in each apartment. The energy use for domestic hot water is measured separately in all five centres of domestic hot water preparation together with the energy gained from the solar panels in each building.

The use of energy for common areas can be calculated as a residual post when the total energy use for the five buildings is measured and the total amount of bought energy in all apartments and the use of energy for domestic hot water for the area are subtracted.

The outdoor temperature is measured at one measuring point for the whole area. In one of the five buildings, the indoor temperature in all eight apartments is measured.

3.11 Results from the measurements

3.11.1 Sound

Measurements of internally generated sound produced by the ventilation unit and transported in the ventilation system were made in a four room apartment. The results are shown in Table 3.2. According to the Swedish passive house criteria, the sound levels may not exceed sound level B.

Table 3.2 Measured sound levels in one four room apartment and allowed levels according to sound level B.

Room	Measured sound level [dB(A)]	Sound level B [dB(A)]
Bedrooms	19, 19, 22.8 and 23	26
Kitchen	26.9	35
Bathrooms	31.4 and 34.9	35
Hallway	35.1	35

The ventilation unit is placed in a closet close to the entrance of the apartment. To increase the accessibility of the closet, there is no doorstep between the hallway and the closet. This can account for some noise leaking from the ventilation unit in to the hallway and explain the somewhat higher sound level measured in the hallway.

3.11.2 Airtightness

The general contractor was not sure if they would be able to make the building as airtight as stated in the requirements for the project; 0.4 l/s m^2 at 50 Pa. They had never built this airtight before and had not always measured the airtightness in earlier projects.

The final measurements showed an average air leakage of 0.2 l/s m^2 for all buildings. The area referred to is the surfaces facing outdoors. However, no measurements were made without differential pressure across apartments. Thus, the leakage through the building envelope alone is equal to or smaller than 0.2 l/s m^2 (if the area towards adjacent apartments were completely airtight, all the leaking air would go through the building envelope and thus be equal to 0.2 l/s m^2).

The airtightness differs much between apartments with the two different roof constructions, with a higher air leakage in the apartment buildings in 2.5 storeys. The outer wall construction was the same in the two types of buildings but the roof construction differed and might have caused a difference in the air leakage. One explanation could be that the nails in the roof construction in the higher building were too long for the space built for installations and might therefore have reached and perforated the plastic foil. Also, the plastic foil in this roof construction was stapled to the roof truss with a stapler, which might let trough air as well. By using a deeper installation layer in future roof constructions, just as was used here in the outer walls, the airtightness in the roof construction could be improved.

3.11.3 Energy demand for space heating

The energy used for space heating was measured in four apartments, one of each size, in one building (Figure 3.16). This measurement was used as a base for the calculation of energy use for space heating for all apartments in the area as described in Section 3.10. The mean value of the annual space heating use during the period 070201 - 080201 was 7.6 kWh/m^2a.

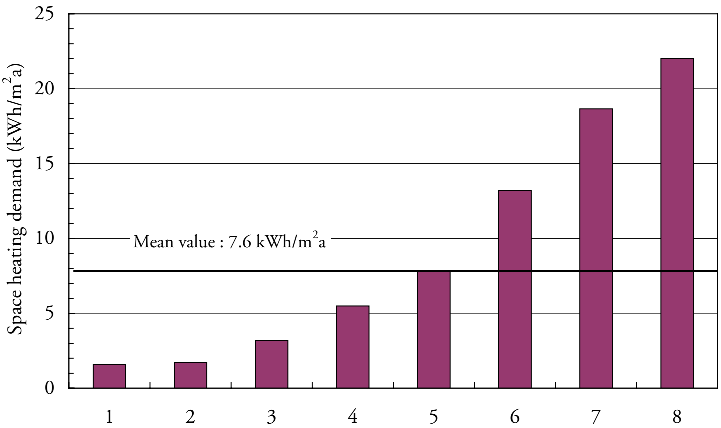


Figure 3.16 *Measured annual space heating demand in eight apartments during the period 070201 - 080201.*

3.11.4 Space heating demand revised to a normal year

The period for measurement 070201 – 080201 was somewhat warmer than a normal year. To be able to compare the measured figures with other projects, the measured energy use for space heating will be revised according to degree days using data from SMHI (SMHI, 2009) as described in Chapter 1. The degree days in 2007/2008 are compared to degree days in a normal year as presented in Table 3.3, where the ratio is called the correction factor and used for recalculating the measured energy use for space heating into what would be needed during a normal climatic year.

Using the measured energy use for space heating during the period 070201 – 080201 as a base, the annual energy use for space heating, for a normalized year, is 9 kWh/m^{2}a.

Table 3.3 Calculation of correction factor, degree days.

	Degree days 2007/2008	Degree days Normal year	Correction factor energy space heating
Feb 07	545.1	559	1.03
March 07	425.6	534	1.25
April 07	279.9	389	1.39
May 07	140.1	166	1.18
June 07	8.1	30	3.70
July 07	0.0	0	0.00
Aug 07	36.7	21	0.57
Sep 07	169.7	181	1.07
Oct 07	374.4	339	0.91
Nov 07	479.5	462	0.96
Dec 07	498.7	571	1.14
Jan 08	492.3	609	1.24
Year	3450.1	3861	1.12

3.11.5 Domestic hot water

The volume of domestic hot water used during the period 070201 – 080201 was measured in each apartment (Figure 3.17). The bought volume of domestic hot water varied from 1.5 m^3/year to 68.1 m^3/year, with a mean value of 28 m^3/year.

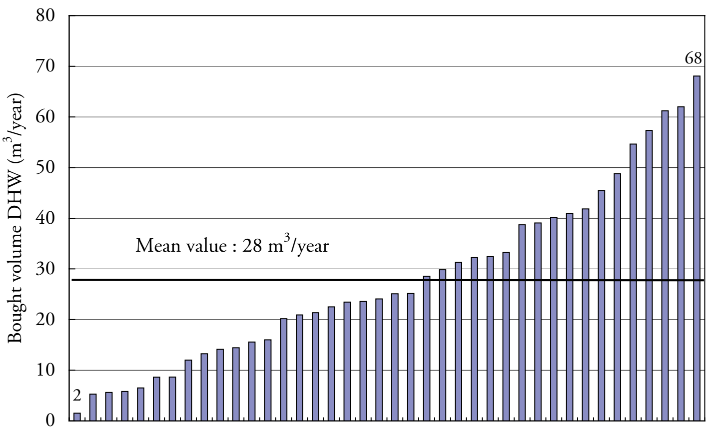


Figure 3.17 *Measured annual bought volume of domestic hot water during the period 070201 to 080201.*

The total energy used for domestic hot water production was measured in each of the five buildings. The energy use for domestic hot water heating for each apartment was calculated using each apartment's percentage of the total used volume of DHW in the building, multiplied by the total annual amount of energy used for DHW in the building.

The annual bought energy for domestic hot water in the 40 apartments during the period 070201 – 080201 is presented in Figure 3.18 and varies from 0.9 kWh/m^{2}a to 42.8 kWh/m^{2}a with a mean value of 14.5 kWh/m^{2}a. Note that the bought energy for DHW is only a part of the total DHW demand due to the contribution from the solar collectors.

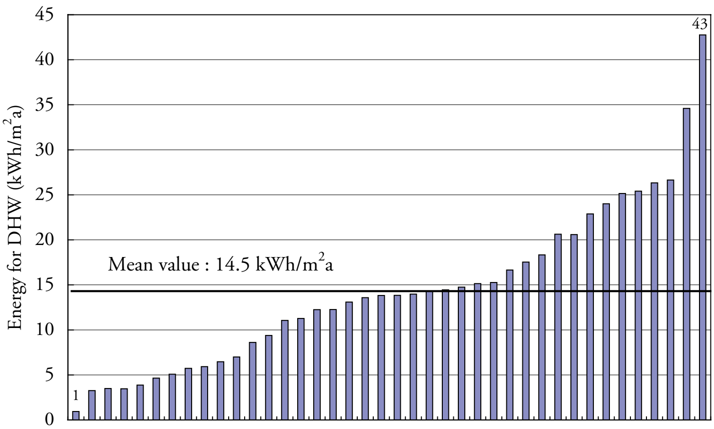


Figure 3.18 Annual bought energy for domestic hot water during the period 070201 - 080201.

3.11.6 Domestic hot water – solar gains

The solar panels on each building contributed with energy for domestic hot water production. The actual use of energy for domestic hot water in the apartments including the production from the solar panels during the period 070201 – 080201 is presented in Figure 3.19. The total energy use for domestic hot water varies between the apartments from 1.8 kWh/m^{2}a to 64.4 kWh/m^{2}a, with a mean value of 25 kWh/m^{2}a.

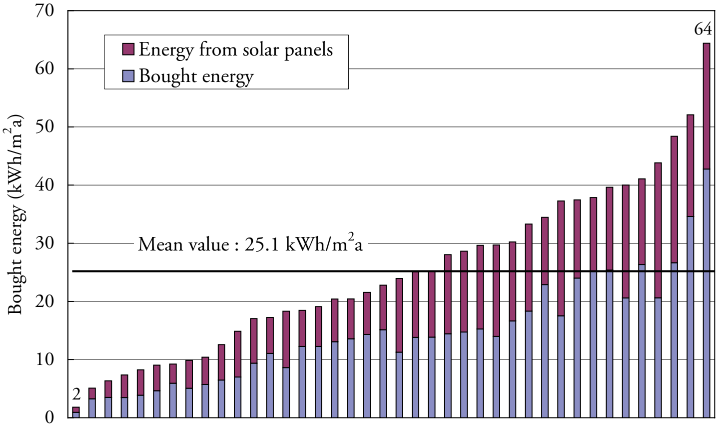


Figure 3.19 Total use of energy for domestic hot water heating.

Initially, there was some trouble in some of the buildings with the temperature sensors in the solar panel system. This gives a difference between the buildings in the percentage of the bought energy for domestic hot water and the contribution from the solar panels. The cover of the solar panels for production of domestic hot water is presented in Table 3.4.

Table 3.4 Production of domestic hot water and solar contribution during 070201 - 080201.

	Solar energy (kWh/a)	Bought energy (kWh/a)	Sum (kWh/a)	Percentage solar
Building 5	5905	7234	13139	45%
Building 7	5588	9978	15566	36%
Building 9	6533	5804	12337	53%
Building 11	7161	7600	14761	49%
Building 13	7538	14917	22455	34%
All buildings	32725	45533	78258	42%

3.11.7 Fan electricity

The electricity used for the fans in the ventilation units was measured by the client in four apartments, one of each size, as presented in Table 3.5. In the smaller apartments of 62 and 70 m^2, the measured power was 49 W and in the larger apartments 81 W.

Table 3.5 Electricity use for fans in ventilation unit.

Area (m^2)	Electrical power (W)	Bought energy (kWh/a)	Bought energy (kWh/m^2a)
62	49	429.2	6.9
70	49	429.2	6.1
105	81	709.6	6.8
107	81	709.6	6.6

3.11.8 Electricity for common areas

The energy use for common areas is calculated by using the measured total energy use for the area with five buildings as a base and from that subtracting the energy use for domestic hot water and the total measured household electricity (including space heating). A mean value of the electricity used for common areas during the period 070201 – 080201 is for the five buildings calculated to 4.6 kWh/m^2a. The energy use for common areas includes electricity for outdoor lighting on façades and between the buildings, pumps used in the solar system and domestic hot water pumps.

3.11.9 Household electricity

Since the measured total bought electricity in each apartment includes both the use of household electricity and the electricity used for space heating, the figure of household electricity is calculated by reducing the total electricity use by the measured figures of electricity for space heating.

In Figure 3.20, the use of household electricity is presented during the period 070201 - 080201. The household electricity is calculated using the figures of electricity use for space heating revised according to degree days. The use of household electricity varies very much between the apartments; from 9 kWh/m^2a to 64.5 kWh/m^2a with a mean value of bought house hold electricity of 33.8 kWh/m^2a.

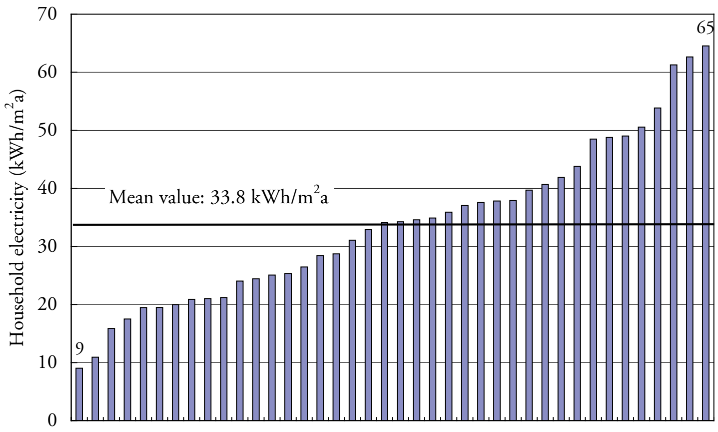


Figure 3.20 *Bought household electricity during 070201 - 080201; electricity for space heating revised according to degree days.*

3.11.10 Total energy use

The annual measured bought energy demand in the five apartment buildings is presented in Figure 3.21, together with the measured mean energy use for the area with five buildings, broken down by different energy items.

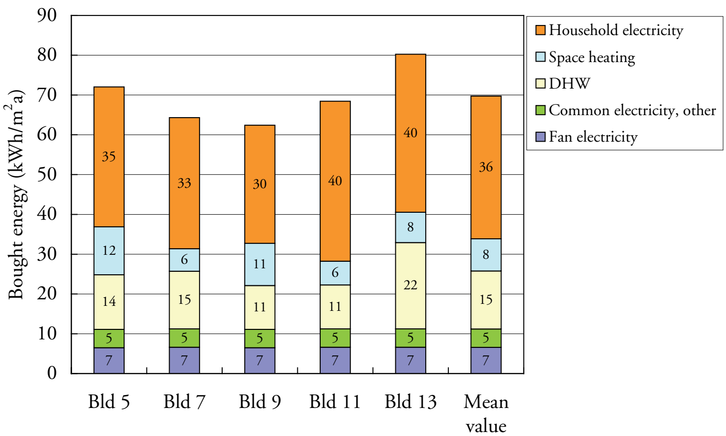


Figure 3.21 *Measured total annual energy use in the five buildings during the period 070201 to 080201.*

The mean value of total bought energy in the five buildings was 69.8 kWh/m^2a, where the major item was household electricity that represented approximately 50% of the total amount of bought energy, heating of domestic hot water used 30% and only 11% of the total bought energy was used for space heating.

The total bought energy in the five buildings with the space heating demand revised according to degree days is presented in Figure 3.22.

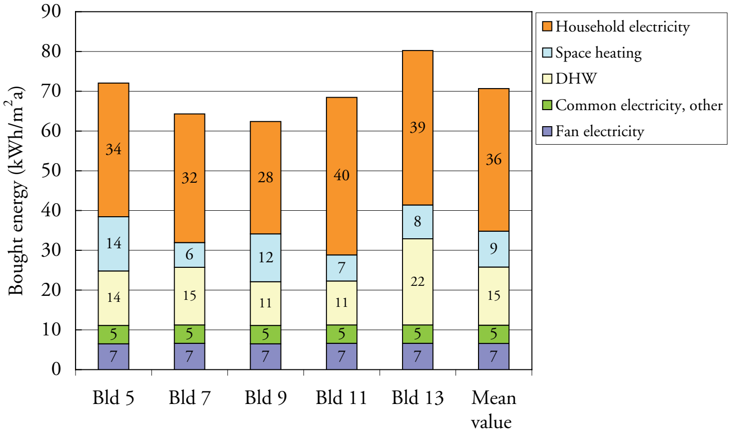


Figure 3.22 *Total bought energy during the period 070201 – 080201 where the space heating demand is corrected for a normalized year.*

The annual total amount of bought energy in each apartment during the period 070201 – 080201 is presented in Figure 3.23. The total energy use is there distributed on the living area and includes energy for space heating, domestic hot water, electricity for common areas and household electricity. The measured values vary from 44 kWh/m^2a to 133 kWh/m^2a with a mean value of total bought energy of 70 kWh/m^2a.

The heated floor area in the apartments is 62 m^2, 70 m^2, 105 m^2 and 107 m^2. In Figure 3.24 the total amount of bought energy is shown, where the apartments with the same heated area are put together. The mean value of the total energy use in the apartments with a heated floor area of 62 m^2 was 75 kWh/m^2a, in those with a heated floor area of 70 m^2 65 kWh/m^2a, in those with 105 m^2 the average energy use was 67 kWh/m^2a and in the apartments with a heated floor area of 107 m^2 the average amount of total bought energy was 69.8 kWh/m^2a.

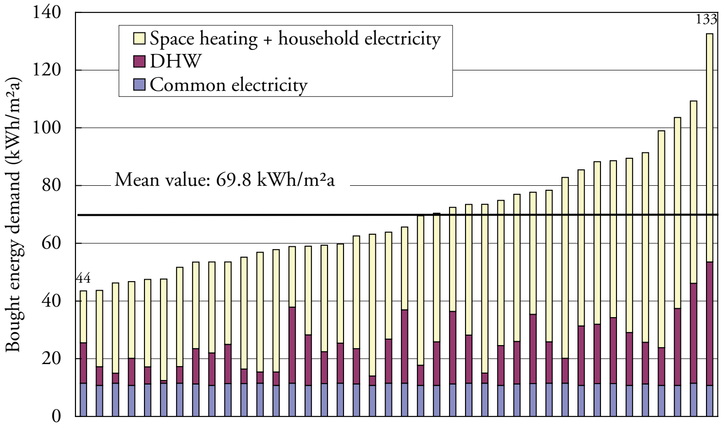


Figure 3.23 *Total bought energy in Oxtorget during the period 070201 to 080201. Each bar represents the values for one apartment, in total 40 apartments.*

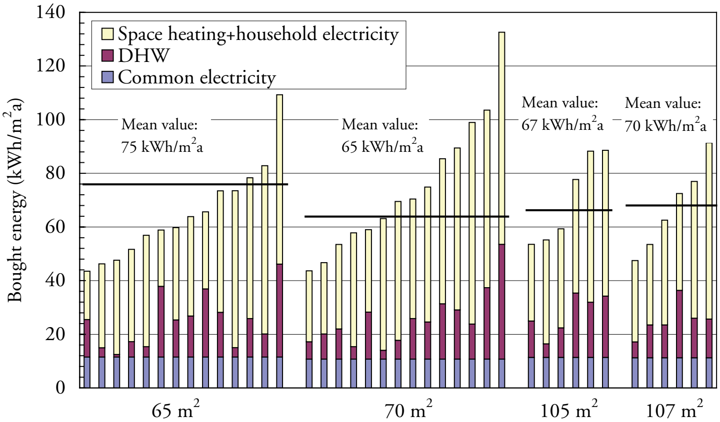


Figure 3.24 *Bought energy for each apartment during the period 070201 to 080201, sorted by apartment size.*

3.11.11 Peak load for space heating

In four apartments in one building, one apartment of each size, measurements were made of the bought energy for space heating and the indoor temperatures. The amount of bought energy for space heating was registered by the client every 24 h. By dividing the highest measured value of bought energy by 24 h; a good approximation is achieved showing the maximum peak load for space heating for each of the measured apartments during the period 070201 - 080201, see Figure 3.25 and Figure 3.26.

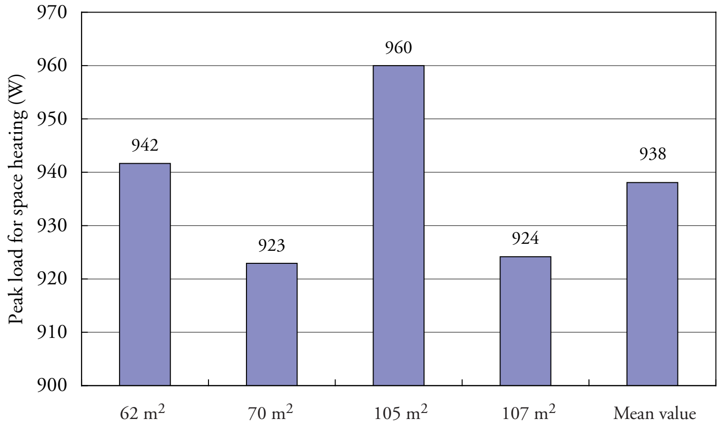


Figure 3.25 *Maximum power used for space heating in four measured apartments during the period 070201 - 080201.*

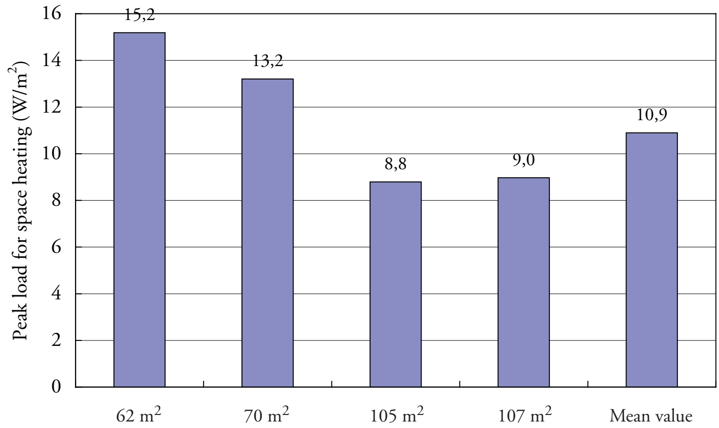


Figure 3.26 *Peak load for space heating in four measured apartments, divided by heated floor area during the period 070201 - 080201.*

The available installed heat load in the heating batteries in the supply air was 900 W in the smaller apartments (62 – 70 m^2) and 1800 W in the larger apartments (105 – 107 m^2), see Table 3.6. When the available power installed in the apartments is compared with the maximum power used, the smaller apartments use 100% of the available heating in the batteries during the coldest day and the larger apartments use half of their available power on the day with maximum heating demand.

Table 3.6 Power used for space heating in four apartments.

Area (m^2)	Available power (W)	Available power load (W/m^2)	Maximum used power (W)	Available power used (%)
62	900	14.5	942	105
70	900	12.9	923	103
105	1800	17.1	960	53
107	1800	16.8	924	51

3.11.12 Indoor and outdoor temperature

The indoor temperature was measured in one building with eight apartments, with one meter in each apartment. The outdoor temperature was measured in one place.

The variation of the indoor temperatures in the different apartments together with the outdoor temperature is presented in Figure 3.27. Due to troubles with some of the meters, some data are missing during the summer months, as can be seen by a straight line in Figure 3.27. Measured temperatures are missing during the periods 070515-070521 and 070731 – 070813. In the graph, the missing temperatures are replaced by mean values of the measured temperatures right before and right after the meter was broken.

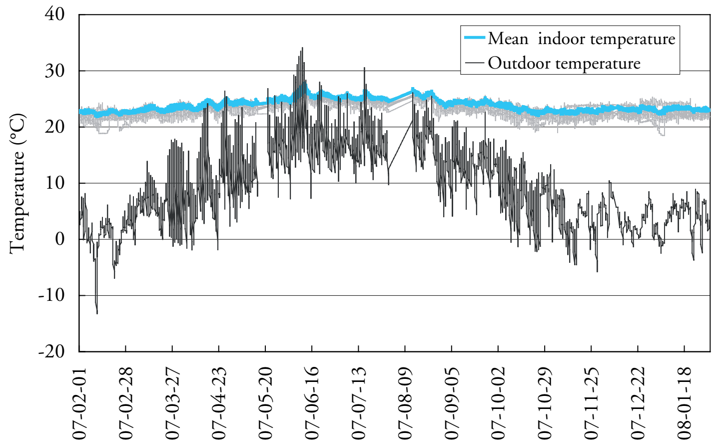


Figure 3.27 *Indoor and outdoor temperature during 070201 - 080201.*

The mean value of the indoor temperatures measured in each apartment varies between 20.6°C and 26.5°C. The measured indoor temperature did not exceed 30°C in any of the apartments. This might be due to the well thought-out solar shadings in all buildings that protect the apartments from too much solar radiation and thus excessive indoor temperature in summer. The measured indoor temperature during summer in the eight apartments varies as presented in Figure 3.28.

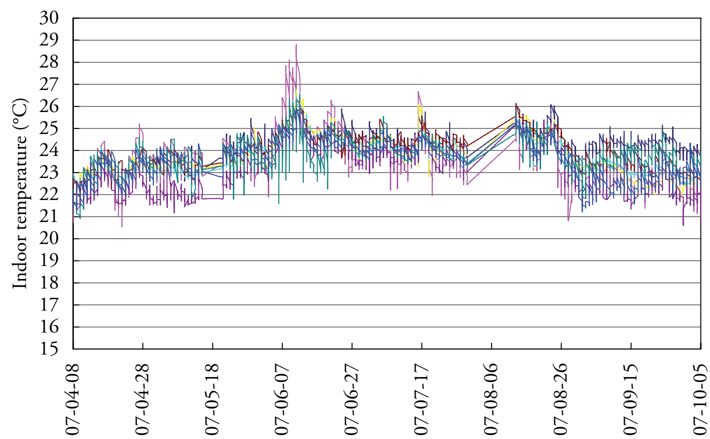


Figure 3.28 *Measured indoor temperature in eight apartments during spring, summer and autumn 2007, with missing temperatures during time period 070515-070521 and 070731 – 070813.*

The lowest outdoor temperature during the year of measuring was on February 11, 2007, with a measured temperature of -14.7°C. The indoor temperature in the eight measured apartments during February 2007 is presented in Figure 3.29. The lowest outdoor temperature was reached on February 11 but the lowest indoor temperatures were measured on February 13 and 14, which is a result of the thermal inertia of the building construction.

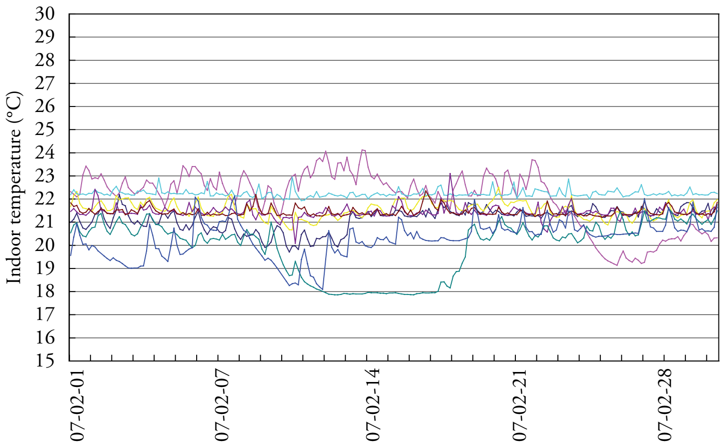


Figure 3.29 Indoor temperature in eight apartments during February 2007.

In one apartment, the indoor temperature during this cold period reached a minimum 18°C as can be seen in Figure 4.29. According to the interview made with the tenants living in this apartment, the low temperature is reached since the family tried not to turn on their heating battery in the supply air system to see how they could manage without any additional heating. The measured indoor temperature of 18°C is therefore only a result of internal gains from the tenants and neighbours.

The mean value of the annual indoor temperatures in the eight apartments is presented in Figure 3.30. It can be seen that even though the outdoor temperature is low, the mean value of the indoor temperature in the apartments does not drop below 20°C. Also in the warm season the indoor temperature only occasionally exceeds 25°C. The line drawn in the diagram is when the indoor temperature equals the outdoor temperature.

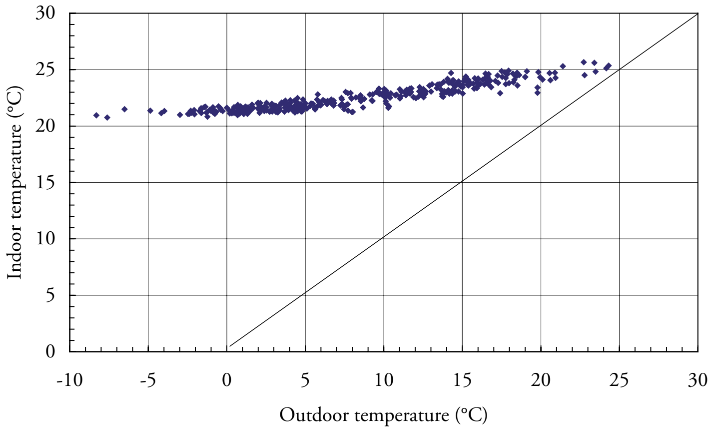


Figure 3.30 *Mean value of indoor temperatures in the eight apartments during the period 070201 to 080201. The line represents when the indoor temperature is equal to the outdoor temperature.*

3.12 Correlation between measured and calculated figures

The energy demand and peak load for space heating in one of the five buildings in the project was simulated in DEROB-LTH v1.0 (Kvist, 2006) as described in Section 3.3. The calculated results of these simulations are summarized in Table 3.7. Thermal losses caused by specific thermal bridges were not included in the calculated results.

Table 3.7 Calculated energy demand and peak load for space heating.

Indoor temperature (°C)	Peak load for space heating (W/m^2)	Energy demand for space heating (kWh/m^{2}a)
20	8.3	9.8
22	9.1	12.8

The indoor temperature was measured in building 13, where the mean value of the indoor temperature during the cold season (070202 – 070430 and 071001 – 080201) was 21.8°C.

3.12.1 Peak load for space heating

The peak load for space heating was measured in four apartments in building 13 during the period 070201 – 080201 with a measured mean value of 10.9 W/m^2 (Figure 3.26). The measurements and the calculated values at an indoor temperature of 20 ° C and 22 ° C are presented in Figure 3.31, together with the indoor temperature in each apartment measured at the time for peak load for space heating.

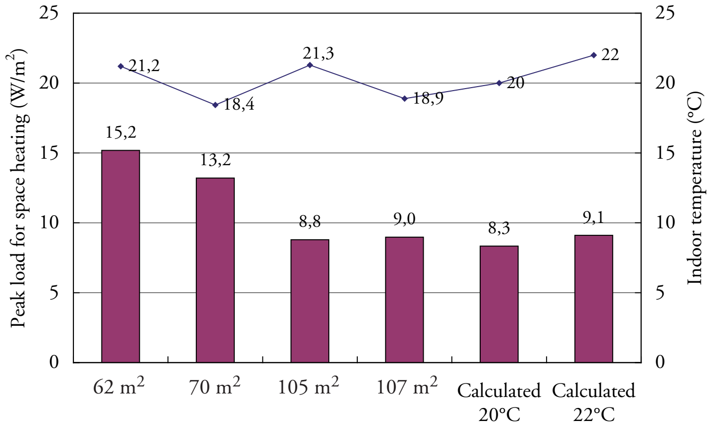


Figure 3.31 *Peak load for space heating (bars) and indoor temperatures (curve) in four apartments during the period 070201 – 080201 together with calculated values at indoor temperatures of 20° C and 22° C.*

The mean value of the peak load for space heating measured in building 13, 10.9 W/m^2, was higher than the calculated values. Looking at an indoor temperature of 22°C, the difference between measured and calculated figures is 1.8 W/m^2. The higher measured peak load for space heating might be caused by e.g. specific thermal bridges not included in the DEROB-LTH simulation, higher assumed internal gains than in reality during this period and a difference in climatic data used in the simulations compared to the normal year according to SMHI.

The measured peak load for space heating does not appear at the time for the annual lowest measured indoor temperature. As can be seen earlier in Figure 3.27, the measured indoor temperatures are lower at other times of the year than what can be seen in Figure 3.31.

3.12.2 Energy demand for space heating

The building construction used in the simulation was in two storeys (building type A). To be able to compare the calculated values with measured values, the energy use in the two buildings with two storeys are used; numbers 5 and 9. However, in buildings 5 and 9 the actual energy use for space heating is not explicitly measured, it is calculated based on the energy use for space heating in building 13 as a percentage of the total energy use between the apartments with the same floor area.

The energy use for space heating in buildings 5, 9 and 13, using measured figures for the period 070201 – 080201, is presented in Table 3.8, together with the mean value of the measured energy demand for space heating for all five buildings and the calculated values at an indoor temperature of 20 °C and 22 °C. The normalized energy demand for space heating is also presented where both the outdoor temperature during the measuring period 070201 – 080201 and the climate data used in the simulations (Meteotest, 2004) are revised to a normal year (SMHI, 2009).

Table 3.8 Measured and estimated energy demand for space heating.

Building number	Energy demand for space heating (kWh/m^2a)	Energy demand during a normal year (kWh/m^2a)
5	12.1	13.6
9	10.6	12
13 (measured)	7.6	8.5
All buildings	8.1	9
Calculated 20°C	9.8	9.2
Calculated 22°C	12.8	12

As can be seen from the mean value for all five buildings, the measured energy use for space heating was lower than the calculated value, compared with a calculated indoor temperature of both 20°C and 22°C. In building number 5, the energy use for space heating was higher than calculated when revised to a normal year. The measure energy use in building 9 was lower than the calculated values at an indoor temperature of 22°C and the measured building 13 has a lower energy use for space heating than calculated at both indoor temperatures.

3.13 Discussions and conclusions

There are many good experiences to pass on from the building process in the Värnamo project.

Before the planning process started, the client learned what signifies a passive house and knew both what to order and what to expect from the finished project. The strict specifications passed on to the planning group and later the general contractor made it easy for them to know what to aim for with their work.

The weekly meetings on site held by the general contractor gave the working team a great sense of commitment and pride in their work. Surely this is reflected in the good final result.

The measurements were used by the client to charge the tenants the costs for their energy use, which made it necessary to sort up the measurements. A noteworthy feature of this project was that the measurements were received by people who were curious about the results and had the competence and interest to use the measurements to check up on any faults and defects with the project. When the measurements are used like this in practice by the client, measurements become a natural part of the building project and save money for the client when the results are used as part of the daily management of the buildings.

The siting of the ventilation unit in the walk-in closet was a good solution. The measured internal sound levels were very low and the quiet solution was confirmed by the tenants who all said to be most satisfied with the indoor sound levels.

The daily mean value of energy use for space heating in the apartments during the measuring period 070201 – 080201, together with the correlating outdoor temperature, is presented in Figure 3.32. The four apartments where energy use for space heating was measured are included in the graph. When the outdoor temperature drops below zero, there is a lot of difference in energy use for space heating between the apartments. This shows that there is no obvious correlation between a lower outdoor temperature and a higher energy use for space heating in the apartments. The low correlation indicates that the energy performance of the building is very good and the energy use for space heating is more up to each tenant than due to a low outdoor temperature.

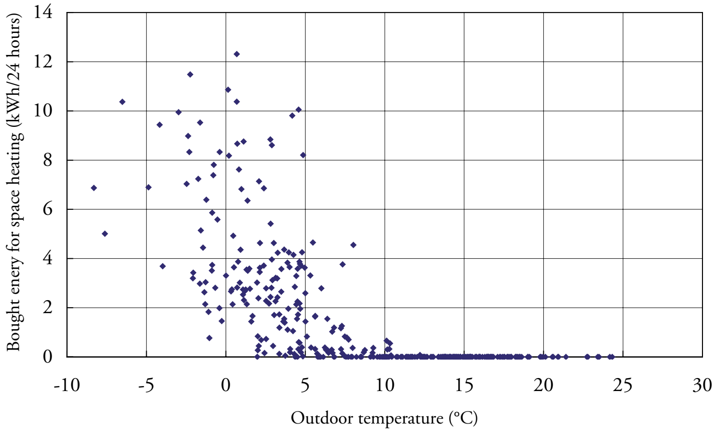


Figure 3.32 *Mean value of bought energy for space heating at different outdoor temperatures.*

The measured energy use for space heating was very low in this project and the indoor temperature as measured was at comfortable levels all year. As planned, the solar shadings protected the apartments from excessive indoor temperatures in summer. Some tenants nevertheless complained that indoor temperatures were occasionally too low. Looking at the energy used for space heating in the apartments during the coldest outdoor period, it can be seen that the use of energy for space heating does not differ much between the apartments, even though the size of the apartment varies. In two of the measured apartments the indoor temperature did not reach the required 20°C during the period 070201 - 080201. Since the measurements showed that the maximum heating power in the batteries was used in both these apartments at the measured peak load for space heating, but the indoor temperature was below 20°C, it can be seen that a heating battery with a higher power should have been installed. In the two larger apartments that were measured, the available power of 1800 W in the heating battery was only partly used.

4 Apartment buildings in Frillesås

In Frillesås, south of Gothenburg on the Swedish west coast (57°19’0”N), the local public housing company has built 12 apartments as passive houses. The apartments were finished in December 2006, when the tenants moved in. The client, Eksta Bostads AB, has been using solar panels for domestic hot water in their building stock since the early 1970s. A future goal for the client is to reduce the use of electricity by 2% per year and owned square metre of living area. In line with this goal, the energy for space heating in these buildings is supplied by district heating and the energy for domestic hot water is supplied by solar panels and district heating when needed.

4.1 Building construction

The 12 apartments are situated in three buildings with four apartments in each building, see Figure 4.1. Two of the buildings, numbers 23 (building A) and 27 (building C), were built identical with two two-room apartments of 68.2 m^2 and two four-room apartments of 97.9 m^2. The building in the middle, number 25 or building B, was built somewhat different with four three-room apartments of 82.7 m^2. The ceiling height is 2.6 m in all apartments.

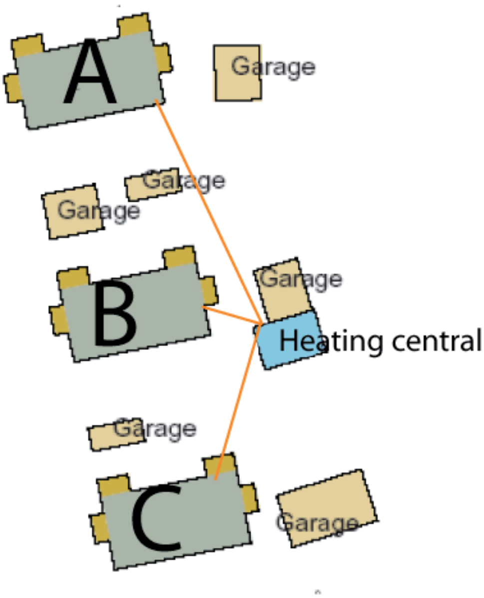


Figure 4.1 Situation plan of the apartments, Karl Johans väg in Frillesås.

Each apartment has either a balcony on the upper storey or a patio on the ground floor as seen in Figure 4.2.

Figure 4.2 Picture of the apartments in Frillesås.

The bathroom floor cover is quarry tiles and the rest of the apartment floors have a wooden surface material. The indoor walls are wallpapered and the bathroom walls are tiled. The U-values of the constructions and components are set out in Table 4.1.

Table 4.1 U-values of the building envelope.

Building envelope	U-value [W/m^{2}K]
Ground floor (excl. foundation)	0.11
Exterior walls	0.11
Roof	0.08
Windows, average	0.85
Entrance door	1.0

4.1.1 HVAC system

Each apartment has a small ventilation unit installed, placed in the kitchen, with an air to air heat exchanger of high efficiency. All units have two fans with five different settings, each with a rated output of 58 W, both running 24 hours per day. The apartments are heated by the supply air. During cold periods, when the exchanged heat is not enough for keeping an indoor temperature of 20°C, space heating is supplied in the supply air duct by a heating coil, with a maximum power of 1.0 kW (10.3 – 14.7 W/m^2).

The heating coil in the supply air is run by domestic hot water. This circulating hot water also runs through a small heating coil cast in the bathroom floors to give additional comfort. The water runs in the coil all year round and cannot be turned off by the tenants because of the risk of Legionella bacteria. It is therefore very important to keep the circulating water above 50°C. The temperature is controlled by a sensor connected to the circulating pump. The use of this type of domestic hot water system is no longer allowed according to Swedish building regulations.

To avoid internal noise from the air supply unit, adequate silencers were mounted in the ventilation system; two on the supply air system and one in the exhaust air system, mounted close to the ventilation unit, see Figure 4.3.

Figure 4.3 Silencers mounted in the ceiling in the apartments in Frillesås.

The supply air diffusers were placed in the ceiling in the bedroom and in the living room. The exhaust air terminals were placed in the bathroom, kitchen and in the walk-in closet. The filters in the ventilation unit are changed twice a year by the caretakers employed by the client.

Outdoor air is supplied from grilles mounted in the gable façade. Extract air is exhausted on the roof. A by-pass function is automatically regulated by sensors mounted in the exhaust air pipes to let in outdoor air without preheating in summer. The by-pass function is blocked out at low outdoor temperatures by sensors placed in the outdoor air duct as in the Värnamo project.

4.1.2 Domestic hot water

The domestic hot water is prepared by solar collectors mounted on the roof of a separate apparatus building; the "Heating centre" in Figure 4.1. All pumps and water heaters as well as the electricity distribution board for all buildings are placed in the apparatus building. Approximately 52 m^2 of solar panels were mounted on the roof, see Figure 4.4.

Figure 4.4 Solar collectors on the roof of the apparatus building.

The water and energy saving mixer taps used in the apartments are designed to be pressed all the way out to the left before they supply only hot water and only when the tap is pressed further upwards does it give maximum water flow.

4.1.3 Household appliances

The combined refrigerator/freezer in the two room apartment uses 376 kWh/a according to the producer. The washing machine uses 1.02 kWh of electricity for each wash. The condensation dryer is equipped with a heat pump and uses only 2.1 kWh per program. The household appliances used are listed in Table 4.2.

Table 4.2 Components used in the buildings.

Product:	Producer:	Name of product:
Windows	NorDan A/S	ND Sikkerhetsvindu /ND Fagvindu/ ND Fast karm / ND Sikkerhetsdør
Entrance door	Dooria	YD 1217 Varberg
Washing machine	Miele	W1713
Tumble drier	Husqvarna	QW490A
Mixer tap	Gustavsberg	Nordic TT
Freezer/Fridge	Miele	KFN 8462 SD
Cooker	Electrolux	Insight
Kitchen fan	FRANKE	

4.2 Simulations

One of the three buildings in the Frillesås project was simulated in the simulation program DEROB- LTH v1.0 (Kvist, 2006). The building simulated was of the building type A or C, with two and four room apartments; see Figure 4.5.

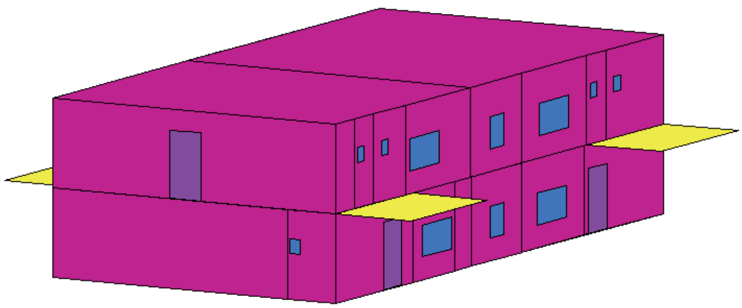


Figure 4.5 3-D Model of the simulated building in Frillesås using DEROB – LTH v 1.0.

In the simulation, the following input data were used:

Heated area:	330 m^2
U-values:	Floor facing ground: 0.11 W/ m^2K
Outer wall:	0.11 W/ m^2K
Walls separating apartments:	0.08 and 0.18 W/ m^2K
Inner wall:	0.2 W/ m^2K
Floor:	2.89 W/ m^2K
Roof:	0.08 W/ m^2K
Outer door:	1.0 W/ m^2K
Windows:	0.7 W/m^2K
Ventilation:	
Air leakage:	0.05 ach
Mechanical ventilation:	0.5 ach
Efficiency of heat exchanger:	80%
Ventilated volume:	85%
Orientation:	The long side wall of the building with the balconies and the patios on the ground is almost facing south; it is rotated 11 ° anti-clockwise from south
Soil resistance:	2.37 m^2K/W
Ground reflection:	20%
Internal gains:	4 W/m^2
Indoor temperatures:	The indoor temperature was set to 20°C and 22°C respectively

For the studies of space heating demand and peak load for space heating, the maximum accepted indoor temperature was set to 25°C. Above this temperature, the occupants were assumed to reduce the temperature by using shading devices and/or opening windows.

Climate data: The simulations were made with climate data for Göteborg with a maximum outdoor temperature of 29.8°C, a minimum outdoor temperature of -16.7°C and a mean value of the outdoor temperature of 7.2°C (Meteotest, 2004).

4.2.1 Calculated results

With an indoor temperature set in the simulations to 20°C, the peak load for space heating was calculated to 10.8 W/m^2 and the energy demand for space heating to 14.8 kWh/m^2a. When the building was simulated with an indoor temperature of 22°C, the peak load for space heating was calculated to 11.8 W/m^2 and the energy demand for space heating to 18.9 kWh/m^{2}a. Additional energy demand caused by specific thermal bridges must be added to the calculated result. The simulations were based on placing the heating coil after the heat exchanger. Since the heating coil was in actual fact placed before the heat exchanger, the bought energy for space heating and the measured peak load will be higher than the simulated values.

4.3 Tendering

The client wanted to work with a contractor that he had good relations with, had worked with before and had great confidence in. The client engaged a local firm that fulfilled all these three wishes as the general contractor in the project. This type of engagement was not unique because it was a passive house project; the client normally purchases their projects this way. The general contractor used competitive tendering to have tenders from 2 – 3 subcontractors for each trade. The subcontractors that received the invitation to tender had earlier worked with the general contractor with good results; only subcontractors that the general contractor wanted to work with got the chance to give a bid. The subcontractor with the lowest price got the contract. Since it was the first time the general contractor built a passive house; external help from Lund University/LTH was needed to find suitable components for the buildings.

4.4 Planning deviations

The contractor had trouble finding entrance doors with the required U-value of 0.6 W/m^{2}K. The producer of the door used in the project at Oxtorget, Värnamo, wanted to evaluate that door before using it in additional projects. German doors with a low U-value were available but fabricated opening inward and have to be changed to suit the Swedish market. A regular door costs between SEK 4000 – 5000 and the only offer received for a passive house door was SEK 10 000 /door. Finally, a normal type of door was used and a glazed vestibule was built outside the entrance, to ensure a low thermal loss. The vestibule was designed as a buffer zone and for wind protection (Figure 4.6). The vestibule was not heated and was ventilated by two vents.

Figure 4.6 Glazed vestibules, Frillesås.

4.5 Training

In December 2005, the Swedish passive house architect Hans Eek gave a training lecture for all carpenters participating in the project, which also included a study visit to the terrace houses in Lindås; the first passive houses in Sweden. Not only the carpenters who would be on site participated, the carpenters making the prefabricated constructions, the foundation contractor and the electrician also took part in the training. The general contractor decided that if more training was needed regarding specific detailed solutions, instructions would be given on site right before the work was performed.

The airtightness and the careful construction work were the two main impressions gained by the participants from the visit to Lindås. The carpenters said that the training visit was very positive, that it was good to look at an already built passive house construction. The general contractor observed that no new materials were used; it was all traditional materials but built with a high accuracy and more insulation and plastic foil than usual. The contractor said that using traditional materials makes it easier to implement passive houses on the conservative building market.

4.6 The construction stage

4.6.1 Foundation construction

The work on the foundation started in November 2005. The foundation construction was founded on a layer of crushed aggregate. On top of the crushed aggregate layer there was 200 mm of expanded polystyrene insulation (EPS) covered with plastic foil and then another layer of 100 mm of EPS insulation. 100 mm of concrete cast on site covered the two layers of EPS insulation (Figure 4.7).

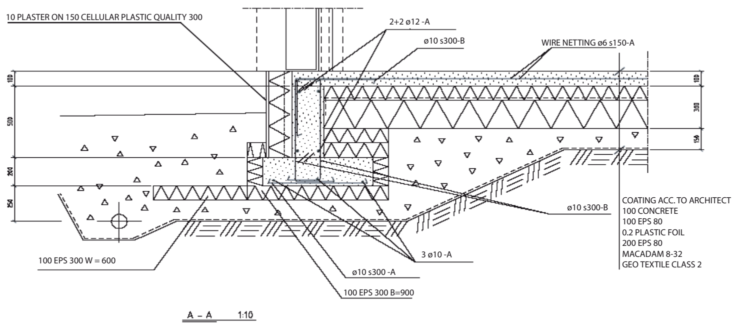


Figure 4.7 Foundation construction (Drawing: WSP Construction).

The work with the slab on the ground started in February 2006. There was no electrical coil that could heat up the concrete and thus speed up the drying process. The requirement for moisture content in the concrete slab before floor covering was a RH of 85% or lower. The drying process worked as normal and measurements before the surface material was applied showed a moisture content of 85% in the concrete at a depth of 4 – 5 cm.

The electrician in the project suggested that, in order to increase the airtightness of the electrical installation in future projects; the main electrical wire should be placed in the slab instead of in the outer walls as in this case. This could not only increase the airtightness but also decrease the time needed for additional sealing work.

4.6.2 Load bearing structure

All three buildings were of two storeys separated by a 300 mm prefabricated filigree floor. The filigree system consisted of 45 mm prefabricated reinforced concrete finished with a layer of concrete cast on site. The prefabricated beams had a w/c ratio of 0.35. The added concrete had a w/c ratio of 0.5. The floor used here; prestressed and 300 mm, was extra thick compared with a normal thickness of 230 mm. This extra thickness was partly due to the loadbearing construction but also to ensure that no sound would pass between the floors.

As for the concrete slab, the requirement for moisture content in the concrete construction before floor covering was a RH of 85% or lower. Measurements of the drying out process of the concrete in the load bearing structure were made to ensure a sufficiently low RH value before the flooring material was added. Unfortunately, the drying out process of the concrete cast on site in the structure took a long time, even though an electrical coil was cast in the upper part of the floor to speed up the drying process. The electrical heating coil was placed on top of the reinforcing mesh, in the top part of the concrete cast on site. The slow drying out process delayed the finishing of the building. If the coils had been placed closer to the precast units, maybe the drying process would have been quicker. The best solution of a quicker drying process would however have been to use concrete of higher quality, thus a lower w/c ratio.

The loadbearing structure in the internal walls was prefabricated and made of an insulated steel stud construction, covered on both sides with gypsum boards. On the walls around the bedrooms an additional gypsum board was mounted as a noise barrier. On the internal walls separating the apartments, three gypsum boards were mounted according to fire regulations since each apartment is a separate fire compartment. The apartment separating walls are insulated. This measure was taken for the tenants to be able to have different indoor temperatures and not affect or be affected by the neighbours. Another reason for the insulation was to prevent sound from travelling between the apartments.

4.6.3 Exterior walls

The exterior walls were prefabricated with an insulated wooden core construction, completed on site with expanded polystyrene insulation (EPS) that covered both the inside and the outside of the wooden construction. On the outside of the walls, the wooden facade material was mounted on wooden frames attached to the polystyrene (Figure 4.8).

Figure 4.8 Outer walls covered by expanded polystyrene insulation (EPS).

The prefabricated parts of the walls were mounted in three days. The risk of moisture content in the construction was minimized when the walls and roof were mounted in such a short time. The walls were 6 metres high and 2.5 metres wide, high enough to cover two storeys and thus avoid joining two parts together in the middle. The high walls secured the airtightness and therefore the quality of the project.

The moisture content in all wooden sills was measured before the polystyrene insulation was mounted. The general contractor usually measures the moisture content in the wood sills in all their projects, so this was nothing special for the passive house construction. To protect the wooden sill from moisture in the concrete slab, a sheet of soft plastic is put between the sill and the concrete on both sides of the wall, see Figure 4.9. The internal gypsum boards in the outer walls were protected from moisture in the concrete construction by ending the boards a bit above the concrete. In future projects, instead of using a wooden construction, a metal sill could be used to decrease the risk of moisture problems. According to the structural engineer, this might not cause any extra thermal bridges but the steel studs may be unstable when not loadbearing.

Figure 4.9 Moisture protection below the wooden sill construction.

The EPS insulation on the inside of the walls was cut on site, making the window bay bevelled. The carpenters found that if they used brick wedges when cutting the polystyrene, the bevelled construction was easy to make.

On the inside of the wall, plastic foil sealed the construction and was covered with wooden frames together with insulation. The plastic foil was large enough to reach from floor to ceiling. Since the plastic foil could be mounted without cutting, the sealing work ran very smoothly. It was however said by the carpenters that it was quite hard to make the buildings airtight around doors and windows. Both the carpenters and the local manager had opinions on the way the airtightness process was carried out. They all agreed that a work checklist would have eased the work on site, where all working operations could have been written down. This could ensure in future projects that no working operations are neglected and that the process is carried out the right way. The carpenters said that it was difficult to know how to reach the goal set up for the airtightness. How much work is enough to make sure that not too much or too little time and effort is used? A trial test of airtightness might have helped, but an effective production does not allow making a trial test for airtightness in one apartment. The contractors want to do the same sub-operations in all the apartments to make the production effective. To almost finish one apartment to be able to perform a test of the airtightness would have caused an interruption in the production.

4.6.4 Roof construction

After the prefabricated part of the outer walls was finished, the roof was mounted and covered with roofing felt. This wooden construction was closely sealed with plastic foil between the apartments and the attic, see Figure 4.10. Loose wool insulation was put on the plastic foil after the airtightness measurements.

Figure 4.10 The attic, before the insulation was put in place.

The attic is ventilated by two air vents. The roof had a micro porous membrane attached to the tongue where moisture easily gets through but not water, since the water molecules are too large.

4.6.5 Windows and doors

Experiences from earlier apartment buildings built by the client showed that the tenants preferred windows that open outwards (Drehkipp type). At the time of purchase, it was difficult for the contractor to find windows with both a low U-value and a Drehkipp construction on the Swedish market. Finally, Norwegian windows were bought. The windows consisted of three panes; two 4 mm panes with low emissivity coatings (4ES) and with 16 mm gaps filled with argon gas (16G) between the panes and in the middle a 4 mm pane; 4ES + 16G + 4 + 16G + ES4. Both the regular windows and the bathroom windows had a total U – value of 0.7 W/m^{2}K according to the producer. The bathroom windows had a sandblasted middle pane, so-called Matelux. It allows low emissivity coatings on the outer and inner pane but cannot be seen through. Normally, textured glass panes are used to prevent a view into the bathroom, but textured glass can not have low emissivity coatings. Using the sand blasted pane kept the low U-value on the bathroom windows.

To mount the windows, first the glazing unit had to be taken out of the frame and then the frame was mounted in the wall. Then the glazing unit was placed into the frame again to make sure the window was right in place. To be able to adjust the window, the glazing unit had to be taken out of the frame again. It turned out to be impossible to adjust the window when the glazing was still in the frame. A handle on the side of the pane stopped the window from opening 90 degrees, necessary for adjustment. The carpenters suggested that the handle should be detachable from the frame when adjusting the window. It was the first time the carpenters worked with windows like these that came assembled, not in separate parts.

The balcony door also had three panes; two 4 mm panes with low emissivity coatings (4ES) and argon in the 12 mm gaps between the panes (12G) and in the middle a 4 mm pane ; 4ES + 12G + 4 + 12G + ES4, giving a total U-value of 1.1 W/m^{2}K for the door according to the producer.

The entrance door had a round window, 35 cm in diameter. The total U-value of the door, according to the producer, was 1.0 W/m^{2}K.

4.6.6 HVAC system

The apartments are heated by air. Each apartment has its own small ventilation unit mounted in the kitchen; the placement was inspired by the Lindås project. The ventilation flow at its highest settings was 50 l/s per apartment. A gulley was put under the washing machine, where the foul water from the unit was discharged. A better placement for the units would have been in the bathrooms. Since the ventilation unit in the kitchen was not built-in, the noise from the fans could easily spread in the open planning of the apartments.

To avoid any freezing problems in the heating coil in the supply air, the exhaust air is pre-heated before it enters the heat exchanger (Figure 4.11). If the heating coil had been placed to heat the supply air directly before it enters the apartment and the fans in the heat exchanger for some reason had stopped, the outdoor air might have gone unheated through the heat exchanger and there was a risk of freezing the heating coil, if the outdoor temperature was below 0°C. With placing the heating coil in the exhaust air outlet, the air is always heated when reaching the heating coil.

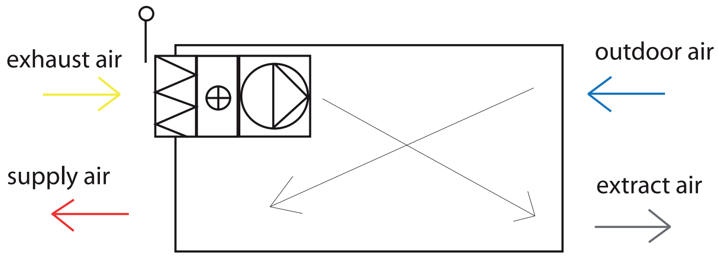


Figure 4.11 Heating coil placement in the heat exchanger.

However, by placing the heating coil in the exhaust air, the power added to the supply air will decrease the efficiency of the heat exchanger. This will cause a higher energy use for space heating, but it was seen to be necessary to avoid any freezing problems in the heating coil.

The temperature drop over the heating coil was by the HVAC-consultant designed to be 5°C (from 65°C to 60°C) with a water flow of 0.09 l/s. The peak load of the heating coil was calculated to 1.89 kW, according to Equation 4.1.

$$Q = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \qquad \text{Equation 4.1}$$

Where

Q = Power in the heating coil (kW)
$\dot{V}$ = Volume flow (m^3/s)
ρ = density of water (kg/m^3)
c_p = heat capacity of water (kJ/(kgC)
ΔT = temperature difference

The efficiency of the heat exchanger was measured in 2010 in a test performed by the Test lab at the Swedish Energy Agency to be approximately 80% (Statens energimyndighet, 2010). With the heating coil placed in the exhaust air and a heat exchanger efficiency of 80%, the maximum power supply to the apartments is calculated to 1.5 kW. The rest of the space heating power in the heating coil will be lost to the extract air.

In the planning process a framework document was made for the ventilation system by the HVAC-consultant. When the project started, the subcontractor for the HVAC system had not yet been engaged, which made it impossible to include them in the initial training about the principles of building a passive house. This might be one of the reasons that the information that the houses were planned to be heated by the ventilation air was not grasped by the subcontractor. The detailed drawings of the ventilation system were made by the sub-contractor but not suitable when using an airborne heating system. No insulation was planned for around the pipes. The subcontractor thought the project meetings took too much time and that he did not get paid for participating in meetings in this project. Since the subcontractor did not participate in the meetings, it took a long time before it was discovered that the drawings were not suitable for the project. The drawings were given to me for evaluation and I found that we needed to improve the ventilation solutions to make these houses work like passive houses.

To ensure a well functioning building, the HVAC consultant made complete documents for the ventilation system. The pipes were now larger and insulation was added around the pipes. These adjustments were made late in the project and there was no space in the suspended ceiling for the larger construction. The subcontractor together with the HVAC consultant then decided to put the pipes in the attic. The perforated plastic foil was closely sealed at all places where the pipes went up into the attic. In this improved solution, additional silencers were added to make sure no internal noise was generated from the fans in the heat exchanger.

4.6.7 Solar panels and domestic hot water

The domestic hot water is supplied by solar panels and district heating on less sunny days. The company that normally produced the solar collectors used by the client had changed to only selling the parts for the units. Therefore, the carpenters mounted the units together on the roof, using drawings to make the solar panels work as approved by SP Technical Research Institute of Sweden.

The size of the solar panels, 52 m^2, was mainly chosen to cover the roof of the apparatus building than to be optimized for the assumed domestic hot water demand. There is a risk of overheating or excessive losses in the solar system if the solar panels are too large (Andrén, 2001).The domestic hot water is heated to 60°C. When the temperature in the solar collector system exceeds 30°C the solar system starts to heat domestic hot water to the system. The liquid in the solar collectors goes in to a heat exchanger, heating water for the domestic system. The pump for this water starts when the temperature difference between the liquid at the top of the water tank and on the solar side of the heat exchanger is at least 5°C. Additional cold water is mixed with the solar heated water to reach the temperature level of 60°C. If the temperature of the solar heated water is not high enough, the water is heated further by district heating.

The placement of water pipes in the rooms coming up from the slab on the ground was not good. The pipes were not easy to separate in the mounting process and were not insulated. The hot water flowing through the uninsulated pipes might give additional space heating to the bathrooms.

4.7 Economy

In the very beginning of the project, the client estimated a cost of SEK 12 000 /m^2 for the apartments at Karl Johans väg. The piece of land cost MSEK 1.3; approximately SEK 110 000 per apartment. After the finalization of the project it turned out that the total production cost of the apartments and the garages was approximately SEK 14,500 /m^2 including the piece of land, connections for water and sewerage system, connection to district heating and VAT. This was a more exclusive project than regular apartments built by Eksta, regarding surface materials. A regular building project of about 50 ordinary apartments would have had a production cost of about SEK 13 000 – 14 500 /m^2 according to the client.

The additional costs for building passive houses was estimated by the client to total SEK 150 000 – 200 000 for the project, or SEK 200 /m^2. The additional cost was mostly for using more hours in the construction work. The general contractor said that an ordinary apartment takes approximately 800 h to finish. In this project each apartment took 1000 h. The additional time needed was mostly for making the project as airtight as required. The general contractor had estimated an additional cost of 15 – 20% since this was something they had never built before. Thanks to this, the general contractor kept to his budget. The costs for consultants were 8.5% of the total cost, and the contractor 86% of the total cost. The consultant costs were high in relation to other projects. The client thought this cost could be cut by half in the next passive house project.

The monthly rent for these passive house apartments varied in 2006 between SEK 5500 and SEK 7900 (SEK 960 /m^{2}a – SEK 977 /m^{2}a). In addition, the tenants pay for their own use of electricity and domestic hot water. Space heating “according to passive house standard” is included in the rental cost. The meters for domestic hot water and space heating were placed in the bathrooms.

4.8 Measurements

The measurements of bought energy for space heating, domestic hot water and household electricity started on February 1, 2007 in all apartments. The tenants had then been living in their apartments since December 1, 2006. The measurements were commissioned by the client and executed by SP Technical Research Institute of Sweden. No separate measurement of the fan electricity was made; in this project it was included in the measurement of household electricity. The indoor temperature was measured in all apartments. The solar fraction of the solar panels was also measured. Solar radiation and outdoor temperature were measured at one metering point.

In one apartment detailed hourly measurements of the indoor climate were made, starting on February 1, 2007 and proceeding for 6 months. No tenant was living in this test apartment during the time for these measurements, which included measurements of supply and exhaust air temperature, the operative indoor temperature in all rooms in the apartment, the efficiency of the heat exchanger together with the relative humidity (RH) in the exhaust air in kitchen and bathrooms. Also outdoors, measurements of diffuse and direct solar radiation were measured, together with outdoor temperature and wind velocity.

The supply air temperature was measured by sensors mounted inside the supply air terminals and the temperature of the exhaust air was measured by sensors hanging outside the exhaust air terminals.

Before the tenants moved in, the airtightness of the building envelope was measured in all apartments. The measurements were performed when all holes had been made for building installations.

4.9 Results from the measurements

4.9.1 Airtightness

The required airtightness of the climate shell was set by the client to 0.25 l/s,m^2, with a leaking area including all surfaces of the building facing outdoors (equal to a leakage flow of 77.8 l/s in buildings A and C (311 m^2) and 68.8 l/s in building B (275 m^2)).

To measure the airtightness of the building envelope, the apartments were put under the pressure of ± 50 Pa. The area used in all measurements included the walls between the apartments and the outer walls/ceiling/foundation facing outdoors.

Building A was measured first and proved to be very airtight. The mean value of the measurements showed an air leakage of 0.18 l/s, m^2. The measurements continued with Building B, but the results showed that it was not that airtight. The measured mean value of the airtightness in building B was 0.33 l/s, m^2 and the building needed to be sealed before the measurements could continue. The leaks were closely sealed by the carpenters, not only in building B; building C was also sealed in the same way as building B to avoid air leakage in the measurements.

Air was found to leak through the joints between the concrete beams, where air was leaking from the apartment below. Also around the windows, air was leaking. All the joints connecting the concrete beams were sealed with silicone. The carpenters said that the process of making the building more airtight took approximately three days. The electrical sockets that were mounted in the wall between the apartments caused a considerable air leakage. This could not be sealed by the carpenters; using airtight electrical sockets in the walls between the apartments might have been a good solution to avoid this air leakage.

When the airtightness in building B was measured again after the sealing of the building envelope, it was discovered that when overpressure was applied in the building, the plastic foil on the attic in building B rose like a big balloon. Air went from one apartment to another without any obstruction. The plastic foil mounted in the internal wall between the apartments was not sealed with the reinforced plastic foil in the attic (Figure 4.12).

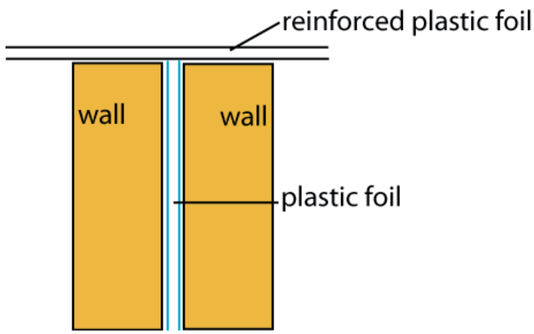


Figure 4.12 Plastic foil in internal walls meeting reinforced plastic foil in the attic.

This air leakage only appeared in building B since the construction of building B did not allow the wall between the apartments to go through the attic up to the roof, see Figure 4.13. Then it would have needed to pass a roof truss, which was impossible. In buildings A and C, the wall between the apartments was straight, all the way up in the attic, and the plastic foil was easy to seal. The plastic foil in building B was closely sealed by the carpenters, after the leakage was discovered. This shows the importance of measuring the air leakage at both over and under pressure and in all buildings.

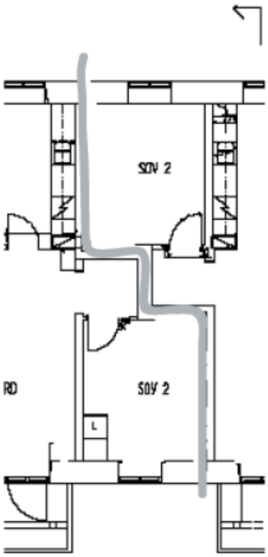


Fig 4.13 *Construction of the wall separating apartments, building B.*

Since building C was sealed in the joints just like building A and B after the first measurements of airtightness were made, the air leakage through the climate shell in building C was very low.

The total average air leakage in the three buildings was 0.19 l/s,m^2. In Table 4.3, the measured results are presented where the area used in all measurements includes the walls between the apartments and the outer walls/ceiling/ground facing outdoors.

Table 4.3 Airtightness at 50 Pa for all 12 apartments including surfaces to adjacent apartments.

Building	Apartment number	Air leakage ($l/s,m^2$)	Average air leakage($l/s,m^2$)
A	1	0.11	
A	2	0.15	
A	3	0.16	
A	4	0.24	
A			0.17
B	1	0.11	
B	2	0.15	
B	3	0.21	
B	4	0.29	
B			0.19
C	1	0.14	
C	2	0.21	
C	3	0.21	
C	4	0.33	
C			0.22

Two apartments in building B were measured with backpressure by creating the same pressure in adjacent apartments as in the studied apartment. This way of measurement with no differential pressure across the walls separating the apartments shows how much air leaks through the climate shell from the studied apartment to outdoors. The results of the backpressure measurements are presented in Table 4.4.

Table 4.4 Airtightness at 50 Pa for the building envelope alone, measured with no differential pressure across the inner surfaces of the two apartments in building B.

Building	Apartment number	Air leakage ($l/s,m^2$)
B	1	0.08
B	2	0.11

4.9.2 Moisture

The measurement of relative humidity in the load bearing filigree floor system started in May 2006. The measurement was performed by SP Technical Research Institute of Sweden. Early measurements showed high moisture content in the concrete and to avoid building in too much moisture, the drying process was closely followed. The electrical coil in the concrete was supposed to speed up the drying process. But it also made the indoor climate too warm to work in. To keep a good working environment, the coils needed to be turned off.

Twelve holes for measurements of temperature and relative humidity were drilled in the concrete to three different depths; 92 mm, 106 mm and 120 mm. 92 mm is 40% of the depth of the concrete cast on site (230 mm). 120 mm is 40% of the total depth of the beams (300 mm). 106 mm is between these two depths. The gauges were placed at two places on every depth; one in the middle of the beams (longest time for dry-out) and one at the end of the beams. The local manager checked the gauges once a week. The temperature varied significantly and it was impossible to compare the results to see a trend in the humidity change. The electric coil in the concrete also made the temperature in the concrete really high at some measurements. This method of measuring the relative humidity was not suitable for this project. New measurements were performed by SP Technical Research Institute of Sweden, this time according to the Swedish “RBK-method”.

There were five points of measurement, two on the ground floor of buildings B and C, and three on the floors one in each building. In building A, the flooring material on the ground floor was already laid at this time, so no measurements were made there. The measurements in the floor were made in between the heating coils in the concrete. The three depths for measurements were 75 mm, 150 mm and 225 mm. The results are shown in Table 4.5. The relative humidity in Table 4.5 refers to corrected RH at 20°C including uncertainties in measurements. To be able to put on the flooring material, the relative humidity in the concrete needed to be below 90%.

The results showed that in the concrete slab in both buildings B and C, the relative humidity was low (Table 4.5). The measurement in the floor showed a higher level of relative humidity.

Table 4.5 Measurement of moisture content in the concrete.

Building A:			
Measurement point:	A2 (75 mm)	A2 (150 mm)	A2 (225 mm)
Date:	2006-10-23	2006-10-23	2006-10-23
Temperature, concrete: (°C)	25.4	25.4	25.4
RH concrete: (%)	85.8	89.8	90.3

Lower floor buildings B and C:		
Measurement point:	B1	C1
Date:	2006-10-23	2006-10-23
Temperature, concrete: (°C)	24.5	27.0
RH concrete: (%)	81.3	76.2

Upper floor, Building B:			
Measurement point:	B2 (75 mm)	B2 (150 mm)	B2 (225 mm)
Date:	2006-10-23	2006-10-23	2006-10-23
Temperature, concrete: (°C)	25.9	25.9	25.9
RH concrete: (%)	90	92.5	91.9

Upper floor, Building C:			
Measurement point:	C2 (75 mm)	C2 (150 mm)	C2 (225 mm)
Date:	2006-10-23	2006-10-23	2006-10-23
Temperature, concrete: (°C)	26.2	26.2	26.2
RH concrete: (%)	85	90.2	88.4

The evaluation of the relative humidity in the floor was based on measurements at three different depths (moisture profile) by using the mean value of the highest and the lowest measured value in the measured points (Sveriges provnings & forskningsinstitut, 2006b). This gave the results of 88.1% RH in A2, 91.3%RH in B2 and 87.6% RH in C2. Long discussions were held about these results between the experts at SP, the constructor in the planning group, the client and us, before the building process continued. The question was how high a risk there was of possible future problems caused by the high moisture content if the flooring material were added and the apartments were finished. The building process was postponed for a few weeks but finally it was decided to continue. Before the flooring material was added, the carpenters cleaned the concrete constructions meticulously.

4.9.3 Energy demand for space heating

The energy use for space heating is measured in each apartment by the client. The total amount of bought energy for space heating is continuously measured for all buildings in the district heating centre in the apparatus building. During the period 070201 – 080201, the mean value of bought energy for space heating in the 12 apartments was 18.3 kWh/m^{2}a (Figure 4.14). The three buildings have almost the same design. Two buildings, building A and building C, are exactly the same with two four room apartments and two apartments with two rooms. Building B has four three room apartments. In most of the apartments there are two tenants. The energy use for space heating in the apartments nevertheless varies a lot, as seen in Figure 4.14.

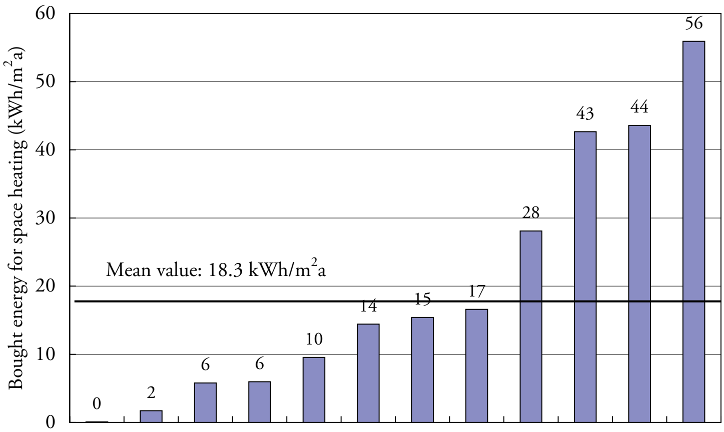


Figure 4.14 Bought energy for space heating during the period 070201 – 080201.

The total annual bought energy for space heating in the 12 apartments varied during the measuring period 070201 – 080201 as presented in Figure 4.15. There have been some initial troubles with some of the ventilation units in the apartments. According to Figure 5.15, the ventilation units in apartments 8 and 12 use energy for space heating even during the warmest months. The unit in apartment 12 was corrected after complaints by the tenant. The unit in apartment 8 was changed using the guarantee from the producer of the ventilation units. The ventilation units in apartments 10 and 11 had a broken by-pass valve. Since these faults were corrected during the measuring period, it needs to be considered that some figures of the energy use for space heating might be too high or too low compared to a year with well functioning ventilation units and heating coils. If the energy use for space heating in apartments 8, 10, 11 and 12 are ignored, the heating season starts in October and ends in May.

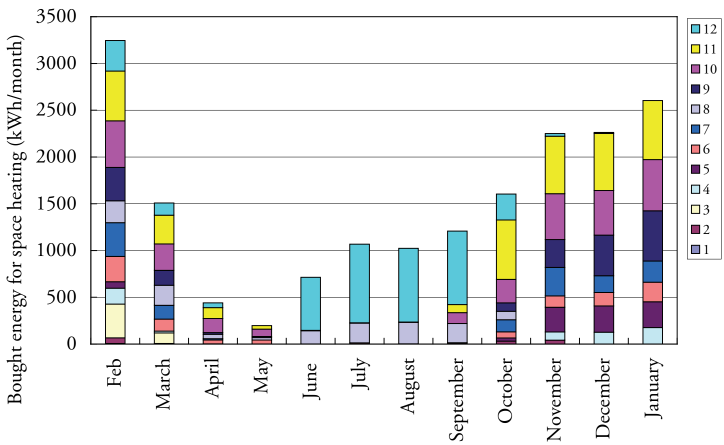


Figure 4.15 Bought energy for space heating during 070201 – 080201.

When talking to the management staff of the area, it was found that the heating level in the ventilation unit in the apartment with the highest energy use has been programmed to a supply air temperature of 33°C by mistake. After complaints from the tenant about excessive indoor temperatures, the supply air temperature was adjusted to 21°C in July 2008. Since there are only 12 apartments, the decrease in the energy used for space heating in one apartment strongly influences the mean value of the total energy use. When the energy needed for space heating during the period 071110 – 081110 is examined, the mean value of bought energy for space heating is seen to have decreased to 14.3 kWh/m^{2}a, see Figure 4.16.

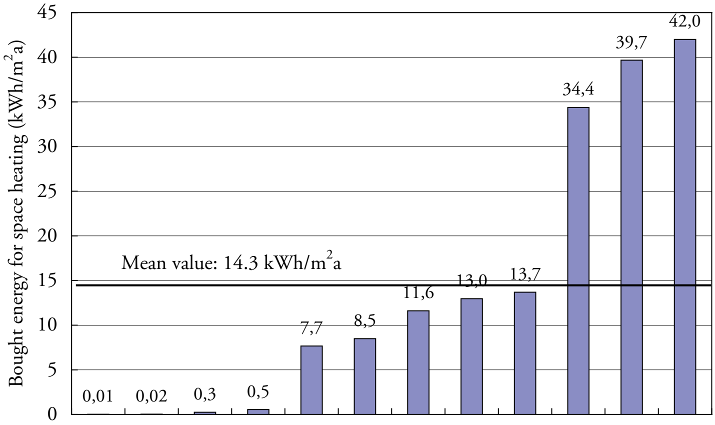


Figure 4.16 *Bought energy for space heating during the period 071110 - 081110.*

The difference in energy use for space heating between these two periods could also be due to differences in outdoor climate. The number of degree days in Frillesås, using climate data for Gothenburg (SMHI) was in 2007 2536 days and in 2008 2619 days. The degree days in Gothenburg for 2007 and 2008 compared to a normal year are presented in Figure 4.17. As can be seen, both 2007 and 2008 differ from a normal year but the somewhat higher number of degree days in 2008 compared to 2007 confirms that it is the tenants' behaviour and not a much warmer winter period in 2008 that is the major reason for the decrease in energy use for space heating.

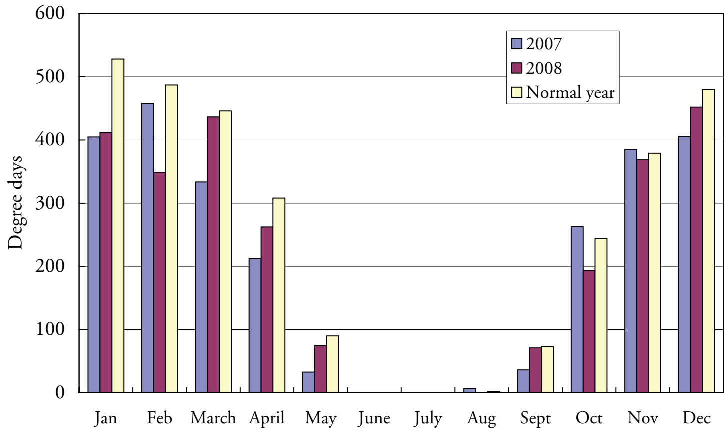


Figure 4.17 *Degree days in 2007, 2008 and a normal year (STIL).*

4.9.4 Space heating demand revised to a normal year

Using the degree days presented in Figure 4.17, the bought energy for space heating is adjusted to a normal year (SMHI, 2009) as described in Chapter 1. The annual bought energy for space heating, revised to a normal year, is presented in Figure 4.18.

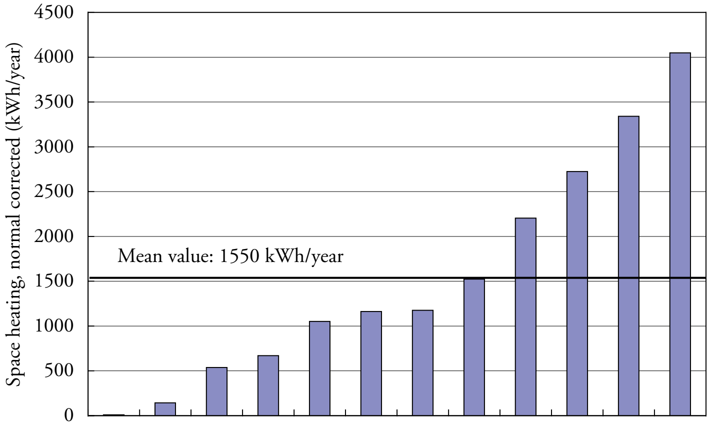


Figure 4.18 Bought energy for space heating 070201 – 080201, revised according to a normal year.

The mean value of the bought energy for space heating divided over the living area is raised from the measured 18 kWh/m^{2}a to 18.8 kWh/m^{2}a when the measuring period 070201 – 080201 is revised to a normal year (Figure 4.19).

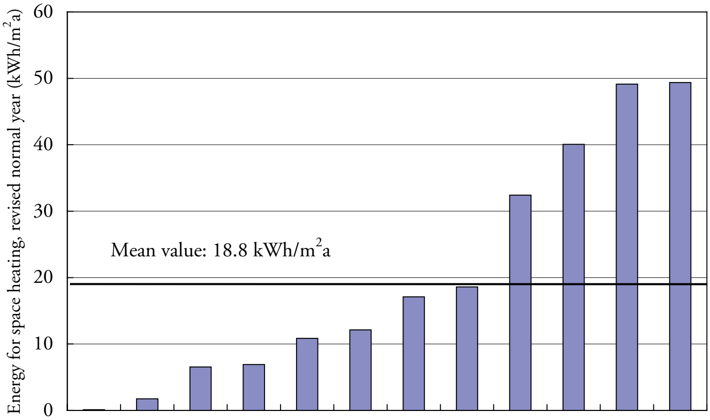


Figure 4.19 *Bought energy for space heating divided over the living area during the period 070201 – 080201, revised according to a normal year.*

4.9.5 Domestic hot water

The total amount of bought energy for domestic hot water, as for the space heating, is continuously measured for all buildings in the district heating centre in the apparatus building. The energy produced for domestic hot water by the solar panels is also measured in this centre. The volume of bought domestic hot water measured in the apartments contains domestic hot water from both solar panels and district heating. The volume of domestic hot water used, in m^3, is measured in each apartment.

There was no separate measurement of energy use for domestic hot water in the apartments. The energy use for domestic hot water is calculated using the measured volume of domestic hot water as a base as shown in Equation 4.2. The energy use for domestic hot water presented here includes the domestic hot water heated by both district heating and solar panels.

In Figure 4.20, the measured volume of domestic hot water use during 070201 – 080201 is presented.

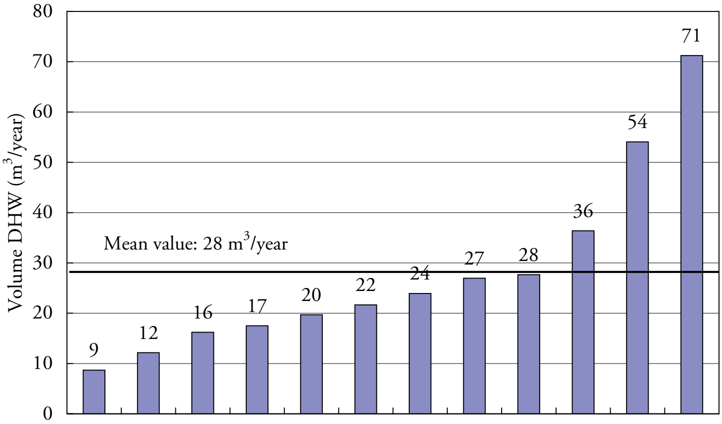


Figure 4.20 Measured volume of domestic hot water 070201 – 080201 (m³/year).

$$Q = V \cdot \rho \cdot c_p \cdot \Delta T \qquad \text{(Equation 4.2)}$$

Where

Q = Energy for heating domestic hot water (kWh)
ρ = density of water (kg/m^3)
c_p = Heat capacity of water (J/kgK)
V = Volume of domestic hot water (m^3)
ΔT = difference in temperature of ground water and supply temperature of domestic hot water

The energy use for domestic hot water is calculated using following data:
Volume V of domestic hot water as seen in Figure 4.20 (m^3)

ρ = 1000 kg/m^3
c_p = 4.18 kJ/kg°C
ΔT = $T_{DHW} - T_{Cold\ water}$ (°C)

The domestic hot water temperature varies between 60°C and 63°C. In this calculation it is set to be 60°C. The cold water temperature is not measured but is assumed by both the HVAC consultant and the caretaker at Eksta separately to be 8°C according to the caretaker at Eksta, Tobias Andersson, and the HVAC consultant Per-Erik Andersson-Jessen (conversation, 2010-03-23).

The calculated total energy use for domestic hot water in the 12 apartments including energy from solar panels and district heating during the period 070201-080201 is presented in Figure 4.21.

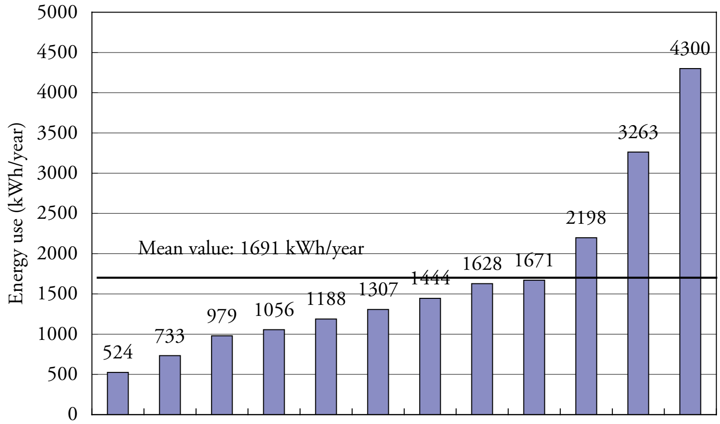


Figure 4.21 *Calculated energy use for domestic hot water supplied by solar panels and district heating during the period of 070201 – 080201.*

According to statistics (Statens Energimyndighet, 2009d), the energy use for domestic hot water in Sweden is approximately 1000 kWh/person, year. The first 9 measured apartments in Figure 4.21 have 1 or 2 tenants, which corresponds well to the statistics. Apartment 1 in Figure 4.21, with the lowest consumption, has tenants who travel a lot and spend much time abroad which explains the low annual use of domestic hot water. In the two apartments with the highest consumption, apartments 11 and 12 in Figure 4.21, the families consist of 5 or 6 persons.

The mean value of the energy use for domestic hot water per heated living area distributed by solar panels and district heating was 15 kWh/m^{2}a during the measuring period 070201 - 080201, as presented in Figure 4.22.

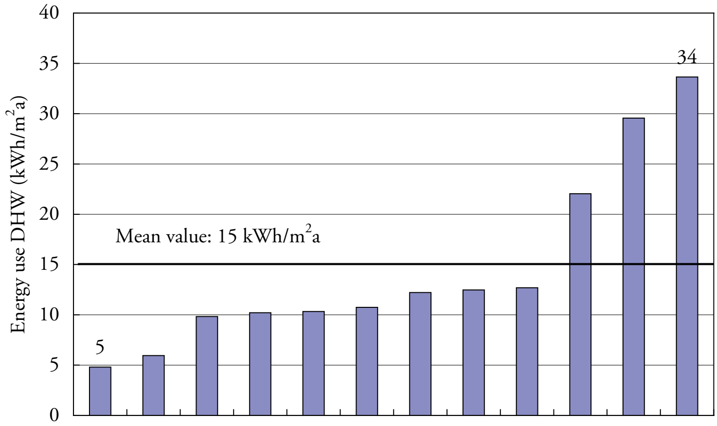


Figure 4.22 *Calculated energy use for domestic hot water per living area distributed by solar panels and district heating during the time period of 070201 – 080201.*

4.9.6 Domestic hot water – solar gains

Measurements of the total bought energy from district heating and the energy production from the solar panels were made by the client. The district heating is used for both domestic hot water and space heating. The energy from the solar panels only contributes to the domestic hot water heating.

The monthly total energy use for domestic hot water production and energy for space heating during the period 070201 - 080201 is presented in Figure 4.23, separated in the energy use of district heating and the contribution from the solar panels.

To know how much energy from district heating is used for domestic hot water production, the measured annual energy used for space heating is subtracted from the total measured annual amount of bought district heating and the result is the energy use for domestic hot water. To this value, the measured solar thermal contribution is added and the sum is the energy use for domestic hot water. The monthly energy use for domestic hot water, separated into district heating and energy from solar panels is presented in Figure 4.24. The solar fraction for the domestic hot water use is 50%.

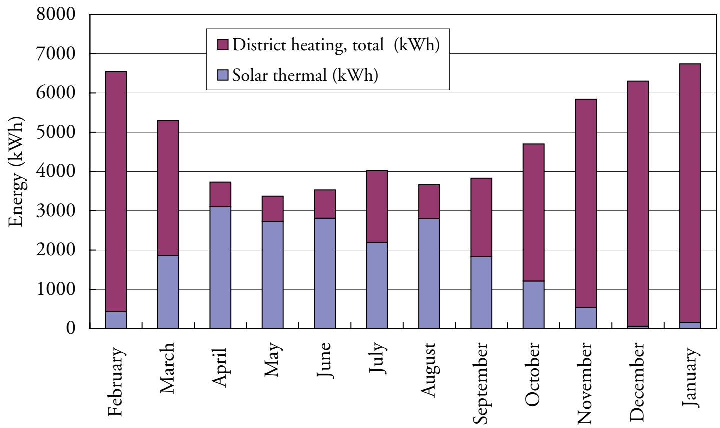


Figure 4.23 *Solar thermal and district heating contribution to the total energy use of DHW heating and space heating 070201 – 080201.*

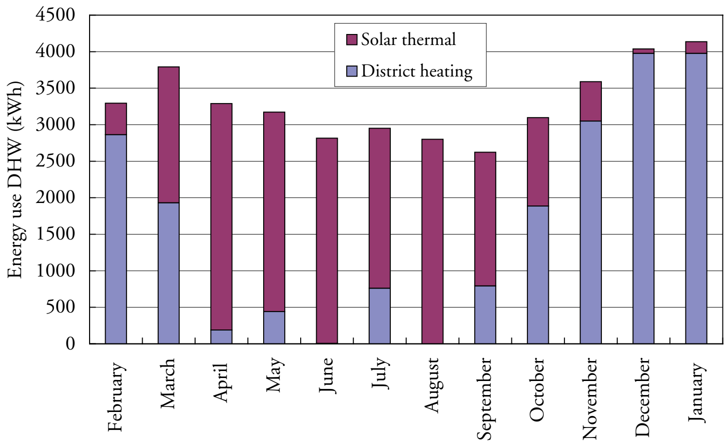


Figure 4.24 *Energy use for domestic hot water including bought energy for district heating and energy from the solar panels.*

4.9.7 Electricity for common areas

The meters for the common electricity were changed during the time for measurement (070201-080201). The measured figures for common electricity presented therefore refer to the period 090101-091231. The energy use for common electricity includes three pumps for the solar system, one pump for the domestic hot water circulation, electricity for outdoor lighting on façades and between the buildings and car engine preheaters. The total measured use of electricity for common areas was then 16.7 kWh/m^{2}a.

The somewhat high electricity use for common areas can be explained by a high power consumption of the domestic hot water circulation pump. The rated output of the circulating pump for domestic hot water circulation is 1.1 kW at a flow of 1.6 l/s. The flow in the circulating pump and therefore the electrical power consumption can vary. The circulating pump was dimensioned for a water flow of 1.2 l/s and the power needed for the pump was then 765 W. According to the caretaker, the pump needed to run at approximately 90% of its rated output to keep a water temperature above 50°C, further described in Subsection 4.10.3. The energy need for the circulating pump at different power consumptions is presented in Table 4.6.

Table 4.6 Electrical power consumption of domestic hot water pump.

Electrical power (W)	Time (h)	Energy use (kWh/year)	Area (m^2)	Energy use (kWh/m^{2}a)
1100	8760	9636	988	9.8
990	8760	8672	988	8.8
765	8760	6701	988	6.8

The electricity for common areas, excluding the energy used in the circulating pump, varies between 6.9 and 9.9 kWh/m^{2}a depending on the electrical power consumption.

4.9.8 Household electricity

The household electricity is measured in each apartment and the tenants pay for their own use of electricity. The annual use of household electricity during the period 070201 – 080201 is presented in Figure 4.25.

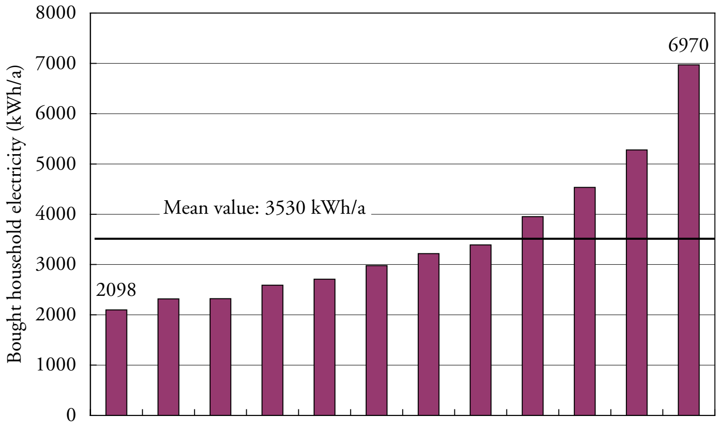


Figure 4.25 *Annual use of household electricity 070201 – 080201, per apartment.*

The annual use of household electricity, divided by heated living area, is presented in Figure 4.26, with a mean measured value of 42.9 kWh/m^2a.

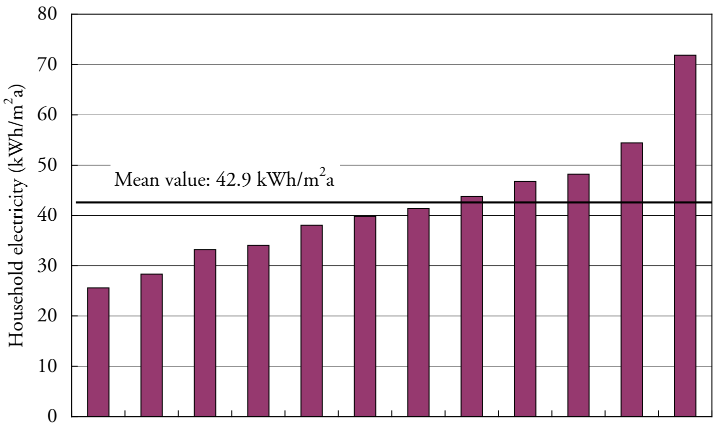


Figure 4.26 *Use of household electricity during the period of 070201 - 080201.*

The number of tenants varies between the apartments and heated area. Taking into account the number of persons in the apartments, the use of household electricity varies from 880 kWh/person,year to 2590 kWh/person, year, see Figure 4.27.

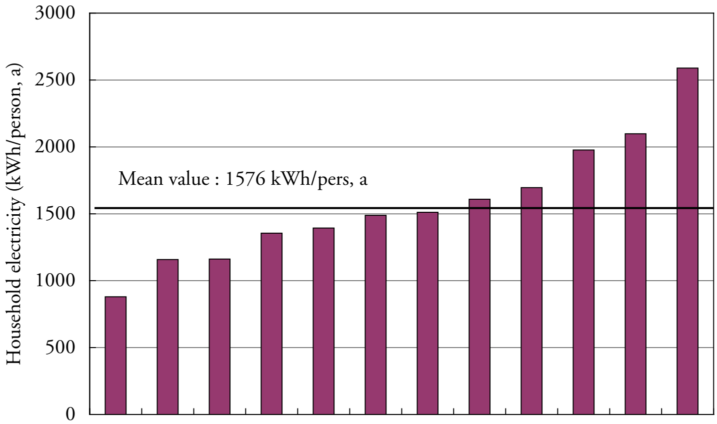


Figure 4.27 *Annual use of household electricity divided by number of persons and heated living area.*

4.9.9 Total energy use

The total measured amount of bought energy for all apartments is presented in Figure 4.28, including energy for space heating, domestic hot water, common electricity and household electricity. The annual total bought energy varies a lot between the apartments, from 66.5 kWh/m^{2}a to 127.7 kWh/m^{2}a, with a mean value of total bought energy of 92.9 kWh/m^{2}a.

The mean value of the energy use for space heating, domestic hot water and common electricity during the period 070201 – 080201 was 50 kWh/m^{2}a . This should be compared to the energy limit of 110 kWh/m^{2}a in the Swedish building code.

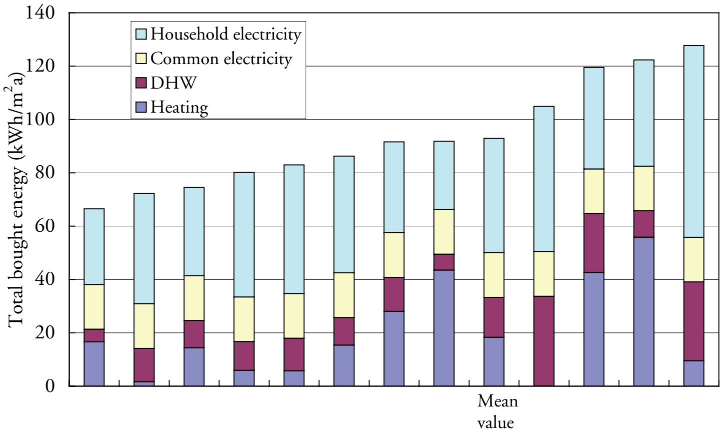


Figure 4.28 *Total bought energy for the 12 apartments during the period 070201 to 080201.*

The heated floor area in the apartments is 68 m^2, 82 m^2 and 97 m^2. Figure 4.29 shows the total amount of bought energy, where the apartments with the same heated area are put together. The mean value of the total energy use in the apartments with a heating area of 68m^2 was 104.9 kWh/m^{2}a, in those with a heated floor area of 82 m^2 the energy use was 78.4 kWh/m^{2}a and in the apartments with a heated floor area of 97 m^2 the average amount of total bought energy was 96.8 kWh/m^{2}a.

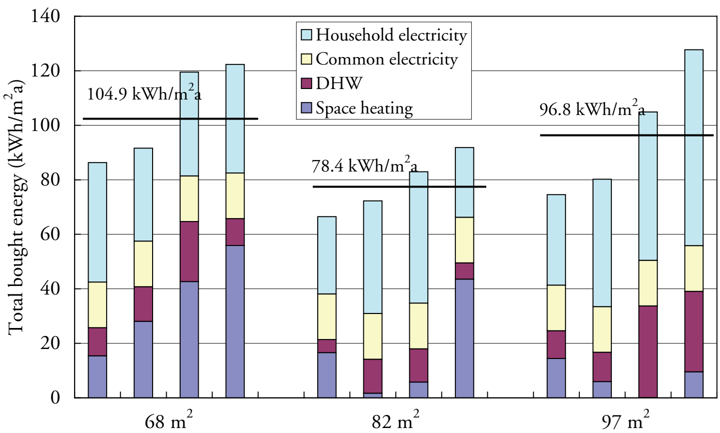


Figure 4.29 *Bought energy broken down by the three different heated floor areas.*

The energy use varies a lot between the apartments and between the buildings, but the energy items have the same proportions in the three buildings (Figure 4.30), with the major energy use for household electricity. Of the mean value of energy use in the three buildings, household electricity represents 46 % of the total energy use, common electricity use 18%, 16% of the total bought energy was used for domestic hot water and 20% for space heating.

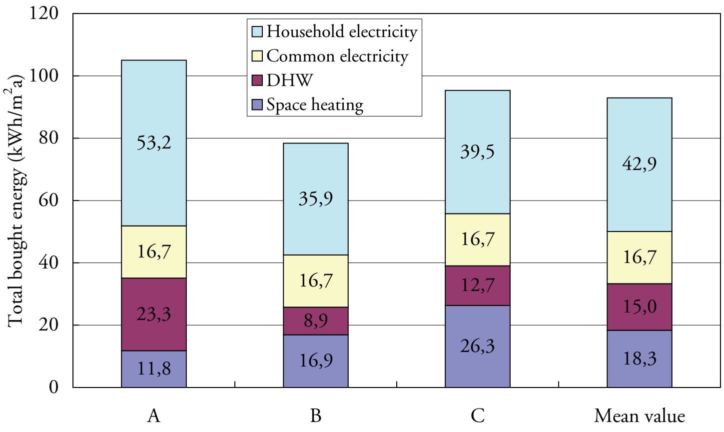


Figure 4.30 *Bought energy broken down by the three different buildings, presented together with the mean value of the buildings.*

The total energy demand is somewhat increased when the measured energy for space heating is revised to a normal year. The mean value of annual bought energy for space heating, domestic hot water and common electricity for a normal year was 50.5 kWh/m^{2}a. If household electricity is added, the mean value is 93.4 kWh/m^{2}a (Figure 4.31).

After the ventilation unit was adjusted in the apartment with the highest energy use for space heating, the total energy use was measured as described in Subsection 4.9.4, the mean value of total energy use during the period 071110 – 081110, including energy for space heating, domestic hot water and common electricity, was 51.5 kWh/m^{2}a. If household electricity was added, the bought energy was 94.8 kWh/m^{2}a (Figure 4.32). The energy use for domestic hot water during this time was measured to 20.5 kWh/m^{2}a; 5 kWh/m^{2}a higher than the year before. This explains why the total energy use was higher during this later measuring period even though the energy use for space heating had decreased.

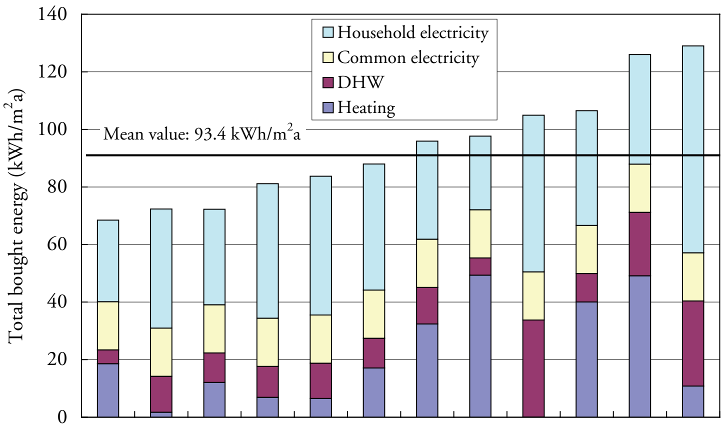


Figure 4.31 *Total annual bought energy demand, with space heating revised to a normal year.*

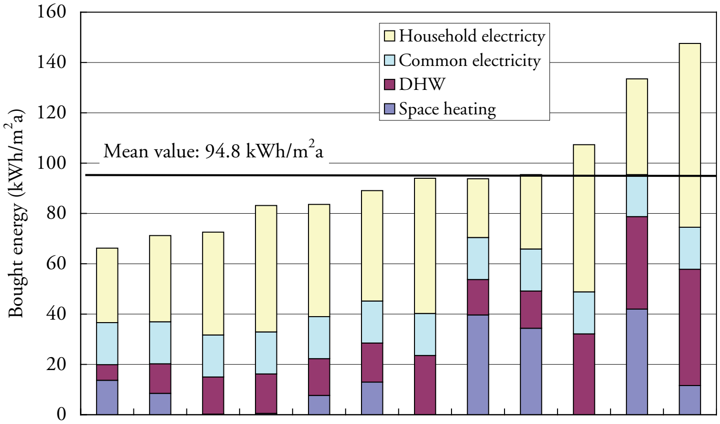


Figure 4.32 *Total bought energy during the period 071110 to 081110.*

4.9.10 Peak load for space heating.

The energy use for space heating is measured in the apartments each day. The peak load for space heating is calculated by dividing the measured energy use for one day by 24 hours.

The peak load for space heating during the period 070201 – 080201 in the 12 apartments is presented in Figure 4.33. The daily mean of the space heating peak load in all apartments was 11.3 W/m^2. Most tenants have their highest power use between February 21 – 27, two had it in mid October when they turn on their heating coil for the first time after summer, two had it in early January and one in the middle of March.

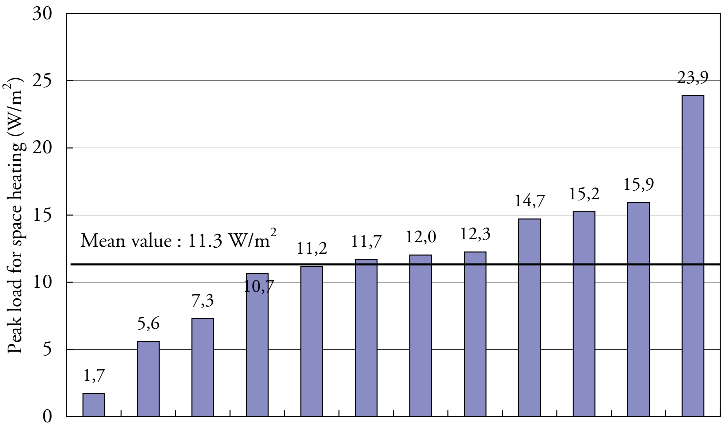


Figure 4.33 Peak load for space heating during 070201 to 080201.

As for the measured energy for space heating, there is a great variation in the peak load for space heating between the apartments. In Figure 4.34, the peak load for space heating is presented for apartments with the same living area. It can be seen that the average peak load for space heating is higher in the smaller apartments and decreases when the heated area increases, when the power consumption is divided by living area. This is also the measured result when looking at the highest power consumption for space heating in absolute figures for the apartments as presented in Figure 4.35.

A smaller apartment usually has a higher density of internal gains. An expected measured result of the maximum power use in the apartments should be an increase when the living area increases. The measured decrease in the power use in absolute figures in the larger apartments does not agree well with the hypothesis.

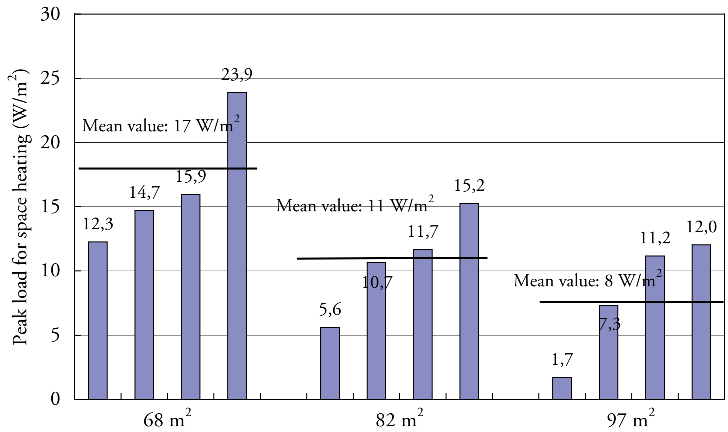


Figure 4.34 *Peak load for space heating per m² during the period 070201 to 08020, presented for apartments with the same living area.*

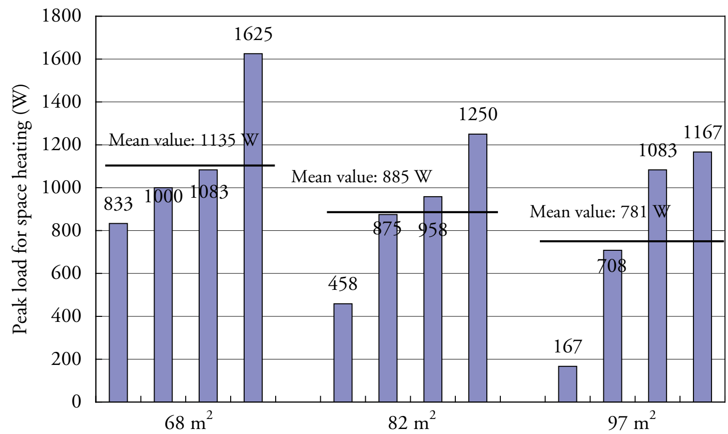


Figure 4.35 *Peak load for space heating during the period 070201 to 08020, presented for apartments with the same living area.*

The available power for space heating is dependent on the flow rate and temperature difference of the hot water in the heating coil. The hot water flow in the heating coil in the ventilation system was designed to be 0.09 l/s with an estimated temperature difference of 5°C between the supply and return water in the heating coil. The maximum heating power emitted to the exhaust air is then 1.89 kW and with a heat exchanger efficiency of 80%, 1.5 kW can be emitted to the supply air. The maximum power used in one apartment during the measuring period was 1.625 kW, as presented in Figure 4.35. The possibility of a higher power consumption than should be available for space heating in the apartment can be due to a temperature drop higher than the 5°C in the heating coil, a higher water flow through the system or a heat exchanger of different efficiency.

The circulating hot water system runs through the heating coil in the supply air system and continues on to the heating coil in the bathroom floor. The circulating hot water is also used for domestic hot water, which makes it most important to keep a temperature above 50°C on the circulating water to avoid Legionella bacteria. The return water temperature is measured in the circulating pump and continuously checked by the caretaker. There have been some difficulties in reaching 50°C on the return water and to solve this problem the flow in the circulating pump in the domestic hot water system has been raised.

As with the losses in the domestic hot water system, it is difficult to know what flow actually runs through the system, since it is not measured. Looking at the design data for the heating coil in the supply air system, the water flow should be 0.09 l/s in each coil, giving a peak power load of 1.5 kW available in the supply air system in each apartment. The actual peak load measured in one apartment was 1.625 kW, which might be caused by a rise of the water flow to 0.093 l/s if the water temperature difference over the heating coil is kept at 5°C and the efficiency of the heat exchanger is kept at a level of 80%.

Keeping the water flow in the circulating system at 0.09 l/s, the temperature difference over the circulating water in the heating coil needs to be 5.2°C to reach 1.625 kW or if the efficiency of the heat exchanger is 86%, it is possible to get 1.625 kW emitted from the heating coil.

According to measurements of the efficiency of the heat exchanger, it is probably not possible to reach an efficiency as high as 86%. Since the circulating pump has been moved into a higher gear to avoid Legionella bacteria it is most probable that the high common electricity use is due to a higher water flow in the heating coil.

4.9.11 Indoor and outdoor temperature

The indoor temperature was measured by the client in all 12 apartments for one year, together with outdoor temperature as presented in Figure 4.36. The measurements were commissioned by the client and made by SP Technical Research Institute of Sweden. The lowest outdoor temperature was measured to -9.9°C and the highest outdoor temperature to 31°C during the period 070201 and 080201. The lowest outdoor temperature was registered on February 10, 2007. The sensors measuring the indoor temperature were placed 1.1 m above the floor, protected from direct sunlight and from radiation from lamps. The highest measured indoor temperature was 28.4 °C and the lowest measured indoor temperature was 17°C during the same period. The annual mean value of the indoor temperatures varies between 26.8°C and 20.4°C.

The measured indoor and outdoor temperatures during the heating season (October – May) are presented in Figure 4.37.

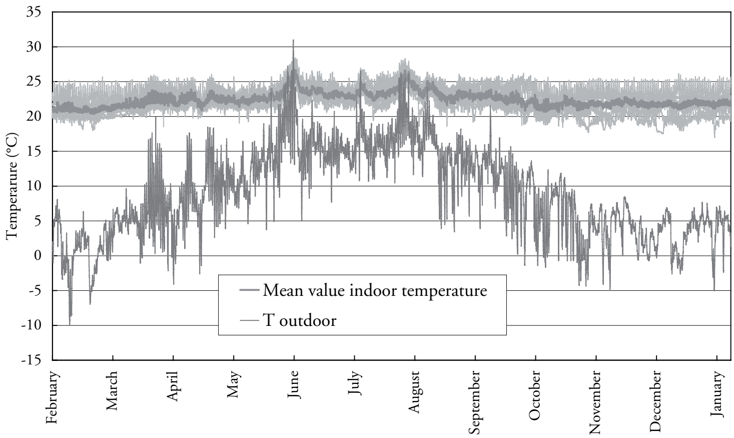


Figure 4.36 *Measured indoor and outdoor temperatures from 070201 to 080201.*

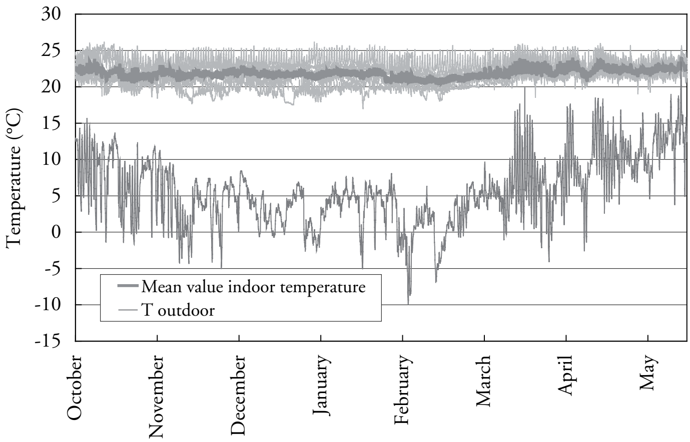


Figure 4.37 *Indoor and outdoor temperatures, October to May.*

The mean value of the indoor temperature was above 20°C during the entire heating season. There was one apartment that had a lower indoor temperature for a long period of time. These tenants did not mention the low indoor temperature in their interview, but said they had trouble with too high indoor temperatures.
During February, which was the coldest month during the period 070201 – 080201, the indoor temperatures and the outdoor temperature vary according to Figure 4.38.

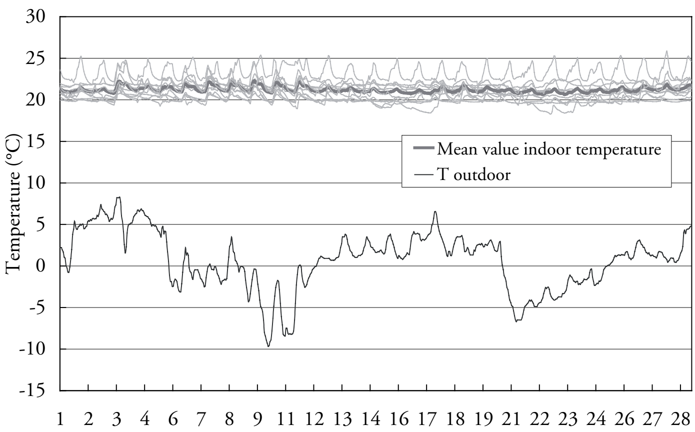


Figure 4.38 *Indoor temperatures in all apartments and outdoor temperature measured during February 2007.*

In most apartments, the indoor temperature was around 20°C all February and the mean value of the indoor temperature in all apartments varied between 20.4 and 22.1 °C. In apartment 1 in Figure 4.37, the indoor temperature was much lower, with a minimum temperature of 18°C measured on February 22. These low indoor temperatures were not mentioned by the tenant as a discomfort in the interview, neither were the tenants away during this period.

4.9.12 Operative temperature

The operative indoor temperature was measured in four rooms in the test apartment during the period 070201 - 070327. The operative temperature is calculated as the mean value of the indoor air temperature and the mean radiant temperature from surrounding surfaces (SOSFS 2005:15). To measure the operative temperature, a sensor was mounted in front of the windows, 1.0 metre into the room and 1.1 metre above the floor; one in each room. To simulate an internal gain, a cylinder with a hole was placed in each room with a bulb mounted in each cylinder, giving off 75 W in the living room and 60 W in the other rooms. According to the Swedish HVAC-handbook, these internal gains correlate to a woman or a child in each room (60W) and a man or two children in the living room (75W) (Bigélius & Svennberg, 1974). No shadings or curtains were used in the apartment, see Figure 4.39.

Figure 4.39 *Measurement of operative temperature in one bedroom in the test apartment.*

The measured operative temperature during the test period 070201 – 070327 is presented in Figure 4.40.

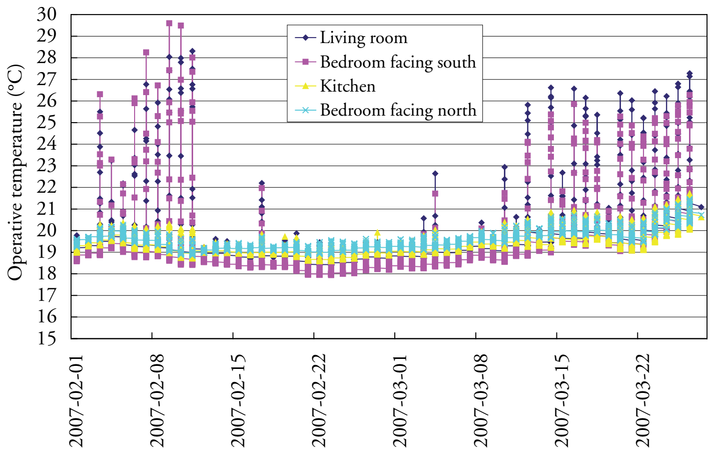


Figure 4.40 *Measured operative temperature in test apartment 070201 - 070327.*

The highest operative temperature was measured in the bedroom facing south, during the first week of February. The measured operative temperature in the apartment varied between 29.6°C and 17.9°C. The mean value of the measured operative temperature in all four rooms in the test apartment is presented in Figure 4.41.

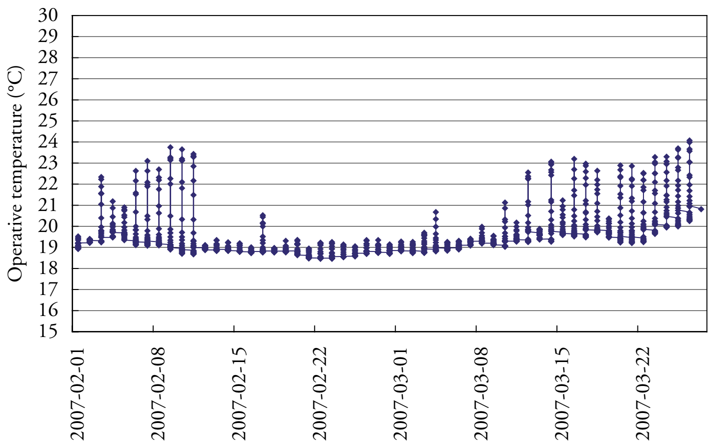


Figure 4.41 *Mean value of measured operative temperature in the test apartment, 070201 - 070327.*

The indoor air temperature was also measured in the test apartment as presented in Figure 4.42. The indoor temperature meter was placed on the wall in the small hallway between the bedroom and the living room so as not to be reached by radiation from the sun or a lamp.

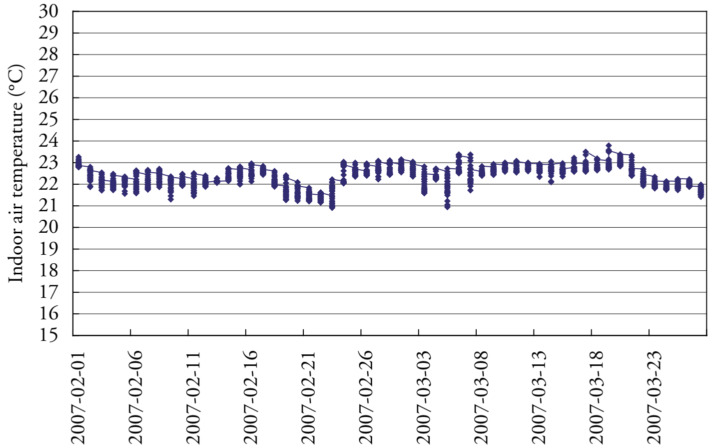


Figure 4.42 *Measured indoor air temperature in the test apartment 070201 - 070327.*

The measured mean operative indoor temperature is compared to the measured indoor air temperature in the test apartment (Figure 4.43), and it can be seen that there is a slight difference between the measured temperatures. This difference might need to be taken into consideration when the indoor climate is specified by the client. Often a value of the operative indoor temperature is required but the indoor temperature is measured. The difference in operative temperature and indoor air temperature might explain if the tenants talk about excessive indoor temperatures even though it is not visible in the measured indoor temperature results. The operative (experienced) temperature may be quite different from the air temperature.

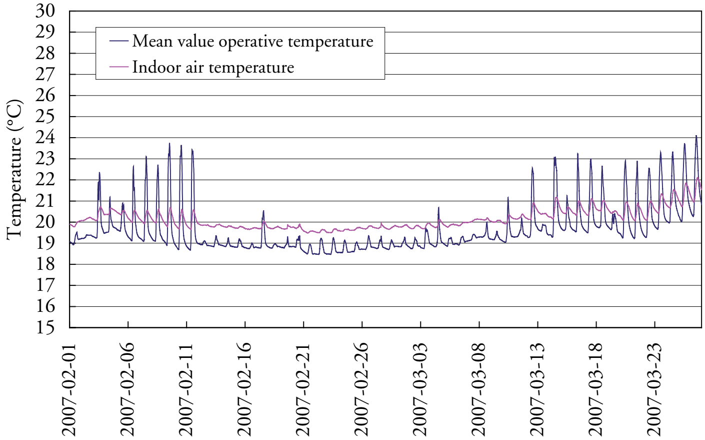


Figure 4.43 *Mean value of operative temperature and indoor temperature in the test apartment 070201 – 070327.*

4.10 Correlation between measured and calculated figures

4.10.1 Peak load for space heating

The simulations made in DEROB – LTH comprised one building of type A or C with two apartments of 97 m^2 and two apartments of 68 m^2. The calculated peak load for space heating was 10.8 W/m^2 at an indoor temperature of 20°C and 11.8 W/m^2 at an indoor temperature of 22°C as presented in Section 4.2.

The space heating demand measured in the apartments is the energy bought by the tenant. Since the heating coil is placed in the exhaust air, only approximately 80% of the bought energy for space heating is actually used in the apartments. To be able to compare the simulations made in DEROB-LTH and the actual space heating demand in the apartments, the bought energy for space heating is here decreased by 20%, since the efficiency of the heat exchanger is assumed to be 80%. The decreased measured peak load for space heating is presented in Figure 4.44, together with the indoor temperature measured in the apartments at the time when the peak load was measured.

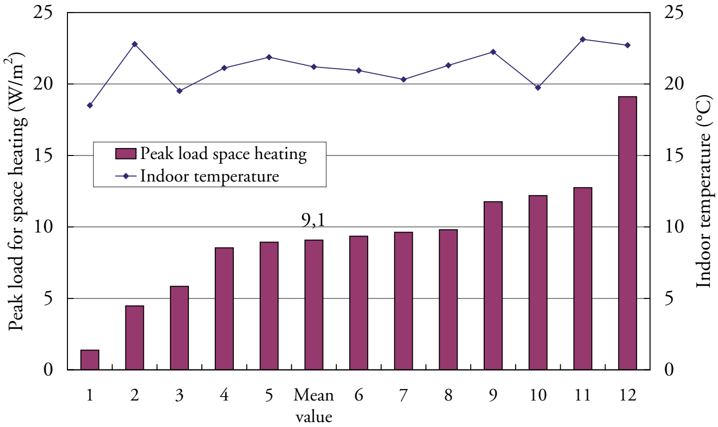


Figure 4.44 *Peak load for space heating, decreased by 20% and measured indoor temperatures at the time of the peak load during the period 070201 - 080201.*

The measured values of the peak load for space heating for the total of 8 apartments in building A and C are revised according to the placement of the heating coil in the exhaust air and compared with the calculated values made in DEROB-LTH at a calculated indoor temperature of 20 °C and 22 °C. There are four apartments in each building, two on the ground floor (2 and 3) and two on the upper storey (1 and 4) with entrances on the outside of the building. The placements of the apartments are presented in Figure 4.45.

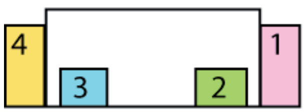


Figure 4.45 *Placement of apartments in the building.*

The comparison is presented in Figure 4.46. The measured values of peak load for space heating are mean values for the highest measured energy use for 24 hours during the measuring period 070201 – 080201. The calculated peak loads for space heating are the maximum calculated power use for one hour.

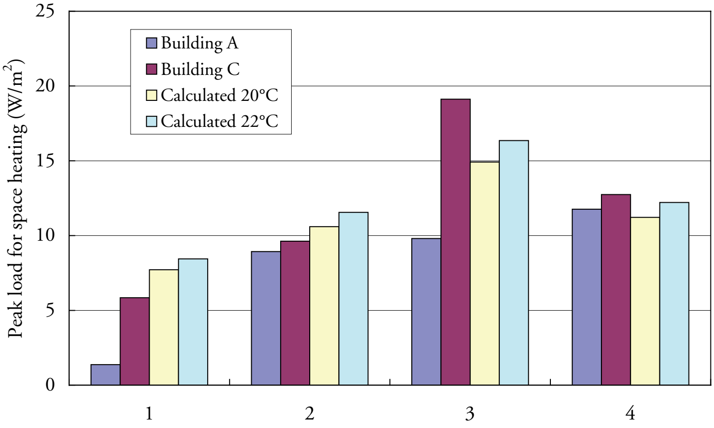


Figure 4.46 *Measured mean value of peak load for space heating in all apartments in two apartment buildings compared to calculated values during the period 070201 - 080201.*

The peak load for space heating measured in the apartments appears at different times of the year. Most common was however a peak load for space heating measured some time during the period February 21 – 27. The outdoor temperature was then between -7°C and 1.5°C. The peak load for space heating in the simulations was on February 3, with a lowest outdoor temperature of -16.7°C.

The simulated values for the apartments 2 and 4 are quite similar to the measured peak load values but the results also show major differences between measured and calculated values; too low values in building A apartment 1 and too high values in building C apartment 3.

In the interviews with the tenants in building A, apartment 1, they confirmed that they almost never had turned on their heating coil in the supply air system. They said that they did not think it was needed since the indoor temperature was at a comfortable level all year round.

The high energy use in building C, apartment 3, has already been discussed and was due to a high programmed temperature in the supply air unit.

4.10.2 Energy demand for space heating

The energy demand for space heating is calculated in DEROB-LTH as presented in Section 4.2. The energy use for space heating was calculated to 14.8 kWh/m^2a at an indoor temperature of 20°C and to 18.9 kWh/m^2a at an indoor temperature of 22°C.

The annual mean bought energy for space heating in the eight apartments in buildings A and C during the period 070201 – 080201, together with the simulated space heating demand at an indoor temperature of 20°C and 22°C respectively, are presented in Figure 4.47. The apartments 1 – 4 are placed as earlier shown in Figure 4.45. The bought energy in Figure 4.47 has been decreased by 20% according to the placement of the heating coil in the exhaust air and the efficiency of the heat exchanger of 80%. The bought energy for space heating in the eight apartments is not revised to a normal year. The measured year was warmer than a normal year and warmer than the climate used in the simulation. The mean value of the indoor temperature in the apartments during the heating period October – May was measured to 22°C.

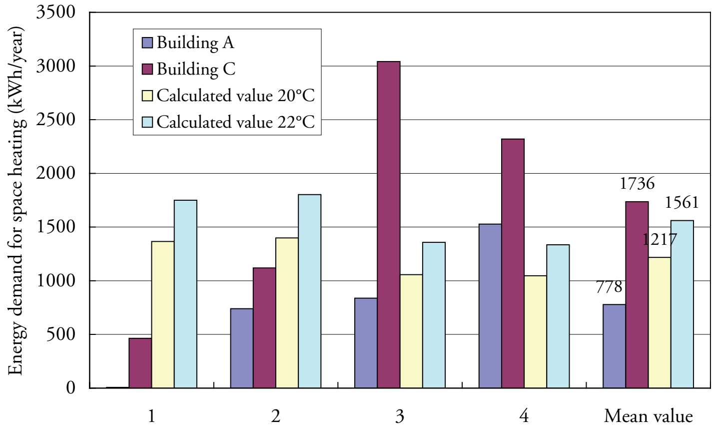


Figure 4.47 *Annual bought energy / simulated annual energy demand for space heating.*

The correlations between the calculated and measured figures are not so good. As for the peak load for space heating, apartment 1 in building A pulls down the mean value of the energy use and apartment 3 in building C lifts up the mean value for building C. The individual behaviour of the tenants strongly influences the annual amount of bought energy in the buildings.

If the bought energy for space heating is divided by the heated area, it differs much between the apartment buildings. The measured values, with a decrease of 20% from the bought energy according to the placement of the heating battery, and calculated values for both an indoor temperature of 20°C and 22°C, are presented in Figure 4.48. Here, building B is also included. The mean annual bought energy for space heating in all apartments is almost what was calculated; 14.7 kWh/m^{2}a of measured bought energy for heating compared to the calculated value of 14.8 kWh/m^{2}a.

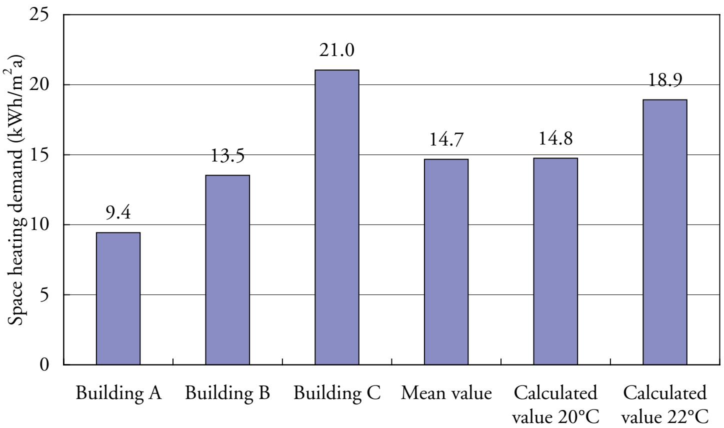


Figure 4.48 Measured and simulated energy demand for space heating.

However, the measured year was warmer then normal and warmer than the climate data used in the simulation. The measured and simulated figures of annual energy use are both revised to a normal year using climate data from SMHI (SMHI, 2009). The measured energy use for space heating is also decreased by 20% according to the placement of the heating coil. The revised results are presented in Figure 4.49.

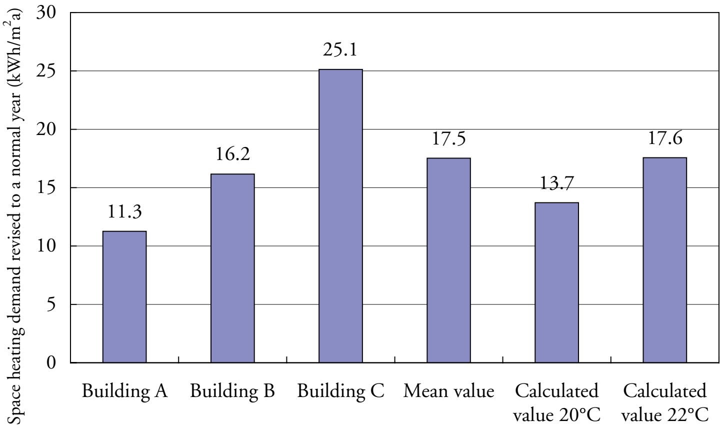


Figure 4.49 *Measured and simulated energy demand for space heating revised to a normal year .*

The mean value of the energy use for space heating when revised to a normal year correlates well to the revised calculated figures at an indoor temperature of 22 ° C.

4.10.3 Energy losses

The apparatus building with all technical equipment, including the district heating centre and the solar system, is placed separate from the apartment buildings as shown in Figure 4.49. The circulating domestic hot water, delivering energy for both space heating and domestic hot water in the apartments, is connected to this building. The water is circulating 24h a day, all year round. This is the main reason why the heating coils in the heat exchangers must be placed in the exhaust air outlet, where the air is always warm and there is no risk of freezing in the circulating water.

The pipe used for domestic hot water is also used for the heating coils in the supply air system, something that is no longer allowed by the Swedish building code, BBR. The pipes are laid in the ground from the heating centre to each of the three buildings, see Figure 4.50.

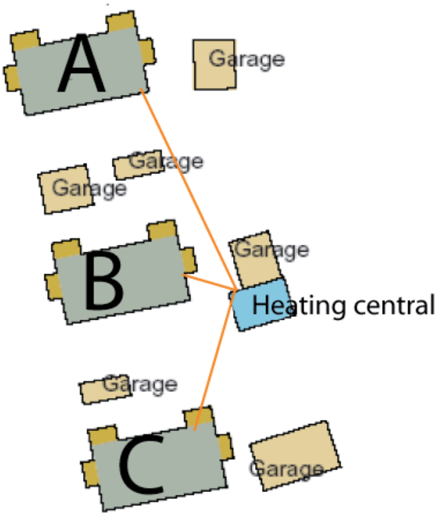


Figure 4.50 *The location of the apparatus building (Heating centre) in Frillesås.*

The distribution pipes used in the ground are usual standard pipes used for heating mains. They are each insulated with 27 mm of insulation, see Figure 4.51. The supply pipe has a dimension of 28 mm and the return pipe 18 mm.

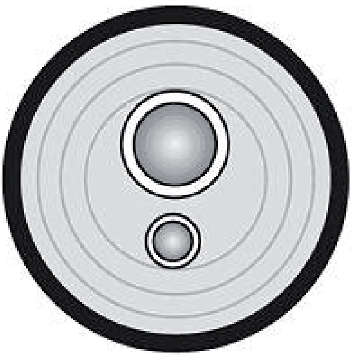


Figure 4.51 *Distribution pipes for domestic hot water, placed in the ground (Picture: Uponor, 2006).*

The thermal losses from these types of pipes can be calculated using a diagram made by the retailer (Uponor, 2006). The retailer has no diagram for the specific pipes used in this project with the supply pipe of 28 mm and the return pipe of 18 mm, but recommends using the diagram where both the pipes are 25 mm (Isaksson, 2008). To be able to use the diagram, the temperature difference, ΔT, needs to be calculated according to Equation 4.3.

$$\Delta T = ((T_{w1} + T_{w2})/2)\text{-}T_0 \qquad \text{Equation 4.3}$$

Where

T_{w1} = water supply temperature
T_{w2} = water return temperature
T_0 = ambient temperature

The temperatures are continuously measured by the client and can be easily read off in a web-based measuring program. At the end of November 2009, the temperature T_{w1} was measured to 58°C and the return temperature to 49°C. The ambient temperature was assumed to be -3°C according to the producer's manual. This gives a ΔT of 56.5°C which corresponds to a thermal heat loss from the distribution pipes of approximately 14 W/m.

The distance from the heating centre to building 27 is approximately 24 m, to building 25 approximately 10 m and to building 23 approximately 43 m. This gives a total length of 77 m for the distribution pipes which corresponds to a distribution power loss of 1078 W. The water in the pipes runs 8760 h/year. Based on this, the energy loss in the distribution pipes is calculated to 9443 kWh/year.

The distribution losses are calculated for each month by using the power loss and multiplying this by the number of hours per month. The calculated energy for distribution losses, the measured energy gained from the solar thermal system and the energy bought monthly from district heating for space heating are shown in Figure 4.52.

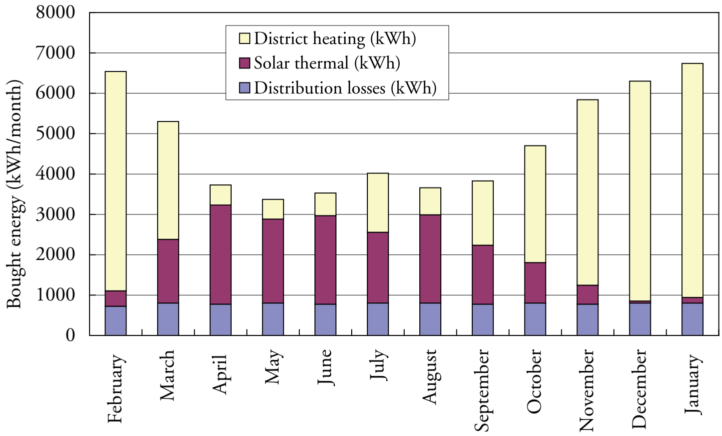


Figure 4.52 *Bought energy for space heating (district heating), energy gain from the solar panels and calculated distribution losses, 070201-080201.*

The amount of produced energy (solar and district heating) should cover the measured energy use for space heating, domestic hot water and the distribution losses. When these energy consumers are subtracted from the produced energy, it is seen that there is an unknown energy item left each month; additional losses, see Figure 4.53. The additional losses are visible especially in the cold months.

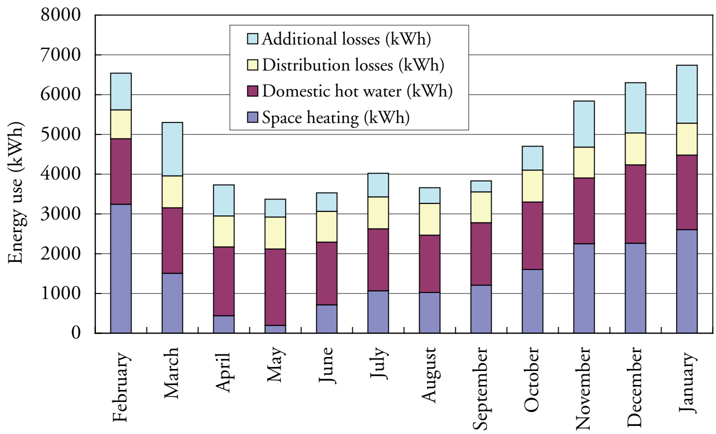


Figure 4.53 *Energy use during the period 070201-080201 divided into energy for space heating, domestic hot water, distribution losses and additional losses.*

In the bathroom in each apartment there is a small heating coil. The coil is actually the supply water pipe that is drawn in a small additional loop, with a diameter of 15 mm. The additional energy “losses” in the cold months could be explained as the heat used in these small heating coils.

The solar panels are placed on the roof of the heating centre. The size of the solar panel system was chosen so it would fully cover the roof. This might have been too large a system in summer, where the heating losses as seen in Figure 4.52 could be explained as too much hot water production during the sunniest months. The caretaker of the apartments reports however that the solar panels have been draining waste water at only one time in 4 years. He also used a thermal camera to investigate if there was a thermal leakage somewhere else in the apparatus building but did not find anything.

With these measurements it is impossible to know for certain where the additional losses arise. To get more information, the supply and return temperatures of the water in the heating coil should be measured, together with the rate of flow of the water. This would measure the energy use in the heating coil and decrease the insecurity regarding the energy losses.

4.11 Peak load for space heating – power sources

In some of the apartments, the annual use of energy for space heating was low during the measuring year, but the use of household electricity was very high as can be seen in Figure 4.54.

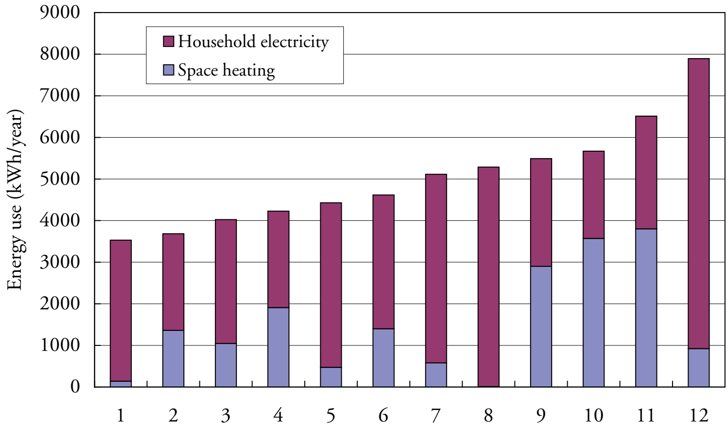


Figure 4.54 *Energy demand for space heating and household electricity in all apartments during the period of 070201 – 080201.*

In the simulations the internal gains were set at 4 W/m^2. When the use of household electricity is quite high, as in these measurements, the internal gains might be higher.

The measured peak load for space heating was measured and is previously presented in Subsection 4.9.11. The use of energy for household electricity during the day for each apartment's peak load for space heating was also measured. The sum of household electricity use during the 24 hours on the day the peak load for space heating was registered is divided by 24, getting an average power load for household electricity. Approximately 80% of the supplied household electricity is assumed to be usable for space heating (Sandberg, 2008 and Bagge, Elmroth & Lindstrii, 2004). The sum of the peak load for space heating and the usable power for household electricity for the 12 apartments are presented in Figure 4.55, together with the mean indoor temperature in the apartment during the same day.

The mean value of the usable power load for household electricity was 4.2 W/m^2 on the day of peak load for space heating. The peak load for space heating and household electricity between the apartments varies by a factor of three. In one of the apartments (3), the electrical power use for household electricity was higher than the peak load for space heating during the coldest day. The mean value of the indoor temperatures at the time when the peak load for space heating was needed does not vary much between the apartments.

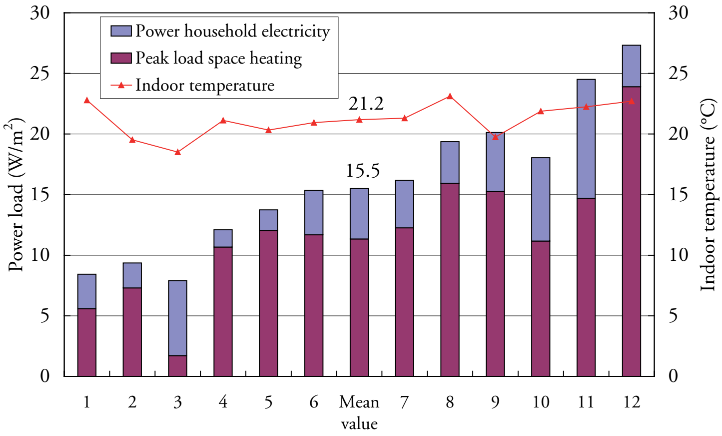


Figure 4.55 *Peak load for space heating in 12 apartments, corresponding mean value of the power of the household electricity and the mean indoor temperature.*

The number of tenants in the apartments also contributes to the internal gains by e.g. 80 W heat produced by a 40 year old male and 68 W produced by a 40 year old female (Bigélius & Svennberg, 1974). These internal loads from tenants, based on the answers in the interviews regarding the number of tenants living in the apartments, are added to the measured peak load for space heating and the usable power of household electricity, and presented in Figure 4.56.

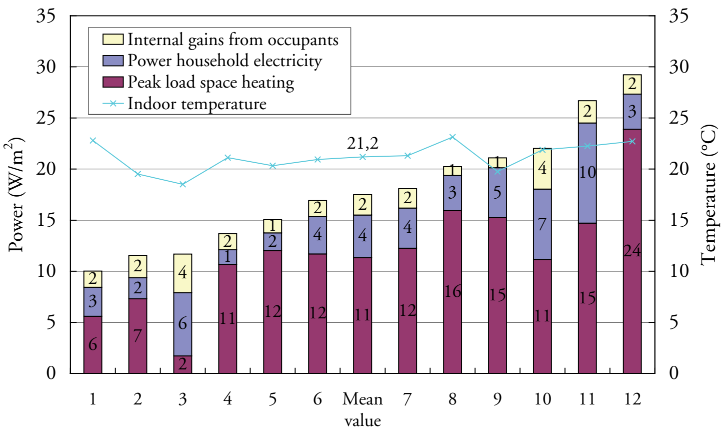


Figure 4.56 *Peak load for space heating, household electricity, calculated internal gains generated by the tenants and measured mean indoor temperature.*

The calculated mean value of the total internal gains from occupants was 6.2 W/m^2, with a variation from 3– 12 W/m^2. Only in two of the 12 apartments were the internal gains from the tenants and the usable internal gains from household electricity below 4 W/m^2 as used in the simulations.

Is the somewhat high use of household electricity a result of a deliberate choice by the tenants to raise the internal gains in order to raise their indoor temperature? To be able to use the internal gains from household electricity, the additional contribution must be received during the heating season. In Figure 4.57, the distribution of the annual bought household electricity in the 12 apartments during the measuring year is presented. In Figure 4.58, the use of household electricity in all apartments in August is compared with the electricity use in February. August was the warmest month and February the coldest during the measuring period of 070201 – 080201.

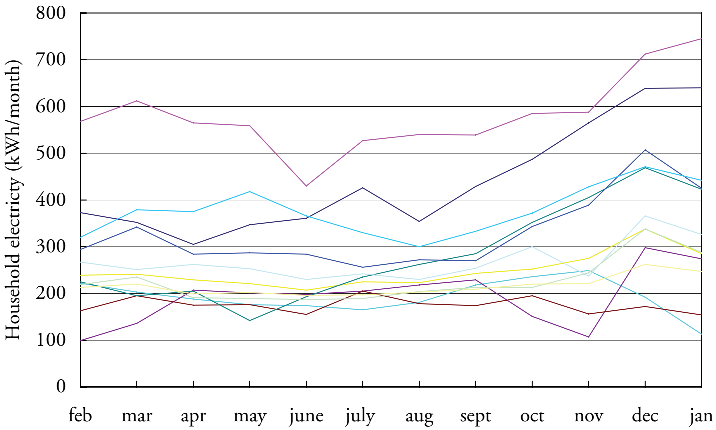


Figure 4.57 Bought household electricity in all apartments 070201 – 080201.

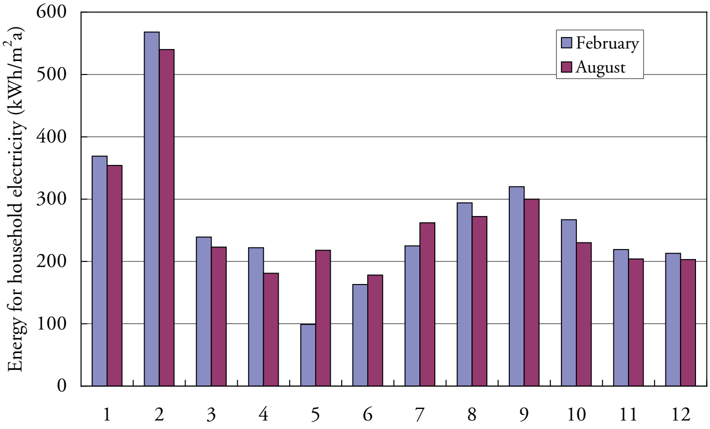


Figure 4.58 *Use of household electricity in all apartments in February 2007 and August 2007.*

In Figure 4.56 there are no distinct higher levels of bought household electricity during the coldest months. This is confirmed in Figure 4.58 where it can be seen that there was only a small difference in the electricity use between the warmest and the coldest month, except for one apartment. The tenants living in this apartment told in the interviews that they mostly live abroad during winter, which explains their much lower electricity use in February. The explanation for the difference in the use of household electricity between August and February could be that more lamps are used in February since it is darker.

The measured results show that the use of household electricity is not dramatically increased during the heating season. This correlates well to the answers received from the tenants in the interviews that the household electricity was used for household appliances, television sets, computers etc; not for additional space heating to their apartments.

As described in Subsection 4.9.11, one tenant used all power available in the heating coil for space heating during the highest power outtake, but mostly the highest power use was measured to be lower or much lower than what was installed. Since more power was available for space heating the supply air at the measured time for highest power use, it is most unlikely that the household electricity was used for additional space heating.

4.12 Discussions and conclusions

To build passive houses was nothing special to the client in this project. Passive houses were just a natural development from their regular standard for new build apartments and the housing company had for a long time been using solar panels and district heating for energy supply. The client used the same general contractor that was usually building their apartment buildings and the contractor used the same building constructions that were regularly used in their apartment buildings, only decreasing the U-values and increasing the airtightness a little bit more. The measured total energy use in the passive houses in Frillesås was much lower than the maximum energy levels set in the Swedish building code.

The results from the simulated values of energy demand for space heating at 20 °C and the measured annual energy use for space heating had a high accuracy. If the figures were revised to a normal year the accuracy was high at a simulated indoor temperature of 22 °C which also was the measured mean value of the indoor temperature during the heating season. However, the energy use in each apartment had a strong influence on the mean value of energy use in the three buildings, due to the fairly small number of apartments. It was seen that only one very high consumer of energy use for space heating was due to a considerable rise in the mean value of energy use for space heating for the total area.

The reduction in the energy use for space heating after the adjustment of the supply air temperature shows the importance of information to the tenants on how the heating system works. It also shows how important it is to have easily manageable devices, where it should be obvious for the tenants if something is wrong and how to correct it. There is a great need of products suitable for both the most skilled computer engineer and the person who has no experience at all of technical products. The products must be easy to use for everyone.

By looking at the reasons for energy losses in this project it can be seen how important it is for all persons involved in the project to have a holistic approach. The energy losses in this project are found at the interfaces between different contractors. It is important to keep the function of the whole project in mind, not only the energy efficiency of each contractor's part, to get an overall low energy use in the finished project.

It was possible to detect high energy withdrawals when the energy use could be easily monitored in a supervisory system. The caretaker of the buildings used the well functioning supervisory system to detect easily when something seemed not to be right in the system, saving both time and money by obviating the need for fault location in the system. The on-line supervisory system is continuously used to check up on the energy distribution system.

It was of major importance for the client in this project to decrease the use of electricity in its building stock. Looking at the measured figures in this project it can be seen that the use of household electricity is the major item in the total energy use in the apartments. The client did his best to decrease the use of household electricity by choosing the most energy efficient white goods; the most expensive tumble dryer was chosen even though the price definitely did not correspond to the energy saved in money. According to the interviews, most household electricity is used by the tenants for computers, television sets and the washing machines. To decrease the use of household electricity in the apartments is therefore quite difficult for the client. In projects built by the client after the passive houses in Frillesås, electricity has been produced by PV-cells. By selling to the tenants' electricity produced by the sun, the client can influence the impact due to the high use of electricity even though he can not influence the actual electricity use.

5 Single-family house Villa Malmborg, Lidköping

In Lidköping (58°27’55”N) close to Lake Vänern, the Malmborg family is living in their single-family passive house shown in Figure 5.1. The family consists of two adults and two children. The house was built by Vårgårdahus in an area of expansion for single-family houses and was finished in April 2007. In this chapter, this single family house will be evaluated both regarding the building process and the actual performance after the family moved in.

Figure 5.1 Villa Malmborg.

Before 2007, the Malmborg family was living in a single family house built in the 1970s that had a really nice garden but was starting to get old and needed extensive maintenance in a near future. The family started to think of building a new house instead of starting to renovate the old house and remembered to have seen a television programme where the passive houses in Lindås were presented. After doing some more research regarding passive houses they realized that a passive house was exactly what they wanted to build. They contacted the architect Hans Eek and together they got in contact with Vårgårdahus, a single family house company building wooden houses made in their small factory, who never had built a passive house before. However, the general manager at Vårgårdahus at that time thought the concept was the right way for the future and that they were willing to build such a house.

The expectations of the family before moving in to their new home was to have a house that was heating itself – that they should not have any energy supply to the house and that it was going to be a terrific house with a low need of maintenance and a free view from the garden.

5.1 Building construction

The house was built in two storeys with a total living area of 171 m^2. On the ground floor is the kitchen, dining room, living room, a small bathroom and a room for work and a small sound proof studio for music. On the second storey are three bedrooms, a common room and a bathroom. Figure 5.2 shows the layout of the house. The ceiling height on the ground floor is 2.6 m. The upper floor has an inclined ceiling, going from 1.8 m to 3.5 m, see Figure 5.3.

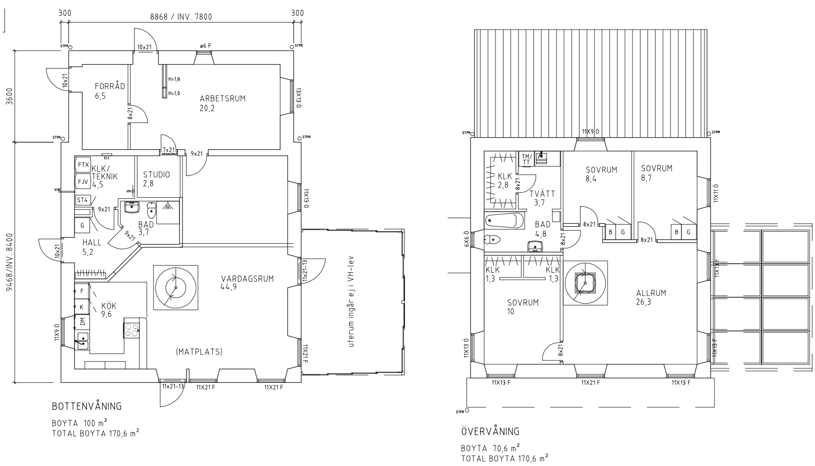


Figure 5.2 First and second storey of Villa Malmborg (Drawing: Vårgårdahus).

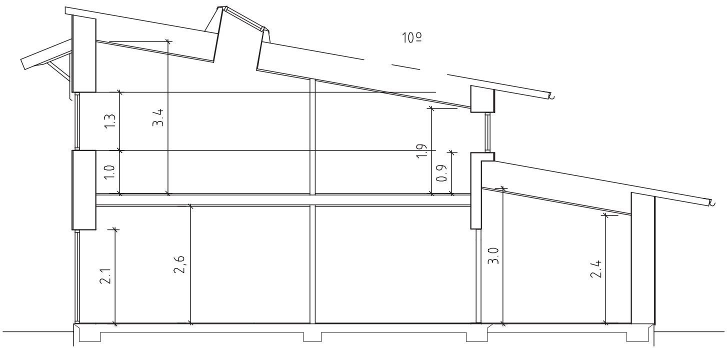


Figure 5.3 Section of Villa Malmborg (Drawing: Vårgårdahus).

The U-values of the constructions are presented in Table 5.1.

Table 5.1 U-values used in the construction of Villa Malmborg.

Building envelope	U-value (W/m^2K)
Ground floor	0.10
Exterior walls	0.09
Roof	0.07
Windows, average	0.85
Entrance door	1.0

5.1.1 HVAC system

The building is heated by air. A mechanical ventilation unit was installed on the ground floor with an air-to-air heat exchanger. The heat exchanger has a supply air heat recovery efficiency of approximately 85% according to the producer. The ventilation rate is 0.35 $l/s,m^2$ as prescribed in the Swedish building code. The kitchen fan is not connected to the heat recovery system. Additional heat during cold days is supplied to the supply air by a waterborne heating coil connected to the district heating system with a capacity of 2.5 kW (14.7 W/m^2).

There is an automatic by-pass function for the heat exchanger, controlled by sensors in the exhaust air pipes. When the by-pass function is active the outdoor air goes directly to the supply air system without passing the heat recovery or heating coil. This by-pass function is necessary in the summer to ensure a comfortable indoor temperature. If the indoor temperature gets higher than normal, for instance when there is a party, but the outdoor temperature is +5°C or below, the by-pass function is automatically blocked.

The total air flow at full speed is 70/70 l/s. When the occupants leave the house, the speed of the fans can be decreased to a low-speed level. If the indoor temperature then drops below the thermostat setting, the fan automatically speeds up until the temperature is at the right level. There are two fans in the unit, each with a rated output of 210 W.

The filters in the ventilation unit need to be changed approximately twice in three years. If they are not changed, the efficiency of the heat recovery decreases and more electricity is needed for the fans. On the supply air system, two silencers were mounted; one on each supply pipe. There is one silencer mounted on the exhaust air system and one additional silencer on the exhaust air pipe that goes in to the recording studio (working room).

In the bathroom, there is an electrically heated towel rail installed for additional comfort; a LVI TFR 62-C with a maximum power of 80 W, manually regulated.

5.1.2 Domestic hot water

The domestic hot water is heated by district heating. No solar collectors were installed.

5.1.3 Household appliances

The household appliances used in the project were chosen by the client and are presented in Table 5.2. In their choice of household appliances the client focused on silent and energy efficient products.

Table 5.2 Household appliances.

Product	Brand	Notation
Dishwasher	Cylinda	DM92
Fridge/Freezer	Cylinda	KFT 3203-2
Stove	Cylinda	IH263
Cooker	Cylinda	IB30
Kitchen fan	Cylinda	Dragö EC90
Washing machine	Cylinda	FTL46
Tumble drier	Cylinda	TK40
Microwave oven	Cylinda	IM20

5.2 Simulations

During the planning process, many different models of the building constructions and different designs of the house were tried in the simulation program DEROB-LTH v 1.0 (Kvist, 2006), to achieve an optimal construction. It was important to ensure that it would be feasible to build the house in the factory with the available equipment and that the peak load for space heating would be at the passive house level. At the time when the simulations were made, no Swedish passive house criteria were yet available. The target was to be able to heat the building by air at normal ventilation rates, but the German passive house standard was also used for inspiration.

The simulations that were made had a great focus on peak load for space heating and annual energy demand for space heating. This focus unfortunately made the general manager to somewhat disregard other important issues like indoor temperature levels in summer.

The result of the simulations showed that the insulation thickness in the outer wall construction and the total window area were the two parameters that had the greatest influence on the final result. The insulation thickness in the outer wall was a critical factor due to limitations in the factory where the wall should be built. In the ceiling in the upper floor an operable skylight was placed for ease of window ventilation. The house as simulated in DEROB-LTH is presented in Figure 5.4.

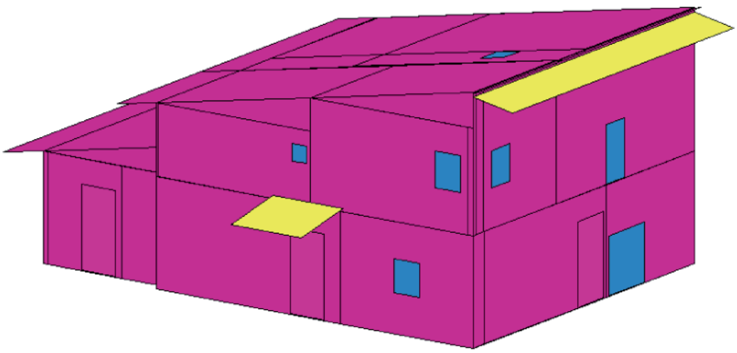


Figure 5.4 Villa Malmborg as simulated in DEROB-LTH v 1.0.

The following input data was used in the simulations:

Living area: 171 m^2
U-values: Floor facing ground: 0.103 W/m^2K
Outer wall: 0.091 W/m^2K
Floor between upper and lower storey: 0.20 W/m^2K
Inner wall: 0.47 W/m^2K
Roof: 0.068 W/m^2K
Outer door: 1.4 W/m^2K
Windows: 0.72 W/m^2K (not operable)
0.85 W/m^2K (operable)
1.0 W/m^2K (skylight window)
Ventilation:
Air leakage: 0.05 ach
Mechanical ventilation: 0.5 ach
Efficiency of heat exchanger: 80%
Ventilated volume: 85%
Orientation: The building was rotated 45° anticlockwise from south, where the façade with the solar shadings and largest windows are in the south west direction.
Soil resistance: 2.29 m^2K/W
Ground reflection: 20%
Internal gain: 4 W/m^2
Indoor temperatures: The indoor temperature was set to 20°C and 22°C

For the studies of energy demand and peak load for space heating the maximum allowed indoor temperature was set to 25°C. Above this temperature, the occupants were assumed to reduce the indoor temperature by using shading devices and/or opening windows.

Climate data: The simulations were made with climate data for Jönköping with a maximum outdoor temperature of 27.7°C, a minimum outdoor temperature of -18.9°C and a mean outdoor temperature of 5.4°C (Meteotest, 2004).

5.2.1 Calculated results

With an indoor temperature set to 20°C the peak load for space heating was calculated to 12.6 W/m^2 and the annual energy demand for space heating to 24.9 kWh/m^2a. When the building was simulated with an indoor temperature of 22°C the peak load for space heating was calculated to 13.8 W/m^2 and the annual energy demand for space heating to 31 kWh/m^{2}a. Additional energy demand caused by specific thermal bridges should be added to the calculated results.

5.3 Tendering

It was at first very difficult for the family to find a company that was willing to build a passive house. Together with architect Hans Eek they contacted many companies in Sweden that were building single family houses, but all said no. Finally they got in contact with Vårgårdahus, who decided to build the house. Vårgårdahus produces all their single family houses indoors in their factory in Vårgårda. A local contractor that had worked with Vårgårdahus before was engaged to erect and finish the house on site. The local contractor carried out the foundation work, the construction work and the building services. Since it was the first time that Vårgårdahus built a passive house; external help from Lund University/LTH was needed to find suitable components for the buildings and advice for the building constructions.

5.4 Planning deviations

The single family houses made by Vårgårdahus are all made by mounting together prefabricated wall modules. To modify the regular production of the outer walls in this project as little as possible and therefore limit the additional building cost, the original idea of the outer wall construction was to double the wall modules that were regularly used in the Vårgårdahus houses. This would have lowered the U-value of the wall in a way that was possible to build in the factory. Unfortunately, this double wall construction with a total of 380 mm of mineral wool insulation gave too high values of peak load for space heating in the DEROB-LTH simulation. The exterior wall was then improved by trying many different designs. The combination of a total of 485 mm of insulation, where 335 mm was mineral wool and 150 mm was expanded polystyrene insulation (EPS) was seen to give a much better result regarding calculated peak load for space heating and energy demand for space heating and was decided on. It was practically solved by using a double wooden prefabricated wall construction and before the two walls were joined together on site, additional EPS insulation was added between the inner and outer wall blocks.

The area where Villa Malmborg was built is an area connected to the district heating system of Lidköping. According to the regulations, all new houses built in this area should be connected to the district heating system in order to try to make the district heating system financially viable. The district heating system was a costly process for the local district heating company. Heating mains with the pipes for district heating were laid out from the thermal power station in the centre of Lidköping out to the Majåker area where Villa Malmborg was built. The manager of the district heating company estimated the cost per building site to be SEK 108 000. (It was less expensive to connect dwellings located closer to the main town.) As a down payment each client paid SEK 23 000 to the district heating company to connect their dwelling to the district heating system. Since the heating mains cost much more than that per building connected to the system, each connection this far away from the district heating plant meant a financial loss for the district heating company. This loss needed to be covered somehow and was usually covered by running costs; payments for energy use. The losses for the district heating company would be even larger if some people in the area decided not to connect to the district heating system, since there would be no payments for connections.

The receipts from energy use were also important for the district heating company, making it somewhat difficult for the company to applaud energy saving measures in view of the current billing system. This financial problem was due to a political decision made in 2005. At that time the system for paying variable costs per kWh in the district heating system in Lidköping was changed. Earlier the cost was different depending on what was used as fuel for district heating. This made the price vary considerably during the year. The customers complained and wanted a fixed price per kWh all year round. The district heating company listened to the customers and set a fixed price per kWh based on the Retail Price Index (RPI), the fixed costs, the efficiency of the distribution system, the average price per MWh and the amount of MWh consumed in the household. In a passive house with solar collectors, the main purchase of district heating will be during the cold months when the fuel for district heating is the most expensive. Such days used to be expensive days to buy district heating, but after the change to the fixed price cost model these days cost as much as any other day. The local district heating company therefore thought that the energy used in a passive house should cost more. To change this, the company needed a political decision.

After a long process, Villa Malmborg was allowed not to connect to the district heating system. Instead of district heating, Villa Malmborg was planned to have solar collectors for domestic hot water production. A total solar collector area of 10 m^2 (2.5 m^2/ person living in the house) was planned to be mounted on the fixed solar shading on the upper storey facing south with an angle of inclination of 27°. The round storage tank was planned to contain 750 litres and would be well insulated to minimize heat losses to its surroundings. An immersion heater was planned to be mounted in the storage tank.

For the additional energy needed in the supply air system, an electrical heating battery was suggested. However, this was not an option for the client who wished to be independent of electricity for heating. Another solution was to combine the solar collectors with a pellets furnace for auxiliary heating. A water jacketed pellet furnace on the Swedish market usually had by then a total rated output of 3-12 kW. It could in principle be placed anywhere in the building, since the ashes end up in a box that can be pulled out and emptied. The furnace has a door that gets warm when in use. The rest of the furnace is insulated and does not get warm. 85% of the heat in the furnace is used for heating water, the rest, about 2 kW, is thermal losses, heating the surrounding air through the furnace door. Since the total peak load for space heating of Villa Malmborg was calculated to 2.3 kW, the heat losses from the pellet furnace would give too large an additional heat contribution most of the year.

The client wished to have a fireplace in the glazed patio (Figure 5.5). If the pellets furnace were placed there, the thermal losses from the pellets furnace could heat the patio. The pipes from the furnace to the storage tank would then have had to be carefully insulated when drawn through the house to avoid losses, and when bringing the pipes through the outer wall the holes would need to be closely sealed. Unfortunately, this turned out to be too expensive a solution for the client. There was no cost difference for connections between the systems; the difference was in the investment cost for the furnace and solar collectors.

Figure 5.5 Glazed patio (photo: M. Malmborg).

The least expensive solution for the client except using electricity for heating was to connect to the district heating system after all. Since a decision had already been made that the client did not have to be connected to the system, a new discussion had to take place with the local district heating company, to find if the house was allowed to be connected again. Finally it was decided that the house could connect to the district heating system. To be allowed to connect the house to the system, the solar collectors had to be removed from the planned domestic hot water system. The local district heating supplier said that with solar collectors the temperature of the return water from Villa Malmborg into the district heating system would not be as low as they required. The client was not so happy about this solution, but could not see any other choice than to omit the solar system.

The total planning process took much more time than assumed. First the application for a building permit took a long time. This was partly because the design drawings used in the application were changed according to new wishes from the client. Also, the process of finding a suitable heating system, appealing against the connection to the district heating system and later on to be allowed to connect to the district heating system, took time.

5.5 Training

Before the work on site started, half a day of training was held at Vårgårdahus. The contractor, the carpenters at Vårgårdahus, the staff at Vårgårdahus working with the project, the architect and the client all participated in these four hours of training. The electrician and the plumber did not participate. They had a run-through with the project leader at Vårgårdahus later.

During the training session first the architect Hans Eek described the basic ideas of a passive house, showed some examples from earlier projects and talked about what is important to bear in mind during the building process. The architect described the criteria for a passive house and how these requirements were to be fulfilled, and the importance of thinking of the building as a system, the importance of airtightness and to combine it with a mechanical ventilation system. The talk about airtightness covered both the question about energy efficiency and the importance of avoiding moisture in the construction.

The training session then had a more specific discussion about construction details. Illustrations were shown for the difficult erection components, one by one. The details were discussed between the carpenters and the structural engineer to be able to find the best way of mounting the wall panels. All connection points of the panels were creatively discussed and the mounting process was solved for all panels at this meeting.

During the training it was discussed how the building process should be handled if it rained. Normally, Vårgårdahus erects a single-family house in one or two days, not caring about the weather. The erection of the house was supposed to start on October 9, 2006. It would be difficult to dry out the construction if it rained this day. A tarpaulin was suggested to cover the building site, but it was not possible to have a large tarpaulin hanging in the way when the panels were lifted from the trailer. Everyone; the general manager and the building contractors, agreed that if it rained this day, they would need to wait with the erection. They also agreed about the importance of having a large tarpaulin on site, to cover the building site if it started to rain during the day and when leaving at night.

5.6 The construction stage

5.6.1 Foundation construction

The work with the foundation started at the end of May 2006. Since the soil is clay, the foundation was reinforced by 12 driven piles. The foundation was then filled up with crushed aggregate, 300 mm of cellular plastic and the concrete slab on top was 200 mm. The permissible relative humidity levels in the concrete slab before the floor covering is applied are regulated in the Swedish building code BBR (Boverket, 2009a).

An electrical coil was supposed to be cast in the concrete slab to speed up the drying process of the concrete, but was forgotten by Vårgårdahus and was discovered by the client on the day before the concrete was cast. To be able to cast the slab the next day as planned and not have to postpone the casting process, Vårgårdahus decided not to bother about the heating coil. The coil was only supposed to be placed in the slab as a safety margin and they thought it was not really necessary. It was however very much missed by the tenant.

5.6.2 Loadbearing structure

The loadbearing structure consisted of the outer wooden wall frame construction and was prefabricated in the Vårgårdahus factory. A steel beam, IPE 270, mounted in an inner wall complemented the load bearing structure on the ground floor.

5.6.3 Exterior walls - prefabrication

The exterior walls consist of a wooden frame construction with mineral wool, wind board, air gap and outer wooden surface material. The outer wooden wall panels were prefabricated in a factory on work tables. The work tables were welded on the floor and could not be moved sideways. To be able to build the walls as thick as needed for the house to reach passive house level, the outer walls were made in three layers; the passive house wall would have been too thick to be able to flip in the work tables if made in one piece. This was the reason all panels in the walls consist of two wooden frame constructions later mounted together on site with a layer of expanded polystyrene insulation (EPS) between them (Figure 5.6).

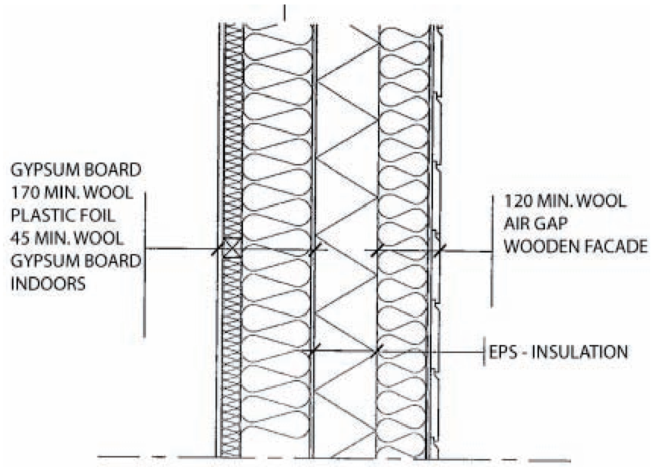


Figure 5.6 Outer wall construction (Drawing: Vårgårdahus).

An ordinary house from Vårgårdahus usually consists of eight building panels or a few more if made with a dormer. Villa Malmborg was not chosen from the standard catalogue but specially designed by an architect. The double wall construction and the architectural design made this house contain 40 wall panels. Since the walls were designed specially they were not of standard height and the plastic foil rolled out on the wall construction was not wide enough to cover the whole wall in one piece and had to be joined together in the factory. The plastic foil was attached with staples to the wooden frame. Another set of wooden frames was mounted on site on top of the first frames for additional sealing of the plastic foil.

It usually takes 4 to 5 days for the carpenters (212 working hours) to produce eight panels for a regular house at the factory of Vårgårdahus. The factory manager had here reserved eight days in the factory for producing the passive house panels. The additional time in the factory was needed because of more panels but also partly because of the new way of building the panels; to seal the plastic foil carefully and for the new type of construction. It turned out that the factory manager had estimated too many days for the work; it only took 5½ days to finish all 40 panels; 340 h working hours were together needed for the carpenters in the factory. The carpenters making the walls had special financial terms for this project, usually they do piecework but here they had a special agreement with additional time. The production worked very smoothly when there was no tight schedule. On site the wall panels had a high accuracy and fitted perfectly with each other, a bonus from not having the production under pressure of time.

5.6.4 Exterior walls – work on site

The original day for mounting the prefabricated constructions on October 9, 2006 was used since there was no rain. It took a total of five days to erect the house; a house made by Vårgårdahus in two storeys usually takes two days to mount on site. The erection on site was made by six carpenters from the contractor and three carpenters from Vårgårdahus. The carpenters from Vårgårdahus normally work at the factory but were here helping the contractor on site on how to mount the panels in the right way and supervised the handling of the plastic foil to get the required airtightness. Normally, Vårgårdahus do not send their carpenters on site; this was an exception to guarantee that the panels were mounted correctly. No additional drawings were needed during the building process, only a few explanatory sketches. The project leader and the structural engineer were instead on site on several occasions to solve difficulties.

First, the inner wall panels were mounted, see Figure 5.7. Steel angles cast in the concrete slab showed where to put the wall on the slab. A thin layer of expanded plastic was placed underneath the wall, protecting the wall construction from the moisture in the concrete. A layer of expanded polystyrene (EPS) insulation was glued on the gypsum board on the surface on the inner part of the wall (Figure 5.8). The EPS insulation was sawn up on site to make the insulation panels fit perfectly (Figure 5.9).

Figure 5.7 Moisture protection of wooden beam construction.

Figure 5.8 Polystyrene glued on the gypsum board.

Figure 5.9 Polystyrene sawn up on site.

Glue was also put on the edges of the polystyrene, making the panels adhere to each other. The carpenters who glued the polystyrene onto the inner part of the outer wall said that they felt insecure since it was the first time for them to do this. They said it was tricky not to have anyone to ask if they were mounting the right way or not. They did not know how long it would take for the glue to harden and for how long the polystyrene would therefore stay flexible. It was important to be able to move the polystyrene somewhat, when mounting the exterior part of the outer wall. The glue made the polystyrene bend in a concave shape. Mounting the polystyrene at the factory would not be a better option, said the carpenters, since it would be needed to be completed on site.

After the EPS insulation was mounted, the floor was mounted on top of the outer walls. It was important to make sure that the plastic foil within the panels put up on the first storey was not crinkled in the corners when the floor construction for the second storey was put on (Figure 5.10). After the floor construction was in its place, the outer wall panels on the second storey were put in position (Figure 5.11).

Figure 5.10 *Floor mounted on top of the walls with carful folding of the plastic foil.*

Figure 5.11 *Outer wall slab mounted on the outside of the EPS insulation.*

The façade material is wood panelling, primed with ferrous sulphate mixed with silver stain. The silver stain was added to see what was painted, since ferrous sulphate is transparent. The silver stain will fade as time goes by. It was recommended to paint the facades once more when mounted. When painting the façade with ferrous sulphate it is important to cover window sills etc since ferrous sulphate might cause spots. To simplify erection of the exterior walls, the lowest wooden panel on all wall panels was detached and mounted back again later, see Figure 5.12.

Figure 5.12 Lowest wooden panel detached to facilitate the mounting process.

The prefabricated inner parts of the outer walls were completed on site with a 45 mm wooden frame construction on the inside of the plastic foil (Figure 5.13). After the pipes and electrical wires and sockets were mounted, this installation layer was insulated with mineral wool and finally a gypsum board was mounted on the inside.

Figure 5.13 *Wooden frame construction for installations.*

The internal walls were a 95 mm wooden frame construction with mineral wool, covered on both sides with 13 mm gypsum boards.

At the end of the first day of erection, tarpaulins were spread over the building. Unfortunately there were not enough tarpaulins to cover the whole building. During the night there were a few showers. In a few places of the construction, some rain had penetrated between the insulation and the plastic foil. On the part of the building where there was no tarpaulin, there was about 2 cm of water on the concrete floor. This was removed by the client, using a vacuum cleaner. Later, the plastic foil was lifted up from the wall and the mineral wool was dried by fans. This drying process continued for three weeks, until the insulation was dry.

On the second day of erection there was also a light rain. It was difficult to decide if the work should continue. The carpenters thought there was too much fuss about it and thought they should continue. In normal houses, the rain never stops an erection process. This decision took a lot of time to make. There was no one on site taking the lead and no one was the obvious leader to make these important decisions. Finally, after calling and discussing with the staff at Vårgårdahus, it was decided to continue with the erection process. And since the discussion took so much time, the rain had stopped.

5.6.5 Roof construction

The roof construction has a slope of 10°, from the south façade to the north façade. The roof is covered with steel sheeting mounted directly on the roofing felt. The felt was nailed to a layer of matchboards, covering 500 mm of loose wool insulation. A plastic foil was placed under the loose wool insulation followed by a wooden frame construction of 45 mm insulated with mineral wool. Below, there was a layer of wooden panelling and then the ceiling material (Figure 5.14).

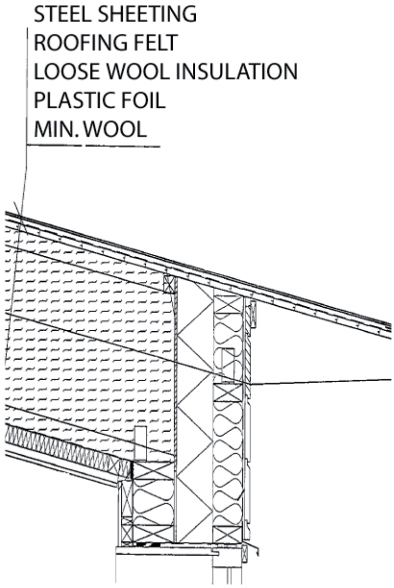


Figure 5.14 Roof construction (Drawing: Vårgårdahus).

The loose wool insulation was poured in to the construction through a hole in the plastic foil where the tube spreading the insulation could be put. After pouring in the insulation, the hole was carefully sealed with an additional layer of plastic foil. The carpenters said that the mounting of the loose wool insulation went smoothly since it was so well planned during the first day of training. It did however turn out to be somewhat difficult to get the connection between the roof and the skylight airtight.

5.6.6 Windows and doors

The windows were bought from SP-windows, with a total U-value of 0.71 W/m^{2}K for the fixed windows, and 0.85 W/m^{2}K for the operable windows. The glass, the distance between the panes and the gas in the gaps were the same in both window types. This glass combination was also used in the terrace doors and resulted in a total U-value of the doors of 0.95 W/m^{2}K.

The delivery of the windows to the factory was delayed. Usually, the windows are mounted at the factory and in this project they were supposed to be mounted in the outermost outer wall construction. Since the windows were still not delivered when all wall panels were finished, the factory manager decided that the windows had to be mounted on site. The windows were mounted on the fourth day of the erection process on site. The late delivery of the windows turned out to be a good thing. The carpenters realized during the mounting process that they would never have been able to saw out the bevelled window bays in the polystyrene if the windows had already been mounted in the prefabricated outer wall. Also, mounting the windows on site made the construction easier to insulate and to get airtight.

The polystyrene was cut out in the window openings, angling the window bays to get more light into the rooms. In the openings, nail plates were holding the three wall sections together (Figure 5.15).

Figure 5.15 Nail plates in window openings.

Plastic foil was fastened using a stapler on the window bays, connected to the plastic coming from the wall construction. The windows were supposed to be mounted 31 mm inwards from the outer façade, flush with the inner wooden panel according to the architect. Unfortunately, at this position only polystyrene was available to attach the windows to. Therefore, additional metal plates were mounted in the window openings to be able to attach the windows. The carpenter said that if the windows had instead been placed flush with the façade, the window sill would have been able to be mounted in the wooden framework of the outer wall.

5.6.7 HVAC system

The ventilation unit was placed in a separate room close to the outer wall together with the connection to the district heating. It was the same carpenters from the contractor who built the house who mounted the ventilation system. The balanced ventilation system had an air flow of 70/70 l/s.

In the inspection report for the ventilation system there were some remarks made by the inspector; for instance there was no supply air in the studio and in the store room there was neither supply nor exhaust air, only two transfer units. The inspection report also noted a lack of condensation insulation beneath the heat exchanger and that the heat exchanger was not sealed round the incoming water pipes in the floor in the appliance room. Furthermore, external pvc pipes were not insulated.

The store room was only ventilated by transfer units because in the planning process the room was supposed to be used as a storage room. This room has therefore a limited field of application, mainly since it is not heated by the supply air. It is important that the ventilation system installed is suitable for different kinds of usage of the rooms, to make it a flexible building.

The client experienced excessive sound levels in the ventilation system, especially in the bedrooms on the second storey, even though the HVAC consultant claimed to have made proper acoustic calculations. The producer of the ventilation unit mounted two additional silencers, one in the supply air duct and one in the exhaust air duct, to decrease the sound levels. This was possible since the room where the ventilation unit was placed was quite big since the water boiler to the solar system was supposed to be placed there. Now, there was enough space to remove the ceiling in the room, add the silencers and mount back the ceiling. After the silencers were mounted, the measured sound levels were reduced drastically.

The client had major problems adjusting the distribution of heating in the coil in the ventilation system. It turned out that the regulation system for the heating coil in the district heating system is not compatible with the heating coil in the ventilation unit. The result of this limitation is that the automatic function, to get a water flow in the heating coil in the ventilation unit to heat the supply air when necessary, is not working. Even though many experts had been asked, it has not been possible to solve the communication problem with the connection. Now, according to the tenants, the district heating subcentre is programmed to have a continuous flow of 20 °C and the temperature of the supply air is regulated by the heating coil in the ventilation unit. The regulation in the ventilation unit is programmed by the tenant to switch on and off the heating distribution in the coil at two set indoor temperatures, with a gap of 3 °C between on and off. The regulation is programmed by the producer to distribute a lower supply air temperature at night time.

According to the client, the inert construction does not respond well to the lowered temperature at night and the lowered indoor temperature occurs in the mornings instead of during the night. The lower temperatures in the mornings are confirmed in the measurements of indoor temperature. The tenants wish to switch off the programmed lowering function. Unfortunately, the display for programming the regulation is much too complicated and not user friendly. Not to risk ruining anything else, the tenants have decided to keep the program with the lowered distribution temperature at night.

During the cold winter in 2009, the tenant turned up the distribution temperature on the district heating to 23 °C. This gave a warm supply air temperature according to the tenants and increased the indoor temperature as required.

5.6.8 Solar panels and domestic hot water

The domestic hot water is supplied by district heating. The district heating subcentre installed has the power to fit an ordinary house, with a much higher energy demand for space heating. The temperature of the return water in the district heating heat exchanger gets too high in this passive house, which has an energy demand almost only for domestic hot water. The high temperature causes no faults in the energy supply to the house, but is sending out alarms to the district heating company. This alarm was the reason the district heating company wanted no solar collectors combined with their connection. Since the district heating sub-centre for the house was not adjusted to the small amount of energy needed, the temperature of the return water was too high anyway, even without using solar collectors.

A sub-centre for the district heating system suitable for lower energy withdrawals is definitely needed to be developed in a near future. Another solution might be to connect the passive house to the return water from the house that is situated before it on the district heating grid.

The district heating subcentre is leaking heat to the room where it is placed, but this does not cause any problems for the family. On the contrary, the room where the subcentre is placed has been a perfect drying room for wet thermal trousers and mittens. The bathroom is placed right above the district heating subcentre and gets floor heating from the heat leakage in the room below.

5.7 Additional experiences

When the erection process of the house was finished, in November 2007, a meeting was held at Vårgårdahus where the carpenters discussed impressions and experiences in the work on the project. Only the carpenters usually working at the factory at Vårgårdahus did participate in this meeting, not the hired contractor. The carpenters said that one of the positive things with the erection process was a great commitment on site and the external interest with visits from the media, from interested people at the local authorities and others. Technically, the wall panels fitted extremely well in the construction and eased the working process considerably. The erection process that was discussed and decided with the structural engineer and others at the opening meeting worked very well on site. The carpenters were happy that they succeeded in building the house and thought that everyone working with the erection process was very skilled. The carpenters also thought they were lucky that almost no rain came during the erection process and that the delay of the windows was a lucky coincidence that increased the standard of the final result.

On site the carpenters said it had been unclear who was in charge of the erection process and they also thought it uncertain who was in charge of the constructions and who to call if for instance they had questions about the constructions of the wall panels. It was difficult to know what panel was supposed to be mounted where.

The managing director at the company Vårgårdahus was replaced in autumn 2006. When he was replaced, the attitude towards the project also changed; it became more important to finalize the project than to build a house that could be reproduced. This reduced interest in building passive houses in the company occurred before the evaluation of the building process and the house and before the financial evaluation. During spring 2007, the company was thinking of how they should continue with building energy efficient buildings. The basic passive house idea, with an installation layer to protect the plastic foil, was decided to become a standard solution in all their buildings and would face a broader market. If the heating system of their houses had been changed from the heat pump that was normally used to an air-to-air heat exchanger and the possibility to get a more airtight building, Vårgårdahus thought it would have been difficult for the customers to compare a Vårgårdahus with other single family houses. Vårgårdahus said that customers want to be able to compare – so Vårgårdahus decided to keep the use of heat pumps in their houses. If the customer wants to choose another heating system, it is their responsibility. Vårgårdahus does not want to be responsible for another type of heating system.

Vårgårdahus started to discuss if they could have one production line with passive houses that ran parallel with standard houses. Instead of taking any decision, a turbulent time at Vårgårdahus started in the autumn of 2008 when the financial crises hit the building sector. Many carpenters and employees were dismissed and the company was no longer interested in building passive houses.

5.8 Economy

Villa Malmborg was built in 2006 and the costs should be looked at in that perspective. The cost for the building site was a single payment by the client of SEK 103 400 or SEK 21.75 /m². The connection cost for water and drainage (without VAT) was SEK 26 940 plus SEK 24.50 /m². The connection to the electricity grid cost SEK 17 500. An application for a building permit cost approximately SEK 30 000.

To connect the house to the district heating system, the client paid SEK 40 000. Every year the client pays a fee of SEK 777 (2006) and the flexible cost was SEK 0.55 /kWh.

Vårgårdahus estimated the additional investment cost to be 10-20%. According to the project leader at Vårgårdahus, this can be improved considerably in the future when the process runs more smoothly.

The planning process took much more time than for an ordinary building project; the project leader used about 250 h hours more than in a normal project, the architect, the salesman, the person at Vårgårdahus responsible for the project each used about 100 h extra hours. Some of the additional time used by the project leader was explained by the extra visits he made to the site compared with ordinary projects. The project leader thought that most of the additional time was needed because this was a first time project and did not conform to the regular routines regarding deliveries and performance on site. The project leader said that he had not enough time in this project to analyse problems that came up. He would have needed someone who took over his other projects, so he could have had more time for this project. In future projects, the project leader estimates that the architect will need about 10 additional hours for planning a passive house and the structural engineer about 20 additional hours.

The house was very well covered by the media, which also took time from the persons involved in the project. Local newspapers, national newspapers, television and radio were reporting about the project. This gave Vårgårdahus a lot of publicity, advertising that needs to be considered when the total economy of the project is summarised. This marketing value is hard to put a price on.

The company Vårgårdahus will not continue with passive houses at the moment. They saw a risk that the passive house project took a long time to finish. It was important for the company to produce many houses every year because they make money on each closed deal. Even if they get paid more for a passive house it was not seen to be profitable when the production time was so long.

5.9 Measurements

All measurements made in this project were commissioned by the client and carried out by Eje Sandberg and Per Wickman at ATON Teknikkonsult, except for the measurements of airtightness that were made by SP Technical Research Institute of Sweden.

The main purpose of the measurements was to verify that Villa Malmborg fulfilled the passive house criteria set up by FEBY (FEBY, 2007); U-value of windows below 0.90 W/m^{2}K, sound class B in bedrooms, maximum 52°C supply air temperature, airtightness of at least 0.3 l/s,m^2 and the peak load for space heating of maximum 12 W/m^2. The passive house criteria set up by FEBY had not been made when Villa Malmborg was built, but it was important for Vårgårdahus to get confirmation that Villa Malmborg was an approved passive house if it were duplicated and put on the market.

Measurements were made of the sound levels in bedrooms, the efficiency of the heat exchanger and the peak load for space heating. The internal gains were known by help from the tenants. The maximum temperature of the supply air could not be measured. Measurements of the U-value of the windows were not a part of the commission; it was here assumed that the U-values reported by the producer were accurate.

The bought energy for domestic hot water was measured separately from March 5, 2008. Before this date, the measured bought energy from district heating includes both energy for space heating and energy for domestic hot water. The energy use for space heating is therefore equal to the total bought energy from district heating, less the measured energy used for domestic hot water. To know the energy use for space heating, the use of domestic hot water must be known.

The measurements made by ATON Teknikkonsult were performed during first four measuring periods between February 1 and March 10, 2008 (Sandberg, 2008). The time for the measuring periods were chosen to have small contributions from solar radiation and a cold outdoor climate. Unfortunately, the actual outdoor temperature was warm for the season during the time when the measurements were made. It was also seen that the measurements were made somewhat late according to internal gains from solar radiation. A third thing that might cause a wrong diagnosis of the energy use of the building was that the meters for the domestic hot water were mounted late during the measuring period.

Because of the many uncertainties in the measurements, a second measurement was made in December 2008 (week 48 – 50) by ATON Teknikkonsult to confirm the first measurements but also with a focus on the system efficiency of the ventilation system (Sandberg, 2009).

5.10 Results from the measurements

5.10.1 Sound

The experienced high sound levels from the ventilation system were a problem for the client, especially in the bedrooms on the upper storey. Measurements of the actual sound levels were performed by Aton Teknikkonsult using a **Bruel & Kjaer 2215** Precision Sound Level Meter in February 2008 (Sandberg 2008). The measurement was made in two of the bedrooms on the upper floor with two meters mounted in each room, placed according to Figure 5.16. The supply air units are mounted in the floor in both bedrooms.

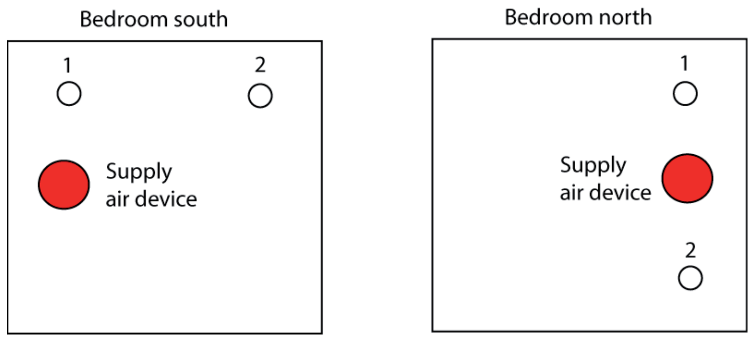


Figure 5.16 Measuring of sound levels in two bedrooms on the second storey .

To measure the different sound levels, the fans in the ventilation unit were regulated from low speed, medium speed to high speed. The air flow at high speed was 70 l/s; the design air flow rate as required in the Swedish building code. The meters were placed 1.2 m above floor level. The results of the measurement are presented in Table 5.3.

Table 5.3 Measured sound levels in two bedrooms in Villa Malmborg (Sandberg 2008).

Sound level in Bedroom North Measuring point 1 (dBA)				Sound level in Bedroom North Measuring point 1 (dBC)		
	16000 Hz	2000 Hz	31.5 Hz	16000 Hz	2000 Hz	31.5 Hz
Fan operation at low speed	24	24	24			
Fan operation at medium speed	28	28	28	51	51	51
Fan operation at high speed	38	38	38			
Sound level in Bedroom North Measuring point 2 (dBA)				Sound level in Bedroom North Measuring point 2 (dBC)		
Fan operation at low speed	25	25	25			
Fan operation at medium speed	29	29	29	53	53	53
Fan operation at high speed	37	37	37			
Sound level in Bedroom South Measuring point 1 (dBA)				Sound level in Bedroom South Measuring point 1 (dBC)		
Fan operation at medium speed	34	34	34			
Sound level in Bedroom South Measuring point 2 (dBA)				Sound level in Bedroom South Measuring point 2 (dBC)		
Fan operation at medium speed	35	35	35			

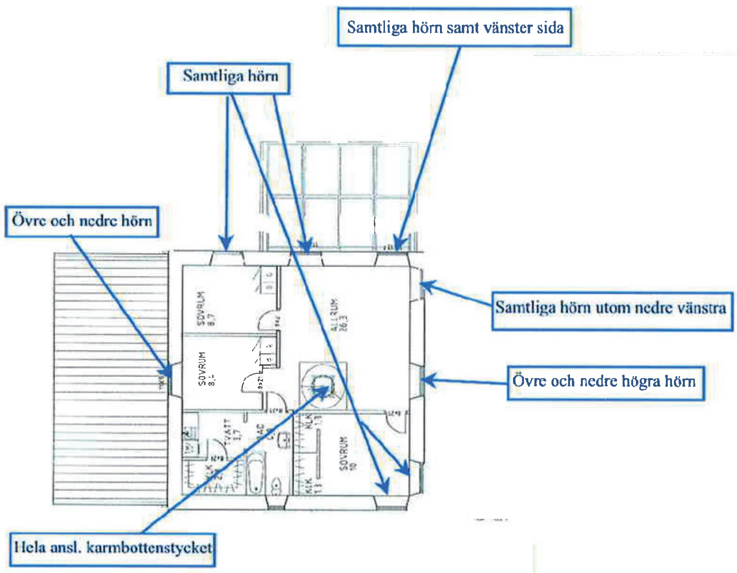
The sound level B required by FEBY is equal to a sound level of 26 dB(A) in bedrooms according to the Swedish standard SS 02 52 67 (SIS,2004). As can be seen in Table 5.3, the sound reaches a highest level of 38 dBA in bedroom north when the fans run at high speed. The allowed sound level of 26 dBA was exceeded at all four measuring points as soon as the fan was at medium speed. To be able to distribute the space heating demand in winter, the fans need to be run at high speed. The clients' experience of excessive sound levels was hereby confirmed.

To decrease the sound levels, two silencers were mounted in the ventilation system as described in Subsection 5.6.6. After the silencers were mounted, another measurement was made of the sound levels that showed a level of 23 dB(A) in the bedrooms which is below the allowed sound levels in sound class B.

5.10.2 Airtightness

The measurement of airtightness was performed by SP Technical Research Institute of Sweden in January 2007. The measurement was made according to European Standard EN13829:2000 (SIS, 2000a). A thermal camera and tracer gas were used as a complement to the measurement of the airtightness with pressurization.

Six measurements were made to get the complete value of the airtightness of the building. The pressure was lowered and raised until ± 55 Pa was reached. The mean value of the airtightness at ± 50 Pa was measured to 0.44 l/s,m^2. Air leakage was detected around windows and door openings and their connections to the outer wall construction, see Figure 5.17. No air leakage was detected in the connection between the building elements in the walls or in the connection of the elements on the first and second storey.



Second floor

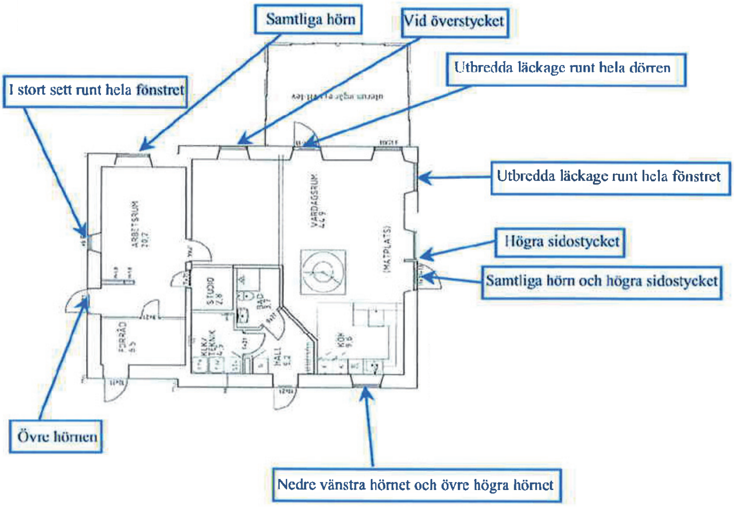


Figure 5.17 Air leakage detected on first and second storey (Illustration: SP Sveriges Tekniska Forskningsinstitut).

According to the architect's drawing, the window was to be mounted in the outer part of the outer wall. The window would then have had to be mounted in the EPS-insulation, which was not practically doable as described in Subsection 5.6.6. To be able to mount the window with its original placement, additional metal plates were placed in the window openings, see Figure 5.18. The detected air leakage around the window was probably a result of the metal plates and shows the importance of communication between the architect and the carpenters to make sure that the set up design can be mounted in a proper way.

Figure 5.18 Additional metal plates in window opening to be able to mount the windows.

The leaks were closely sealed by the carpenters and a second measurement of the airtightness was performed, with a result of 0.17 l/s,m^2 at underpressure and 0.24 l/s,m^2 at overpressure which is below the requirement of 0.3 l/s,m^2 (FEBY, 2007).

5.10.3 Energy use for domestic hot water

The energy use for domestic hot water was not measured separately but calculated based on the used volume of domestic hot water. The volume used for domestic hot water was measured by ATON Teknikkonsult. There was a great daily variation in the use of domestic hot water, but the weekly accumulated use was mostly the same, giving an average value of 164 l/day.

Using the Equation 5.1, the energy use for domestic hot water can be calculated.

$$Q=V \cdot \rho \cdot c_p \cdot \Delta T \qquad \text{Equation 5.1}$$

Where

Q = Energy for heating domestic hot water (kWh)
ρ = density of water (kg/m^3)
c_p = Heat capacity of water (J/kg,K)
V = Volume of domestic hot water (m^3)

ΔT = difference between ground water temperature and supply temperature of domestic hot water (K).

The mean value of the cold water temperature was measured by ATON to 8°C and the maximum temperature of the domestic hot water to 50°C, giving a ΔT of 42°C. The annual energy use for domestic hot water can then be calculated to 2919 kWh/year or 17 kWh/m^2a.

The energy used for domestic hot water was also measured by the client. He assumed that during the warm season when the heating coil in the supply air unit had been switched off for a long period of time, the total amount of bought energy from district heating was the only energy for domestic hot water. The measured daily energy use for domestic hot water was according to the client 10 kWh per day. This gives an annual energy use for domestic hot water of 3650 kWh/year or 21.3 kWh/m^2a.

According to Swedish statistics the average use of domestic hot water in single family houses is 42 l per person and day (Statens Energimyndighet, 2009d). Four persons should, using this statistic, use 168 l/day. The measured value by Aton Teknikkonsult in Villa Malmborg of 164 l/day is very close to the statistics.

5.10.4 Energy demand for space heating

The energy use for space heating is the total bought energy from district heating minus the measured energy used for domestic hot water. The total amount of bought district heating energy was analyzed based on the energy bills received from the client in 2008 and 2009 and on the measurements of domestic hot water use made by ATON Teknikkonsult and by the client.

The energy bill is sent from the district heating company, who measures the actual energy use once a year. The total bought energy from the district heating system is presented in Table 5.4.

Table 5.4 Measured bought district heating.

Date	December 31 2007	December 23 2008	December 29 2009
Measured value (MWh)	2.5	10.4	19.5
Annual energy use (MWh)		7.9	9.1
Annual energy use of space heating and DHW (kWh/m^2)	46.0	53.2	

Since two different measurements were made of energy use for domestic hot water as described in Chapter 5.10.3, two different values of energy use for space heating will be presented here.

Using the domestic hot water use measured by ATON Teknikkonsult, the energy demand for space heating was 29 kWh/m^{2}a in 2008. If the use of domestic hot water is assumed to be at same level in 2009 as it was in 2008 when the measurement was made, the energy demand for space heating in 2009 was 36 kWh/m^{2}a.

If the bought energy for domestic hot water is set to 10 kWh/m^{2}a for both 2008 and 2009, as measured by the client in 2008, the energy use for space heating was 25 kWh/m^{2}a in 2008 and 32 kWh/m^{2}a in 2009 (Figure 5.19).

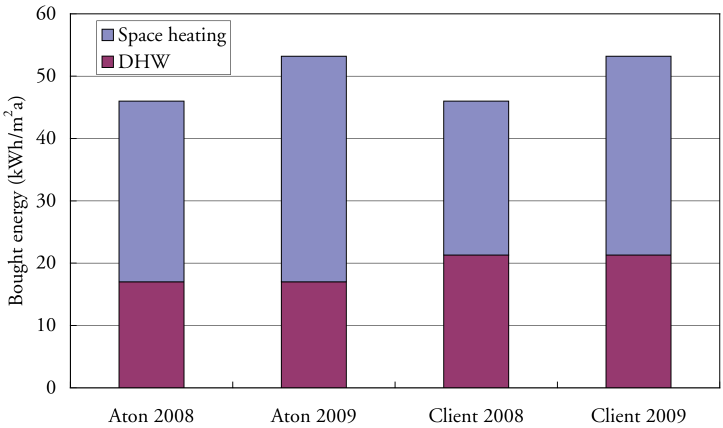


Figure 5.19 *Bought energy for space heating and domestic hot water in 2008 and 2009.*

5.10.5 Space heating demand revised to a normal year

The energy use for space heating is revised according to degree days for 2008 and 2009 using data from SMHI (SMHI, 2009) and normal year temperatures reported for Jönköping airport. The annual correction factor for 2008 was 1.16 and for 2009 1.05. The normally corrected energy use for space heating in 2008 was 34 kWh/m^{2}a (ATON) or 29 kWh/m^{2}a (Client). In 2009 the normally corrected energy use for space heating was 37.8 kWh/m^{2}a (ATON) or 33 kWh/m^{2}a (Client), see Figure 5.20.

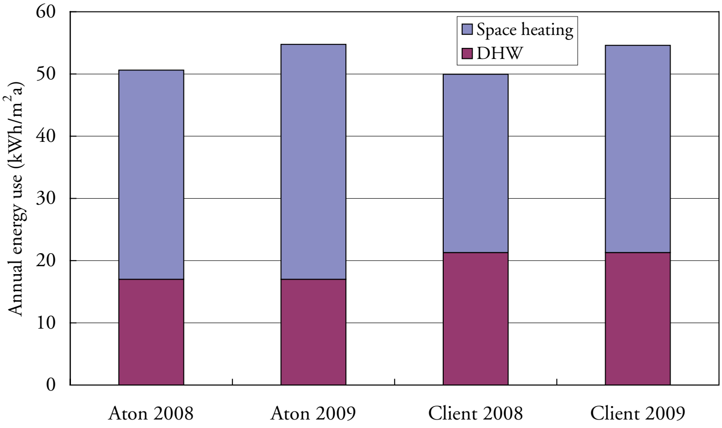


Figure 5.20 Annual energy use, space heating demand revised according to a normal year

5.10.6 Fan electricity

The power used in the fans in the ventilation unit was measured by ATON Teknikkonsult to 195 W (SFP value 2.8 kW/m^{3}s) at a supply air flow rate of 64 l/s and an exhaust air flow rate of 68 l/s, (Sandberg, 2008). If the air flow rate had been kept at this level all year (8760 h), the energy use for the fans would have been 1708 kWh/year (10 kWh/m^{2}a). According to the client, the air flow has been decreased to a lower rate occasionally. Since the time when the air flow rate was decreased is not measured, the annual energy use for the fans can not be exactly determined.

5.10.7 Household electricity

The total use of electricity in Villa Malmborg is analyzed based on the electricity bills sent to the client, see Table 5.5. There was no specific measurement made of the electricity used for the fans in the ventilation unit; it is all included in the measured figures of household electricity.

Table 5.5 Annual use of household electricity.

Year	2008	2009
Annual electricity use (kWh)	6897	7684
Annual use household electricity (kWh/m^2)	40.3	44.9

The average annual use of household electricity in single family houses in Sweden was 6100 kWh/a in 2006 (Statens Energimyndighet, 2009a). The use of household electricity in Villa Malmborg was somewhat higher but if the figures are decreased by the calculated electricity use in the fans in the ventilation unit the use of household electricity in 2008 was 5189 kWh (30.3 kWh/m^{2}a) and 5976 kWh (34.9 kWh/m^{2}a) in 2009, which are both below average.

5.10.8 Total energy use

The total annual bought energy, including household electricity, is presented in Figure 5.21. The electricity use in the fans in the ventilation unit is included in the figure for household electricity. Two bars are presented for each year due to the two separate measurements of energy use for domestic hot water.

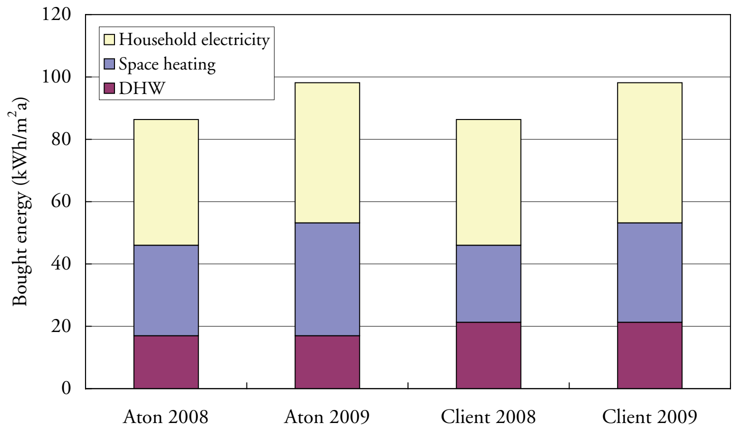


Figure 5.21 Total annual bought energy, Villa Malmborg.

When the energy for space heating is revised according to a normal year as presented in Subsection 5.10.5, the total bought energy in 2008 and 2009 varies according to Figure 5.22.

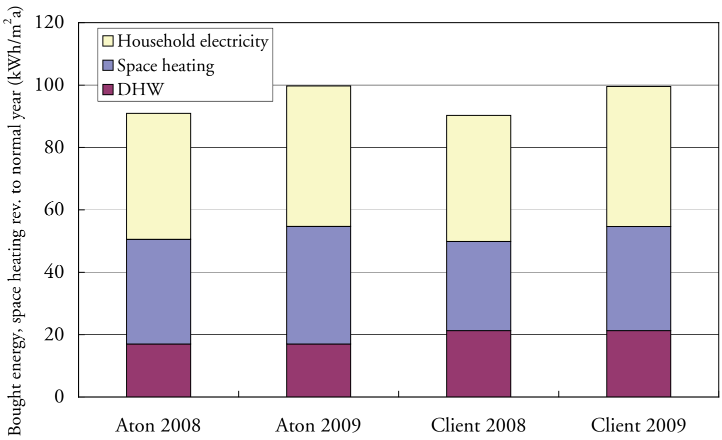


Figure 5.22 *Total annual bought energy, Villa Malmborg, space heating revised according to a normal year.*

As can be seen in both Figure 5.21 and Figure 5.22, the total energy use is higher in 2009 than in 2008 for both energy for space heating and use of household electricity. This higher energy use in 2009 can have many different causes. The tenants have seen that their energy bills have increased and explain that they have somewhat changed their behaviour from the first year of residence to the following year. In the first year they said it was more of a sport to try to keep the heating coil shut off as much as possible. Now they have increased their indoor temperature and have been more concerned about having a comfortable indoor climate than keeping their energy use at a low level.

Another explanation could be that the communication between the heating coil in the ventilation unit and the district heating subcentre is still not functioning well and the tenants are turning up the heat when they feel it is necessary. This lack of automatization could cause a higher energy use for space heating.

5.10.9 Peak load for space heating

The measured values of energy demand for space heating were not that detailed that it was possible to read out the peak load for space heating. The peak load for space heating was instead calculated by ATON Teknikkonsult based on a number of measured values during the period February 1 – March 10, 2008 (Sandberg, 2008).

The method used by ATON to evaluate the peak load for space heating was to make a static energy balance of the supplied energy (district heating, solar gains, internal gains from persons and household electricity) and assume that the sum of these parameters equals the energy losses from the building by transmission and by ventilation losses; the ventilation and transmission losses should be compensated for by the internal gains to get an energy balance of the house. All parameters that influence the energy balance of the building were read before and after the measuring period or measured during the measuring period. By subtracting all known parameters from the bought energy for space heating using the static method, a factor of losses for the climate shell of the building and the ventilation losses were estimated. The factor of losses was multiplied by the difference between the indoor temperature and the design outdoor temperature, giving the power losses for the building. Four measuring periods were used; February 1 – 7, February 7 – 23, February 25 – March 3 and March 3 – March 10, 2008.

The parameters included were:

- Bought energy (district heating)
- Bought electricity
- Used domestic hot water
- Number of tenants
- Outdoor temperature
- Indoor temperature
- Ventilation losses (Mechanical and air leakage (windows closed))
- Solar radiation

The bought energy from district heating included both energy for domestic hot water and energy for space heating. The use of domestic hot water was not part of the energy balance of the building, but had to be measured in this case so that the bought district heating could be reduced and the energy use for space heating thus calculated. The domestic hot water meter did not start until March, giving an approximation of this value during the first measuring periods.

The household electricity could not be specifically measured, only read from the electricity bill. The waste heat from the household electricity that could be usable in the static energy balance is assumed by ATON to be 80% of the bought household electricity.

2008 was a warmer year than normal and the figures used in this approximation were not revised according to a normal year. The measurements started late in the year and the solar radiation was therefore somewhat high. The solar radiation was not measured; climate statistic data for the nearby town Skara was used.

The result of this calculation showed that the power losses for the building were 26 W/m^2 at an indoor temperature of 20 °C and a design outdoor temperature of -14.4 °C.

This analysis of the peak load for space heating was made under circumstances that made the results unreliable. The outdoor temperatures were high for the season and the solar gains in the last measuring periods were large. For that reason, a complementary measurement was made in January – February 2008 (Sandberg, 2009). The same method for analysis was used as in the previous measurement. The total power losses were at this time calculated to 20 W/m^2 at a design outdoor temperature of -14.4 °C. This measuring period was seen by ATON to be more precise, but still included some uncertainties.

5.10.10 Indoor and outdoor temperature

The indoor temperature was measured by ATON using Tiny Tag meters. Both the indoor temperature on the ground floor, on the second storey and outdoor temperature were measured. The measured temperatures during February 2008 are presented in Figure 5.23.

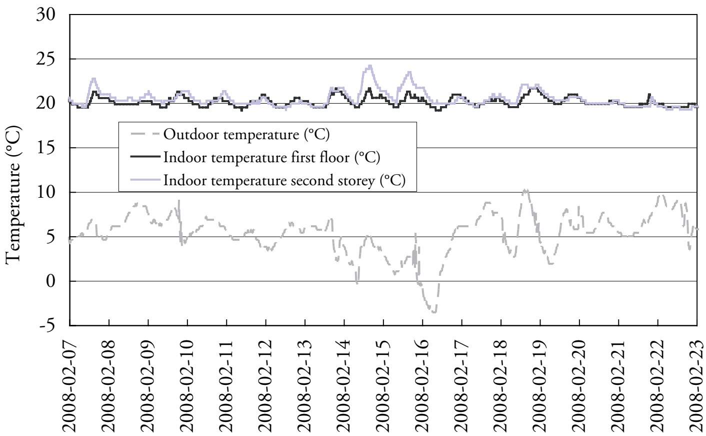


Figure 5.23 Measured outdoor and indoor temperature during February 2008.

The lowest indoor temperature was measured in the morning on February 23. The indoor temperature was then 18.8°C on both storeys. As can be seen in Figure 5.24, the indoor temperature varies during the day. The highest indoor temperature on the ground floor was 21.6°C and measured in the afternoon on February 13. On the second storey the highest indoor temperature was 24.1°C, measured in the evening on February 14. The higher temperature on the second storey as seen in Figure 5.23 was also confirmed by the tenants, who have experienced a difference in indoor temperature between the two storeys since they moved in. In Figure 5.24 the variation of the measured indoor temperatures in both storeys on February 14, 2008 is presented together with the outdoor temperature.

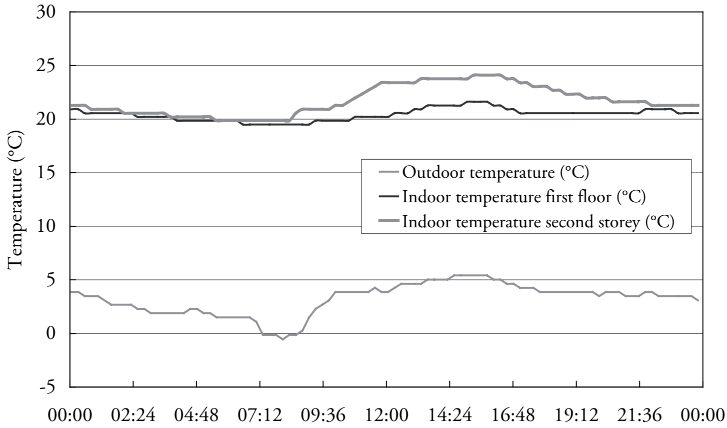


Figure 5.24 *Indoor temperatures on both storeys and outdoor temperatures in February 14 2008.*

During these 24 hours the indoor temperature varies from 19.5°C to 20.9°C (ground floor) and 19.9°C to 24.1°C (second storey). When the temperature variation during the measuring period is studied, the lowest indoor temperature on both storeys is measured between 5 am and 8 am. This could possibly be caused by the lower night temperature, programmed in the ventilation unit. Since the passive house gives a high time constant, the lower night temperature preset in the ventilation unit might not show until the early morning hours. In the interviews, the tenants expressed that the low morning temperatures were something they experienced as a great discomfort.

The indoor temperature was also measured during summer. The measurements were made as previously using Tiny Tag meters. The meters were placed in the living room on the ground floor, in the supply air unit in the hallway on the ground floor, in one bedroom and in the common room on the second storey. The outdoor temperature was measured with the meter placed on the north façade.

During the early summer months, the tenants reported excessive indoor temperatures on the second storey, which was experienced by them as a great inconvenience. The situation became aggravated since the windows in the common room, the central room on the upper storey, were non operable and there were no solar shadings on the windows facing east, see Figure 5.25, 5.26 and 5.27. The choice of non-operable windows was to get as small window frames as possible to get a really nice view from the windows, as can be seen in Figure 5.26.

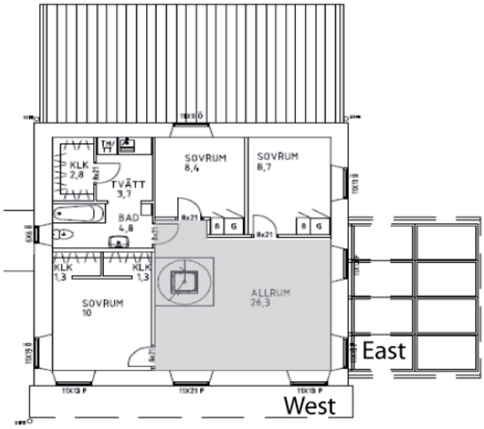


Figure 5.25 Common room on second storey (shaded).

Figure 5.26 Non operable windows on second storey, left window facing east.

Figure 5.27 Lack of solar shadings on eastern façade.

The only operable windows on the second storey were the ones in the bedrooms and the skylight. To be able to let out the warm indoor air in the common room, the air therefore had to pass through the bedrooms, giving too high an indoor temperature also in these rooms. Not much air found its way out through the skylight, as planned in the design of the building. The measured indoor temperature in the common room on the second storey during the summer of 2008 is presented in Figure 5.28 together with the outdoor temperature. As can be seen in Figure 5.28, the outdoor temperature is occasionally very high for Swedish conditions, which indicates that the meter, placed on the north façade, might occasionally have been reached by solar radiation.

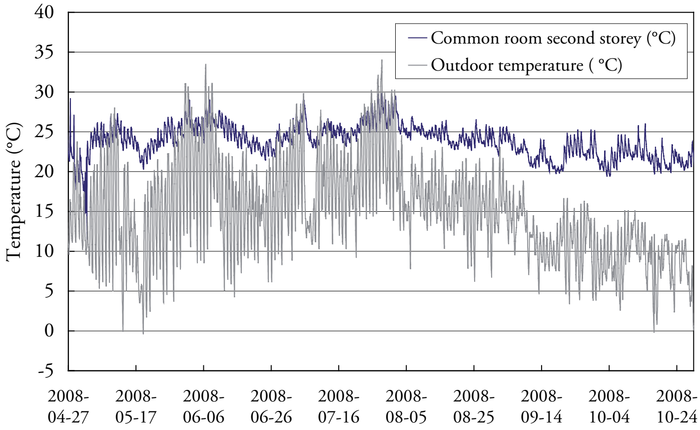


Figure 5.28 *Indoor temperatures in common room and the outdoor temperature, May 2008 – October 2008.*

An external thermistor sensor connected to a Tiny Tag meter was placed on the surface of the inner pane of the window facing east in the common room. The surface temperature is received by measuring the resistance in the sensor. The thermistor was of the model NTC 10K, 12 Bit, constructed for measurements requiring high accuracy. The measured surface temperatures are presented in Figure 5.29. It is difficult to measure surface temperatures on glass panes since the sensor must not absorb heat from solar radiation, something that might have happened in these measurements and needs to be taken into consideration.

The solar radiation causes high surface temperatures on the inner pane during morning hours, especially in the first summer months. There was a great variation in the measured surface temperature during daytime. When the temperature variation on June 9, one of the days with the highest measured surface temperatures, is examined in detail, it is seen that the temperature varied from 25°C to 95°C measured at 10.45 am (Figure 5.30).

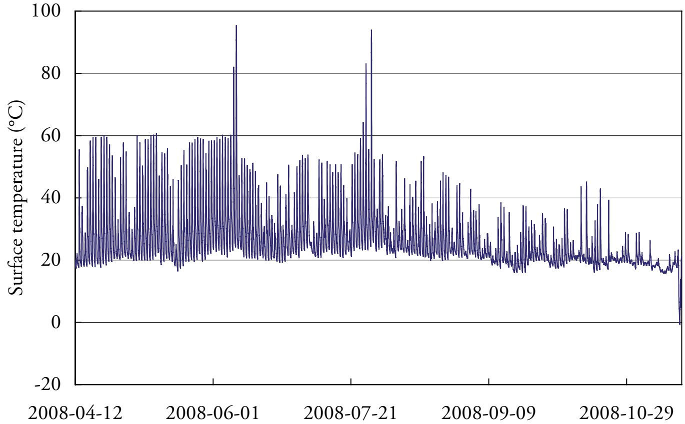


Figure 5.29 *Surface temperature on inner pane of window facing east in common room second storey.*

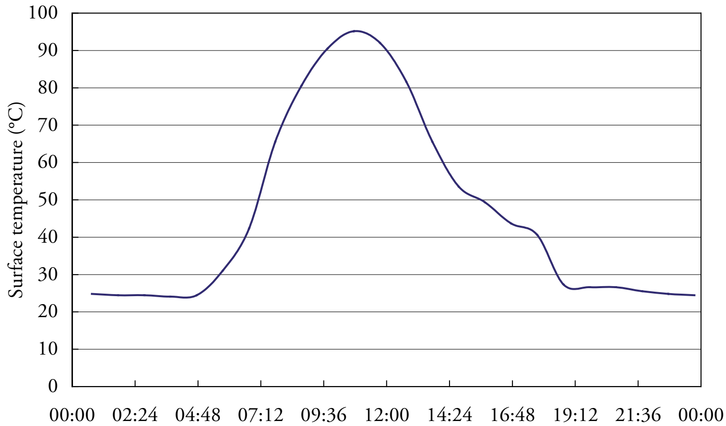


Figure 5.30 *Surface temperature of inner pane on June 9 2008.*

The client tried to prevent the solar radiation, also during the measuring period, by piling pillows in the window. This, together with the great fluctuation in the surface temperature, made the window crack. Vårgårdahus paid for a new window, but this time an operable window was mounted, resulting in a much better indoor climate for the tenants. The family has also installed Venetian blinds and roller blinds in the rooms.

A well planned solar shading system could have avoided the high indoor temperatures. The tenants also express a feeling of being shut in when the windows could not be opened, which promotes both operable windows and these in combination with a solar shading system.

5.10.11 Efficiency of the heat exchanger based on the exhaust air

The efficiency of the ventilation system, based on the temperature in the exhaust air, was measured by ATON Teknikkonsult on three different occasions. First it was measured during February 6 – February 23, 2008, February 25 – March 10, 2008 and secondly on November 24 – December 12, 2008.

There were two reasons why the exhaust air efficiency and not the supply air efficiency was measured, which was the value presented by the producer of the ventilation unit. First, it was impossible to measure the supply air temperature since the meter in that case would have had to be placed too close to the supply air heating coil. Second, the measurement of the exhaust air efficiency includes the losses in the ventilation system and possible imbalance in the air flow and thus gives a correct measurement of the ventilation losses from the building.

The air flows were measured using tracer gas according to method A3 BFR T32:1987 based on an indoor temperature of 20°C and an air pressure of 1013 mbar. N_2O was used as the tracer gas and the dosage was made by Brooks Instrument 5851S. The analysis of the gas mixture was made by MIRAN 203. The power of the fans was measured by EMU 1.44 and the static pressure was measured by Whöler GMBH DM10. The temperatures were logged during two weeks and were instantaneously controlled by Quartz instrument digi-thermo 10. Leakage between supply and extract air was measured using tracer gas.

The air flows were measured to 64 l/s in the supply air and 68 l/s in the exhaust air. The two fans in the ventilation unit together were measured to use 195 W and the SFP value was measured to 2.8 kW/m^{3}s. Only a small leakage of 2-3 % was detected between supply and extract air (Sandberg, 2008).

The efficiency of the heat exchanger was calculated within this research according to Equation 5.2 based on the temperature measurements of made by ATON Teknikkonsult.

$$\eta_{exhaust\ air} = (T_{indoor} - T_{exhaust})/(T_{indoor} - T_{outdoor}) \qquad \text{Equation 5.2}$$

Where

$\eta_{exhaust\ air}$ = the efficiency of the heat exchanger according to exhaust air (%)
T_{indoor} = the indoor air temperature (°C)
$T_{exhaust}$ = the exhaust air temperature (°C)
$T_{outdoor}$ = the outdoor air temperature (°C)

The indoor temperature was measured in two places in the house and the mean value of these two measurements was used in the calculation as the indoor temperature. The exhaust air temperature was measured right after the ventilation unit but also in the cowl to make sure that the power emitted from the ventilation unit did not affect the temperature of the exhaust air. The temperature difference between the meter placed close to the unit and the meter placed in the cowl was less than 0.5°C and was assumed to be negligible.

The efficiency of the ventilation system based on exhaust air during this measuring period was relatively stable around 63% at different outdoor temperatures, see Figure 5.31. Later during this first measuring period, starting with February 25, a lower efficiency was measured with a mean value of 55%.

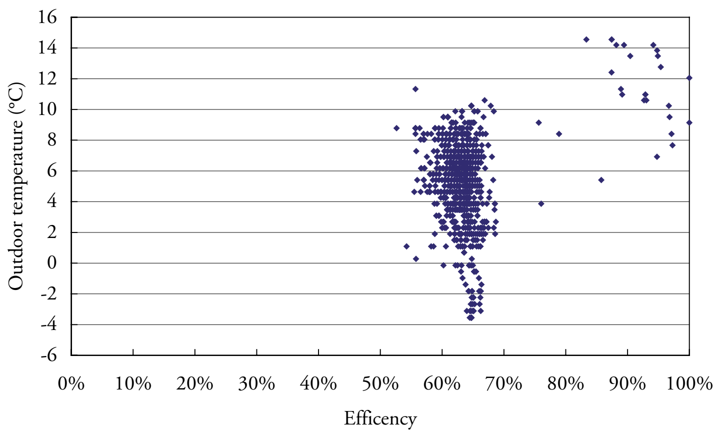


Figure 5.31 *Efficiency of the heat exchanger based on exhaust air at different outdoor temperatures, February 6 – 23, 2008.*

However, the measured efficiency of the heat exchanger presented here needs to be corrected with respect to the heating power emitted from the fans. The exhaust air fan is placed in the ventilation unit before the heat exchanger. It will therefore raise the temperature of the extract air before it enters the heat exchanger. The temperature rise caused by the fan will be reduced in the exhaust air by the efficiency of the heat exchanger. Still, the temperature rise of the exhaust air, because of the power in the fan, causes the calculated efficiency of the heat exchanger to be too low.

During the measuring period in November 2008, the exhaust air efficiency of the ventilation unit was measured by ATON to 50% at a mean outdoor temperature of 3.5°C during the measuring period. If the heat from the exhaust air fan was excluded, the efficiency of the ventilation unit based on exhaust air was measured by ATON to 59%.

5.10.12 Efficiency of the heat exchanger based on supply air

According to the producer, the heat exchanger should have a supply air efficiency of 82%. This is the supply air efficiency without additional heat gained from the fans. The efficiency is calculated according to Equation 5.3 (Bagge et al, 2004).

$$\eta_{sypply\ \ air} = (T_{supply} - T_{outdoor})/(T_{extract} - T_{outdoor}) \qquad \text{Equation 5.3}$$

Where

$\eta_{supply\ air}$ = the efficiency of the heat exchanger according to supply air (%)
T_{indoor} = the indoor air temperature (°C)
$T_{extract}$ = the extract air temperature (°C)
$T_{outdoor}$ = the outdoor air temperature (°C)

The moisture in the indoor air is however included in the measured efficiency. The moisture is recycled and transmitted to the supply air and might cause a lower efficiency when the exhaust air is used as a base. According to the placing of the heating coil in the ventilation unit, a meter in the supply air duct will be too much affected by its radiation. Because of this, it was not possible to measure the supply air efficiency for a long period of time, only momentarily when the heating coil had been switched off.

During the measuring period on November 20, 2008, the efficiency of the ventilation unit according to the supply air was measured by ATON. The heating coil was switched off manually during the measuring period of two hours. The outdoor temperature during the measurement between was +2.7 °C and +4.3°C. The supply air temperature and supply air moisture content were measured using Tiny Tag loggers every 5 minutes.

The results showed the ventilation unit to have an efficiency of 88% using the supply air. Since the radiation from the supply air fan was needed to be taken into account, the corrected efficiency according to supply air was 79%.

The much lower measured value of 58% - 63% received when the measurement was based on the exhaust air can be explained by different factors, e.g. inaccuracy in measured values, an unbalanced air flow, leakage within the ventilation unit or a leakage in the by-pass damper.

As mentioned before, a measured inaccuracy in the exhaust air temperature when the meter was placed in the box for exhaust air in the ventilation unit was first measured to 0.5°C. Additional measurements in the cowl for three weeks showed only a difference of 0.1 °C in the exhaust air temperature measured in the unit, which shows that the lower efficiency cannot be a result of incorrect measured temperatures in the exhaust air caused by thermal radiation from the exhaust fans.

The ventilation rate of the supply and exhaust air in the house was measured with tracer gas, but no imbalance was found. The balance was confirmed by an additional measurement of the ventilation flow made by the OVK-inspector.

Any possible leakage over the by-pass damper was not measured.

5.11 Correlation between measured and calculated figures

In this comparison, only the measured energy use for domestic hot water and thereby space heating, made by ATON Teknikkonsult, will be used. The measured energy use for space heating in 2008 was 29 kWh/m^{2}a, or 34 kWh/m^{2}a if revised according to a normal year. The mean value of the indoor temperature was measured to 20.2°C during the period 080206 – 080223 and 21.7°C during the period 080409 – 081124.

With an indoor temperature set to 20°C, the annual energy use for space heating was calculated in DEROB-LTH to 25 kWh/m^{2}a or 24.6 kWh/m^{2}a when the climate data used in the simulation was revised to a normal year. When the building was simulated with an indoor temperature of 22°C the annual energy demand for space heating was calculated to 31 kWh/m^{2}a or 30.6 kWh/m^{2}a revised to a normal year, see Figure 5.32.

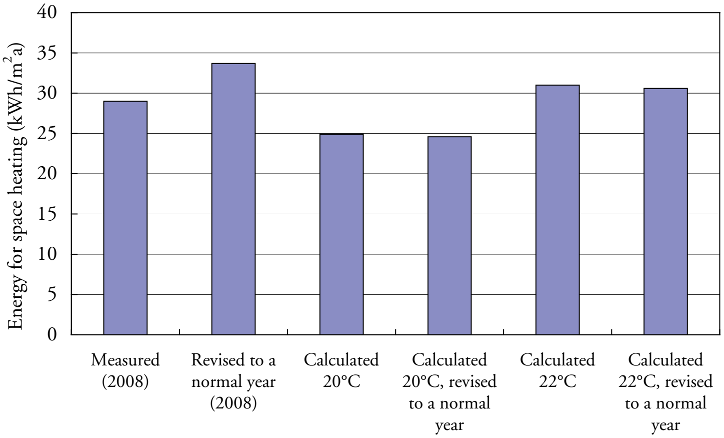


Figure 5.32 Measured energy demand for space heating in 2008 measured by Aton and revised to a normal year, compared to calculated values in Derob- LTH.

The method used for evaluation of energy use and peak load for space heating was in this project tried for one of the first times and it was unknown how well the measured values represent reality. There are however great differences between calculated and measured values of peak load for space heating, which needs to be further investigated. The measured and calculated values are presented in Table 5.6. One probable reason for the inaccuracy between the calculated values and measured values could be the difference in efficiency of the heat exchanger used in the simulations and the actual measured value. Another important parameter could be thermal bridges, which were not studied in detail in the planning process.

Table 5.6 Peak load for space heating.

	Measured (ATON)	Simulated (20°C)	Simulated (22°C)
Peak load for space heating (W/m^2)	24	12.6	13.8

5.11.1 Simulation of space heating demand using different levels of the heat exchanger efficiency

In the original simulation made in DEROB – LTH v.1.0 as presented in Section 5.2, a balanced air flow of 65 l/s (0.5 ach) was used with a heat exchanger efficiency of 80%. To get a space heating demand close to reality in the eight volumes in the simulation, the air flow was added as "Forced ventilation" into the volumes in the original DEROB-LTH simulation. With an efficiency of 80%, that gives an air flow of 13 l/s to the volume where the heat exchanger was placed. An infiltration of 0.05 ach was added in the schedules with an assumed ventilated volume of 85%, giving an infiltration of 0.0425 ach in the original simulation. The peak load for space heating was then calculated to 12.7 W/m^2 and the energy for space heating to 24.9 kWh/m^{2}a.

To see how the efficiency of the heat exchanger affects the space heating demand of the building, different efficiencies were tried in DEROB-LTH v1.0. In these following analyses, the actually measured total air flow of 70 l/s in the house was used and added in DEROB – LTH as unintentional losses, i.e. added to the unintentional infiltration losses of 0.05 ach. The total volume of the house is 433 m^3. A ventilation air flow of 70 l/s is equal to an air change rate of 0.58 ach. The efficiency of the heat exchanger was varied from 0 to 100%.

When the ventilation was added as unintentional losses in the original simulation instead of "Forced ventilation" but the rest of the original input data were kept the same, there was a slight difference in the simulated results; with an air flow of 65 l/s and a heat exchanger efficiency of 80%, the peak load for space heating at an indoor temperature of 20°C was calculated to 9.8 W/m^2 (instead of 12.7 W/m^2) and the energy demand for space heating was 15.9 kWh/m^{2}a (instead of 24.9 kWh/m^{2}a). As can be seen, the calculated results for both energy demand for space heating and peak load for space heating were lower when the ventilation was added as unintentional losses.

The simulated energy demands and peak loads for space heating for different heat exchanger efficiencies are presented in Figure 5.33.

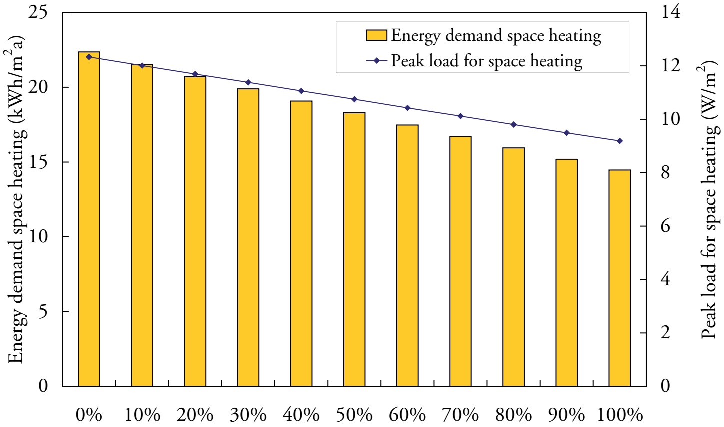


Figure 5.33 *Energy demand for space heating (kWh/m^{2}a) and peak load for space heating (W/m^2) at different heat exchanger efficiencies.*

The difference between the heat exchanger efficiency of approximately 80% presented by the producer and the efficiency of 50% measured by ATON is equal to a difference in energy demand for space heating of 2.4 kWh/m^{2}a (-13%) or a peak load for space heating of 1.0 W/m^2 (-9%). The differences are not severe and a lower heat exchanger efficiency seems not to be the single reason for the higher measured peak load and energy use for space heating compared to simulated values.

5.11.2 Thermal bridges

The larger use of energy for space heating compared to simulated values could also be explained by thermal bridges. The construction drawings show well thought through designs regarding thermal bridges, but there might be thermal bridges in the joints between the panels or between the outer walls and the foundation construction. In Figure 5.34, the risk zones in the construction are circled by the designer.

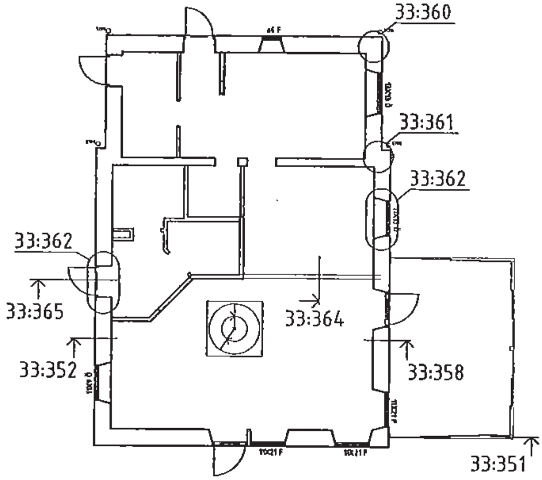


Figure 5.34 Circled risk zones for thermal bridges (Drawing: Vårgårdahus).

Some of the assumed risks for thermal bridges in the construction are here studied in detail to see how they influence the peak load and energy use for space heating and indoor surface temperatures. The Swedish Standard SS-EN ISO 10211:2007 was used as a basis for the calculation (SIS, 2007a). The thermal bridges were calculated according to Equation 5.4:

$$\Psi = L_{2D} - \Sigma U_j l_j \text{ where } j = 1 \text{ to } N_j \qquad \text{Equation 5.4}$$

Where

Ψ = linear thermal transmittance (W/mK)
L_{2D} = thermal coupling coefficient from two-dimensional calculation W/(mK)
U = thermal transmittance (W/m^{2}K)
L = length (m)

The simulation program Heat 2.71 (Blocon) was used to calculate three of the circled thermal bridges in Figure 5.33, assumed to have the most influence on the energy use for space heating in the construction.

The first thermal bridge studied was the foundation concrete slab construction and the connection between the slab and the outer walls (Figure 5.35).

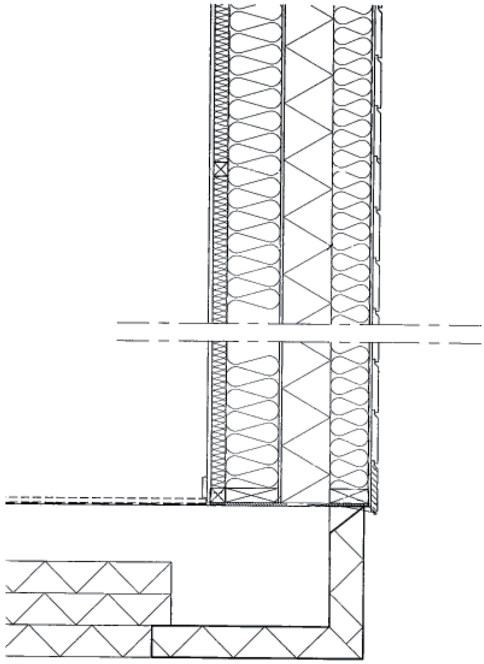


Figure 5.35 Foundation construction (Drawing: Vårgårdahus).

The foundation construction consists of 300 mm of expanded polystyrene insulation (EPS) insulation below the 200 mm concrete slab with 100 mm of EPS insulation on the outside of the concrete slab. The outer wooden wall is in three layers with a core of EPS insulation as described in Subsection 5.6.3.

The simulation was made using a floor width of 4 m according to the standard (*B*'>8m). The thermal flow in the simulated construction can be seen in Figure 5.36.

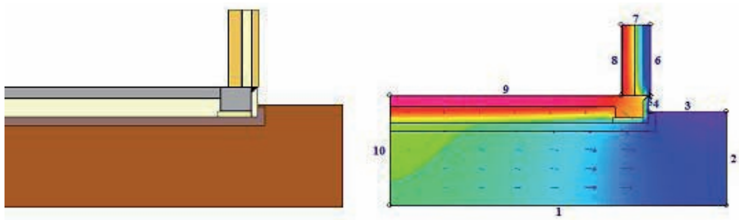


Figure 5.36 Thermal bridge simulation of foundation construction.

The total length of the thermal bridge round the whole foundation slab was 43.5 m. The Ψ – value of the thermal bridge was calculated to 0.18 W/m. This is a relatively high value according to recommended values for passive house constructions (Hastings & Wall, 2007) and needs to be further developed in future constructions.

The second thermal bridge analyzed was the attachment of the windows to the window sill. The three blocks in the outer wall needed to be held together with a steel plate to get a stable construction, see Chapter 5.6. There were four of the metal plates mounted in each window, each measuring 80x240x2 mm. The thermal flow in the construction can be seen in Figure 5.37.

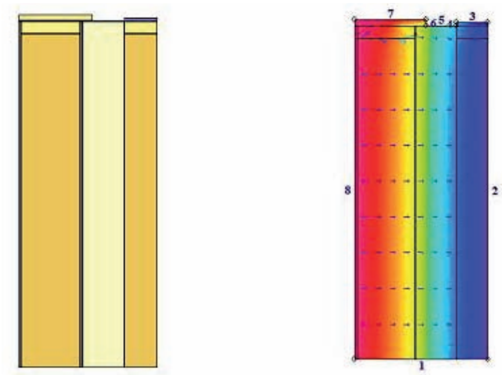


Figure 5.37 Thermal bridges around window.

The Ψ – value of the thermal bridge around the window was weighted based on the Ψ – value of the thermal bridge including the metal plates and the Ψ – value for the window sill without the metal plate, giving a Ψ – value for the construction of 0.05 W/mK. The length of this thermal bridge in the total construction was 109.6 m.

The third thermal bridge was in the connection between the outer wall and the floor on the second storey, see Figure 5.38. The vertical panels were connected with a masonite board. The thermal flow in the construction is illustrated in Figure 5.39.

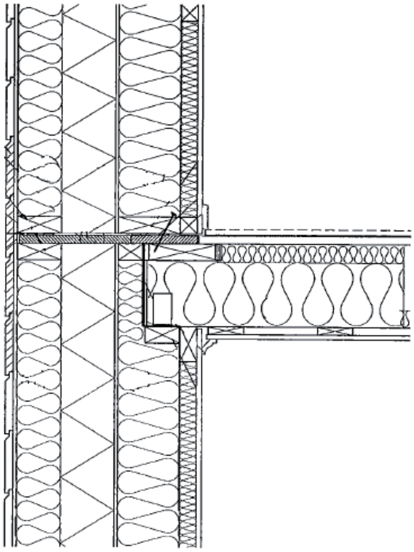


Figure 5.38 Connection between two vertical panels and the floor.

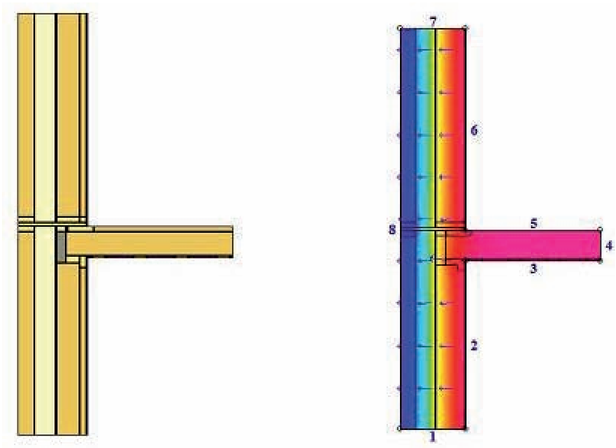


Figure 5.39 Thermal bridges at connection between floor and outer wall.

The calculated Ψ – value of this connection was 0.16 W/mK and the total length of the thermal bridge around the construction was 36.3 m.

The Ψ – values calculated here are somewhat high, but vary a lot depending on whether internal areas or external areas are used. In this simulation, the areas in the middle of the constructions were used to correlate with the simulation of the whole building made in DEROB-LTH, where the mid value was used.

These three thermal bridges together cause a calculated thermal loss of 19.5 W/K. The transmission losses caused by thermal bridges are calculated according to Equation 5.5.

$$\Sigma\Psi \cdot L \cdot (T_{outdoor} - T_{indoor})\ [W] \qquad \text{Equation 5.5}$$

Where

Ψ = linear thermal transmittance (W/mK)
L = length (m)
$T_{outdoor}$ = outdoor temperature
T_{indoor} = indoor temperature

The coldest day in 2008 was March 23, with a measured mean outdoor temperature of -9.9°C for 24 hours. The transmission losses caused by the thermal bridges were calculated to 525 W (3.1 W/m^2).

The annual energy use for space heating caused by the calculated thermal bridges presented here was calculated by adding the thermal bridges in the original simulation of the building in DEROB-LTH v.1.0.

With an indoor temperature of 20°C the calculated energy demand for space heating in DEROB – LTH when the thermal bridges were added was 35.7 kWh/m^{2}a, and at an indoor temperature of 22°C, 43.4 kWh/m^{2}a. When these figures are compared to the original simulated figures as earlier presented in Section 5.2, the thermal bridges are seen to cause an increase in the annual energy demand by 10.8 kWh/m^{2}a at an indoor temperature of 20°C and 12.4 kWh/m^{2}a at an indoor temperature of 22°C, see Table 5.7.

Table 5.7 Calculated figures for annual energy demand for space heating.

Year	Calculated 20°C	Calculated 22°C	Calculated 20°C incl thermal bridges	Calculated 22°C incl thermal bridges
2008 (kWh/m^{2}a)	24.9	31.0	35.7	43.4

The accuracy between the measured energy demand for space heating and the simulated values when thermal bridges are added is studied for both 2008 and 2009. The figures measured by ATON, together with the revised figures for these years, are compared with the different simulations made of the project in Figure 5.40. It can there be seen that the simulated result at an indoor temperature of 20°C when thermal bridges are included is very close to the measured data in 2009 revised to a normal year.

The mean value of the indoor temperature was measured to 20.2°C during the period 080206 – 080223 and 21.7°C during the period 080409 – 081124 as presented earlier. At an indoor temperature of both 20°C and 22°C the simulated values including thermal bridges and revised to a normal year are higher then the measured value in 2008 revised to a normal year. This indicates that the calculated values of the thermal bridges are higher than the thermal bridges in the real construction. A future follow-up on the thermal bridges would be to investigate the construction with a thermal camera.

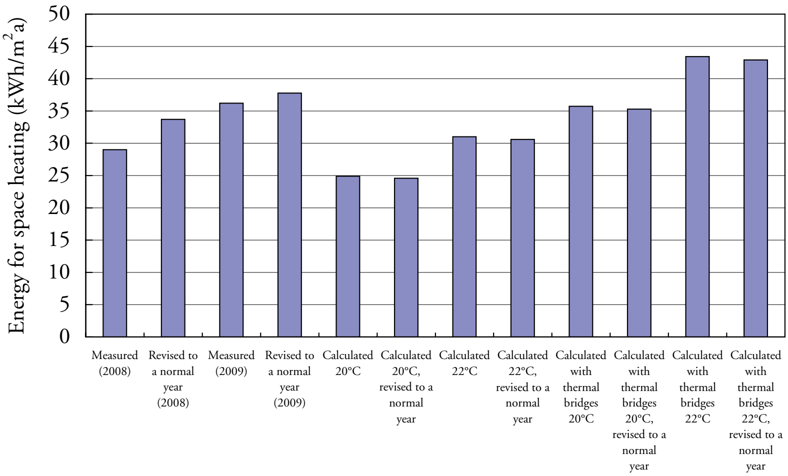


Figure 5.40 Measured and simulated energy demand for space heating.

5.12 Discussion and conclusions

The energy use for space heating revised to a normal year, domestic hot water and common electricity in this project was measured to 61 kWh/m^2a in 2008 and 67.8 kWh/m^2a in 2009. This is much lower then the maximum limit of 110 kWh/m^2a set by the Swedish building regulations. However, the initial expectation from the family was that no energy would be needed for the house at all. It is important that people involved early in the process give the clients the right expectations. No matter how good the finished building is; if the building does not correspond to the set up expectations there is a high risk that the tenants are dissatisfied with their new living. Fortunately, this was not the case in this project.

Vårgårdahus changed their general manager and the person responsible for Villa Malmborg many times during the building process. The change of persons involved a change in attitude regarding the project; from being the future product for the company to trying to finish the project as soon as possible. To get a high quality product and a well functioning final result, it is important that someone is responsible for the project all the way from start to finish, and for the initial high standard to be maintained.

It was difficult to get adequate and reliable measurements to confirm the energy performance of the building. The parameters included in the energy balance were all associated with uncertainties and when these are added together, the total risk of an inaccurate measured result is very high. In future projects, a separate measurement of the energy use for space heating is necessary to be able to measure the peak load for space heating, especially if the measured figures are used in the guarantee from the producer to the client or similar. If the building is to be compared with the building code, specific measurement of the energy use for domestic hot water must also be made and the use of electricity for fans and pumps must be measured separately. It is however important that the measurements are very cost effective to make it affordable for the client. To buy a house is a large investment and it is easy for the client to omit the measurement if it is expensive and the client sees no additional value in the measured result. Preferably, the equipment for space heating, domestic hot water distribution and the electricity distribution centre should always be equipped with meters. This will make the measurement very cost effective and easy to follow for the tenant.

The electricity use for the fans in the ventilation unit was measured by ATON Teknikkonsult to an SFP of 2.8 kW/m^{3}s. If the fans were running at this level all year, the electricity use can be calculated to approximately 1700 kWh/year. According to the Swedish passive house criteria (FEBY, 2009) the recommended total energy use in buildings should be calculated by multiplying the electricity use by a factor 2 (FEBY, 2009). Since the electricity use in the fans is included in the energy item common electricity, it needs to be included in the total energy use. When multiplied by 2, the use of energy for the fans is 20 kWh/m^{2}a. The energy use for space heating was 34 kWh/m^{2}a in 2008 and 37.8 kWh/m^{2}a in 2009, revised to normal years. It is obvious from these figures that the electricity use for the fans is at an exorbitant level. More energy efficient fans are available on the market, EC-fans, which should always be used in future projects.

The measurements, the calculations and the interviews confirm in this project that the building construction could be somewhat improved. For instance, the connection between the outer walls and the foundation concrete slab was seen to have a high calculated thermal bridge value and the tenants describes a sort of draught on the ground floor, which might be caused by the thermal bridge. Also, the inconvenience caused by the non operable window on the second storey was well documented but could easily be avoided in future projects by well planned solar shadings and operable windows.

A development of both products and systems is necessary so that district heating can be used as energy source in energy efficient single family houses in a way that is optimal for both the house owner and the owner of the district heating system. The expansion of the district heating system is a costly process for energy companies and maybe it is necessary to rethink the expansion of the systems to make it profitable also when the energy use in buildings decreases. In Norway in areas where a connection to district heating systems is mandatory, this has become a barrier when building low-energy buildings. The result has been that the planned low-energy buildings are built as regular buildings (Thyholt & Hestnes, 2008). New sub centres designed for the right energy demand need to be produced and it should be possible to use these in combination with solar panels. It is important that the products installed in private homes are working satisfactorily and are suitable for each family's need. The lack of suitable products for low energy single family houses has been pointed out before, for instance in two single family houses in Malmö (Bagge et al, 2004).

To build a passive house as a private owner has not been at all easy for the family. The final result is however very good and the family gets on very well in their house. There has been a need of information and support to the family through the building process which the housing company was not able to give. Instead the family got information through this research project and by the Internet. To ease the process for future families building single family passive houses, a neutral information source should be available; preferably one in every local community. The families could there get basic information about passive houses from someone with no interest in making money from the family. The families could get help to order the right thing from the building companies and discuss different options and choices and their influence on the final result.

6 Apartment buildings in Alingsås, Brogården

Alingsås (latitude 57°55’48 N) is a small but growing town close to Gothenburg on the Swedish west coast, with a very committed local government, working with a holistic approach to the energy use in the community. In this chapter, the renovation process of the demonstration building in Brogården is described, together with measured results in the evaluation made after renovation.

Already in August 2005, the general manager at the public housing company Alingsåshem decided that the next renovation of a building within their housing company should be performed in a new direction compared to what they had done before. The buildings that were in line to be renovated within their building stock were the Brogården area that contained 40 apartment buildings with a total of 300 apartments (Figure 6.1). It was decided to start with renovating one building with 18 apartments as a demonstration project to see if it was possible to renovate the building to work as a passive house. The project in Brogården has been a part of the SHC-IEA Task 37 that was running from 2005 – 2010 (IEA, 2006).

During the period 1965 – 1975 the Swedish government decided to build one million apartments in ten years, to get rid of the housing shortage (Berggren, Janson & Sundqvist, 2009) These buildings were mostly prefabricated and their design was to a high extent optimized to achieve a rational building process. The same building construction as in the apartment buildings in Brogården was used in many of these projects, and buildings with the same design from this period can be found in almost every city in Sweden. Most of these buildings are now in need of renovation, just as the buildings in Brogården, since many materials and functions have worn out. The experiences from the demonstration project in Alingsås are therefore usable not only for the other apartments in Brogården, but also in approximately 350 000 apartments with almost the same design all over Sweden, giving a great energy saving potential (Berggren, Janson & Sundqvist, 2009).

Figure 6.1 Apartment buildings in the Brogården area, Alingsås.

6.1 Background

To reduce the energy use in the existing building stock, it is most important to take the opportunity to take energy efficient measures when renovation of a building is anyway needed. As presented in Subsection 1.4.5, major renovations of buildings are also regulated according to the European Building directive (European parliament, 2010f). It is stated in the Directive that "major renovations of existing buildings should be regarded as providing an opportunity to take cost-effective measures to enhance the energy performance of a building". Major renovations are cases such as those where the total cost of the renovation related to the building shell and/or energy installations such as space heating, hot water supply, air-conditioning, ventilation and lighting is higher than 25% of the value of the building, excluding the value of the land upon which the building is situated, or those where more than 25% of the building shell undergoes renovation. Previous research has shown that it is possible to renovate existing buildings to passive house standard in mid-European countries and in that way achieve an energy level of approximately 25 kWh/m²a (IEA, 2006) for space heating. However, already realized European renovation projects have also shown that to make renovation of existing buildings into passive houses affordable it is recommended to wait until the buildings need to be renovated in any case (IEA, 2006).

Alingsåshem, the public housing company in Alingsås owns about 3000 apartments in Alingsås and the surrounding communities. Their building stock is continuously renovated as needed and in 2005 it was time to renovate the Brogården area, built in 1970. Brogården is a popular area to live in but the tenants had complained about draughts and uneven indoor temperatures. Even though earlier renovations of other apartments in the building stock owned by Alingsåshem have been extensive, problems with draughts and uneven indoor temperatures have in some cases not disappeared after renovation. Many of the decisions made in the renovation project Brogården were based on the experiences from the earlier renovation project in Östlyckan, where 325 apartments were renovated during 4.5 years and finished right before the renovation of the Brogården area started. The board of Alingsåshem decided to have the comfort of the tenant in major focus when renovating the Brogården area.

Renovating to passive houses both includes a high indoor comfort for the tenants and gives a much lower energy need for space heating, a figure that before renovation was too high in the Brogården area. A major renovation was also needed to modify the buildings in the area to be suitable for elderly or disabled persons; the goal was that 60% of the apartments in the area should be accessible for disabled persons after renovation.

6.1.1 Decision

The starting point in the renovation of the Brogården area was that the brick facades were worn out and needed to be changed, see Figure 6.2.

Figure 6.2 Worn out façade brick.

When the façade material needed to be changed anyway, the additional expense for adding new and more insulation was seen to be not that high. This made the decision to renovate to passive houses easier. Also, the windows and the ventilation system needed to be changed in the renovation, which was a very good starting point for an energy efficient renovation.

The damage to the brick façades was due to frost splitting but also to expansion of the mortar used when it absorbed acid rain, which exerted high pressure on the brick. The façade material needed to be changed but it was important for the client to ensure that the bright appearance of the area, like that created by the yellow brick façade, was retained after renovation.

It was decided that first one building with 18 rental apartments and a heated area of 1274 m^2 would be renovated. The project would serve as a demonstration project and the main purpose was to learn from this renovation and then use the experiences in the renovation of the rest of the apartment buildings in the area.

The general manager at Alingsåshem saw that the major profit of this renovation was that the tenants would get a better indoor climate with no draughts, filtered supply air and even indoor temperatures. The client also saw big advantages with the apartments being renovated to be suitable for elderly and disabled people. As a bonus, the apartments would also be very energy efficient.

Before the renovation started, the client carefully considered what the character of the area was and the way a major renovation that remedied the shortcomings but kept all the qualities of the area was to be performed. The renovation should make Brogården an area that was attractive, safe and comfortable.

The major targets with the renovation were early specified in the project;

- Enhanced indoor comfort using windows with low U-value and mechanical ventilation with heat exchanger
- Lower total energy use in buildings
- The tenants should take an active part in the renovation through meetings and information letters
- The tenants should after the renovation be able to have an influence on their indoor climate and energy use
- The technology installed should be easy to use and maintain
- The accessibility for disabled persons in the Brogården area should be at least 60% of the total number of apartments
- The level of rent should be stable in a long term perspective

In 2005, the general manager of the client sent an application to the Swedish Energy Agency to get some funding for the demonstration project. The funding was supposed to cover additional costs in the project for the planning process, detailed design solutions, management of the project during the building process, additional support from experts and monitoring of the renovated building with measurements and experiences from the building process.

Within the application, the target for energy use after renovation was set and it was said that the basic methods and systems used for passive houses would be utilized. The following specific requirements regarding the renovation were specified in the application sent to the Swedish Energy Agency:

U-values:	Windows: 0.85 W/m2K
Acoustics:	Swedish Class B, including walls between apartments and floors. In living rooms and bedrooms this means that 26 dB(A) is the highest allowed sound level from interior installations and in kitchens 35 dB(A) is allowed. Noise from outside should not be higher than 26 dB(A) in rooms and 31 dB(A) in kitchens (SS 02 52 67 edition 3, 2004)
Household appliances:	Energy efficient household appliances should be used.
Air heat exchanger efficiency:	85% (yearly mean value) 75% (at design outdoor temperature).
Solar collectors:	Yes, for domestic hot water
Drainage heat exchanger:	No
Energy source:	District heating
Solar shading:	No additional. Balconies will give shading.

6.1.2 Tenants

The general manager of Alingsåshem wants all their tenants to be part of a long-term sustainable living. To know what expectations and needs the different tenants living in the building stock of Alingsåshem have for their living situation, a deep study of the tenants was performed concurrently with the planning process of the renovation of the apartments in Brogården.

Initially, the renovation was planned to be performed from the outside so that each apartment could be renovated for maximum one week, making it possible for the tenants to stay in their apartments during the renovation. There was at that time no intention to change the layouts of the apartments, only to make sure that the bathrooms were suitable for disabled persons. During the planning process, when the renovation assumed a greater scope, it was realized that it was necessary to evacuate the tenants during the renovation.

When it was decided to evacuate, the need of more detailed information to the tenants became obvious. An empty apartment was used as a full scale demonstration apartment, where the tenants could meet and ask their questions regarding the renovation to Alingsåshem but also physically experience a renovated apartment. Meetings were held in this demonstration apartment once a week after the decision regarding renovation was taken, for the client to keep a continuous dialogue with the tenants. To inform the tenants about passive houses and the renovation project, the client had a public information meeting in a large tent just before the renovation started in April 2007.

A local news sheet called Brogårdsbladet has been distributed to the tenants, where both the client and the contractor gave information about the building process. Information about the renovation process has also been broadcast on a local television channel.

To be able to raise the rent after renovation, it was necessary for each tenant to agree to the rental raising measures taken. Examples of measures taken that allowed a rent rise were larger living rooms, renovated kitchens and a new ventilation system.

After the renovation of the whole Brogården area is finished, there will be two common premises in the area for the tenants to continue the get-togethers and the social relations that started in the demonstration apartment, which have been highly appreciated among the tenants.

6.2 Status of the building before renovation

Before the renovation started the condition of the demonstration building was investigated. The status of existing insulation in the building constructions, the airtightness of the climate shell and possible high moisture content in the building materials were investigated. The investigation was made by Ingemar Nilsson and Mats Tornevall at SP Technical Research Institute of Sweden in January 2006 (SP Sveriges tekniska forskningsinstitut, 2006) (Figure 6.3).

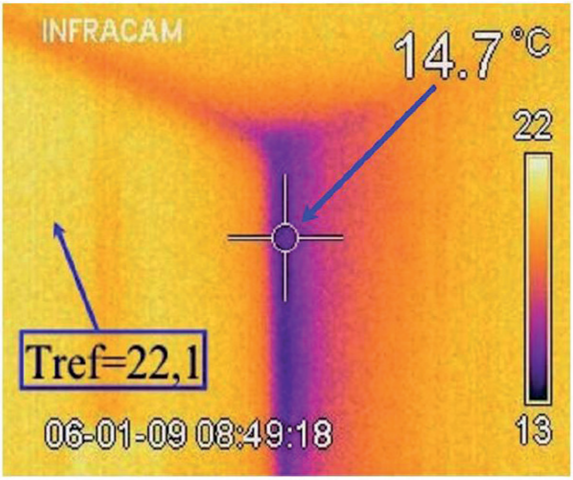
Figure 6.3 *Mats Tornevall and Ingemar Nilsson of SP, Sveriges tekniska forskningsinstitut, investigating an apartment.*

In the initial investigation, the apartments were put under an underpressure of 26 – 30 Pa and the surfaces were looked at using an IR-camera. The camera could discover surface temperatures lower than the surroundings to point out any air leakage (diffuse edges) or water content (sharp edges). Air leakage detected by the infrared camera was also measured with a meter to determine air velocity in the leaks. Any moisture content was investigated with a moisture indicator. The moisture contents in the wooden constructions were measured with a resistance meter. The result from the initial investigation showed high moisture content in all bathroom floor constructions. In addition, the supply and exhaust air terminals were in some apartments totally silted up.

The major air leakages in all apartments appeared at the joints between the prefabricated wall elements. Cold floors were common in all apartments along the outer walls, due mostly to air leakage but also to transmission losses. Outdoor air was also detected to be leaking through the outer walls, mainly in the gable junctions. Generally, there was air leakage from the balcony door in the apartments. In some apartments, the windows had come off the outer walls and air was leaking into the apartments with a measured velocity up to 3.5 m/s.

Even though the tenants complained about low indoor temperatures, measurements made of the indoor air temperature before renovation showed temperatures around 21 – 22°C. Measurements of surface temperatures on walls, floors and ceilings showed much lower temperatures than the surrounding indoor air temperature, which is known to cause discomfort. In many apartments there were also temperature differences between floors, in different part of walls etc.

To further investigate the reason for the discomfort of the tenants, the airtightness was measured in detail in six apartments according to the standard EN 13829 (SIS, 2000a). Using an infrared camera, the air leakage in each of these apartments was detected. The outdoor temperature at the time of the measurement varied between -2.4 to +1.5 °C. The mean indoor air temperature in the measured apartments was 20.9 °C. The mean value of the air leakage in all apartments was measured to 2 l/s,m^2 at ±50 Pa (surface related to leaking area) including areas between apartments. A photograph of the air leakage between two prefabricated concrete walls is presented in Figure 6.4.



Lufttemperatur 23,3 °C
Lufthastighet: 0 m/s
Kommentar: Nedkylning i ytterväggshörn. Sannolikt inblåsning i konstruktionen.

Figure 6.4 *IR-camera photograph showing air leakage in the junction between two prefabricated concrete walls, outdoor temperature between - 13 to -7 °C, no wind and clear skies (Picture: SP Sveriges tekniska forsknings institut, 2006).*

The indoor acoustics status was also investigated before renovation and showed a need for improvement.

During this investigation, many tenants were at home and told they experienced low indoor temperatures in their apartments during winter. Some said that they were adding space heating to their apartments by opening the kitchen oven and some had additional oil-filled electrical radiators to plug in when needed.

6.3 Building construction before renovation

The demonstration building was in three storeys with two stairwells. Three apartments on each floor shared a stairwell, making a total of 18 apartments. The floor plan before renovation is presented in Figure 6.5. The window area was approximately 13% of the net heated area. Each apartment had its own balcony, a facility that was very important for the client to keep after renovation to increase the quality of life for the tenants.

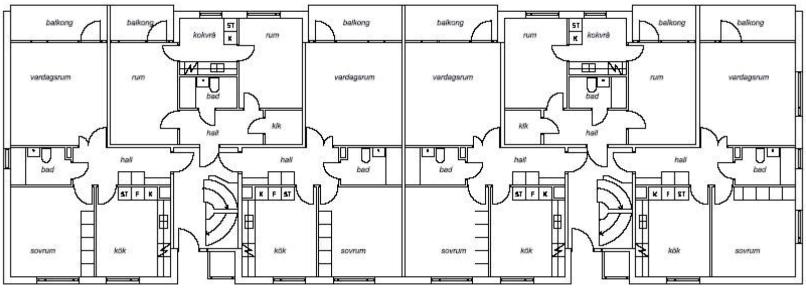


Figure 6.5 *Original floor plan of the demonstration building in Brogården (Drawing: efem arkitektkontor).*

The original concrete slab construction was founded on plinths and consisted of two layers of concrete with a layer of sand between. Below the concrete slab there was a drainage layer of crushed aggregate. The concrete quality in this building was K250. The thermal losses through the original concrete slab were severe. A major challenge in this project was to reduce these transmission losses.

The original loadbearing frame was made of prefabricated concrete. The gables and apartment dividing transverse walls were used as the loadbearing structure. This structure is called a book shelf shell or a lamella shell and was the most common building system during the period 1960 – 1975. A loadbearing floor construction separated each of the three storeys. The loadbearing gable walls were made of 150 mm concrete covered on the outside with 100 mm of insulation and 60 mm brick. The internal plastic skirting boards were worn out and needed to be changed.

Before renovation the outer walls on the long sides consisted of a wooden construction with total 130 mm insulation and 120 mm brick, see Figure 6.6.

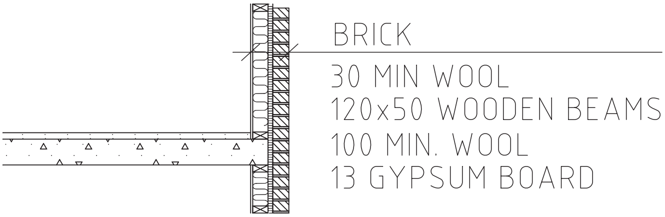


Figure 6.6 *Long side wall construction before renovation.*

The balconies were inset into the wall construction and the floors of the balconies were therefore part of the concrete floor construction in the apartments, see Figure 6.7. This caused a large thermal bridge and discomfort for the tenants (Figure 6.8).

Figure 6.7 *Original balcony construction inset into the apartments.*

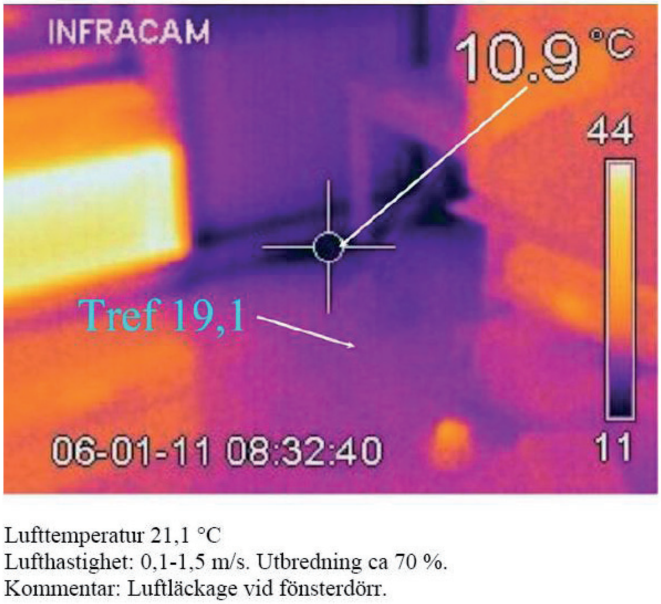


Figure 6.8 *Cold surface area on inside of the outer wall in the balcony construction. Outdoor temperature +1.0° C to +3.0 °C, windy, cloudy (Picture: SP Sveriges tekniska forskningsinstitut, 2006).*

The original attic roof construction was insulated with 180 mm mineral wool together with cellulose insulation, see Figure 6.9.

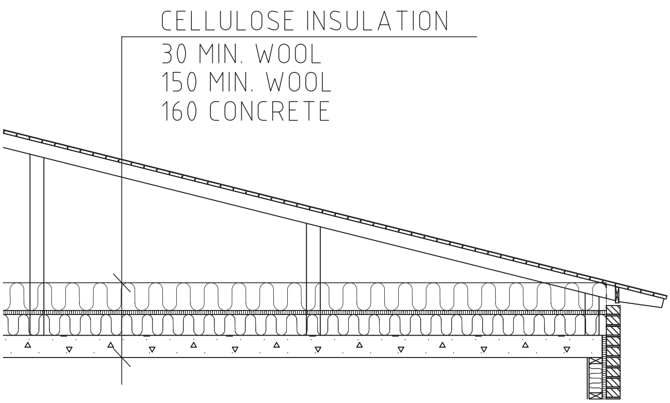


Figure 6.9 *Original roof construction, Brogården.*

The existing double glazed windows were renovated in 1985. The outer window panes of the original windows were then removed and replaced by an LE - double pane construction (2-pane D4-12, air in the gap and the pane equal to Optifloat), giving a 2+1 window. The U-value of the existing window after this pane replacement was 1.85 – 1.9 W/m^{2}K (incl. frame). However, the U-value of the window was still too high, causing a cold draught, and the windows needed to be changed. Another reason for the change of the windows was that the window frames were made of PVC, something that was not acceptable in the Alingsåshems building stock in view of their environmental policy.

The U-values of the constructions before renovation are presented in Table 6.1.

Table 6.1 U-values, before renovation.

Building envelope	U-value [W/m^{2}K]
Ground floor (excl. foundation)	0.38
Exterior walls	0.3
Roof	0.22
Windows, average	2.0
Entrance door	2.7

6.3.1 HVAC-system before renovation

The existing ventilation system consisted of two exhaust fan systems, one used for each stair well, where the exhaust fans were placed in the attic. There was no heat exchanger in the original ventilation system. Each apartment had exhaust air terminals in the kitchen and in the bathroom. The supply air was provided either by opening windows or air slits at the top of the windows.

Before renovation, the air flow rate in the bathrooms was 10-15 l/s and in the bedrooms 10 l/s, according to a ventilation inspection report from 1993. During the investigation of the status of the existing building in January 2006, some of the tenants said they experienced that the indoor air was too dry and some had placed out small bowls with water in their apartments to increase the moisture content in the indoor air. It was also revealed that the exhaust air fans in the attic were not working. Since the last ventilation inspection was made in 1993, no one knew how long the ventilation system had not been working.

The original drainage system consisted of white plastic pipes. These pipes were filmed and it was found that they were brittle and needed to be changed or repaired.

Before renovation, energy for space heating, domestic water and household electricity was included in the rent. Energy for space heating and domestic hot water was distributed by district heating. The existing water borne heating radiators were worn out.

6.4 Building construction after renovation

After renovation, there were 16 apartments in the demonstration building compared to 18 apartments before renovation. The three apartments in each stair well on the ground floor were reduced to two apartments, with four rooms one and one with two rooms together with one storage room connected to the stair well. The sizes of the new large apartments, apt 2 and apt 4, were 98m^2 and 99 m^2. The old layout was kept on the second and third storeys, with two room apartments with a living area that varied between 50 m^2 to 68m^2. The new layout of the ground floor is presented in Figure 6.10.

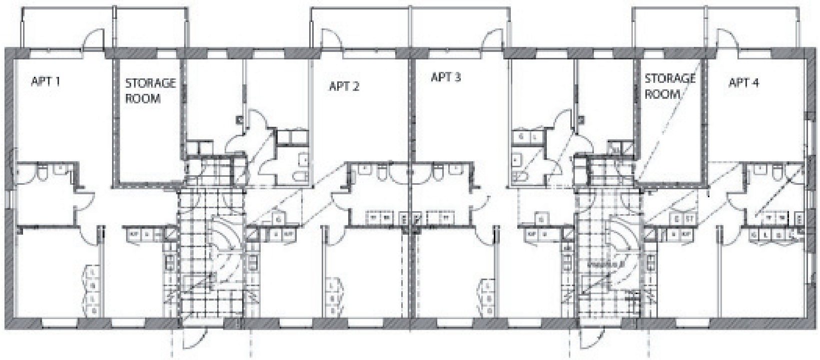


Figure 6.10 *New layout on the ground floor, left stairwell (Drawing: efem arkitekter).*

The ceiling height had to be lowered in some parts of the apartments to be able to mount ventilation ducts. The lowest ceiling height after renovation was 2.20 m.

LED-lightning was installed in the stairwells. Entry phones were installed in all apartments.

Lifts were needed in some of the buildings in the Brogården area to increase the overall accessibility. It was however not necessary to install lifts in all buildings, since not all apartments needed to be suitable for disabled persons. It was decided to not install lifts in the buildings in the area that were founded on a slab on the ground, which was the reason that no lift was installed in the demonstration building.

The part of the foundation construction that was above ground was insulated on all sides with 270 mm of EPS insulation. On the inside, the top layer of the existing concrete slab was removed together with the levelling sand layer. 40 – 60 mm of cellular concrete was added together with a layer of expanded polystyrene insulation (EPS) of approximately 60 mm.

The original load bearing concrete construction was kept after renovation. The outer walls along the long sides were new built with a steel construction and a total of 480 mm insulation. The façade material was brick panels and cement fibreboards. The new balconies were founded on plinths and were separate from the building. The balconies were made of prefabricated concrete and mounted on site. The tenants were able to choose if they wanted their balcony to be glazed.

To achieve a good indoor acoustic comfort, an insulated 70 mm steel beam was added to the apartment dividing walls and complemented with a double layer of 13 mm gypsum boards.

In the attic, the original insulation material was removed and on the existing concrete 300 mm of new loose wool insulation was added. The roof was extended to cover the new, thicker walls. The existing roof felt covering was kept. On the outside on the existing roof felt a board of 100 mm mineral wool was added to reduce overnight cooling by radiation and thus avoid moisture problems on the inside of the wooden roof construction. The layer of mineral wool was covered with new roof felt.

The new windows were low energy windows with triple glazing. The outer panes have low emissivity coating and the gaps are filled with krypton gas. The window frame is highly insulated (4LE/4 Float – 4LE+kryptongas – 10/14 VK list). There were no Venetian blinds installed, since it was seen by the client as the property of the tenant. The new windows were mounted with well thought-through solutions to ensure an airtight construction.

The U – values of the renovated constructions are given in Table 6.2.

Table 6.2 U-values before and after renovation.

Construction	U-values before renovation (calculated) [W/m^2K]	U-values after renovation (calculated) [W/m^2K]
Floor construction (excl. foundation)	0.38	0.16
Exterior wall	0.3	0.11
Roof	0.22	0.3
Attic floor		0.13
Windows (incl. frame)	2.0	0.85
Entrance doors	2.7	0.75

6.4.1 HVAC system after renovation

Instead of a new radiator system, the apartments were heated by preheated supply air after renovation. A separate ventilation unit was installed in each apartment with an air to air heat exchanger with additional heat to the supply air added by a heating coil. The units were placed in the bathrooms to minimize internally generated sound and to have connection to the drainage system. There were two AC-fans in each ventilation unit with a rated power of 58 W for each fan. The smaller apartments had a total air flow of 30 l/s and the larger apartments a total air flow of 45 l/s. All ventilation units had a by-pass function to let in unheated outdoor air in summer.

The heating coils installed in the ventilation units each had a capacity of 1.2 kW or 1.77 kW depending on the size of the apartments; 17.6 W/m^2 – 24 W/m^2 in the small apartments and 17.8 W/m^2 in the large apartments. The tenants were able to increase the output from the heating coil to increase the indoor air temperature, using a display in the ventilation unit. The original district heating connection was kept for the energy used in the waterborne heating coil in the ventilation units.

The indoor temperature in the apartments was set to be 21°C. An electrical towel rail of 70 W was installed in the bathrooms to give additional space heating if needed.

Kitchen fans were installed in each apartment. The outlets from these fans were not connected to the ventilation system. The kitchen fans were equipped with a timer.

The stairways were separately ventilated with a ventilation unit placed on the third floor in each stairway. The ventilation units had an air-to-air exchanger with an efficiency of 80% according to the producer. A heating radiator was mounted on the ground floor in each entrance. The radiator should cover the thermal losses in the hallways on very cold days. Since the apartment walls facing the hallway were not insulated, a low temperature in the entrance hall might have an influence on the indoor comfort in the apartments. The temperature in the hallway might drop drastically when the automatic door opener is needed to be used. The radiators each have a heating power of 867 W.

In each storage room, a small separate ventilation unit was placed with an air-to-air heat exchanger. This heat exchanger had an efficiency of 85% according to its producer.

6.4.2 Domestic hot water system after renovation

The original district heating supply system was kept for distribution of domestic hot water to the buildings. All water taps in the building were replaced by new taps with low flow function. After renovation, each tenant paid for their own use of domestic hot water, with the use explicitly shown on the monthly rental bill.

6.5 Simulations

The constructions planned for the renovation were used as input to the simulations with the program DEROB – LTH v1.0 (Kvist, 2006). The peak load for space heating and the energy demand for space heating were calculated for many different alternatives and solutions during the design process. The targets for the energy use set up by the client were to renovate the building to a passive house. There are at present no regulations regarding power or energy levels for renovated passive houses. The basic thought of passive houses – to be able to heat the building with the ventilation air that is needed in any case – was used instead of limitations of figures.

The building was built up in DEROB-LTH in a 3-D model as shown in Figure 6.11. In the simulations, the three storeys in the building were calculated separately, because of limitations in the simulation program. Also each stair well was simulated, giving a total number of six simulations added together to get the result for the whole building. All three storeys were simulated using a ceiling height of 2.5 metres.

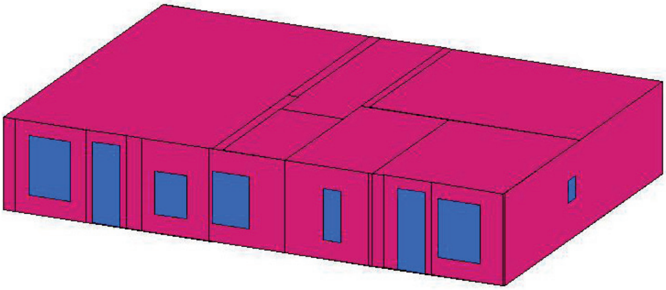


Figure 6.11 *Ground floor in the simulation of the project in Brogården in DEROB - LTH.*

There were many changes in the design of the demonstration building during the long planning process of the project. The simulation presented here is what was set when the decision was made to actually carry out the renovation as passive houses, and was not the final design. The simulations of the actual built project are presented in Section 6.15.

Input data used in the simulations in DEROB – LTH:

Heated area: 686 m^2

U-values (W/m^2K):	Floor facing ground:	0.29
	Exterior long side wall:	0.11
	Exterior gable wall:	0.14
	Roof:	0.09
	Exterior door:	0.85
	Windows (incl frame):	0.88
Ventilation:	Air leakage: 0.1 ach	
	Mechanical ventilation: 0.5 ach	
	Efficiency of heat exchanger: 80%	
	Ventilated volume: 85%	
Orientation:	The building was not rotated from south. One of the gable walls of the building was facing direct to south, with the long side walls with the balconies facing east.	
Soil resistance:	2.44 W/m^2K	
Ground reflection:	20%	

Internal gains:	3.5 W/m^2. No internal gains were added in the hallways or in the storage room.
Indoor temperatures:	In the simulations, the indoor temperature in the apartments was set to 20 °C and 22 °C respectively. The indoor temperature in the storage room and entrance hall was set to 15 °C. For the studies of energy demand or peak load for space heating, the maximum acceptable indoor temperature was set to 26 °C. Above this temperature the tenants were assumed to reduce the temperature by using shading devices and opening windows.
Climate data:	The simulations were made with climate data for Göteborg with a maximum outdoor temperature of 29.8°C, a minimum outdoor temperature of -16.7°C and a mean outdoor temperature of 7.2°C (Meteotest, 2004)

6.5.1 Calculated results

With an indoor temperature of 20°C the peak load for space heating was calculated to 11.4 W/m^2. The annual space heating demand was then calculated to 23 kWh/m^{2}a. If the indoor temperature in the simulation was set to 22°C the peak load for space heating was calculated to 12.6 W/m^2 and the space heating demand to 28 kWh/m^2,a. To these simulated values, thermal losses due to specific thermal bridges must be added.

6.6 Tendering

Already at the first planning meeting in August 2005, the idea of running the project using partnering was discussed with experiences earned from a similar project in Karlstad. The basic thought with partnering is that everyone involved in the project must always work with a defined target in mind, which was very attractive for the client. As part of the work with partnering, a local contractor participated in the planning process from the very start. During the summer of 2006 the planning process was finished and it was time to invite tenders for the project.

When working with the tendering for the Brogården project, the client came to the conclusion that all future building projects within the company Alingsåshem should be performed using partnering. Because of this decision Alingsåshem needed, during the autumn of 2006, to accept a partnering offer regarding all their building projects, not only the project in Brogården. The start of the renovation of the building was thereby postponed since this took much time. It was decided to choose the general contractor first and finally finish the planning process after that.

During the time for tendering, a lot of work was simultaneously put down by the client on how to work in a partnering project and how to steer the Brogården project in the right direction to get the desired final result.

The general contractor was chosen to be Skanska. The client had the same confidence in two of the bidders, but the contractor chosen had a greater support for passive houses high up in their organization which decided the client according to a conversation with the general manager of Alingsåshem in April 2007. The general contractor was responsible for procuring all sub-contractors and consultants. The participants in the demonstration project are presented in Table 6.3.

Table 6.3 Participants in the project.

Architect	efem arkitekter
Structural engineer	WSP Byggprojektering
Electricity consultant	Picon Teknikkonsult AB
HVAC consultant	Andersson och Hultmark AB
Advice and evaluation	Lund University, Energy and Building Design

Contractors:

General contractor	Skanska
Ground work	Landskapsgruppen
Plumbing	Alingsås Rör
Electricity	Elteknik EEA AB
Ventilation	Bravida

6.7 Planning deviations

The kitchens on the second and third floors were originally planned to be kept and only slightly renovated. The kitchen worktop and the splash guard behind the sink were supposed to be changed and one kitchen cabinet moved. But when the renovation of the kitchen started it turned out that the status of the kitchen was too bad to be renovated. A decision was taken to change all the kitchen fixtures.

To avoid draught from the entrances, at first external entrance vestibules were planned. A storage room was planned within this vestibule for trolleys and wheeled walking frames. These entrance vestibules turned out to be an expensive solution since they had to be built on site and were assumed to take a long time to finish. They also deviated from the basic thoughts of the million program building process; simplicity, repetition, rational and efficient and the client wanted to perform the renovation just as efficiently as the building was originally built in 1970. The client wanted to have a very long perspective on the renovation and did not think that external entrance vestibules were efficient enough in the building renovation production.

Late in the planning process, an additional architect was tied to the project. This architect was engaged by the client to ensure the accessibility of the buildings and to keep the expression of the area after renovation.

The tenants had asked for larger apartments in the area. To solve this, the design of the ground floor was changed but not until quite late in the planning process after the additional architect was engaged. It was decided to split up the small apartments in both stairwells on the ground floor and use them as an additional room for another apartment. The remainder of these apartments was turned into a storage room. Owing to this major revision, the ground floor could be looked at as a new produced apartment, something that made it possible to increase the rents from these apartments. It was also decided to change the planned construction of the new balconies, from the original design of being attached to the building to be freestanding on plinths. These late new decisions gave the consultants a short time to revise their designs and made the planning process long and expensive when many solutions had to be redone several times.

6.8 Training

Before the renovation started, a day of training was held in Alingsås where all engaged in the project participated. The day started with information from the client about their thoughts and vision of the result of the renovation; their goals and the importance of accessibility. The client urged all participants to keep the tenant in major focus and to have a holistic approach all through the renovation and not only focus on their special subject. During the day different experts spoke about the basic ideas of a passive house, and stressed the importance of moisture protection and airtightness in the building construction. The contractor and all subcontractors also talked about how they wanted the work with this project and goals were set e.g. regarding the working climate on the building site.

During the lunch break a combined open-air walking and quiz competition was organized by the general contractor where all participants were divided to walk in small groups. The questions were set by the persons who had been talking during the morning and each had asked a question relating to their expertise. The answers from the quiz competition were later discussed all together, giving a great sense of understanding to everyone regarding the major issues of passive houses.

6.9 The construction stage

In April 2008, the work on site finally started. To ensure a final result of high quality and to get a create a good work environment for the carpenters, renovation of the building was carried out under cover of tarpaulins (Figure 6.12).

Figure 6.12 The demonstration building covered during renovation.

6.9.1 Foundation construction

The original foundation construction consisted of a bottom layer of structural concrete, a layer of levelling sand and a top layer of concrete. In the new ground floor construction, it was planned to keep the old structural concrete and, by removing the existing top concrete layer and sand, to create a space for a layer of expanded polystyrene (EPS) insulation, without reducing the ceiling height in the apartments.

The top concrete layer was broken out down to the sand layer (Figure 6.13). A small amount of existing insulation was found on top of the sand. Small pieces of wood from the original wooden formwork were still intact in the concrete.

Figure 6.13 Removing the top layer concrete on the ground floor in Brogården.

After the top concrete layer was taken away, the sand and the thin layer of ground insulation were removed. It was then found that the concrete below was very uneven. There was a variation of 4 – 5 cm in floor level in some of the apartments, making it difficult to add a solid layer of EPS - insulation on top of it. The original planned ground floor construction with 120 mm added EPS insulation in the rooms and 70 mm insulation in bathrooms had to be abandoned.

The constructional designer then suggested to use a new material called cellular concrete, where small balls of EPS insulation were mixed with concrete and poured on the structural concrete. The λ-value of cellular concrete was said to be approximately 0.07 W/mK. It was decided to try to use the cellular concrete, since it then was possible to get an even surface and insulation added at the same time. The thickness of the cellular concrete that was spread on top of the old structural concrete varied from 30 mm to 60 mm, to get an even final concrete construction. On top of the cellular concrete a moisture proof membrane was added, then a layer of EPS insulation of 60 mm. The construction was finished with parquet flooring or plastic matting.

To be able to guarantee a slope in the bathroom floor, there was no EPS insulation added in these rooms. The cellular concrete was not used in the balcony construction.

The carpenters who worked with spreading the cellular concrete said that it took too much time to get an even surface, which was necessary to be able to add the moisture tight membrane. They said that if the cellular concrete was going to be used in following buildings, a thicker layer should be added compared to the demonstration building to be able to work with the material more smoothly.

An alternative to cellular concrete could have been to use vacuum insulation. Vacuum insulation has a fume silica core. It is a volatile material that is compressed and tempered to get stable. The pressed silica is wrapped with aluminium foil that prevents transmission, radiation and convection of heat. The silica core additionally prevents any kind of heat transfer since it is so airtight that a particle of air on one side of the silica particle will not reach a particle of air on the other side of the silica particle. It is a very light material and has a λ-value of 0.005 W/mK or lower at a mean air temperature of 22.5°C. This can be compared to EPS insulation, which usually has a λ-value of 0.034 W/mK. The quality of the material slowly deteriorates.

Unfortunately, vacuum insulation was too expensive an option. The manufacturer offered a price for the vacuum insulation in June 2007. Using standard panels with 15 mm thick insulation, covered with rubber protection on both sides would approximately have cost 60-65 €/m^2 and if the panels needed to have special measures, 10 €/m^2 had to be added to the price. The use of vacuum insulation was discussed by the general contractor but abandoned due to the high cost but also due to the existing floor area that had many uneven corners, making standard blocks of vacuum insulation impossible to use.

The thermal bridge around the ground floor concrete slab was decreased by adding 270 mm of EPS insulation on the outside of the slab, all round the building. The EPS insulation was mounted on a steel construction, see Figure 6.14. This additional insulation construction and the plinths that it was mounted on needed to be finished before the façade brick could be removed.

Figure 6.14 Thermal bridge insulation around foundation slab construction.

6.9.2 Load bearing structure

The load bearing concrete frame, including the gable walls, was kept in the renovation. The concrete gable walls were insulated on the outside with three layers of insulation (Figure 6.15). The plastic foil was attached on the outside of the concrete construction before the insulation was mounted. The plastic foil might be damaged by the somewhat uneven concrete wall. The general contractor therefore suggested an improvement of the construction in the next building by moving the plastic foil to the inside of the wall, together with a gypsum board.

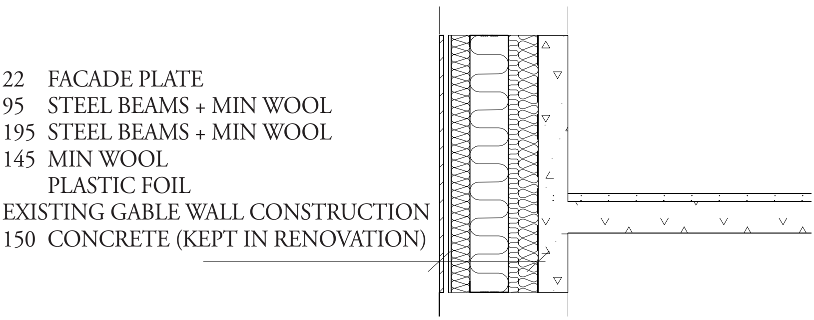


Figure 6.15 Gable wall construction after renovation.

6.9.3 Exterior walls

The existing long side outer wooden wall construction was originally meant to be kept in the renovation. It was closely investigated by SP Sveriges tekniska forskningsinstitut before the planning process started and a 400x400 mm square of the wall of was opened from the inside in one ground floor apartment. There was no moisture damage found in the wall in this investigation. When later during the renovation process façade material on the long side was completely removed from the outside, it was revealed that the insulation was discoloured and might have high moisture content (Figure 6.16). To avoid any moisture problems in the future, the wooden long side construction was completely removed and new outside walls was made. Also, according to the general contractor, the building process became more rational by removing the long side wall.

Figure 6.16 Discoloured mineral wool insulation.

It was uncertain how a new well insulated wooden wall construction would work in this area according to moisture damage. The general contractor chose to use a steel construction in the new long side exterior walls to avoid any moisture problems. The long side wall consisted of three layers of insulation followed by a layer of plastic foil. The long side wall construction is shown in Figure 6.17.

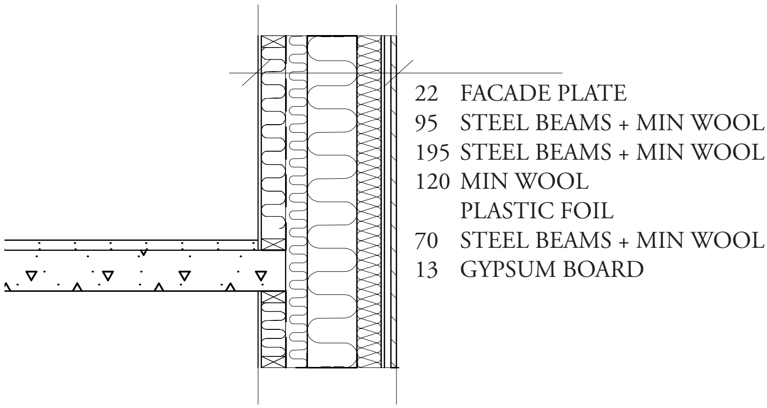


Figure 6.17 Long side wall construction.

By building new exterior walls, the existing air leakage in the junctions between the walls was eliminated. The new construction was closely sealed, to make it as airtight as required by the client; 0.3 l/s,m^2 at +/- 50Pa.

The plastic foil was mounted from the inside of the apartments and was first taped on top of a steel channel on the inside. The steel channel with the plastic foil was then pressed up against the existing concrete ceiling and put in place with vertical beams of 70 mm (Figure 6.18). The vertical beams created an installation layer that effectively protected the plastic foil when water pipes and electrical sockets were mounted. The installation layer was filled up with insulation and the wall was finished on the inside by a gypsum board.

Figure 6.18 *Mounting of plastic foil and wooden beams, creating an installation layer.*

The new façade material was suggested during the planning process to be of plaster, façade brick or boards. According to the general contractor, a plaster façade would have cost approximately half as much as the façade brick. The local housing committee said that there was a preservation order on the area. This determined the use of façade brick to keep the impression of the area and it was decided to use the Marmoroc façade brick system (Figure 6.19) which is made by clay but much thinner than traditional brick.

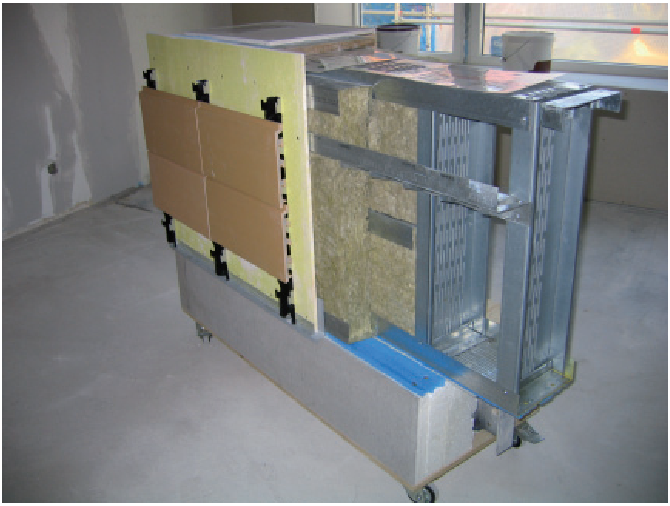


Figure 6.19 Model of exterior long side wall.

The inner walls that were not loadbearing were originally mounted on the surface concrete in the foundation construction. When the surface concrete was removed to add insulation in the construction, it was not possible to keep the inner walls on the ground floor. The general contractor said that the internal walls that were not load bearing on the ground floor needed to be removed to make the renovation production possible. The loadbearing inner walls were separating the apartments. These walls were insulated to decrease the sound transfer between apartments.

6.9.4 Balconies

The original balconies were part of the concrete building construction. This caused large thermal bridges with e.g. low floor temperatures in the rooms situated close to the balconies, as described earlier. It was not possible to reduce these thermal bridges on the floor caused by the balconies by adding a layer of insulation, since there would then have been a difference in floor level between the room and the balcony. This difference in floor level would have made it impossible for elderly or disabled persons to use the balcony; a living quality that was most important for the client to keep in the building after renovation.

Since the façade material, the wooden long side gable construction and the insulation material had to be changed anyway, it was possible to move the long side walls to a new position. The outer part of the old balcony concrete floor was sawn off, giving an even line along the long sides where the new long side walls were placed (Figure 6.20). The new balconies were standing on plinths, mounted on the outside of the façade (Figure 6.21). The gables of the balconies were prefabricated.

Figure 6.20 *Long side walls when the outer part of the existing balconies were sawn off.*

Figure 6.21 *Plinths for balconies cast separate from the building construction to avoid thermal bridges.*

The carbonized concrete in the existing balcony construction was built-in after renovation. According to the contractor, the indoor climate would not be affected when this concrete was placed indoors.

The old colour scheme of the balconies was kept after renovation, to preserve the original look of the Brogården area (Figure 6.22). The plinths where the balconies were mounted can be seen on the ground in the picture taken after renovation.

Figure 6.22 Long side façade with balconies before (left) and after (right) renovation.

6.9.5 Roof construction

The old insulation on the attic floor was removed and after cleaning, new loose wool insulation was added. The loose wool insulation was poured from a pipe suspended on the outside of the building, see Figure 6.23 and spread out to form an even layer and to reach out to the corners of the roof.

Figure 6.23 Pipe for loose wool insulation, added in the attic.

The existing roof truss was extended to cover the new balconies and the thicker outer walls. The roof was insulated on the outside with 100 mm insulation board to avoid internal cold surface temperatures on the wooden tongue (Figure 6.24).

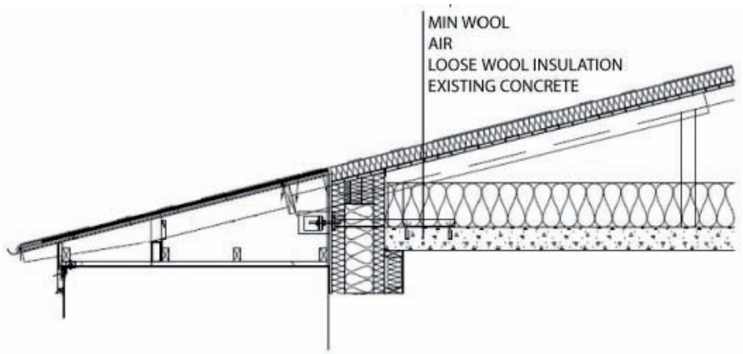


Figure 6.24 New roof construction (Drawing: WSP Construction).

The attic was totally sealed against air and was what in Sweden is called a "klimatvind". The seal against diffusion from the apartments up into the attic was placed in the concrete floor.

To get access to the roof, roof hatches were needed to be mounted, one in each stairwell. It was difficult for the general manager to find airtight roof hatches that were also insulated, which was needed to avoid creating a thermal bridge and thus an increased risk of moisture problems.

6.9.6 Windows and entrance doors

The daylight availability was closely investigated when the new windows and balconies were chosen and the architect made close evaluation of the solar angles before the final design was set. Both fixed and operable new windows were mounted. Both the client and the general contractor had experiences of Dreh-kipp windows to have a high maintenance cost, which was the reason why this type of windows was not chosen in this project.

The window sills were tilted to optimize daylight. The plastic foil was closely sealed around the window openings by the carpenters (Figure 6.25). Additional sealing paste was spread around the window to get an airtight final construction.

Figure 6.25 The sealing of the window sills.

The material used around the windows and the balcony openings is a cement covered board. The material was chosen since it had very good qualities regarding moisture exposure. However, it turned out to be very difficult to work with for the carpenters and very difficult to saw. It was also a very expensive material and was decided to be changed in the future renovation of the area.

The U-value of the entrance doors required by the client, 0.6 W/m^{2}K, was impossible to reach since there were no doors with such low U-value on the market. The general contractor spent much time on finding a suitable entrance door and finally a glazed entrance door with an overall U-value of the 0.75 W/m^{2}K was bought. To get an entrance door with such a low U-value became very expensive.

It was also difficult to get airtight entrance doors for the apartments. Since all apartments had their own ventilation unit, it was important that the apartments were airtight to ensure that the heat exchanger had high efficiency. The airtightness was a new parameter never measured by the door producers; they had only measured the leakage of smoke through the doors. Also the issues of safety (peep-hole) and accessibility (door bell) were parameters that would decrease the airtightness of the doors and needed to be considered. The doors finally installed had no peep hole and no door bell.

6.9.7 HVAC -system

It was important for the client to remove the existing radiators and to make the apartments heated by air. This was mainly for psychological reasons; that the tenants should experience that the building was much improved by the renovation. This was especially important for the tenants who were living in the apartments, evacuated during the renovation and later moving back. If the heating radiators had been kept in the renovation, the client thought it might be difficult for the tenant to see the major improvements made with the building.

In the initial discussions, the HVAC consultant was concerned that the bathrooms could become cold if the radiators were removed. It was then decided to make provision for adding a radiator afterwards if needed by keeping the distribution pipes from the old heating system. One electric towel dryer was installed in all bathrooms to ensure a good indoor comfort. The dryers have a rating of 70 W.

During the planning process there was a discussion to use either a central ventilation system or to use individual ventilation units in each apartment. Initially, the client wanted one ventilation unit in each apartment, which was something of a heritage from the terrace houses in Lindås. A central ventilation system could also have been used with one ventilation unit complemented with a heating coil in the supply air system in each apartment. The central unit would then have had to be placed in the attic, since there was no basement in this building.

Many different placements of the central ventilation unit were tried during the planning process; two examples are shown in Figure 6.26 and Figure 6.27. If one central ventilation unit had been used, a separate room would have been needed to be built around the ventilation unit to have enough space for maintenance. The placement of the ventilation unit in Figure 6.26 would have needed a room for the ventilation unit with a ceiling height greater than the existing roof truss. To avoid a reconstruction of the roof, this alternative was rejected. The more central placement of the ventilation unit as shown in Figure 6.27 allows a higher ceiling height in the room for the ventilation unit, but not high enough regarding current regulations (VVS-Installatörerna, 2002). Besides, both options would have needed a placement of the ventilation ducts far out in the attic where the working space for the contractor was very limited and did not provide a healthy working environment.

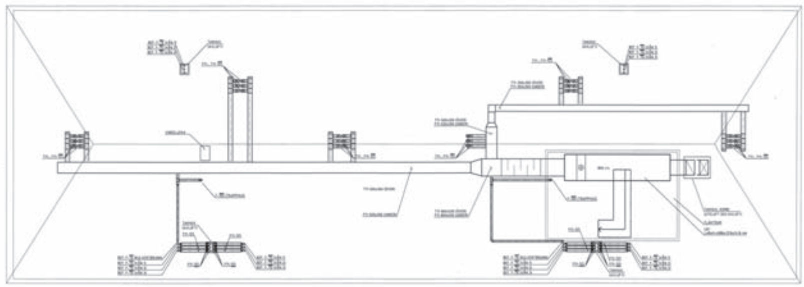


Figure 6.26 Placement of the central ventilation unit in the attic, with supply and exhaust air ducts (Illustration: Andersson och Hultmark).

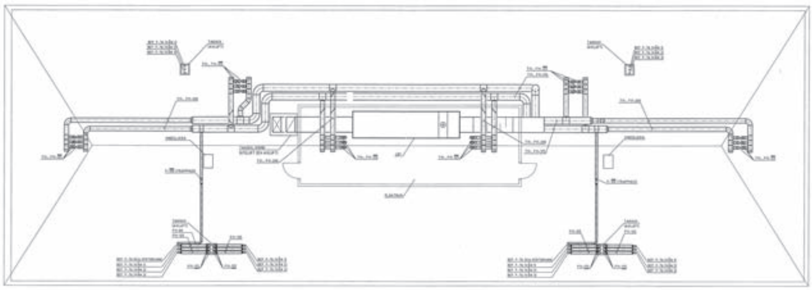


Figure 6.27 Another alternative placement of the central ventilation unit in the attic, with supply and exhaust air ducts (Illustration: Andersson och Hultmark).

The client took the decision to have one separate ventilation unit in each apartment to make it possible for each tenant to vary their own indoor temperature according to a conversation with the general manager of Alingsåshem in April 2007. Also, in this solution there would be no need for long ventilation ducts in the attic or to rebuild the roof. It was planned that all ventilation units should be running on December 20, 2008 to ensure a good indoor climate when the tenants move in on February 1, 2009.

The supply air to each separate unit was admitted through air intakes in the façade and the exhaust air was discharged on the roof. The outdoor air in the supply air duct therefore passed through a room in some of the apartments before it reached the ventilation unit in the bathroom. These ducts were insulated with 50 mm of condensate insulation to avoid a thermal bridge. It was a long process to choose the right supply air terminals.

The terminals had to provide a suitable air distribution both in summer when the by pass function was activated, and in winter when the supply air should warm up the apartment. It was very difficult to find such a terminal that worked perfectly with both heated and unheated air and at such low air flows as needed in dwellings.

The drainage system was changed, due to its age. The original concrete foundation slab was reinforced both in the top and in the bottom of the construction. For this reason it was very expensive to drill in the concrete slab and relining was a more inexpensive solution. The pipes were therefore partly replaced and partly relined.

6.9.8 Solar panels and domestic hot water

To decrease the use of domestic hot water, the baths were removed in the renovation. If it was asked for by the tenant, a new bath was installed.

The energy for space heating and domestic hot water was distributed by district heating also after renovation. The client originally wanted to have solar panels added on the roof of the Brogården area for domestic hot water supply. Since the Brogården area is connected to the district heating system, Alingsåshem decided to let the local district heating company help them out with the solar panels. Alingsåshem has a very close connection to the local heating company, sharing both the basic idea of decreasing the energy demand in the community and also sharing office space to maintain a good co-operation. To make sure the maintenance of the solar panels would be taken care of by experts, the heating company will be in charge of new solar panels, which will be added to the district heating system also connected to Brogården.

6.9.9 Increased accessibility

To increase the accessibility of the apartments, all apartments on the ground floor were given new kitchens. The kitchens had to be removed in any case to make it possible to remove the existing floor construction.

To be able to mount the ventilation ducts and the water pipes in a straight line from the ground floor up to the roof, the walls in the existing bathrooms on all floors had to be moved. It was therefore decided that the bathrooms in all apartments would be made larger and totally renovated instead of the initial thought of only making the bathroom on the ground floor accessible for elderly or disabled persons.

Other changes made to increase the accessibility was e.g. a detailed planning of the usability of each apartment to make sure it was suitable for elderly or disabled persons, renovated entrances to be more distinct to make life easier for the visually handicapped. Also, a bench was mounted outside each entrance for tenants to rest, wait for company and designed to be easy to stand up from.

6.10 Additional experiences

Experiences from all participants – consultants, contractors and the client – were continuously collected during the work with the demonstration project and assembled in a data base. This base was very much used in the following planning process and in the training for the work with the buildings in the next stage. Both large improvements and small details were mentioned. One major experience from the demonstration project, pointed out by all contractors, was the importance of using standard materials with standard sizes.

The team of carpenters working in Brogården was the same as in the contractors' latest job. The local manager estimated that the level of performance was the same in both these projects.

6.11 Economy

According to the client, the cost of the renovation was divided in three parts;

1) Energy saving measures,
2) Improved standard of the apartments paid for by the tenants (5 m^2 larger living rooms, renovated bathrooms etc.)
3) The maintenance cost for the buildings, in any case needed.

The energy saving investment was assumed to be paid back within 10 years, depending on the development of the energy price according to a conversation with the general manager of Alingsåshem in April 2007.

Together with the decrease in the energy costs, it was also very important for the client to make it possible for tenants to stay in their apartments when they get older. There are subsidies from the Swedish National Housing Board if it is possible for people to stay in their apartments when they get older, instead of moving to a nursing home. These subsidies were used by the client (Boverket, 2010).

Since the need of maintenance and higher standard of the building was so extensive, the cost for making the building energy efficient was not predominant in this project. The client made a rough calculation of the goal for the investment cost for each apartment, showing that the cost for the higher standard was approximately SEK 590 000, the energy saving measures SEK 270 000 and the maintenance SEK 140 000, giving a total investment cost of SEK 1 000 000 according to a lecture held by the general manager at Alingsåshem in April 2009. The client has no profit on this project. In their financial calculation, an energy price increase of 5% is assumed. 50 years is used for the calculation.

The actual cost for the renovation of the demonstration building was higher than the goal of SEK 1 million/apartment set up by the client as the total cost. In the renovation of the buildings in the area following the demonstration project, the goal is getting closer but according to the client, it will be difficult to reach this financial level in the buildings where a lift is installed.

It took 11 months to renovate the demonstration project. The rest of the buildings in the area will probably need 6 months to be finished, according to the client, which will reduce the cost of the renovation.

The rental cost in the Brogården area before renovation was SEK 734 /m^2. After renovation, the apartments on the ground floor will have a rent of 1101 SEK/m^2. The apartments on the second and third storeys will have a rent of 893 SEK/m^2. The apartments in the buildings with a lift installed will have an additional rent of 24 SEK/m^2 on the second and third storeys. The higher rent on the ground floor apartments is explained by the new built standard of these apartments. It is very important for the client to keep the rents at a stable level. The levels presented here will not be changed for the following five years.

In all apartments, the move of the balconies increases the rentable area by 4-5 m^2/apartment.

6.12 Energy performance before renovation

The total energy use in the demonstration building was measured before renovation (2004). The demonstration building was then one of four buildings that shared one energy distribution subcentre. The energy use was measured for all four buildings and the energy use for one building was obtained by dividing the measured total energy use by each building's living area. Because of this there might be some small errors in the total energy use presented in Table 6.4.

Table 6.4 Total energy use before renovation.

	Energy use [kWh/m²a]
Space heating	115
DHW heating	41
Household electricity	39
Electricity, common area	20
Total	215

6.13 Measurements

Measurements of actual energy use in the apartments in the demonstration building were made together with the local energy company, Alingsås Energi. The measurement of actual energy use was supposed to start as soon as the tenants moved in on February 1, 2009. However, there was a lack of information between the energy company that owned the meters and the client, who has commissioned the metering. The meters were mounted, but the voltage was not turned on over the meters. This was revealed in April 2009, causing a delay in the measurements. After the voltage was turned on in April 2009 the measurements started and were finished in April 2010.

It was decided to measure the energy use for space heating in one apartment on the ground floor in the north stair well and also in both the central inlets in the two stair wells.

Individual measurement of household electricity and the volume of domestic hot water were made by Alingsås Energi in all apartments since this was paid for by the tenants. Domestic hot water was at first included in the rental cost after renovation. When the individual meter system for domestic hot water was working properly, each tenant paid for their own use of energy for domestic hot water. The household electricity included the electricity used by the fans in the ventilation unit.

The electricity for common areas was measured by Alingsås Energi in the old distribution subcentre, including four buildings, as described in Section 6.12. This made it difficult to know the exact amount of electricity for common areas used in the demonstration building.

The indoor temperature was measured within this study in six apartments, two on each storey, using Tiny-Tag meters.

In the gable apartment on the ground floor, measurements were made within this study of floor surface temperatures and relative humidity and temperatures in the exterior long side wall construction.

6.14 Results from the measurements

6.14.1 Airtightness

The airtightness was in major focus when the exterior walls were reconstructed. The client had negative experiences from earlier renovation projects, where the air leakage remained after the renovation, and wanted to avoid this in the Brogården project. The air leakage in all apartments was measured after renovation by the general contractor. The measurements were made using the European standard EN 13829 (SIS, 2000a), giving a mean value of 0.2 l/s,m^2 at +/- 50 Pa (surface related to leaking area facing outdoors). This was a great improvement compared to the measurements made before renovation, which showed an airtightness of 2 l/s,m^2 at +/- 50Pa.

An infrared camera was used in this measurement as a complement to detect the air leakage. The outdoor temperature was at the time of measurement +2°C. The tenants had not yet moved in when the measurement was made, giving an indoor temperature between +17°C and +19°C, which was lower than in the measurement made with the infrared camera before renovation. The indoor surface temperature in the apartments might therefore be lower in the measurements made after renovation. This makes it difficult to make a direct comparison of the two photographs taken with the infrared camera before and after renovation as presented in Figure 6.28. Still, the large difference in surface temperature in the upper corner on the first measurement due to air leakage is almost invisible on the second picture. This shows a major decrease in the air leakage in the joints between the outer walls. It should be noticed that the surface temperature after renovation was measured to be only 0.5°C lower than the indoor air temperature.

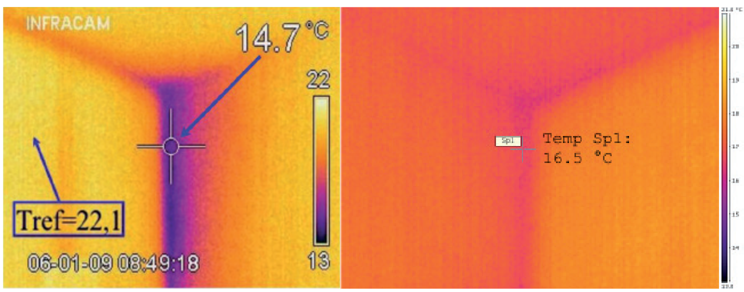


Figure 6.28 *Air leakage in the junction between the wall elements before (left) and after (right) renovation. (Picture: SP Sveriges tekniska forskningsinsitut and Skanska).*

6.14.2 Moisture

The existing long side outer wooden walls were found to be affected by fouling when opened as seen in Figure 6.16. It was uncertain how the existing wall would react according to moisture aspects after renovation and if it might be affected again. Wood is sensitive to moisture and even an environment with relative low humidity content can cause a biological activity on the material e.g. mould growth (Nilsson, 2004). Spores and mycotoxins from mould growth that reach the indoor air can affect health and should be avoided. Earlier research has shown that if mould growth is established on a building material and the relative humidity increases, there is a large chance of future growth on the material (Johansson, 2003).

As a rule, the critical level of relative humidity for wooden materials is higher at lower temperatures and at really high temperatures (Nilsson, 2009). However, the levels differ much between different materials and its history before it is mounted; handling at time for storage, on the building site etc. How dirtied the material is has also a great influence on what levels of relative humidity that is critical for microbial fouling. Another important parameter is the duration of exposure, that has a great influence on fouling and when it appears. If a wooden material is exposed in propitious conditions for fouling but moved to an area with a lower relative humidity, the fouling process can be interrupted. If the material has been dried and the relative humidity in the surrounding increases, the fouling process starts again but from a lower level of spore content than before the drying started. It is though seen to be difficult to know on what level of spore content at the material surface the growth starts.

Current research shows that it is difficult to set simple limited values for mould growth in a wooden material (Nilsson, 2009). Not only the relative humidity in the surroundings and the moisture ratio has an influence on the growth, also the temperature, the air velocity, light and duration of the relative humidity affects the grow rate. Other research presents that there is no risk for mould growth at a wooden material at a relative humidity below 70%, small to moderate at a relative humidity of 70-85% and large risk at a relative humidity above 85% (Nevander & Elmarsson, 1994).

In the Swedish building code published in 2006 (Boverket, 2006a) the levels of relative humidity is regulated to be at the most 75% for building materials where critical levels of moisture content not are well investigated and documented. This was a new regulation in this building code and since this way of moisture content has not been documented like this before there is a lack of such information for many building materials, including wood. The connection between high humidity and mould growth in wooden constructions are studied in the Woodbuild project (Nilsson, 2009).

Available research, together with practical reasons in order to ease the renovation process for the general contractor, was the base for the decision to completely remove the existing outer wooden wall construction and replace it with a new construction as described in Section 6.9.3.

It was discussed in the planning process if it was possible to build a new outer wooden wall construction according to both the regulations and the uncertainties of how wood would be affected due to outdoor climate conditions. It was difficult for both the general contractor and the consultant to know how the outdoor climate would affect on a new wooden wall construction and thereby a risk of new fouling as in the old construction, since the climate was the same as before. To avoid any risks, the new outer walls were decided to be built using a steel construction. However, for future knowledge, the moisture content and the corresponding temperatures at four different depths of the outer wall construction was measured in one place in the western façade and in the outdoor air as a reference. The measurement was performed to investigate what levels of humidity that appeared in the construction and if a load bearing wooden construction could be used in future projects.

Measurements were made of the relative humidity and the temperature in the wall at four different depths. The probes were placed as presented in Figure 6.29. The measurements of relative humidity and temperatures started in 081225 and were finished in 091225.

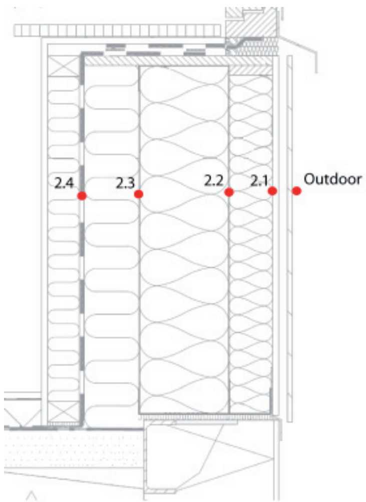


Figure 6.29 *Four measuring points in the outer wall construction and an outdoor reference measurement.*

The number of measurements made each day during the measuring period varies. The calculated mean value of the relative humidity for each 24 hours during the measuring period 2008-12-25 to 2009-12-25 varies as presented in Figure 6.30. The calculated mean value of the relative humidity was above the, in the Swedish building regulation set, critical value of 75% for 219 days in the first measuring point (2.1) and for 142 days in the second measuring point (2.2) during the year of measurement. These periods, however, were cold. In measuring point 2.3 and 2.4 the mean value of the relative humidity was not above 75% at any time.

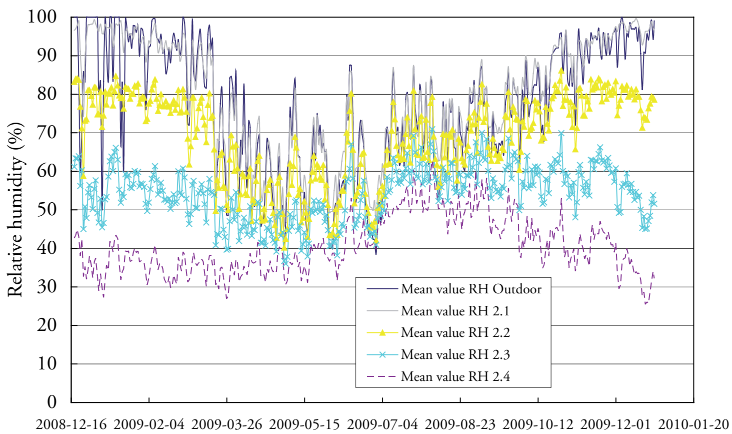


Figure 6.30 Daily Mean value of relative humidity in the four measuring points during the measuring period 081225 – 091225.

Well investigated and documented critical values of relative humidity in correlation with temperature and durability were presented by Viitanen in 1996 (Viitanen, 1996). According to these studies, the critical levels of the measured relative humidity in wood according to initiated mould growth, RH_{crit} (T,t), could be drawn as a straight line as showed in the graph Figure 6.31, valid for a duration of four weeks (Nilsson, 2009). The measured relative humidity and corresponding temperature during the time period 081225 – 091225 varies in the four measuring points as presented in Figure 6.31. Each point in the graph represents a mean measured value for one day and night. The number of days and nights with a mean value of the relative humidity above RH_{crit} (T,t) as set in Figure 6.31 was 20 days in measuring point 2.1 and none in the other points. The limit of duration of a too high relative humidity for four weeks was by these measurements not exceeded.

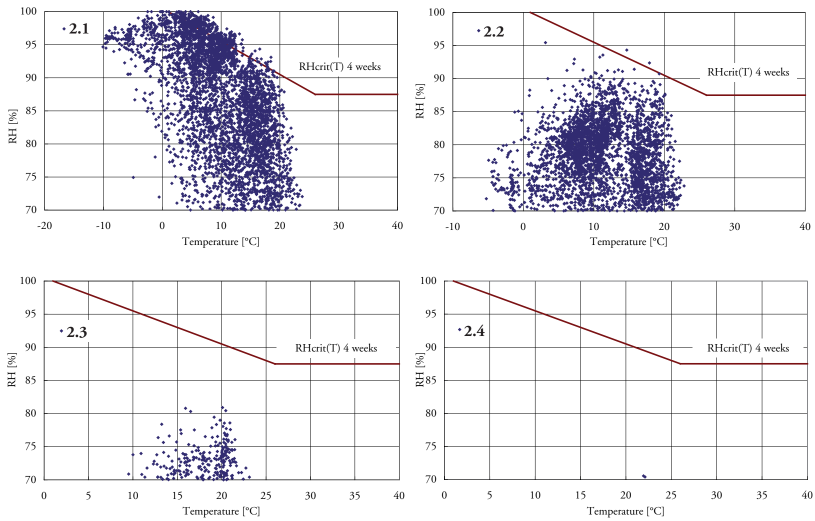


Figure 6.31 *Relative humidity and temperatures in the four measuring points during the measuring period 081225 – 09122. Each point in the graph represents a mean measured value for one day and night (24h).*

The vapour content (*v*) was calculated based on the measured relative humidity as presented in Figure 6.30 and the temperature level in each measuring point, by using an equation for the vapour content at saturation as a function of temperature. The calculated values of the vapour content in the four measuring points together with the measured values in the outdoor reference point for the measuring period 081225 – 091225 are presented in Figure 6.32. It can be seen in Figure 6.32 that the highest vapour content appeared in July 3, 2009.

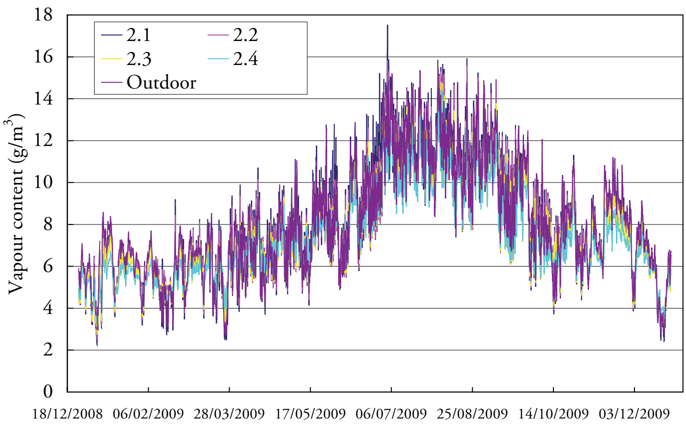


Figure 6.32 *Calculated vapour content in the four measuring points and the outdoor reference point during the measuring period 081225 – 091225 based on all measured values.*

Looking at the vapour content in the wall in July 3 2009 when the highest vapour content was measured, it varies as presented in Figure 6.33 with the highest vapour content in the outer part of the construction and the lowest vapour content in the inner part of the construction.

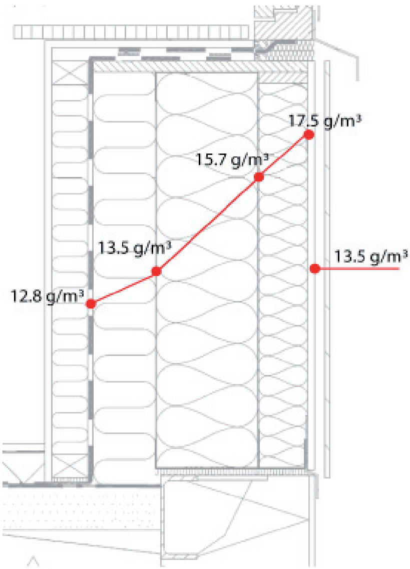


Figure 6.33 *Calculated vapour content in the four measuring points and the outdoor reference point during the day of highest measured values; 090703.*

Higher vapour content causes a vapour transport by diffusion towards lower vapour content. In Figure 6.34 the monthly mean value of the vapour content in the construction is presented. It can be seen in the figure that there is a lower vapour content in the inner part of the construction (2.4) all year. Studying these measurements it appears as if there is a vapour transport towards the most inner layer of the wall construction.

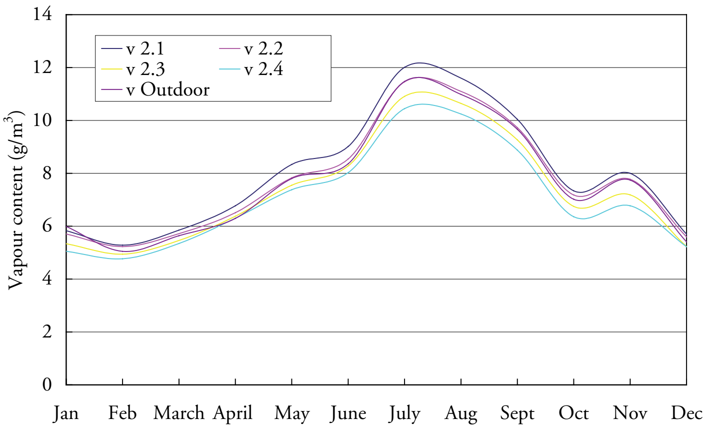


Figure 6.34 *Monthly mean value of vapour content in the four measuring points and the outdoor reference point during the measuring period 081225 – 091225.*

In Figure 6.35 the mean value of the calculated vapour content at different depths of the outer wall construction is presented at four days during the summer 2009, where “-50” (x-axis) is outdoor, “0” is measuring point 2.1, “100” is measuring point 2.2, “300” is measuring point 2.3 and “450” is measuring point 2.4. The highest vapour content in the construction is here calculated to occur in July 1, decreasing to a lower level in August 1 and then rising to a higher level in August 31.

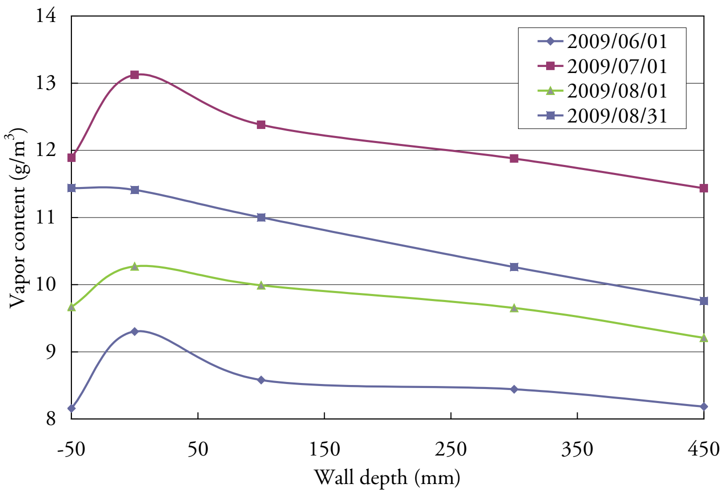


Figure 6.35 Daily mean value of vapour content in the four measuring points and the outdoor reference point during four days of measurement.

Also during winter, the calculated vapour content profile of the construction shows a lower vapour concentration in the inner part of the wall (measuring point 2.4).

According to the results from these measurements and calculations, the moisture content should constantly increase by diffusion in measuring point 2.4; on the outside of the vapour barrier. On the contrary, however, the measurements show a relative humidity below 70% all year round in measuring point 2.4 and not an increasing moisture content. These two results are inconsistent and needs to be further studied.

However, built under these conditions and in this outdoor climate, the measurement of relative humidity in the outer wall construction was below critical values during the four weeks limit as presented in Figure 6.31. Consequently, the risk for mould growth is small. Still, the limit of a relative humidity below 75% was temporary exceeded in the two outer measuring points (Figure 6.30). To further limit the risk for mould growth, a non wooden construction could be used in the outer part of the construction but in the inner part, where the building construction is very well insulated, a wooden construction could be used.

6.14.3 Energy demand for space heating

The energy use for space heating was measured by two meters; one in each stair well where each meter included eight apartments. The total bought energy for space heating for the whole building (both meters) each month during the measuring period 090401 – 100401 is presented in Figure 6.36. The heated area was 1274.4 m^2 giving a mean value of the annual use of space heating of 28.5 kWh/m^2a.

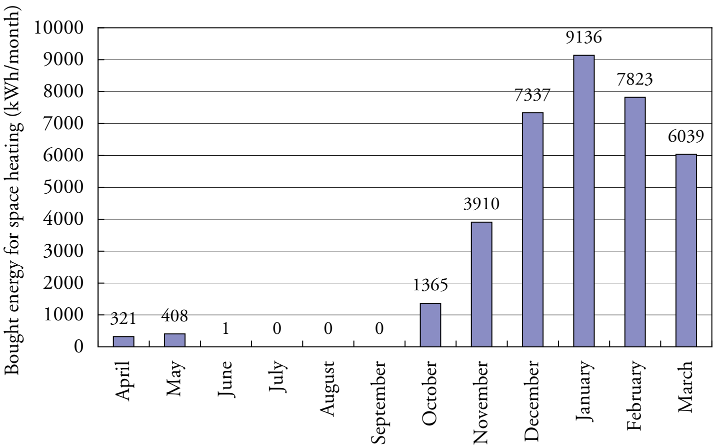


Figure 6.36 Bought energy for space heating each month during the measuring period 090401 - 100401.

In mid October 2009 the outdoor temperature dropped rapidly but there was no response in the ventilation units and no heat was distributed in the heating coils to the apartments. Some tenants got really low indoor temperatures, measured down to 17 °C (Figure 6.37).

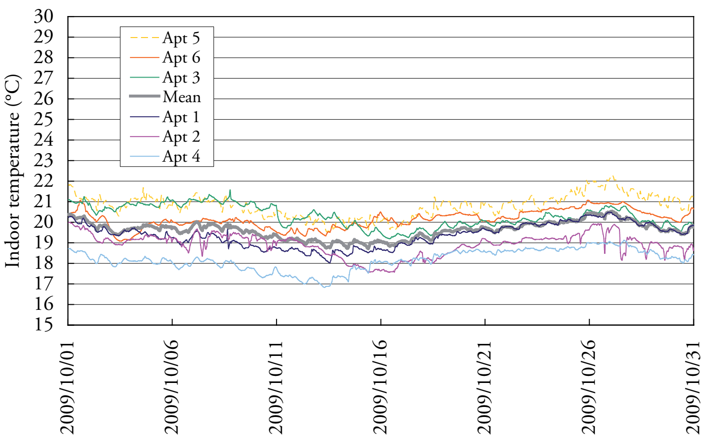


Figure 6.37 Measured indoor temperatures in six apartments during October 2009.

The reason for the lack of heating distribution in the system needed to be found very quickly to ensure the indoor comfort for the tenants. The error was discovered by looking at the measurements of the heating distribution made by the local energy company. It turned out that a valve in the space heating distribution system had been shut off in June, when the renovation of the two other buildings in the area started. Accidentally, no one had remembered to switch on the heating distribution again so no heating water could be distributed to the heating coils. The lack of heating distribution was however easy to see in the measurements of heating water flow and if the measured data had been used more regularly, the two weeks of low indoor temperature for the tenants could have been avoided.

Looking at the measured indoor temperature in October as presented in Figure 6.37, it is seen that there was a need for space heating at this period in many apartments since the indoor temperature was below 20 °C. The number of hours in each apartment when the indoor temperature was below 20 °C and by rights additional space heating was needed is presented in Figure 6.38. The turned off heating distribution between June –October 15 needs to be considered in the annual bought energy for space heating which might have needed to be higher than the measured values.

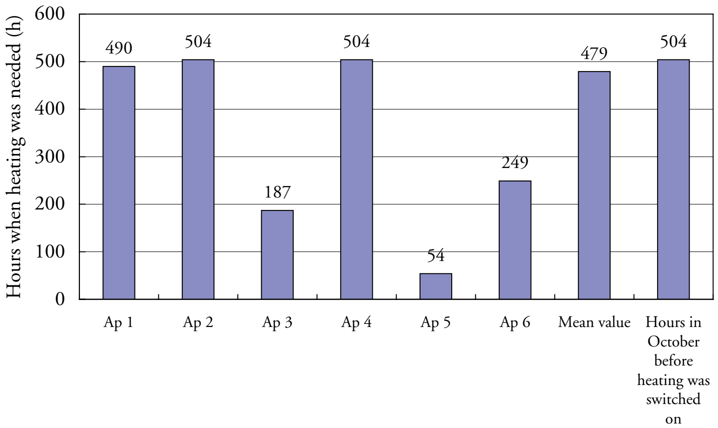


Figure 6.38 *Number of hours when the indoor temperature was below 20°C and additional space heating was needed in the six measured apartments together with the total number of hours before the heating distribution was switched on.*

6.14.4 Space heating demand revised to a normal year

The measured year had a very cold winter compared to a normal year. To be able to compare the measured figures with the simulations made and with other projects, the measured energy use for space heating was revised according to degree days using data from SMHI (SMHI, 2009). The degree days in 2009/2010 were compared to degree days in a normal year as presented in Table 6.5 where the ratio is called the regulating factor and used for recalculating the measured energy use for space heating. The degree days for 2009 were received from the web site of SMHI, but at the time of comparison, the degree days for 2010 were yet not available. The here presented degree days for 2010 were received by telephone from SMHI in May 2010. The regulating factors are multiplied by measured values of energy use for space heating.

Table 6.5 Regulating factor, degree days.

	Regulating factor
April 09	1.1
May 09	1.5
June 09	1.1
July 09	1.0
Aug 09	1.8
Sep 09	1.3
Oct 09	0.8
Nov 09	1.2
Dec 09	0.9
Jan 10	0.9
Feb 10	0.9
March 10	0.9

The annual energy use for space heating revised according to a normal year was 26.6 kWh/m^2a.

6.14.5 Domestic hot water

The volume of domestic hot water used (and bought) was measured in each apartment (Figure 6.39). The annual domestic hot water volume used in each apartment varied from 2.8 m^3/year to 44.2 m^3/year, with a mean value of domestic hot water volume used of 21.2 m^3/year and apartment.

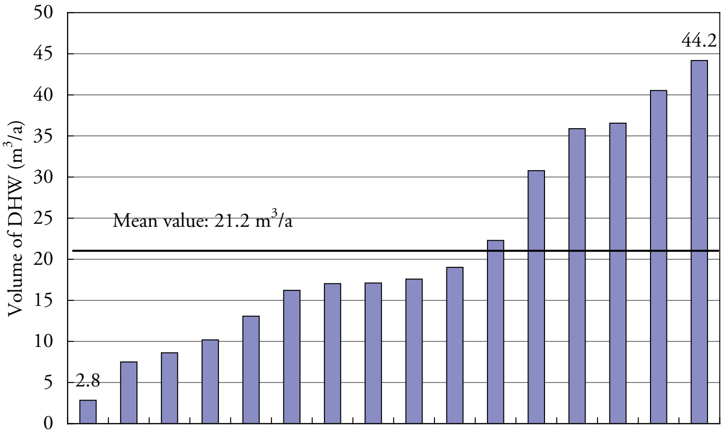


Figure 6.39 *Measured bought volume of domestic hot water in the 16 apartments during the period 090401 - 100401.*

The energy use for domestic hot water was calculated using the bought volume as a base (Equation 6.1).

$$Q = V \cdot \rho \cdot cp \cdot \Delta T \qquad \text{Equation 6.1}$$

Where

Q = Energy use for domestic hot water (kWh)
V = Volume of domestic hot water (m^3)
ρ = density of water (kg/m^3)
c_p = heat capacity of water (kJ/(kgK)
ΔT = temperature difference (K)

The cold water temperature was in the calculation set to 8 °C and the domestic hot water temperature to 60 °C. The calculated energy use for domestic hot water varied then from 3.4 kWh/m^2a to 53.3 kWh/m^2a with a mean value of 16.1 kWh/m^2a during the measuring period 090401 – 100401 (Figure 6.40).

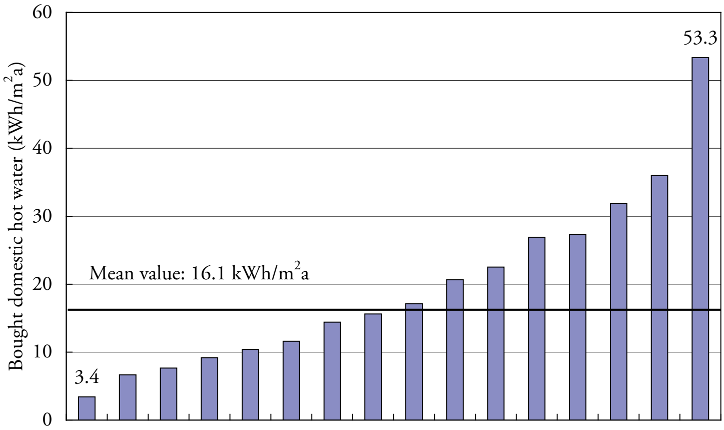


Figure 6.40 *Calculated energy use for domestic hot water per apartment during the measuring period 090401 - 100401.*

6.14.6 Fan electricity

The fan electricity was not measured in this project. The fan electricity is here included in the measured household electricity.

6.14.7 Electricity for common areas

The use of electricity for common areas is here estimated to get an approximate figure, but will not be totally accurate due to many assumptions and insecurities regarding the measured values.

The electricity for common areas was measured in one meter that included four buildings of which one was the demonstration building. Two of the buildings included in the measurements were renovated during the measuring period but the fourth building was not renovated, with tenants still living there. Parts of this fourth building were used as the changing room and lunch room for the contractors and one apartment was used as the general contractor's office. During the measuring period, an additional meter was mounted in one of the two renovated buildings.

The electricity used in the renovation of the two buildings was measured by the general contractor. The measured electricity for common areas for the four buildings was subtracted from the electricity used in the renovation process and then divided over the four buildings. The very approximate annual electricity use for common areas was in this way found to be 23 kWh/m^{2}a.

6.14.8 Household electricity

The use of household electricity was measured in each apartment. The annual electricity use during the measuring period 090401 – 100401 is presented in Figure 6.41. There was a great variation in the use of household electricity between the apartments, with a difference of almost 10 times from the household with the lowest use and the one with the highest; 6.5 kWh/m^{2}a compared to 56.1 kWh/m^{2}a. The mean value of the annual use of household electricity was 20.5 kWh/m^{2}a during the measuring period 090401 - 100401.

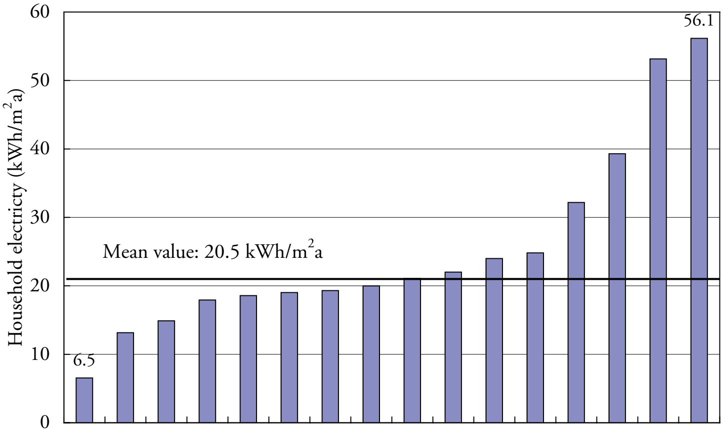


Figure 6.41 Mean value of the use of household electricity in the 16 apartments during the measuring period 090401- 100401.

6.14.9 Total annual energy use

The annual measured energy use in the 16 apartments during the measuring period 090401 – 100401 is presented in Figure 6.42, broken down by energy for space heating, domestic hot water, common electricity and household electricity.

The annual total amount of bought energy in the demonstration building before and after renovation is presented in Figure 6.43, distributed on A_{temp}. In the measured values before renovation, the use of common electricity and household electricity were not separated, giving a bought annual energy use of 215 kWh/m^{2}a. The measured bought energy after renovation, including household electricity, was 88.1 kWh/m^{2}a. The major part of the energy use was for space heating and the second largest energy item was electricity for common areas.

The decrease in total energy use including energy for space heating, domestic hot water, common electricity and household electricity before and after renovation was approximately 60%.

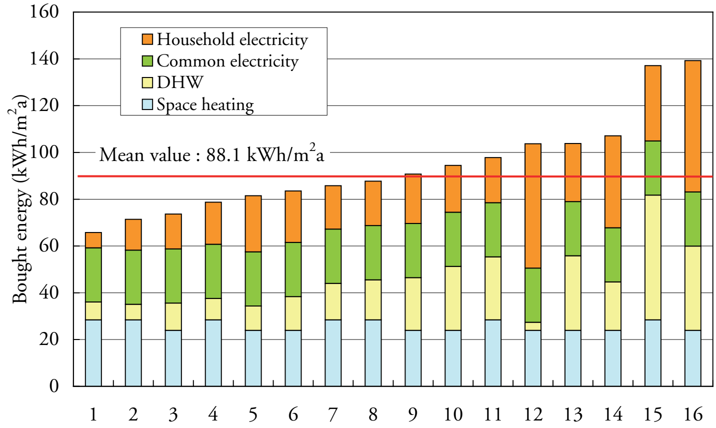


Figure 6.42 *Total annual bought energy, broken down by different energy items during the measuring period 090401-100401.*

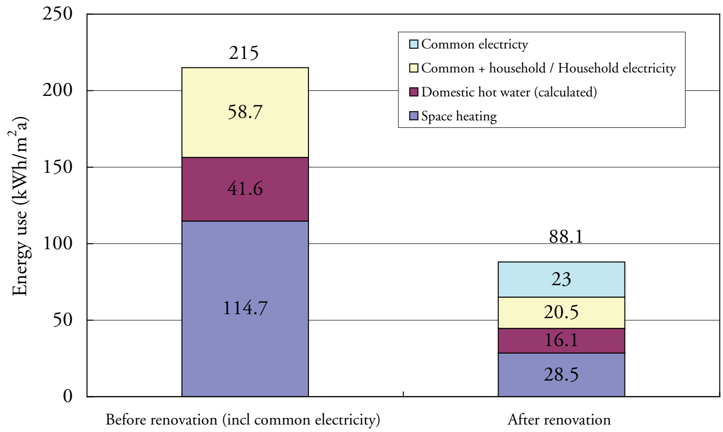


Figure 6.43 *Measured annual bought energy before (2004) and after renovation (090401 – 100401).*

The Swedish building regulations stating the allowed maximum energy use do not include energy for household electricity in the total energy use (Boverket, 2009a). The energy use for space heating, domestic hot water and common electricity was after renovation measured to 67.6 kWh/m^{2}a.

The measured bought energy after renovation revised according to a normal year, including household electricity, was 86.2 kWh/m^{2}a or 65.7 kWh/m^{2}a excluding household electricity, which is the energy use of the building according to the Swedish building code (Boverket, 2009a).

6.14.10 Peak load for space heating

The energy use for space heating was measured in two meters for the whole building. The energy use was measured every 24 hours. The measured energy use for the two meters was added and the highest energy use was noted as the day of peak load for space heating. The peak load for space heating was measured to 14 W/m^2 and was measured on January 11, 2010 after a long period of low outdoor temperatures (Figure 6.44).

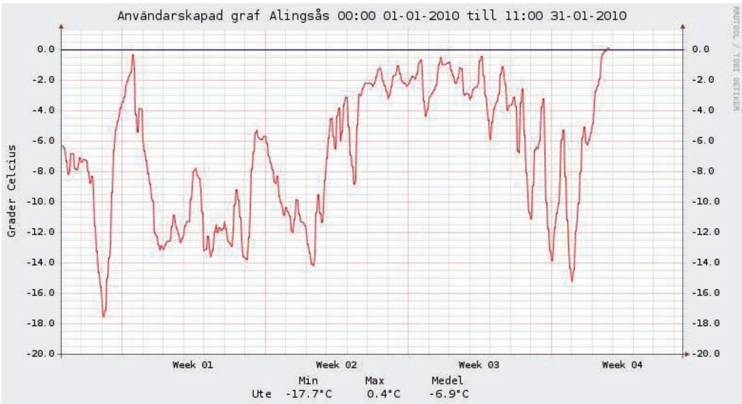


Figure 6.44 Measured outdoor temperature in Alingsås, January 2010 (www.temperatur.nu).

The mean value of the outdoor temperature on January 11, 2010 was -8.7 °C. The coldest day in Alingsås during the winter 2007 – 2008 was on January 3 with an outdoor temperature of -17.7 °C (www.temperatur.nu). The peak load simulated in DEROB – LTH for space heating appeared on February 3 with an outdoor temperature of -16.7 °C.

6.14.11 Indoor and outdoor temperatures

The indoor temperature was measured in six apartments during the measuring period 090401 - 100401. The sensors were placed in one apartment on each storey in each stair well. The measurements were made using Tiny-tag loggers placed so as not to be reached by solar radiation or heat from light bulbs. The measurement in the apartment on the second storey in the north stair well (Apt 2:1) ended on June 8, since the neighbour to the measured apartment complained about low indoor temperatures and it was decided to investigate this further (Apt 2).

The indoor temperature during the summer months was perceived very comfortable in the households living on the ground floor (Apt 1 and 4), according to the interviews with the tenants. However, the tenants living on the third storey reported very high temperatures and discomfort in summer (Apt 3 and 6). The experienced high indoor temperatures were confirmed in the measurements (Figure 6.45). There were no solar shadings in Apartment 6 but the tenant in Apartment 3 had installed Venetian blinds.

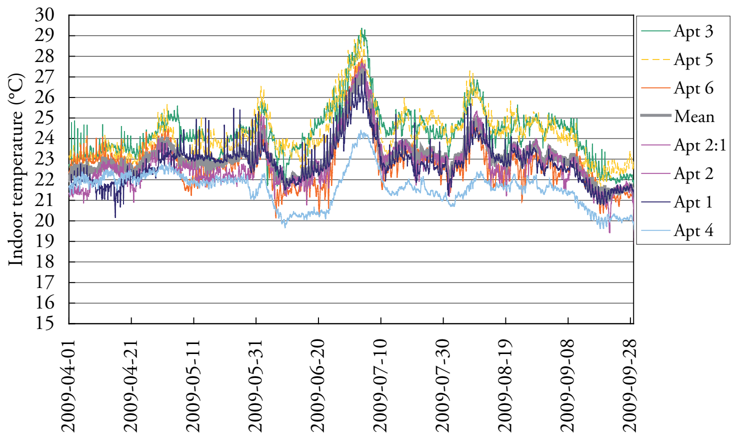


Figure 6.45 *Measured indoor temperature in six apartments in Brogården 090401 – 091001 where meter number 2 (Apt2:1) was switched to the neighbour apartment (Apt 2) on June 8 2009.*

During the cold season, some apartments had low indoor temperatures. The mean value of the indoor temperature in all measured apartments during the period November 1, 2009 to March 1, 2010 varied between 19.4°C to 22.5 °C. The tenants living in the measured apartments on the ground floor (Apt 1 and 4) and the tenant in Apartment 2 continuously reported too low indoor temperatures during the cold season. The measured indoor temperature in the six apartments varied a lot during the winter with especially low temperatures measured in Apartment 2 but also in the other two apartments situated on the ground floor (Figure 6.46), which confirmed the complaints by the tenants.

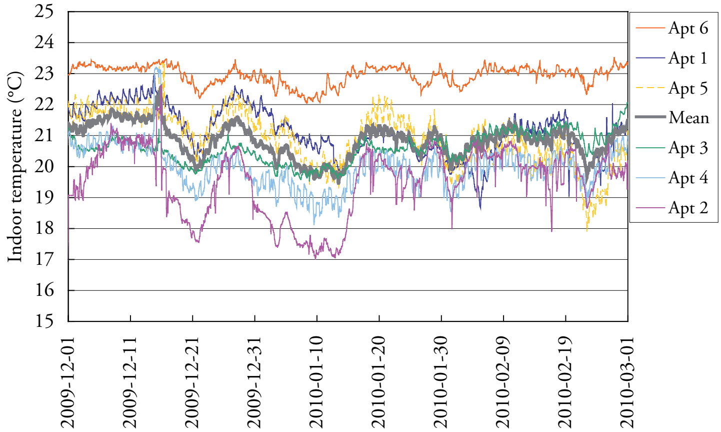


Figure 6.46 Measured indoor temperature in six apartments in Brogården 091201 - 100301.

The reason for the problem with the too low indoor temperatures had to be solved in detail. It was important to investigate if the low indoor temperatures were due to the construction; in that case a new construction was needed in future renovation of these types of buildings in the area.

It turned out that the cold indoor temperatures in Apartment 2 were due to problems in the heating coil. The inlet pipe in the coil was jammed and no heating water could be distributed to the heating coil. The tenant started to report low indoor temperatures already in summer 2009, but it was not until February 2010 that the problem was finally discovered. Before that the tenant had experienced a cold winter with measured indoor temperatures as low as 16.9 °C on both January 9 and January 12.

It was more difficult to find the reason for too low indoor temperatures in the apartments on the ground floor. First, the space heating supply was investigated by looking closely into the district heating distribution. The power for the space heating coil was designed by the HVAC consultant using a supply temperature of 65 °C for the water in the heating coil with a return temperature of 38 °C or 44 °C for the water in the heating coil depending on the desired power consumption. The temperature of the supply and return heating water was measured in both stair wells (heating mains A and B) and in the north apartment on the ground floor; Apartment 1, one of the apartments with too low indoor temperatures (Figure 6.47).

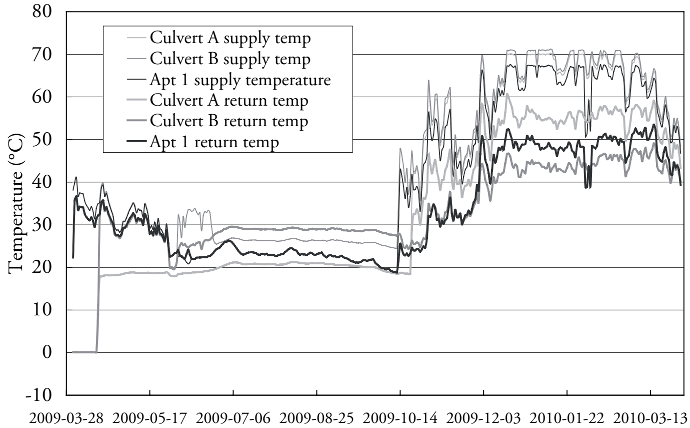


Figure 6.47 *Measured supply (thin) and return (thick) temperature of heating water in the meters placed in heating mains A and B and in Apartment 1.*

Looking at the temperature on the heating water it can be seen that initially when the tenants moved in, the temperatures were too low. The period when the district heating valve was shut can be recognized as the straight lines and it is easy to see in Figure 6.47 that it was switched on on October 15. During the winter 2009/2010, the supply temperature was almost the same in the three measuring points and kept at the level that was used in the design of the heating coils, around 65 - 70 °C. The return temperature was however higher than planned; indicating that the power consumption from the heating coils was not as high as planned. The lowest return temperature, and thus the highest power consumption, was measured in the heating coil in Apartment 1 on the ground floor. From these measurements it could be assumed that the space heating distribution was working in the winter 2009/2010 and was probably not the major source of the too low indoor temperatures.

Still, the tenants in Apartment 1 reported a too low indoor temperature during the winter 2009 – 2010. This apartment had a heated area of 68 m^2 and the measured energy use during 090401 – 100401 was 3350 kWh (49.3 kWh/m^2a). The measured energy use for space heating and measured indoor temperatures in Apartment 1 from November 2009 to

March 2010 are presented in Figure 6.48. The mean value of the indoor temperature was mostly above 20 °C and the daily energy use was on an even level during the total heating season.

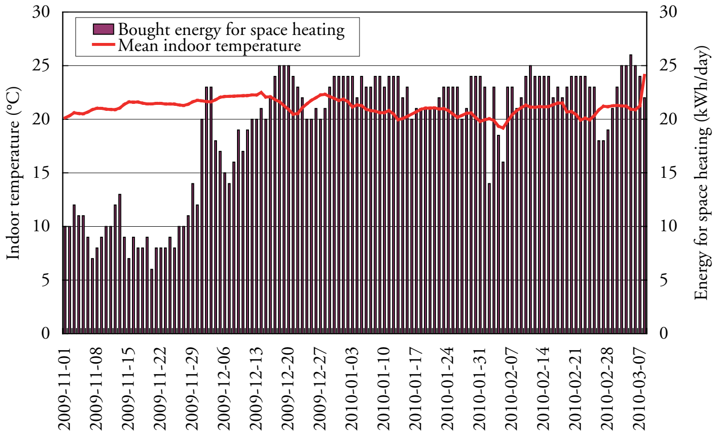


Figure 6.48 Measured daily energy use and mean indoor temperature in the apartment on the ground floor.

The installed heating load in the ventilation unit in this apartment was 1.2 kW at a water temperature of 65/38 °C and a water flow of 0.01 l/s according to conversation with the HVAC-consultant in April 2010. The measured peak load for space heating was 1083 W (15.9 W/m^2), measured on March 5 2010. The highest power consumption was approximately 90% of the available power. The available power in the heating coil seems not to be the reason for the experienced too low indoor temperatures. Also, the actual measured indoor temperatures were more than 20 °C during most of the measured time.

Another reason for the too low experienced indoor temperatures in the apartments on the ground floor could be the limited space for insulation of the slab and thereby low floor surface temperatures. The temperatures in the floor construction were measured in this research in Apartment 1 on the ground floor using a Testo-logger. The measurement period was 090223 – 100205. Four measuring points were placed in the apartment as presented in Figure 6.49; 3.1, 3.2, 3.3 and 3.4. The measuring point 3.1 was placed in the very west corner of the apartment at the junction between the end wall and the long side wall, 3.2 was placed in the same bedroom as 3.1 but further into the centre of the building, 3.3 in the bathroom and 3.4 in the living room, in the corner of the end wall and the long side eastern wall.

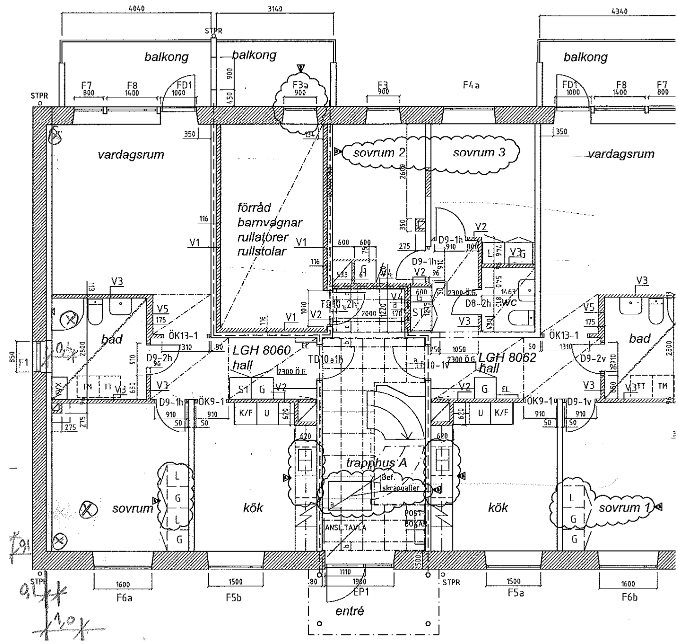


Figure 6.49 Placement of temperature meters in ground floor construction (Drawing: Skanska).

The temperature meters were placed on the moisture proof membrane on top of the structural concrete, covered with 60 mm cellular concrete and 60 mm of EPS insulation. The surface temperature was calculated using Equation 6.2:

$$R/R_{tot} = \Delta T/\Delta T_{tot} \qquad \text{Equation 6.2}$$

Where the R-value for the cellular concrete was 0.86 m^2K/W and the R-value for the EPS insulation 1.77 m^2K/W. The R_{tot}- value was 3.14 m^2K/W. The indoor air temperature was measured in one room in the apartment as presented earlier.

The calculated surface temperatures based on measurements from December 1 2009 to February 5 2010 are presented in Figure 6.50.

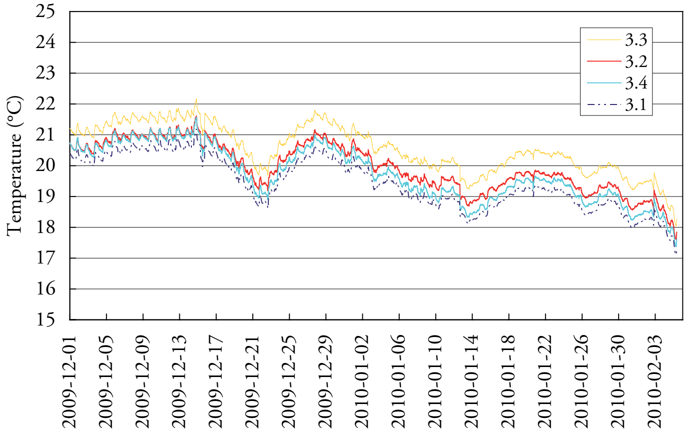


Figure 6.50 *Calculated surface temperatures of the floor at four points in Apartment 1 on the ground floor based on measured data.*

The Swedish Board of Health and Welfare recommends a floor surface temperature of 20 °C – 26 °C and that a floor surface temperature below 16 °C (18 °C for sensitive groups) should be regarded as a limit for nuisance (SOSFS, 2005). The desired temperature of 20 °C was not reached in three of the four measuring points during the entire January 2010. It seems that the experienced low indoor temperature in Apartment 1 on the ground floor was due to too low floor surface temperatures.

The indoor temperature in the other apartment on the ground floor where the indoor temperature was measured, Apartment 4, varied during the measuring period 091101 – 100301 as shown in Figure 6.51. In this apartment, the measured indoor temperature was lower than in Apartment 1. There was one tenant living in this apartment just as in Apartment 1, but this tenant took good care not to use electricity if not absolutely necessary, with very low internal gains as a result. Unfortunately, no additional measurements were made in this apartment. Lots of effort was made by the public housing company to increase the indoor comfort for this tenant. Since the towel dryer that was assumed to add space heating in the bathroom was run by electricity and thereby paid for by the tenant, it was not switched on by the tenant in order to save money. The public housing company decided to pay for the electricity used in the towel dryer to ensure a good indoor comfort for the tenant. The heating supply was also increased to the heating coil in the supply air unit, to raise the indoor temperature.

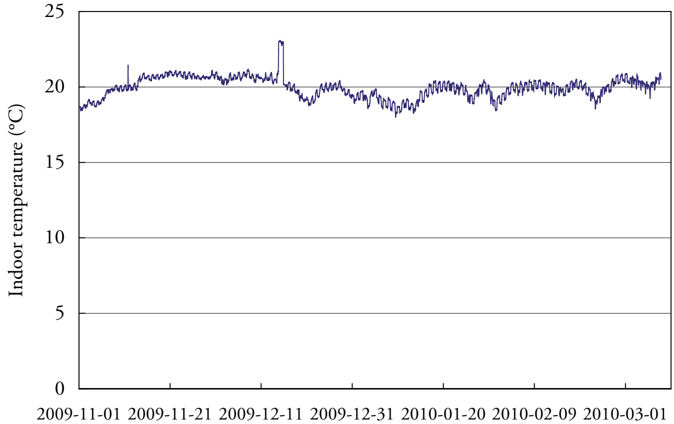


Figure 6.51 *Measured indoor temperature in Apartment 4 during the measuring period 091101 - 100301.*

To achieve a better indoor comfort for the tenants, a new ground floor construction was suggested to be developed for future similar buildings. It is however difficult to find a better solution, including all parameters of economy, an efficient building process, moisture safety, ceiling height and thermal comfort.

Since the apartments were heated by air it might be a good idea to further evaluate the supply air flow in the apartments and see if the warm supply air actually reaches to heat up the entire apartment. Maybe another solution would be needed to cover the space heating demand in the ground floor apartments. These were renovated to be the most suitable apartments for disabled persons and might therefore need a higher indoor temperature than the now measured 20 °C. To be able to keep a good indoor climate, a heating radiator could be installed instead of the heating coil and the heat exchanger in the mechanical ventilation system on the ground floor modified. It is of major importance that the tenants should be able to get their desired indoor temperature.

6.15 Correlation between measured and calculated figures

A simulation was made in DEROB-LTH v 1.0 of the final design of the building. The energy demand and peak load for space heating were calculated using an indoor temperature of 20 °C with an indoor temperature of 18 °C in the entrance and in the storage rooms. The simulated energy demand was 14.5 kWh/m^{2}a and the peak load for space heating 8.8 W/m^2 when no specific thermal bridges were added. If the indoor temperature in the apartments was raised to 22 °C the annual energy demand for the building was calculated to 17.9 kWh/m^{2}a and the peak load for space heating for the building to 9.5 W/m^2. The climate data used in the simulation was revised to a normal year, giving an energy demand for space heating of 13.2 kWh/m^{2}a at an indoor temperature of 20 °C and 16.6 kWh/m^{2}a at an indoor temperature of 22 °C. The measured energy use for space heating revised according to a normal year was 26.6 kWh/m^{2}a and the measured peak load for space heating 14 W/m^2 (Table 6.6).

Table 6.6 Calculated and measured peak load for space heating and energy demand for space heating revised to normal year.

	Energy demand for space heating revised to a normal year (kWh/m^{2}a)	Peak load for space heating (W/m^2)
Indoor temperature 20 °C	13.2	8.8
Indoor temperature 22 °C	16.6	9.5
Measured	26.6	14.0

The great difference between measured and calculated values was most likely caused by specific thermal bridges. The thermal bridges were calculated by the designer in the planning process. It was seen that especially the thermal bridges in the junction between the concrete foundation slab and the outer walls caused large thermal losses with a Ψ-value of 0.44 W/mK in the gable connection and a Ψ-value of 0.21 W/mK along the long side walls. Other thermal bridges were around windows and doors with a Ψ-value of 0.09 W/mK.

When the thermal bridges were added in the DEROB-LTH simulation the peak load for space heating was calculated to 11.9 W/m^2 using an indoor temperature in the apartments of 20 °C and an indoor temperature of 18 °C in the entrance and in the storage rooms. If the indoor temperature in the apartments was set to 22 °C the peak load for space heating was simulated to 12.8 W/m^2. The energy demand for space heating at an indoor temperature of 20 °C was 19.1 kWh/m^{2}a revised according to a normal year and at an indoor temperature of 22 °C in the apartments, the annual energy demand was calculated to 24.3 kWh/m^{2}a revised according to a normal year (Table 6.7).

Table 6.7 Calculated and measured peak load for space heating and energy demand for space heating revised to normal year, specific thermal bridges added in the simulation.

	Energy demand for space heating revised to a normal year (kWh/m^{2}a)	Peak load for space heating (W/m^2)
Indoor temperature 20 °C	19.1	11.9
Indoor temperature 22 °C	24.3	12.8
Measured	26.6	14.0

Adding the three largest specific thermal bridges to the simulation made the correlation between measured and calculated figures more accurate. The difference between measured and simulated figures that can still be seen in Table 6.7 might e.g. be due to a smaller amount of insulation used in the foundation construction than used in the simulation.

6.16 Renovation of the rest of the Brogården area

The client was very satisfied with the result of the demonstration project and in August 2008 the planning process of phase two started, where two more buildings in the Brogården area were renovated. The renovation of these two buildings started in April 2009, together with the planning process of the renovation of the rest of the buildings in the area. There were some major differences in the renovation of the rest of the buildings compared to the demonstration building.

Central ventilation units will be installed in the rest of the buildings in the area. The ventilation units will be placed in a former bedroom on the third storey, changing the original floor plan on these floors. The ducts will be placed in the attic. The apartments will also in future projects be heated by air, with one heating coil placed in the supply air duct in each apartment. The major advantage with this solution was seen by the client to be the lower need of maintenance and change of filters compared to individual units. The client had estimated that approximately 200 h would be needed to change filters in 280 apartments (one small ventilation unit in each apartment). If a central unit was installed in each stairwell, it would according to the client take approximately 30 h each year to change the filters in these units. The cost for the client for one hour was said to be SEK 350, which saves a lot of money by using a central ventilation system. There will be an additional cost for the client for the fan room that needs to be built, but this was said to be paid for by a higher rent from the tenants, when they got a larger apartment since there was no space taken in the bathrooms for the ventilation unit. A central ventilation system is however a more complicated solution regarding fire safety which is a disadvantage compared with separate units.

Based on experiences from the demonstration project, it was decided to simplify the construction of the outer walls in the rest of the buildings in the area. The wall construction in the demonstration building was too expensive, but there was also a need for it to contain fewer materials and the work for the carpenters had to be made easier. A meeting was held on the initiative of the general contractor to find a new and better design for the outer walls. The meeting took approximately two hours and, apart from the general contractor, the designer, the salesman of the outer wall building system, a carpenter and the client were present. It was important for the general manager to involve the carpenter in the development of the new wall design to ensure that it was possible to practically realize the new construction and that it was not too theoretical. In the meeting, the old design was used as a basis together with what the contractor thought needed to be changed. The new design only used two different insulation thicknesses instead of four different thicknesses as in the old design.

The demonstration project had a window construction that contained a material that was very hard to work with for the carpenters; it was both heavy and itchy. It was also very time consuming for the local manager to order the material for this construction. The material used in this original window construction was changed to use wood in future projects. To avoid any moisture damage, the wood construction was closely insulated, to keep it at the right climate.

The time saved using the new outer wall and window designs was approximated by the general contractor to 100 working hours per building. The saving in the cost of materials was estimated to SEK 100 000 per building. The saving in working hours for transport and logistics must be added to these savings. And, most importantly, the saving in the carpenters' health.

Other technical improvements were also made in the new production with for instance a new load bearing construction on top of the window.

6.17 Discussion and conclusions

The measured results of energy use after renovation in this project are impressive and show a high quality product delivered by the general contractor and their sub contractors. The results shows that it is possible to renovate a building to be very energy effective using traditional building materials and with common contractors.

However, the indoor temperature has occasionally been too low in the apartments on the ground floor and too high in the apartments on the third storey, probably due to lack of solar shadings. The low indoor temperature in the apartments on the ground floor is especially unfortunate since these apartments are designed to be suitable for elderly and disabled persons who are often sitting still and also often desire a higher indoor temperature than the normal 20 °C. The sometimes low indoor temperatures during the winter 2009/2010 together with a higher rent after renovation were seen in the interviews to be a bad combination, especially since the tenants living in these apartments were evacuated during the renovation and moved back and could make comparisons between before and after. The ground floor construction and the distribution of energy for space heating in the ground floor apartments needs to be developed further to ensure a good indoor comfort for the tenants.

There was a very long planning process in this demonstration project. It started in August 2005 and was initially thought to be finished in April 2006. The building process was planned to take only two months and to start in May 2006. In June 2006, still in the planning process, the first project leader quitted and handed the baton over to a new project leader. There would be a total of four project leaders in the project until the demonstration building was finished in February 2009. Many issues were redone or repeated when each new project leader took over and some of the initial thoughts, decisions and discussions were forgotten along the way.

The planning meetings were for a long time characterized by discussions with no decisions taken. It usually took a long time before the project leader put his foot down. When the general manager of the client was present at the planning meetings, there was a completely different feeling in the meetings. The air was filled with respect and the meetings took much less time than otherwise. This shows the importance of someone with authority to take decisions participating in the project meetings.

The preservation of the area and accessibility questions in the project took much time late in the planning process. The energy issue then needed to take second place and the major discussions during the planning meetings concerned accessibility. There were long discussions about colour schemes and how large the numbers on the façade must be to be visible for visually handicapped persons, even though the foundation construction had no really good solution. It is a good idea to have someone in the planning group that has the energy aspect as their major interest. This person could guarantee that the initially set up goals regarding energy use and indoor comfort would always be in mind when decisions are taken.

The client said that they have learnt much during the long planning process that was needed for them to be able to carry through the project. Looked at in retrospect, this made it impossible for the general manager of the client to say whether it might have been better to have waited with starting the project until they had learnt enough about how to renovate a project like this, in order to save time and money on the planning process. The early planning process was the learning curve that seemed to be necessary for the client, but might have affected both the cost of the demonstration building and the final result.

The renovation process in the Brogården area is of great national interest since the energy saving solutions have a great duplication factor in the almost 350 000 apartment buildings with the same building construction all over Sweden. Because of this, the Brogården project has attracted much attention both from the Swedish building industry and public housing companies, and many students have made studies of the project. The project has been frequently presented at seminars and at conferences.

Since the project was a part of IEA Task 37, many other countries have also been interested in the project and the presentation of this research study has been requested many times in many different countries. As part of this, a film was produced in Norway about the project (http://www.lavenergiboliger.tv/filmengelsk.html).

Inspired by the project in Brogården, the public housing company Poseidon in Göteborg made an energy efficient renovation of a rental apartment building in the Backa Röd area, finished in 2009. The project leader heard about the project in Brogården and used this information to improve the renovation measures taken in a large ongoing renovation project. This project was not so much in the media but was also documented in a brochure published within the IEA Task 37 Subtask B (IEA, 2006).

Even though the measured figures of the project in Brogården show that it is possible to considerably reduce the total energy use in the building and the media has made sure this information has been nationally spread, not many housing companies have followed, except for the project made by Poseidon. It would be interesting to make a follow-up study of this lack of courage and the reasons why not many companies duplicate the experiences gained in Brogården. New built passive houses are a slow but growing industry in Sweden, but not many renovation projects are made with goals set as high as in Brogården.

7 Common experiences

There are some large differences between the four demonstration projects studied in Chapters 3 - 6, but there are also some similarities. In this chapter, the annual energy use in all projects is compared. Also, the tenants' opinions, received in interviews made after they have been living in their passive house apartments for at least one year, are presented.

7.1 Measurements

The results from the measurement of energy use in each project are presented in the chapter dealing with the project. Here, the results of the measurements made in the four projects are compared. The periods when the measurements were made are not the same for the four projects, but the figures of energy use for space heating are all adjusted to a normal year using climate data from SMHI, in order that the measured figures may be compared (SMHI, 2009).

7.1.1 Energy for space heating

The annual bought energy for space heating varied a lot between the projects. The mean values of annual energy demand for space heating, revised according to a normal year, are presented in Figure 7.1. The energy use in the single family house in Lidköping used here is the value measured by ATON for 2009.

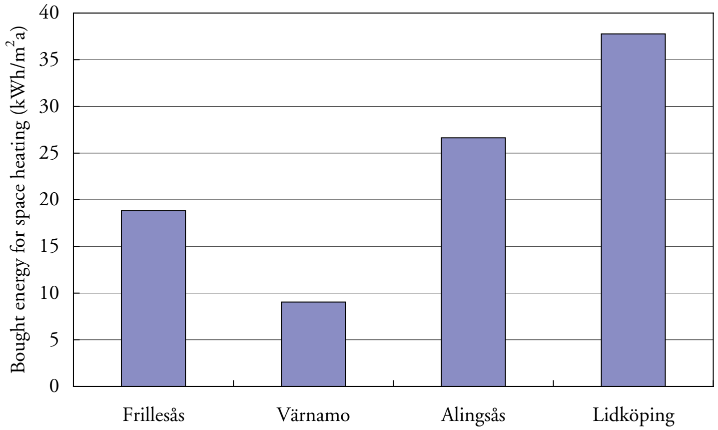


Figure 7.1 Annual energy demand for space heating in the four projects.

7.1.2 Domestic hot water

The annual bought volume of domestic hot water in 25 households in the four demonstration projects (23 participating in the interviews and two additional apartments where the numbers of tenants were known) is presented in Figure 7.2. The annual volume of bought domestic hot water is broken down by the number of tenants living in each apartment. There was a great variation on the use of domestic hot water; from 3.3 m^3/person, year to 24.8 m^3/person, year.

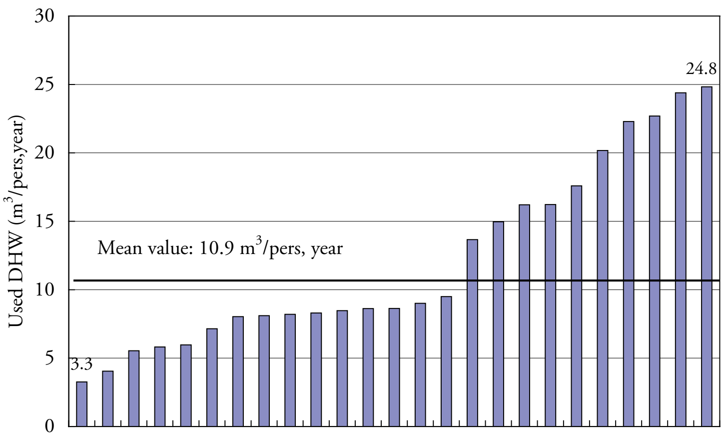


Figure 7.2 Annual used volume of domestic hot water per person in 25 households in the four demonstration projects .

The mean value of the measured annual bought volume of domestic hot water in the 25 households was 10.9 m^3/person and year (29.9 l/person,day). According to Swedish statistics from 2009, the average domestic hot water use in single family houses was 42 l/person,day (15.3 m^3/pers, year) and in multi-family houses the average use of domestic hot water was 58 l/ person,day (21. 2 m^3/pers, year) (Statens Energimyndighet, 2009d).

In the simulation template made by FEBY for use in calculating the total energy use in passive houses, the suggested annual volume of DHW is 18 m^3/pers, year, with a decrease of 20% if the tenants pay for their own consumption or a 20% decrease if energy efficient taps are used. If both these energy saving measures are used, FEBY suggests that the assumed domestic hot water use of 18 m^3/pers, year should be decreased by 36%, which results in 11.5 m^3/pers, year (FEBY, 2009). The measured average domestic hot water use shown in Figure 7.2 is lower than both the domestic hot water use in Sweden according to statistics and the suggested value in the FEBY calculation template.

The five households which consume the most domestic hot water in the four demonstration projects are seen to be found in all four of the projects; there is not a special project that has a higher consumption than the others. Looking at the domestic hot water use behaviour of these five top consuming households based on the interviews, it is seen that one of the five can use both a bath and a shower; the four others only have a shower. The numbers of showers taken in these five apartments each day were said in the interviews to vary from 3 per day to one every other day and the tenant with the bath said it was used once a month. The use of the dish washer varies in these households from not having a dish washer at all to using it every other day. One of the five top consuming households told they turned on their shower and opened the bathroom door to let the hot water contribute by additional space heating on very cold days.

The five households that used the least domestic hot water had no baths and the number of showers were said to be one each day or one every other day. The use of the dish washer varied from being used daily to not having a dish washer. Most of the tenants who used the least domestic hot water were living in Frillesås apartments.

Since there was no major difference in the answers between the top consumers and the one that uses the least domestic hot water, it can be assumed that the tenants either gave an incorrect answer or that the time spent in the shower varies a lot between these two groups.

In the apartment buildings at Oxtorget, no hot water circulation system was installed, which is common in Swedish multi family houses. The client wanted to save the energy used by the circulation pumps and also to avoid the warm circulating water in the buildings. Each building has its own domestic hot water production in a separate unit placed at the end of the building on the ground floor, and the hot water is distributed directly to the apartments from there.

The solution with no hot water circulation system could cause a higher measured domestic hot water use in the apartments that are located furthest away from the domestic hot water production unit when the water has to be transported all through the building before it reaches the taps.

The apartments in Värnamo are placed in the buildings as shown in Figure 7.3, with the domestic hot water production unit placed in a separate store room between apartments A and D. The living area of the apartments presented in Figure 7.3 varies on the second storey depending on whether the apartments were built in one or two storeys.

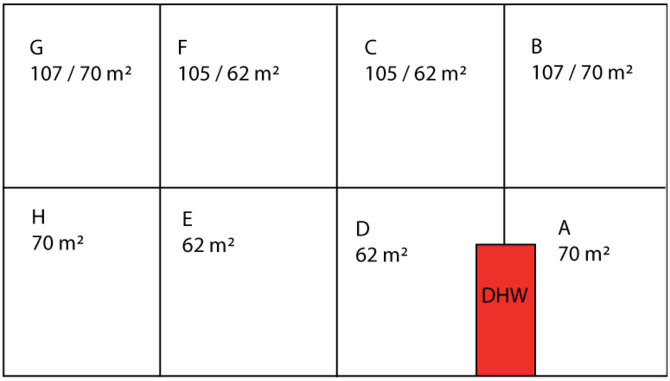


Figure 7.3 Placement of domestic hot water unit in relation to apartments, Värnamo.

The total energy use for domestic hot water for all apartments in the five buildings, including the domestic hot water used from the solar panels, is presented in Figure 7.4. It can be seen in Figure 7.4 that there was no significantly higher use of energy for domestic hot water in apartments G and H that are situated farthest from the domestic hot water unit compared to apartments A,B,C and D .

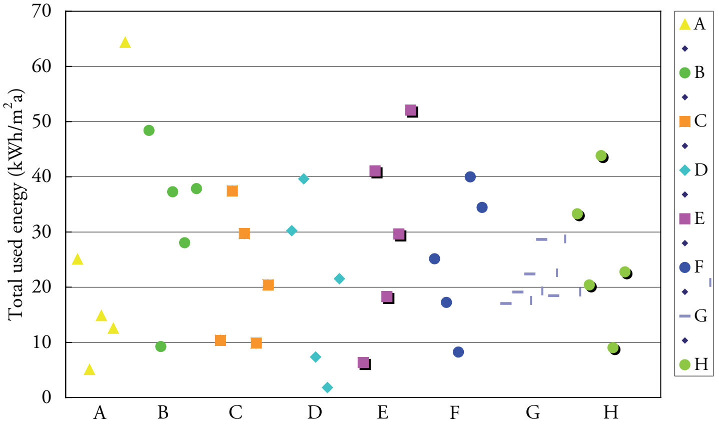


Figure 7.4 *Total annual use of energy for domestic hot water for all 40 apartments, Värnamo during the period 070201 - 080201.*

7.1.3 Electricity for common areas

It was not possible to measure separately the use of electricity for common areas in the Brogården area as explained in Chapter 6. In the single family house in Lidköping, the electricity used for the fans in the ventilation unit is estimated based on the measured power use of the fans in the heating season.

In Värnamo, both the fan electricity and other electricity used for common areas were measured. The mean value of the annual electricity use for the fans was measured to 6.6 kWh/m^{2}a and the electricity use for the common areas was 4.6 kWh/m^{2}a.

In the Frillesås project the annual electricity for common areas was measured which includes three pumps for the solar system, one pump for the domestic hot water circulation, outdoor lighting and the car engine preheaters installed in the garages. It did not include the use of electricity for the fans in the ventilation unit, which was included in the measurement of household electricity. The annual electricity use for the common areas in Frillesås was measured to 16.7 kWh/m^{2}a. The somewhat high electricity use may be caused by the domestic hot water circulating pump. If the circulating pump runs at 90% of its power (990 W) all year to keep the return water temperature above 50°C, 8.8 kWh/m^{2}a is needed, which is 52% of the total measured energy use for common areas.

7.1.4 Household electricity

The annual measured use of household electricity in the apartments that participated in the interviews is presented in Figure 7.5. Within this comparison, for the project in Lidköping the measured electricity for 2009 is used. The annual use of household electricity in all interviewed households varies from 445 kWh/person and year to 2589 kWh/person and year. The mean value of the annual use of household electricity was 1288 kWh/person and year.

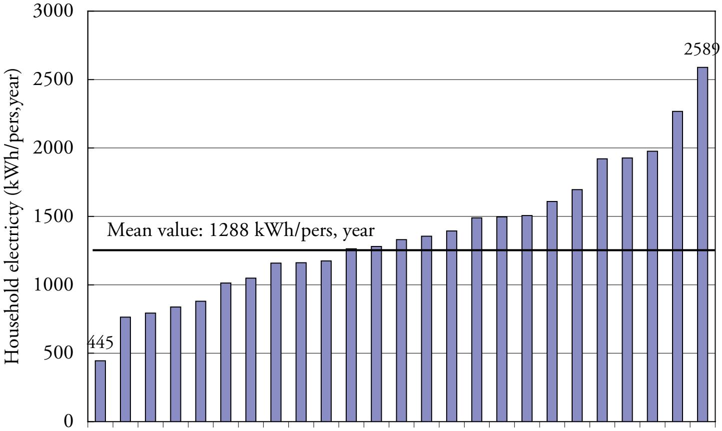


Figure 7.5 Annual use of household electricity .

In the interviews, two of the five households which consumed the most household electricity answered that they perceived the indoor temperature as too cold in winter but none of them said to explicitly use the household electricity for additional space heating. One of them also had problems with excessive indoor temperatures in summer. There was no key factor found here as to which tenants use most household electricity; the number of tenants in top consumer households and the use of household appliances vary a lot. It is however notable that the tenant that used the most household electricity also had the highest measured use of domestic hot water.

The five households that use the least household electricity per person are either single family households or households that contain more than five persons. Two of these interviewed tenants worried much about their electricity bill and two tenants wanted to save energy for environmental reasons. The low use of household electricity seems here to be a result of a deliberate choice by the tenants, for different reasons.

7.1.5 Total energy demand of the buildings

The total energy demand for a building includes energy for space heating, domestic hot water and electricity for common areas, as used in the Swedish Building regulations BBR 16 (Boverket, 2009a). Since the ventilation units used in all the three apartment projects are of the same model and size and the volume of ventilated air is almost equal between the projects, the fan electricity measured in the Värnamo project might also be used in the Frillesås and Alingsås project. The ventilation unit in the single family house is larger with a higher rated output of the fans, and the values measured in Värnamo and the estimated energy use for the fans based on the power use during the heating season is used. In the Frillesås and Alingsås projects, the measured electricity for the fans must then be subtracted from the measured household electricity. Household electricity is however not included in the total energy demand as defined above, which is presented for the four projects in Figure 7.6. The figures used in this comparison for the single family house are those measured by ATON in 2009.

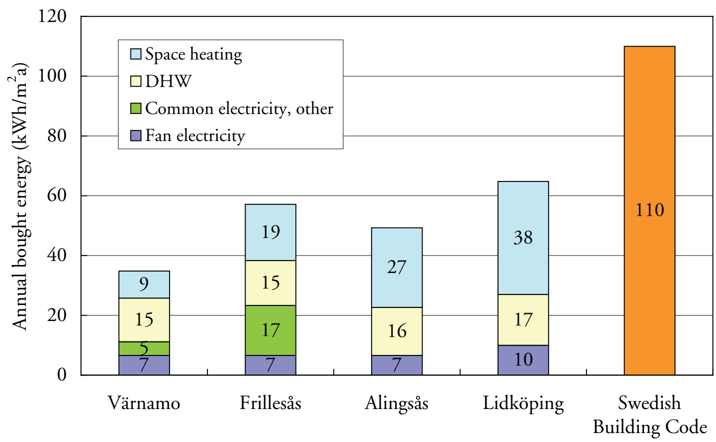


Figure 7.6 *Annual total energy demand measured in the four projects, compared to the specified maximum allowed total energy use in climate zone 3 according to Swedish building regulations.*

The use of electricity for common areas was much higher in the Frillesås project than in the apartments in Värnamo. This could be explained by the high use of electricity in the circulation water pump in Frillesås, with energy use as high as 8.8 kWh/m^{2}a, if 90% of the maximum power of the circulating pump was used as previously described. Also the car engine preheaters contribute to the higher use of common electricity in Frillesås. As can be seen in Figure 7.6, all projects had an annual total energy use that was much lower than the maximum allowed energy use of 110 kWh/m^{2}a in climate zone 3 as set in the Swedish Building code (Boverket, 2009a).

7.1.6 Peak load for space heating

The measured mean values of peak load for space heating in the four projects are presented in Figure 7.7.

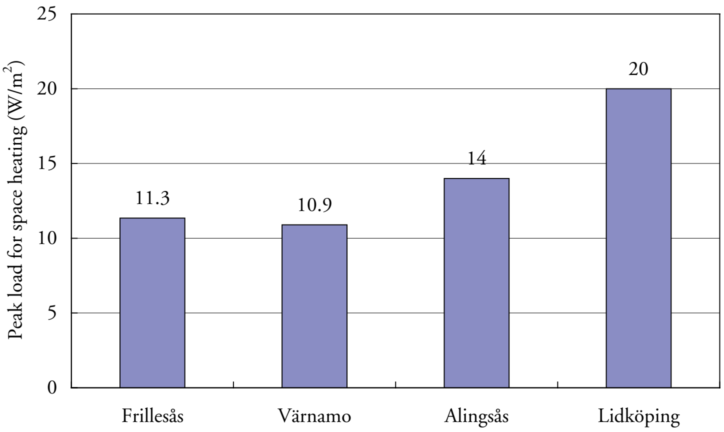


Figure 7.7 *Measured peak load for space heating in the four demonstration projects.*

7.2 Interviews

Interviews were conducted with tenants from all four projects to learn about their experiences from living in a passive house. The tenants in the Värnamo project were interviewed in March 2009, the tenants in Frillesås at the end of August 2009, the tenants in Alingsås in early March 2010 and the family in Lidköping in the middle of February 2010. The tenants got the same questions but their answers might be influenced by the prevailing outdoor climate at the time of the interviews.

The interviews were made in a semi structured way, using the same questions that were used with the interviews in the Lindås project, presented in Appendix A (Boström et al, 2003). A semi structured interview follows a manuscript but lets the tenants talk freely. The interviews took between 1 and 2 hours. All interviews were recorded and later transcribed.

In Värnamo, 7 households (10 tenants) were interviewed in one of the 5 buildings. The interviews were held in the building where the additional measurements of e.g. energy use for space heating were made. In Frillesås all tenants were asked if they consented to being interviewed and 10 of the 12 household (15 tenants) agreed. In Alingsås, the tenants where measurements of indoor temperature were made were invited to be interviewed; 6 household were measured and 5 (5 tenants) agreed to be interviewed. Totally, 23 households or 32 tenants were interviewed about their experiences of living in a passive house. The tenants were mostly interviewed in their own homes; three in the renovated project were however interviewed in the visiting apartment in the Brogården area owned by Alingsåshem.

Here, a summary of the answers in all the interviews is presented. Specific answers are also discussed in the chapters of the four projects (Chapter 3-6). To keep the privacy of the tenants, the interviews will not be described in full.

7.2.1 Background

The tenants have all moved in to the passive house apartments for different reasons but the main reason given for moving was that they liked the location of the apartments. Also, all tenants answered that it was important that these were rental apartments and many said how much they appreciated the good service from the landlord and to be let off maintenance of their dwelling. When the tenants were asked what it was that was especially attractive about the apartments and made them move in, they answered that they wanted to be close to nature, the sea and their relatives. They liked that the grocery store was close and that it also was close to the bus stop. Many tenants were attracted to the new built apartments by new materials and appliances. It was also important to many to have their own entrance to their apartment and to be able to live in an apartment located on the ground floor.

No one answered that they explicitly moved into the apartments because they were passive houses. Three tenants said they were excited when they found out that they were going to live in passive house buildings; “Exciting to live in energy-saving buildings”, “Something new to live in a passive house”, “We wanted to live in an environmentally friendly house”. One said that the excitement appeared after they had been living in a passive house for a while; “I did not believe in this, it was very fishy. It is amazing really, that it can be heated like this, it is a very nice technique”.

Most of the interviewed tenants answered that they were not especially interested in environmental issues before they moved into their apartment. Six household answered yes to the question if the were committed to environmental issues before they moved in to their apartments, and additionally three households said that their commitment has increased since they moved into the passive houses.

7.2.2 Expectations

There were not many tenants who could remember that they had specific expectations before they moved in, only that they hoped it to be comfortable and to get nice neighbours. Most tenants said they were excited about their new apartments and had only happy expectations. Some were also very curious about the apartments and visited the building site on several occasions. One tenant says in the interview that it was not possible to have any expectations on the apartment before she moved in since she had no idea what she was moving into. All she expected was to feel at home.

A few remember that they were concerned that there would be no radiators and one tenant said that she really liked the looks of the apartment so she took a chance to move to such an apartment even though she was sceptical; “it goes if it goes” she said she thought before moving in. One said that he had no expectations but he was very curious about living in a passive house, since he did not know anyone who lived in that kind of a building.

7.2.3 Information

The tenants found out about the apartments in many different ways. For the tenants already living in Brogården, Alingsås, the house owner sent out letters that their apartments were going to be renovated. Other ways to find out about the other projects was through the local community, information from family and friends who were involved or concerned in the building process, information by letter since they were in the local housing queue and information on the internet. Some saw a sign by the road at the building site that they were building apartments and contacted the house owner and some heard it as a rumour in the town. Information was also gained from local newspapers and on the home pages of the house owners.

When the tenants had decided to move to their apartments, all the housing companies had information meetings regarding their new apartments. The meetings were a little bit different between the projects but both individual information and large group meetings were held. A common comment from the tenants from all projects was that the focus of the information was mainly on the heating system and that they would also have wanted to know more about what is a passive house and how it actually works. Many tenants had questions about this at the time of their interview and some asked how the warm supply air could be distributed close to the ceiling in the apartments. “I wish I had been informed about how it actually worked. My thoughts were ‘How can they be so stupid and letting out the warm air in the ceiling?’”. All tenants said that the information received was enough to make them dare to move into the apartments.

Before they moved in some said they had some specific questions that were important to get answers to; how to be able to shut out the sun, if it was possible to be away for a long period of time and what there was then to be concerned about, how to air the apartments properly and who should pay for the electricity used for the fans in the heat exchanger. All apartments are equipped with a binder with information about the apartments in general and brochures about the appliances.

The tenants living in the apartments in Värnamo all received information from the house owner about their future accommodation at a large meeting before they moved in. The apartments were also shown for the public before it was time to move in, and many took the opportunity too look at their apartments at this time. Small models of the building constructions were then shown in one apartment, something that many tenants appreciated, to know what the construction looked like where they were going to live. Most of the interviewed tenants said that they understood from the information that they should avoid touching the ventilation unit as much as possible. Some tenants had informal individual meetings with the house owner in their apartments since they had questions about their heating system and water taps.

In the Frillesås project, most tenants received information about their apartment from the housing company when they signed their contract. Before they moved in, they were invited to an information meeting where the architect Hans Eek described how a passive house worked. Some tenants remember him showing pedagogical pictures of solar radiation at different seasons and how to utilize this in their apartments. Most tenants remembered the description of their ventilation unit presented at the meeting; how to put on the additional heating and how to turn the heating off. They also remember the discussion on how to air their apartment in a good way. Some tenants also had individual meetings in their apartments with the caretaker, mostly if they had any problems or questions. These tenants confirm that after these more detailed meetings, they got the hang of how their heating system worked.

The tenants in the Brogården apartments in Alingsås said that they mostly got their information about the project from an information sheet "Brogårdsbladet" that was published regularly by the housing company and the general contractor of the project. In this sheet they were updated about the future work of the building project and more general information about their future apartments. They also got information from the local television channel regarding the project.

Before they moved in, there was a public meeting in a large tent on the site, where for instance the house owner gave information about technical aspects of living in a passive house. At this meeting, the tenants could also ask questions about their renovated apartments. Most questions then from the tenants regarded rent rises and the removal of the radiators. The housing company had made a full-scale model of how the apartment would look like after renovation in one apartment in Brogården, something that was very appreciated by the tenants.

After the tenants moved in, the house owner Alingsåshem and representatives from the tenants' association had weekly "open house" meetings in one apartment on the ground floor in the first renovated apartment building, where the tenants could go to get answers to their questions or just get a cup of coffee and talk to their neighbours.

The Malmborg family first got most of their information from the architect Hans Eek, which included a study visit to one of the terrace houses in Lindås. Later they also got information by participating within this research and from the internet.

7.2.4 Experiences

The experiences of the living situation in the apartments vary a lot between the tenants. They all agreed however that the apartments were very quiet. If the windows were closed, no sound from outside came in. One tenant expressed that it was almost too quiet and that he felt a bit isolated when he could not hear any sounds from outside. The internally generated sound was transmitted through the concrete in the building construction in all three apartment projects, where dull sounds from the neighbours were heard. No one expressed that these sounds were more distinct compared to other apartments they have been living in; many said these sounds were something they thought were normal for apartment buildings and none answered that they heard any voices from their neighbours. Within the apartments, noise was said in the interviews to travel between rooms due to the gaps below the inner doors. These gaps were understood to be necessary for the circulation of air, but gave the tenants a feeling of never getting any privacy. On the other hand, this construction with no thresholds was very much appreciated by the disabled persons who were interviewed.

Another mutual experience expressed by the tenants in all projects was the indoor air quality; always very fresh air and never a feeling of stuffiness. Some tenants said that the indoor air felt so fresh that they never needed to air their apartment. 30% of the asked tenants said their indoor air was occasionally dry but only two tenants answered that they had experienced static electricity in their apartments.

All tenants except three said they have a bright apartment. All the tenants who experienced their apartments as somewhat dark lived on the ground floor.

Many tenants expressed that they thought the rent was too high, especially when neither the cost of household electricity nor domestic hot water was included in the rent, and in some cases not the energy cost for space heating. They said that their awareness of their energy use had increased when the energy use was explicitly presented on the rental bill. Some tenants explained that they had changed their behaviour because of this, most tenants regarding their use of domestic hot water, but it was also common that the tenants answered that they have changed their behaviour regarding the use of household electricity. Mostly this was put into practice by not using the tumble dryer – more than 30% of the tenants answered that they were not using the dryer since it uses too much energy. There was a difference in the awareness of energy use according to the age of the tenants and their income. The tenants who described the most change in their living behaviour to save money on their energy bill were mostly elderly persons living by themselves.

In the interviews the rent was mentioned to be high, but many tenants also said that they were paying for high service and high comfort, which made the level of the rent fully acceptable.

Several tenants asked for more cabinets in their kitchens and the interviewed larger families suggested more than one WC in a four room apartment. The very energy efficient combined refrigerator and freezer cabinets were said to include too small a freezer for a normal family. The deep window bays were much appreciated by tenants in all projects.

The interviewed tenants living in Frillesås expressed joy regarding the beautiful housing area and its closeness to nature, the sea, local communications, their lively neighbours and the high quality grocery store. “I live in the middle of the four seasons, even though I can’t go out”, one tenant said. They were however dissatisfied with the busy road close by. It was said to cause problems both with noise if the windows were opened too much and also by grime that made the balconies and patios dirty. The grime was also said to be transported into the apartments through the ventilation system and caused black stains around the supply and exhaust air terminals. Another issue mentioned by all interviewed tenants in Frillesås was problems with the glazed entrance vestibule. The tenants said that it was warm like a sauna in the summer and ice cold in winter, with internal condensation on the cold panes. It was said to be impossible to use the space in the vestibule for instance for storage. The entrance door was needed to be closed all year; in summer it would otherwise leak in too much heat and in winter the warm indoor air would leak out. The tenants suggested having some operable windows in the entrance vestibule, to be able to use the space like a hallway.

All interviewed tenants in Värnamo praised the surroundings of the Oxtorget area and how much effort the house owner had put down on the outdoors around the apartments.

Some tenants in the Oxtorget area expressed that they needed to wait for a long time until the water was warm in their taps. This comment depended on how far the tenant lived from the domestic hot water unit, some said it came without any delay and the tenant living farthest said she needed to wait up to two minutes before the water was warm.

In three of the interviewed apartments, condensation had appeared on the outer pane of the windows. The surface of the outer pane in a very energy efficient window will not be heated from indoors, in the same way as the window insulates the indoors from the cold outdoor temperature. On a night with clear skies, the radiation between the sky and the window pane is without resistance and the surface temperature on the window pane approaches the temperature of the sky. The surface temperature can then be lower than the surrounding air temperature. If the humidity of the outdoor air is relatively high, condensation will appear on the outer window pane. The condensation can be prevented by breaking the radiation to the sky by e.g. external solar shadings.

The condensation that had appeared in the three apartments was said to have occurred during morning hours but at different seasons in the different apartments, according to the interviewed tenants. No one said the condensation had been a problem since it had been only for a few hours at a time.

The towel dryers installed in the bathroom have been used occasionally in some of the apartments; it was most common to turn it on when additional space heating was felt to be needed for the entire apartment.

Three of the five interviewed tenants in Brogården have lived in the building for a long time and were only evacuated during the renovation process. The other two interviewed tenants have earlier been living in other apartments in the Brogården area. Because of this, the experiences from the renovated apartments were mainly made by way of comparison with the apartments before renovation.

For instance, all tenants in Brogården said they missed their Venetian blinds that they had before renovation. The tenants made a lot of comparisons with the services included before renovation and after and put that in context with the rise in their rent, especially those who have moved back to their old apartments. All five interviewed tenants had experienced initial problems during the first year with their living situation and especially their indoor climate. They all said that if the indoor climate had been perfect they would have accepted a higher rent, but now other gains experienced in the apartments after renovation were pulled down by the things that were not working and it was difficult to motivate the higher rent compared to that before renovation.

All the interviewed tenants in Brogården were most satisfied with the new entrance, the entry phone and the fresh indoor air.

The family in Lidköping said that a great advantage with their new home was that their indoor air always felt fresh and clean and that they have been less ill since they moved to their new house. But the air change rate of 0.5 ach also gave a feeling of dry air and the family said that the polluted air from the neighbours' fireplaces was let in through the air intake. In the winter of 2010, when there was occasionally high moisture content in the outdoor air together with very low outdoor temperatures, the air intake on the façade was covered by rime, see Figure 7.8.

Figure 7.8 Air intake covered by rime.

When the supply air flow into the ventilation unit decreased, due to the frosted up air intake, there was not enough heated air distributed in the building and the indoor temperature dropped according to the family. To avoid a temperature drop, the air intake had to be manually defrosted by the family members.

The filter in the ventilation unit has been changed by the family twice per year. This is more often than recommended by the producer of the ventilation unit but was seen to be necessary by the family since the filter got very polluted by pollen in spring and by particles from the crops nearby when harvested in the autumn. The family wishes for less expensive filters or filters that can be washed and reused.

The family said they experienced the house as bright and that the tilted window bays are one of the main reasons for this feeling. After the two additional silencers were mounted the ventilation system has been very quiet and no sound from outside was said to be heard except when windows were open.

7.2.5 Indoor comfort

The experienced indoor temperature varied a lot between the projects and sometimes within the projects. The different answers between the projects might be explained by the different seasons at the time of the interviews. Most tenants who experienced an excessive indoor temperature also had a high use of household electricity with many appliances used at the same time and at a long period of time every day; computers, flat-screen television sets etc. The tenants who experienced an inadequate indoor temperature were mostly sedentary. The desired indoor temperature varied between 20 - 23 °C and most tenants answered that they wanted to have an indoor temperature of 22 - 23 °C.

To reduce the indoor temperature, the tenants said they opened the windows and speeded up the fan in the ventilation unit. Some explained that it took a while to learn how to air their apartment in a good way, but when they had figured that out, it worked perfectly. The tenants who experienced that their apartments were too warm said it would be desirable to vary the indoor temperature between rooms and some said that the buildings had too high a thermal inertia; if it got warm in May it would not be cooler inside until autumn.

In winter, to increase the indoor temperature if necessary, the tenants said they raised the temperature setting on the display on the ventilation unit and it was also a common answer that they put on additional clothes; socks and knitted sweaters. Many tenants said that if they used the oven during the cold season, they left the door open afterwards for some additional heat to the apartment. A few even turned the oven on just to heat the apartment, without cooking. Mostly, the tenants answered that they had never experienced their apartment to be too cold. But some tenants who have been really cold switched on their towel dryer in those projects where these were installed. The tenants who were dissatisfied with their indoor temperature all wished to have radiators instead of airborne heating. The other tenants appreciated not having radiators, since they were seen to be dust collectors.

It seemed that the tenants who have not been adjusting their indoor temperature too often on the display in the ventilation unit had mostly experienced a very even indoor temperature and were less dissatisfied than the other tenants. One tenant who had problems with her indoor temperature said that she had been travelling for two weeks and when she came back, she described that the indoor temperature was perfect. “But then, after 14 days I needed to adjust something in the ventilation unit, and then it all went bad again”.

The number of satisfied tenants regarding indoor temperature was high in the Frillesås project, where only two households answered that they were dissatisfied with their indoor climate; one with too low indoor temperature in winter and one with too low indoor temperature in winter and too high in summer. These households also said to have had problems with draught from the supply air terminals. In one of these two apartments, the tenant had bought additional electric radiators that were said to be used from January to March. These radiators were installed after the measuring period was finished and because of this cannot be detected in the measurement of household electricity presented in this study.

Most of the tenants had installed sunblinds on the windows facing south. Some had complemented with venetian blinds, mostly to stop people looking in. The tenants who expressed that they were dissatisfied with their indoor temperature were no exceptions and had also installed sunblinds.

In spite of the installed solar shading devices, some tenants said the indoor temperature sometimes got too high, mostly in summer or when many people came to visit. These tenants had never turned on their heating coil in their ventilation unit.

The floors were explained by the tenants in Frillesås to be warm and many said that they went barefoot when indoors all year round.

The supply air in Frillesås was distributed by nozzles in the supply air device. In the beginning, these caused draught and discomfort among the tenants. When the tenants learned that they could adjust the nozzles, in most cases the draught disappeared. The information on how to adjust the nozzles was spread from one tenant to another and was not information received by each tenant from the house owner.

In the project in Värnamo, 50% of the asked tenants wished to have a higher indoor temperature in winter and the others thought the indoor temperature was perfect. In two of these households, the heating coil in the supply air unit had never been switched on; one in an apartment with a tenant who answered the indoor temperature was too low in winter and one in an apartment where the tenant thought the indoor temperature was perfect all year. In all apartments the measured indoor temperature has been approximately 20 °C but the tenants said they wished to have a temperature of 22 -23 °C. No tenant complained about too high indoor temperatures in summer, they all said that it had been very comfortable indoors during the summers.

Three families live in an apartment that has a two storey design. Two of these families experienced a difference in the indoor temperature between downstairs and upstairs. One of the families said they had a colder upper storey and the other family said the upper storey was too warm. The third family experienced the indoor temperature as perfect all year round on both storeys and had not needed to turn on the heating coil at all.

The indoor temperature experienced in the renovated apartments in Alingsås varied a lot depending on what floor the apartment was situated. The apartments on the ground floor were said to be cold in winter and perfect in summer, the apartment on the second storey was said to be comfortable all year round and the apartments on the third storey had a nice indoor temperature in winter but were too warm in summer. All tenants had a measured indoor temperature in winter of approximately 20 °C but the tenants wished to have an indoor temperature of 22 -23 °C. The indoor temperatures varied in the apartments and were described to be higher in the kitchens and bedrooms and lower in living rooms and bathrooms. On the second and third storey, the tenants said the floors were warm and one tenant said to be barefoot all year round. On the ground floor, the tenants experienced the floors to be cold all year.

The family living in Villa Malmborg said that the indoor temperature was almost the same all year round and increased just as much on a sunny day in January as one in June. The family said that during their first year in the house they accepted lower indoor temperatures. During the second year they said they wanted to live more normally with an ideal indoor temperature of 21 – 23 °C. In summer, there was initially a problem with too high temperatures on the second storey. After an operable window was installed, the situation was said to be much better. The family said that they still experienced a difference in temperature of approximately 3 °C between the upper and lower storeys. They said it could be due to the fact that they were mostly upstairs when they were at home and that the television set and the Play Station that were placed upstairs could generate much heat.

In summer, the indoor temperature in the single-family house was said to be perfect and when the neighbours complained about too high indoor temperatures the family said they had no problems at all, and were sleeping well in a cool house.

The large windows on the ground floor were said to cause a cold draught. The family said they had lit a match in front of one of the windows to see if it actually was draught, but the air was seen to be completely still. Still, the family experienced the windows to be chilling and said that one improvement of their home would have been to have the large floor-to-ceiling windows installed a little bit higher up on the walls to get a warmer floor. Other improvements of their home to get a better indoor comfort would have been entrance doors with a lower U-value, solar shadings on the windows facing east, better insulation on the edges of the foundation concrete slab and as many operable windows as possible.

7.2.6 Suggestions for improvements made by the tenants

There were individual ventilation units installed in all the interviewed households. A usual comment from the interviewed tenants from all four projects was about problems with the regulation of the indoor temperature using the display on the ventilation units. They said it was confusing that when they wanted to change the indoor temperature and altered the figure on the display of the ventilation unit, instead of a change in temperature no response was experienced from the ventilation unit and no change in the indoor temperature level. This occurred both when trying to raise the indoor temperature and reduce the indoor temperature. Some said that if they set the display on 25 °C in the ventilation unit they wanted the indoor temperature to be 25 °C; similar to an air condition system in a car. To avoid this misunderstanding and in some cases frustration in future projects, the display on the ventilation units could have only arrows showing up and down and no explicit figures. Another way could be to describe for the tenant how the ventilation unit works and what the figures actually stand for.

7.3 Discussion and conclusions

The answers from the interviews can be used to confirm the results from the measurements by triangulation and vice versa.

The measured use of domestic hot water was low in all four demonstration projects with an average use of almost half of the statistical average use in Swedish multi family houses. These measurements were confirmed in the interviews where many tenants said to have great awareness of their use of domestic hot water since it was seen on the rental bill and paid for by themselves.

In the Värnamo project, tenants living far from the domestic hot water unit complained that it took time before the hot water reached their tap. This could not be seen in the measurements, where no correlation was found between high use of domestic hot water and placement of apartment relative to the domestic hot water unit.

Many tenants in all four demonstration projects said in the interviews that they had become more aware of their use of household electricity and tried to keep their consumption at a low level. This cannot generally be seen in the measurements, where a high use of household electricity is measured in all projects.

The correlation between the measured indoor temperatures in the four projects and the answers in the interviews varies but in the apartment buildings in Alingsås it is of high agreement. The measured low indoor temperatures in the apartments on the ground floor are confirmed in the interviews; so are the measured too high indoor temperatures in summer in the apartments on the third storey. The variation of the indoor temperature in the single-family house in Lidköping is described by the tenants just as it was measured, with the lowest indoor temperature in the morning hours and a rise in the indoor temperature during the day, especially on the second storey.

The measured levels of internally generated sound from the ventilation unit in the Värnamo project and in the second measurement in the single family house showed a result below the specified sound class B. These measurements were confirmed in the interviews, where the tenants described their apartments as very quiet. Also in the two apartment projects where the sound levels were not measured, all tenants described their apartments as very quiet. A common prejudice regarding mechanical ventilation is the internally generated sound and that it disturbs the tenants. This can here be contradicted by both measurements and answers from the tenants and it is shown that internally generated sound can be avoided by careful planning and skilled contractors.

Another common opinion about mechanical ventilation systems is that they result in poor indoor air quality. According to these interviews, the tenants experience the opposite and all said to have a very fresh indoor air all year round.

Condensation on the outer pane of the window was said in the interviews to have been seen in three apartments of total 23 households participating in the interviews. None of the interviewed tenants said that condensation had been something they have taken any notice of or that it caused any inconvenience.

It seems to be common to believe that passive houses are dark indoors due to limited window areas. The answers from the tenants in these interviews can confirm the opposite, where almost all tenants experience their apartments to be bright and all enjoyed their deep window bays.

An important conclusion from the interviews is that the tenants' expectations on their new apartment were to feel at home. This must not be forgotten – we are building homes for the tenants, not a building to save energy.

8 Passive solar gains and outdoor climate

The use of solar radiation has been known as a passive thermal gain in buildings for a long time. In many European passive house projects, the solar gains could have a major influence on the annual space heating demand and often larger south window areas are placed in passive houses to be able to utilize the solar radiation for space heating (IEA, 2006).

Sweden is a long and narrow country and the climate and the solar radiation vary a lot between the south and north. During the cold season, not much solar radiation is available in any part of the country. In this chapter the influence of solar radiation on the annual energy demand and the peak load for space heating in the demonstration projects is analyzed using measured data of solar radiation. Also, simulations are made in order to see how the building's orientation and location and thereby the solar gains influence the annual space heating demand and the peak load for space heating.

8.1 Measured solar radiation – Frillesås

To be able to investigate the importance of the solar radiation contribution for the energy demand for space heating in passive houses built in a climate with less solar radiation, measurements were made in the Frillesås project of the global and diffuse solar radiation. The measurements were commissioned by the client and performed by SP Technical Research Institute of Sweden during two measuring periods; 070307 – 070716 and 071122 – 080206. Both diffuse and global solar radiation were measured with one measurement every 5 minutes.

The measurements were made in one place, with the meter mounted on the roof of the apparatus building. The metering device can be seen very far to the right in Figure 8.1.

Figure 8.1 Measurement of the solar radiation in Frillesås, metering device mounted on apparatus building far to the right in the picture.

8.1.1 Evaluation method

To evaluate the solar gains and their influence on the peak load and energy demand for space heating in the apartments in Frillesås, the measured global solar radiation was used in an evaluation graph. The graph was based on the European standard EN 832 (SIS, 1999) and was earlier used in SHC – IEA Task 28, developed by Karsten Voss at Fraunhofer ISE Freiburg (Reiss, Russ & Voss, 2005). The standard EN 832 was actually replaced by the standard SS-EN ISO 13790:2004 and later updated to SS-EN ISO 13790:2008 (SIS, 2008) in March 2008, but the old standard was here kept so that the evaluation graph could be used.

The base line used in the graph in the analysis of the measured data is that transmission and ventilation losses (Q_T and Q_v) of a building are covered by solar gains (Q_s), internal gains (Q_I) and additional heat from the space heating system (Q_H). The energy balance of the building is also affected by how much of the internal gains is actually usable in the energy balance and is here taken into consideration by the utilization factor (η). The utilization factor of the internal gains was seen in buildings analyzed within IEA Task 28, using climate data from Freiburg, Germany, to be influenced slightly by the building construction and mainly by the ratio of gains to the losses (Reiss et al, 2005). Almost all of the available internal gains were seen in this analysis to be utilized at high thermal losses in the building and at small solar gains, giving a somewhat high utilization factor. It was also seen that in buildings with extremely low thermal losses, there was no appreciable change in the space heating demand of the buildings when the solar gains increased.

The energy balance used in the evaluation graph is presented in Equation 8.1.

$$(Q_T + Q_v) = \eta \cdot (Q_I + Q_s) + Q_H \qquad \text{Equation 8.1}$$

In the outcome of the evaluation graph, the peak load for space heating according to outdoor temperature is presented, with and without internal gains, together with measured global solar gains broken down by measured intensity. Within this comparison, all energy terms will be related to the habitable floor area (m^2).

8.1.2 Evaluation of measurements

Using the evaluation graph, the utilization of the solar gains on the measured mean value of peak load for space heating for all three apartment buildings in Frillesås was studied. The measured solar radiation data was sorted in relation to the measured peak load for space heating and measured outdoor temperatures in the evaluation graph for both the measuring periods; 070307 – 070716 and 071122 – 080206 (Figure 8.2 and Figure 8.3). Within the graph there are also two lines where the straight line represents the theoretical calculated peak load for space heating with no internal or solar gains at a constant indoor temperature of 20 °C. The dotted line is the calculated peak load for space heating with the internal gains of 4 W/m^2 added. It was in this analysis assumed that the utilization factor η of the internal gains was 100%. The global solar radiation is in the graph divided into three classes; below 25 W/m^2, between 25 – 90 W/m^2 and above 90 W/m^2.

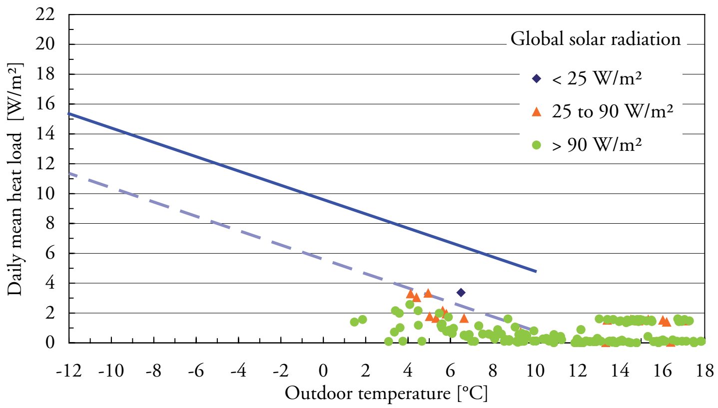


Figure 8.2 *The daily mean peak load in relation to the daily mean outdoor temperature and the global solar radiation in the Frillesås project during the period 070307 - 070716. The straight line is the theoretical calculated peak load for space heating without any internal or solar gains and the dotted line is the calculated peak load for space heating including internal gains (4 W/m²).*

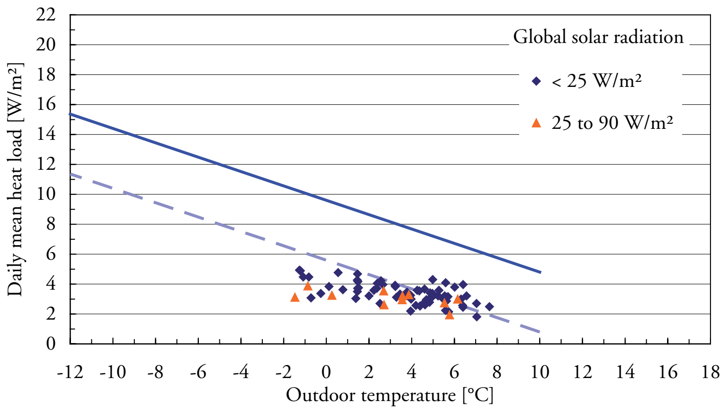


Figure 8.3 *The daily mean peak load in relation to the daily mean outdoor temperature and the global solar radiation in the Frillesås project during the period 071122 - 080206. The straight line is the theoretical calculated peak load for space heating without any internal or solar gains and the dotted line is the calculated peak load for space heating including internal gains (4 W/m²).*

As can be seen in Figure 8.3, when the outdoor temperature decreased and the space heating demand increased, the solar radiation was 25 – 90 W/m^2 or below 25 W/m^2. The high solar radiation, above 90 W/m^2, that could have been utilized for space heating does not appear until spring as can be seen in Figure 8.2.

8.2 Variation of energy demand and peak load for space heating depending on the building's orientation

An orientation of the building with large window areas facing south has traditionally been seen to be preferred in passive houses to utilize the solar gains as much as possible. To see how the solar radiation affects the annual energy demand and peak load for space heating in the three new build demonstration projects, they were rotated from their original position using the dynamic simulation program DEROB – LTH v 1.0, as previously shown in Chapters 3-6. The original simulation models and input data of the buildings were used as presented in earlier chapters.

The projects were rotated three times around their original positions, where each rotation was 90°. The rotation made in DEROB-LTH is the anticlockwise rotation of the x-axis and the whole building starts from the south direction (Kvist, 2006). All simulations were made using the indoor temperature of 20°C.

The window area to living area ratio was approximately 17% in Frillesås, 16% in Värnamo and 15% in Lidköping.

8.2.1 Frillesås

The apartment buildings in Frillesås were originally placed with the long side façades with the balconies almost facing south (Figure 8.4).

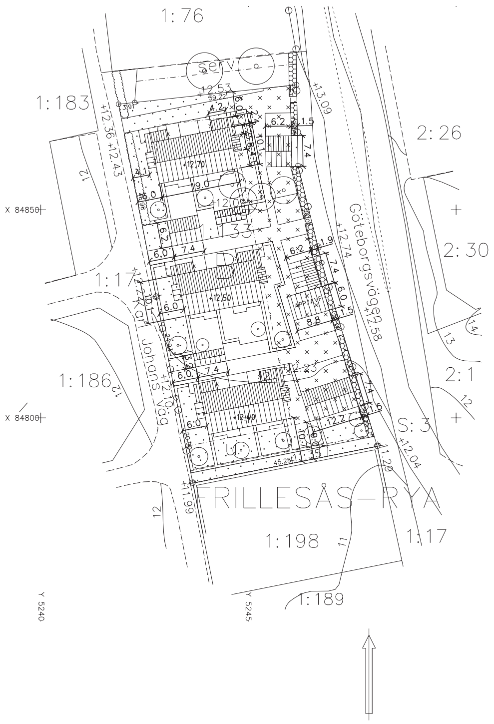


Figure 8.4 *Site plan of the apartment buildings in Frillesås (Drawing: efem Arkitekter).*

The energy demand and peak load for space heating were simulated in one building of type A or C in separate simulations. The main façade was rotated to face east, north and west. The variation of the energy demand and peak load for space heating at different orientations of the main façade is presented in Table 8.1.

Table 8.1 Annual energy demand and peak load for space heating in Frillesås at different orientations of the main façade.

	South	East	North	West
Energy demand for space heating (kWh/m^{2}a)	14.8	16.8	16.4	16.4
Peak load for space heating (W/m^2)	10.8	10.9	10.9	10.9

The original orientation of the building with the main façade facing south resulted in the lowest calculated energy demand for space heating when the building was rotated as can be seen in Table 8.1. The design with the somewhat larger window area facing south seems to utilize the solar gains (Figure 8.5).

Figure 8.5 South façade in Frillesås project.

According to the simulations, it made a difference of approximately 12% to the annual energy demand if the building was rotated facing east, north or west. The peak load for space heating varied only marginally when the building was rotated.

8.2.2 Värnamo

The apartment buildings in Värnamo were built with the façade with the balconies facing south west and the entrance vestibules facing north east (Figure 8.6).

Figure 8.6 *Site plan of the Oxtorget area (Drawing:bsv arkitekter).*

The annual energy demand for one simulated building of type A rotated in different orientations is presented in Table 8.2.

Table 8.2 Annual energy demand for space heating in Värnamo at different orientations.

	South west	South east	North east	North west
Energy demand for space heating (kWh/m^2a)	9.8	11.3	12.3	12.0
Peak load for space heating (W/m^2)	8.1	8.2	8.2	8.2

There was approximately a 13% increase in the annual space heating demand when the building was rotated 90° towards south east. If the original building had been placed with the façade with the balconies facing north east, the annual energy demand would have been 20% higher according to this simulation. The windows in these apartments are mainly facing south, see Figure 8.7, and the solar gains seem to be utilized in a good way. As in the Frillesås project, there was almost no difference in calculated peak load for space heating when the building was rotated.

Figure 8.7 *Apartments in Värnamo, south west façade to the left and north east façade to the right.*

8.2.3 Lidköping

The single family house in Lidköping was built with the main façade facing south west. The annual energy demand at different orientations is presented in Table 8.3.

Table 8.3 Annual energy demand for space heating in Lidköping at different orientations.

	South west	South east	North east	North west
Energy demand for space heating (kWh/m^2a)	24.9	25.9	24.9	24.0
Peak load for space heating (W/m^2)	12.6	12.6	12.6	12.5

In this single family house, there was almost no difference in the calculated annual energy demand for space heating when the house was oriented differently even though the windows on the building placed facing south west and south east were larger then the windows on the north east and north west facades, see Figure 8.8.

Figure 8.8 *South west and south east facade of Villa Malmborg (left) and north west façade (right).*

The peak load for space heating was also kept constant when the building was rotated. It is notable that even though the difference in the calculated figures is very low, the optimal orientation of this building regarding annual energy use and peak load for space heating is, according to the simulations, to turn the building so that the main façade is facing north west instead of the built south west direction.

8.3 Passive solar gains and outdoor climate

The outdoor climate and the available solar radiation vary greatly in Sweden. These differences have a considerable influence on the energy demand of a building for space heating. To be able to set regulations regarding energy use in buildings in Sweden, the National Housing Board has decided to divide Sweden into three climate zones (Boverket, 2009a). The three climate zones are shown in Figure 8.9 with climate zone 3 in the south, climate zone 2 in the middle and climate zone 1 in the north of Sweden. These climate zones are also used in the Swedish recommendations for peak load values for space heating in passive houses (FEBY, 2009) as described in Chapter 2.

Figure 8.9 Swedish climate zones.

Figure 8.10 11 Swedish cities used in the DEROB – LTH simulation (Picture: Lantmäteriet, 2010).

To see how the different outdoor climates in different climate zones influence the peak load and the annual energy use for space heating in a very energy efficient building, the two demonstration buildings originally placed in Frillesås and Värnamo were placed in 11 different Swedish cities with different climate data (Meteotest, 2004) using the simulation program DEROB–LTH v 1.0 (Kvist 2006). The cities used are Lund, Visby, Göteborg, Jönköping, Stockholm (climate zone 3), Karlstad, Borlänge, Sundsvall (climate zone 2) and Östersund, Umeå, Luleå (climate zone 1) as shown in Figure 8.10. The simulations were made using a ventilation rate of 0.5 ach and an air leakage of 0.05 ach.

The result of the simulations of the Frillesås project is presented in Figure 8.11. The simulated value of peak load for space heating increases by 55% when the results using climate data for the town far south (Lund) and far north (Luleå) are compared and the energy demand for space heating is more then 2.5 times higher in the Luleå climate than in Lund in these simulations.

The results of the simulations of the Värnamo project (Figure 8.12) show a difference in peak load for space heating of 52% when the results using climate data for the town far south (Lund) and far north (Luleå) are compared. The energy demand for space heating is 3.5 times higher in the Luleå climate than in Lund in these simulations.

It is notable that the peak load for space heating calculated in both projects using the climate data for Sundsvall in climate zone 2 is higher than the peak load for space heating calculated for Östersund and Umeå that are situated in climate zone 1.

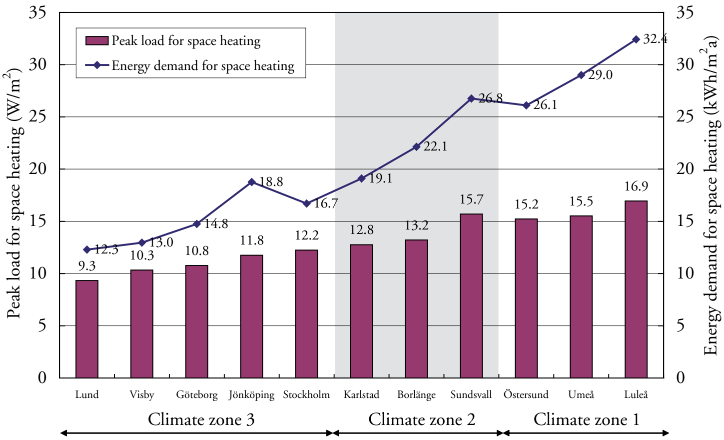


Figure 8.11 *Energy demand and peak load for space heating using the apartment buildings in Frillesås in 11 Swedish cities separated into climate zones (with solar radiation).*

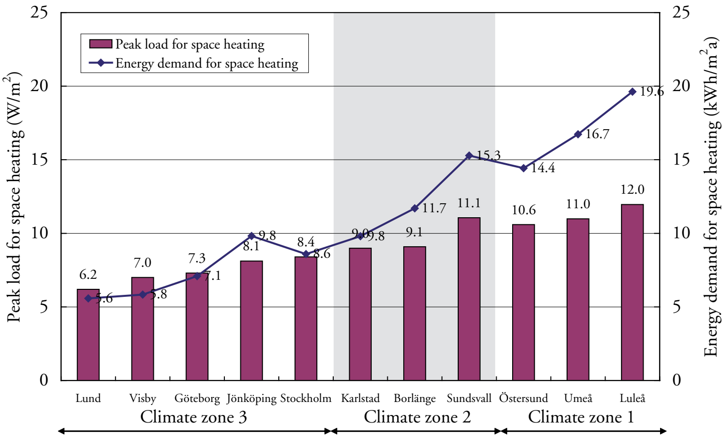


Figure 8.12 *Energy demand and peak load for space heating using the apartment buildings in Värnamo in 11 Swedish cities separated into climate zones (with solar radiation.*

8.4 Discussion and conclusions

The influence of solar radiation on the peak load for space heating was in this study seen to be limited in a building with low thermal losses built in a climate with solar radiation of low intensity during the cold season. Both the analysis of the solar radiation in the Frillesås project using the evaluation graph and the simulations of the three demonstration buildings when rotated in different directions show that the solar gains can not be utilized to decrease the peak load for space heating

In the study of the measured solar radiation in the Frillesås project, the result show solar radiation of low intensity when the peak load for space heating occurs. During the cold season, no solar radiation was measured with intensity above 90 W/m^2. The here measured solar gains give only a slight contribution to the space heating demand.

The rotation of the buildings in the simulation program results in a variation of the annual energy demand for space heating in the two apartment buildings. The single-family house has almost no variation in annual energy demand when rotated. There is no variation in the peak load for space heating in the three projects when rotated.

This confirms findings in the earlier study on the passive houses in Lindås (Wall, 2006) and in two energy efficient buildings in Västra Hamnen in Malmö (Bagge et al, 2004).

Still, larger windows facing south seem to have an influence on the annual energy demand for space heating in the apartment buildings, with a variation up to 20% in the Värnamo project. Different orientations of the larger window area had less importance on the annual energy demand for space heating in the single-family house.

The peak load and energy demand for space heating vary a lot when the buildings are moved between different cities and thereby different climates in Sweden. The results from the simulations show that a combination of less solar radiation and a colder outdoor climate rapidly increases the energy demand for space heating.

The results in these three studies all show that in a Swedish climate, solar radiation can not be utilized for space heating when it is actually needed on cold days. The differences in outdoor climate make it difficult to set one national limiting value on the peak load for space heating in Swedish passive houses. To get one limiting value, the ventilation and transmission losses need to be reduced even more in some areas, which could be difficult and hard to accomplish both economically and technically.

9 Ventilation

It is of major importance to have a well functioning ventilation system in all buildings to ensure a good indoor air quality. In passive houses, the ventilation system plays a key role in many different respects. If it is decided to heat the building by air, a high ventilation rate will increase the possible space heating power distributed by air. Raising the ventilation rate will on the other hand cause higher thermal energy losses from the ventilation system and a higher use of electricity by the fans in the ventilation unit. The ventilation rate also affects the indoor humidity. It is known that insufficient ventilation rates may cause indoor moisture problems, which in turn may lead to major health effects. On the other hand, too high a ventilation rate may increase the rates of emissions from materials and make the indoor environment too dry, showing the importance of a well planned ventilation system. Since the ventilation system is of such fundamental importance in the passive house definition, it will in this chapter be studied in more detail with the focus on ventilation in residential buildings in relation to the demonstration buildings within this study.

9.1 Ventilation rates and their effect on health

When airtight buildings with mechanical ventilation systems are built, it is important to find a balance regarding the best air change rate levels to create both a healthy indoor climate and at the same time keep the energy use at a low level. Requirements regarding ventilation rates in buildings are most often made on a national basis and vary a lot between different countries and their building codes. Often the ventilation rate depends on the living area or the volume of the ventilated building (Thullner, 2010). The knowledge of the connection between suitable air change rates, insanitary levels of concentration of indoor particles and their influence on human health is however limited. There is a lack of information on the effects of ventilation on health, especially in residential buildings.

9.1.1 Ventilation rates and indoor pollutants

The ventilation system should be designed so that the necessary outdoor air flow can be provided to the building. It should also be designed to remove moisture, odours and pollutants from people and building materials (Boverket, 2009a).

According to the National Swedish Board of Health and Welfare (SOSFS, 1999a), if the indoor levels of carbon dioxide regularly exceed 1000 ppm it should be considered as an indication that the ventilation system is not working satisfactorily. Also the Swedish Work Environment Authority recommends that in premises where the pollutants mainly result from humans, the levels of carbon dioxide emissions should be kept below 1000 ppm (AFS, 2000). There are no maximum allowed concentrations of other pollutants or particles in the indoor air in dwellings, according to a study published by the Swedish Board of Health and Welfare (SOSFS, 2006). This lack of limitation is explained by the limited research material yet available concerning the subject.

However, a guideline for a good hygienic indoor climate has been published by Swedvac (Ekberg, 2007) where limitations are set on e.g. levels of concentration of pollutants. According to the Swedish indoor climate guideline document "R1", the concentration of indoor pollutants should be below the values presented in Table 9.1.

Table 9.1 Guideline values for a good hygienic indoor climate (Ekberg, 2007).

Radon	100 Bq/m^3
CO	2 mg/m^3
NO_2	40 $\mu g/m^3$
O_3	50 $\mu g/m^3$
HCHO	50 $\mu g/m^3$

Regarding moisture and microorganisms in dwellings, the general advice from the Swedish Board of Health and Welfare is that if the additional moisture content in the indoor air during winter regularly exceeds 3 g/m^3 air or if the mean atmospheric humidity exceeds 7 g water / kg dry air during an extended period within the heating season, which corresponds to a relative humidity of 45% at an indoor temperature of 21 ° C, an investigation of the building needs to be performed (SOSFS, 1999b). Research has found that the house mite populations in dwellings are larger when the indoor humidity is above 7 g/ kg (Hart, 1998; Korsgaard 1983).

One way to ensure a good indoor air quality at hygienic air flow rates is to use demand controlled ventilation, based on ppm levels of carbon dioxide in the indoor air, mostly applied in meeting rooms. This way of regulating the air flows might however be a problem in those buildings that are heated by air, since the air flow will vary a lot during the day when it is regulated by ppm levels. If the ventilation system is supplemented with a traditional heating system, regulations by measurements of ppm levels is a good way of reducing the energy use for ventilation and at the same time ensure a good indoor air quality. Still, other pollutants must be considered. If the ventilation rate goes down according to measured ppm levels of carbon dioxide emissions, the concentration of e.g. emissions from building materials might get too high. Another risk with regulating the ventilation flow using the carbon dioxide levels is that the indoor moisture content might get too high.

According to the Swedish building code, the ventilation rate in residential buildings should be at least 0.35 l/s m^2, which is further discussed in Section 9.2. The Swedish ventilation rate of 0.35 l/s m^2 corresponds approximately to an air change rate of 0.5 ach in buildings with a normal ceiling height. In Germany, buildings are regulated in the national building code EnEV; currently in EnEV 2009. Hygienic requirements on mechanical ventilation systems are regulated in the standard VDI 6022 (Thullner, 2010). A low energy building should, according to EnEV 2009, have an air change rate $n_{mech} \geq 0.5$. The Austrian building code requires an air change rate of 0.3 ach or 30 m^3/h per person in low energy buildings. The regulations regarding ventilation rates in seven European countries vary as presented in Table 9.2 (Thullner, 2010).

Table 9.2 Required ventilation rates in low energy buildings in seven European countries.

Country	Sweden	Norway	Denmark	Finland	Germany	Austria	Switzerland
Airflow (ach)	$n \geq 0.5$	$n \geq 0.5$	$n \geq 0.5$	$n \geq 0.5$	$n_{mech} \geq 0.5$	$n \geq 0.3$	$n \geq 0.4$

9.1.2 Existing research

During the last decade, problems with allergies, especially in children, have been associated with indoor air pollution and its combination with low ventilation rates. Since the frequency of asthma and allergies in the developed world has increased so rapidly during the last 30 years, it is said to be unlikely to be due to genetic changes (Sundell, 2004). The probability instead is that this is due to environmental changes.

Most research related to air quality and health is focused on schools and non residential buildings. A study made in offices of the effects of variable indoor air quality on performance and productivity (Wyon, 2004) shows that when the outdoor air supply rate went down from 30 l/s per person to 3 l/s per person, the subjects in the test exhaled less CO_2 and because of this decreased their metabolic rate from 1.35 met to 1.0 met, causing a low performance rate; poor indoor air quality was here measured to decrease the performance of office work by 6-9%. The performance rate was measured to be improved again when the outdoor air supply rate increased. Since the productivity in offices rises with a higher air supply rate, a higher ventilation rate might easier be economically defensible in non-residential buildings

In a study of health in non-industrial environments (EUROVEN) it was described that ventilation rates below 10 l/s per person were seen to significantly aggravate health outcomes, particularly the Sick Building Syndrome (Wargocki, Sundell, Bischof, Brundrett, Fanger, Gyntelberg, Hanssen, Harrison, Pickering, Seppänen & Wouters, 2002). A major outcome of this study was that increasing the ventilation rate also decreased the intensity of clinical syndromes and reduced absenteeism among the employees.

In schools, research has found that ventilation rates below 10 l/s per person increase the risk of developing asthma and respiratory allergies (Geelen, Huijbregts, Ragas, Bretveld, Jans, van Doorn, Everetz, & van der Zijden, 2008). According to the ASHRAE standard 62-1999 (ASHRAE, 1999) a minimum ventilation rate for classrooms is 8 l/s per person. Previous research has shown that measured values of ventilation rate seldom fulfil this requirement (Daisey, Angell & Apte, 2003).

In residential buildings, an air change rate above 0.5 ach has been shown to reduce the degree of infestation of house dust mites in Nordic countries (Schäfer, Stieger, Polzius, & Krauspe, 2008). House dust mite is a trigger factor of atopic eczema, prevalence of which has increased in the past decades, especially in western industrialized countries. In a study of the association between ventilation rates in residential buildings and allergic symptoms in children a correlation was found between children with diagnosed rhinitis and eczema and a low ventilation rate in their bedrooms (Bornehag, Sundell, Hägerhed-Engman & Sigsgaard, 2005). No association was found in this study between ventilation rate and medically diagnosed asthma. However, low ventilation rates were found to increase the indoor humidity, the concentration of indoor-generated exposures and, with a higher indoor humidity; increased infestation of house dust mites. A low ventilation rate was in this study found to be a risk factor for physical irritation.

The connection between air change rates in residential buildings and the risk of children developing bronchial obstruction has been measured in a Norwegian study (Oie, Nafstad, Botten, Magnus & Jaakkola, 1999). The result showed that the risk of developing bronchial obstruction was not associated with residential total air change rate. The risk was however increased in buildings with high indoor emissions and a low air change rate (below 0.5 ach).

The possible connection between low ventilation rates and discoloured stains (moisture problems) on building surfaces was closely evaluated in a case study made at SP Technical Research Institute of Sweden (Hägerhed-Engman, Sigsgaard, Samuelson, Sundell, Janson & Bornehag, 2009). The result of the study showed no such association. The reason for the minimized amount of visible mould on the indoor surfaces was assumed to be a combination of simultaneous warm indoor surfaces and low relative humidity in the indoor air. When in this study no visible mould stains were found, mouldy odours were instead traced in order to detect such indoor pollutants. The result showed significant correlation with a low ventilation rate regarding both mouldy indoor odours as well as high concentration of phthalates remaining in the indoor dust. Both mouldy odour and damp stains were more commonly detected in buildings with passive stack or mechanical exhaust ventilation than in buildings with balanced mechanical ventilation. In this study, the connection between children's health issues and their home indoor environment was also looked at. The results showed that the highest odds ratios for having rhinitis were present in children who lived in a mouldy odour home in combination with a low ventilation rate. The study also showed a significant increased risk of asthma and allergies when a low ventilation rate was combined with detected mouldy odours along the skirting boards.

The limited knowledge regarding the connection between ventilation rates and health in residential buildings was further discussed by Sundell, when two research studies were compared; one made in 1887 and the other one was the Swedish study made in 2000 – 2010 (Sundell, 2004; Hägerhed, 2009), referred to earlier . The results from these two studies with such great time span both confirmed that it was known that low ventilation rates, dampness and certain building materials did have an influence on human health, but it was not defined how or why. In present studies, research focuses on what is expected to be found in the indoor air. However, to be able to know what in the indoor air actually causes asthma and allergies, Sundell concludes that further research needs to be done where the unexpected needs to be looked for.

9.2 Ventilation in the Swedish building stock

The ventilation rate in Swedish buildings has been regulated in the building code since the 1960s. Both mechanical and passive stack ventilation is commonly used in residential buildings.

9.2.1 Development towards current requirements on air change rates in residential buildings in Sweden

In the regulations regarding mechanical ventilation for residential buildings in the building code from 1960, the ventilation rates varied with the use of the room. For rooms larger than 8 m^2 the required ventilation was 25 m^3/h; for kitchens the ventilation rate was needed to be 80 m^3/h and for bathrooms 60 m^3/h (BABS, 1960). In a residential building with three rooms and a heated area of 75 m^2 and a ceiling height of 2.5 m, this equals a ventilation rate of 215 m^3/h or 1.1 air changes per hour (ach).

In the next Swedish building code published in 1967, there were requirements on sizes of exhaust air ducts and supply air inlets, to ensure that passive stack ventilation would function. If mechanical ventilation was used, it was specified in these regulations to have a least air change rate according to Equation 9.1.

$$q = 2.2 - 0.004 \cdot G \ (m^3/m^2h) \qquad \text{Equation 9.1}$$

Where q is the ventilation air flow rate and G is the total living area, according to e-mail conversation with Professor Bo Adamson in March 2010.

The new Swedish building code published in 1980 had a major focus on energy saving aspects (SBN 80) as a result of the oil crises in the 1970s. Measures had been taken among house owners during the 1970s to save energy by for example lowering the ventilation rates and sealing the buildings according to e-mail conversation with Professor Bo Adamson in March 2010. Passive stack ventilated new residential buildings were by then measured to have an air change rate of normally 0.1 to 0.3 ach. As a result of these energy saving measures, problems of indoor condensation and mould occurred in the buildings and put indoor air quality back on the scientific agenda. Also new problems relating to health issues occurred in buildings during this period; regarding radon in the late 1960s, formaldehyde in the early 1970s and sick building syndrome (SBS) and house dust mites in the late 1970s (Sundell, 1982). To increase the indoor air quality, the Nordic Committee for Building Regulations (NKB), in the building code published in 1980, attempted to find a balance between energy use and indoor climate. To keep the pollutants at a controlled level, requirements were established regarding air flow rates. The air change rates were set in view of the types and quantities of indoor airborne pollutants known by then, with the primary objective to keep the indoor pollutants at an acceptable level. Any substance in the air that had a documented risk of harmful effect on the occupant's health was needed to be kept at a sufficiently low concentration. The yearly mean value of the concentration of radon daughters in the indoor air was required to be below 70 Bq/m^3 in rooms where people frequently stay. No other approved concentrations of indoor pollutants were set, since it was difficult to follow up when measurements could only be performed on a limited number of pollutants. It was however recommended that building materials known to be high emitters of pollutants and because of this to require higher ventilation rates should be avoided.

Regarding ppm levels of carbon dioxide concentration and human body odour, the outdoor air flow rate in bedrooms was in the 1980s building code required to be 4 l/s per person. A carbon dioxide concentration level of not more than 1000 – 1500 ppm was considered, referring to reports of headaches and general discomfort at higher levels. To keep the concentration of radon daughters below the recommended level, the required air change rate was 0.5 ach. Also the concentration of formaldehyde was kept at a sufficiently low level with an air change rate of 0.5 ach. Since there was a lack of knowledge regarding pollutants from building materials, there were concerns within the NKB whether the level of 0.5 ach was too low.

In the current Swedish building regulations BBR 16, the ventilation rate in residential buildings is required to be 0.35 l/s m^2 living area (1.26 $m^3/h,m^2$), that can be lowered to 0.10 $l/s,m^2$ (0.36 m^3/h) if there is no occupant in the building (Boverket, 2009a). The reduction of air flow rate should not cause any health risks or damage to the building and its installations (BBR 2008 6:251). Otherwise, the ventilation options for non-occupancy according to EN 13779:2007 give a minimum of 0.1 – 0.2 $l/s,m^2$ if national requirements are not available (SIS, 2007b). The National Swedish Board of Health and Welfare recommends the ventilation rate not to be less than 0.5 ach in residential buildings. They also recommend the supply air to be not less than 0.35 l/s m^2 (1.26 m^3/h) or 4 l/s person as set in the building code. The recommended mean value of the air velocity should not exceed 0.15 m/s (SOSFS, 2005).

9.2.2 Mandatory ventilation checks

Air change rates in Swedish buildings are measured in the mandatory ventilation performance checks, as a part of the inspection of the ventilation systems in buildings according to Swedish law (OVK). The inspections are performed by a certified inspector and the main purpose of the inspections is to ensure a good indoor climate in buildings. Single family houses with one or two apartments are excluded from the control. The regulations are continually updated, and the latest version was published in 2009 (Boverket, 2009b). The function of the ventilation system is inspected before the building is taken in use and later on by regular inspections. The period between the inspections depends on the activity in the building and the type of ventilation system that is used. The owner of the building is responsible to make sure the inspections are carried out according to the law. The local authorities supervise the inspections. If the ventilation systems are not working satisfactorily and not adjusted or the inspections are not made according to law, the owner of the building must pay a fine or sanctions are imposed (Plan och Bygglagen, 1987). The local building committee can, if the ventilation system is not improved, decide that the building is no longer allowed to be used or that it is in such bad condition that it needs to be demolished.

9.2.3 Measured air change rates in existing Swedish dwellings

As a part of a major Swedish study (ELIB), the ventilation rates in a statistical sample of Swedish residential buildings were measured during winter 1991/92 (Stymne, Boman, & Kronvall, 1994). The result showed significant differences in the air flow rates in single family houses compared to multi family houses with a variation from 0.2 l/s,m^2 in single family houses up to 0.38 l/s,m^2 in some multi family houses. Approximately 55% of multi family houses measured in the study had a ventilation rate below the required 0.35 l/s,m^2 and up to 85% of the measured single family houses had a too low air change rate. The higher ventilation rates in multi family houses can be explained by the more efficient chimney effect in these higher buildings compared to single family houses and also that mechanical ventilation systems are more common in multi family houses. Single family houses built in the 1960s and the beginning of 1970s had the lowest ventilation rates (0.20 l/s,m^2). However, the measured ventilation rates in terms of litres/sec per inhabitant were also shown in this study to vary with average values between 12 to 18 l/s per occupant.

Also in later Swedish research the measured mean air change rates were seen to be higher in multi family houses than in single family houses, with a mean air change rate of 0.48 ach (total building) in multi family houses and 0.36 ach (total building) in single family houses (Bornehag et al, 2005). Most of the measured single family houses in this study had passive stack ventilation and the multi family houses had mostly mechanical ventilation. The single family houses with supply and exhaust mechanical ventilation system had a higher air change rate than the rest of the single family houses. The measurements showed that the ventilation rate was lower in buildings built in 1961 – 1983, compared to buildings from earlier or later construction periods. Also buildings with a concrete foundation construction and one storey single family houses had lower ventilation rates. In this study, approximately 86% of the measured single family houses and 50% of the multi family houses did not fulfil the Swedish requirement of an air change rate of 0.5 ach.

Ventilation rates that were too low according to their national standards were also detected in measurements of dwellings in other studies in Nordic countries (Oie et al, 1999; T.Kalamees et al, 2009; Bornehag et al, 2005).

9.3 Ventilation in passive houses

The ventilation system in a passive house building has many important functions. As in all buildings, it should mainly contribute to a good indoor air quality regarding indoor temperature, draughts, humidity and carbon dioxide levels. A major difference, however, is that with a sufficiently airtight and well insulated building envelope it is in passive houses possible to use the ventilation system for the distribution of heat, which makes the ventilation system even more important.

The required air change rate in very low energy buildings varies a lot between countries (Thullner, 2010), with e.g. 0.3 ach recommended by the German Passive House Institute (PHI) to 0.7 ach in Norwegian dwellings with a living area below 110 m^2. Most common is an air change rate of 0.5 ach in low energy buildings, as presented in Table 9.2. The variation in ventilation rates makes it complicated to compare passive houses and their energy use since the different ventilation rates have such an influence on the total energy use, both relating to electricity used by fans and the energy needed to heat up ventilated volumes of air.

In a well insulated building construction, the indoor surface temperature is quite high. In cold climates, the relative humidity in the indoor air is low during winter. According to a study made at the German Passive House

Institute, it was possible to set the ventilation rate in passive houses at a lower level than normal. The reason for the lower ventilation rate was that the well insulated surfaces were too warm for condensation to occur, even at a level of 60 % relative humidity in the indoor air. This, in combination with an internal moisture barrier, is the motive to keep the ventilation rates at a lower level in passive houses according to the German Passive House Institute. In this study, appropriate air change rates for low energy residential buildings were set to 0.3 - 0.4 ach and for passive houses it was here recommended to lean towards the lower rate (Feist, 2001). The current German passive house guidelines recommend a supply mean air flow rate of 20-30 m^3/h pers (8.5 l/s pers) and the system should also allow for a minimum air supply setting for times with no occupancy, with a corresponding air flow rate of 0.2 ach (Feist, 2009; Thullner, 2010). The cross sections of the ducts should be chosen so that air velocities are lower than 3 m/s.

9.3.1 Ventilation flow and power distribution based on volume per person

The original German passive house definition is based on how much heat can be distributed in a house with the supply air at normal ventilation rates, set to meet the required hygienic air flow rates (Feist, 2006b). The passive house definition follows the German building code applicable at the time when the standard was made, with a required supply air rate of $\dot{V}$ = 30 m^3/h per person. In the definition, a living space of 30 m^2 per person is set, which gives a ventilation rate of 1 m^3/m^2h. Using Equation 9.2, the peak load for space heating is calculated.

$$P = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \qquad \text{Equation 9.2}$$

Where

P = available space heating power (W/m^2)
$\dot{V}$ = ventilated air flow (m^3/s)
ρ = density of air (kg/m^3)
c_p = heat capacity of air (J/kgK)
ΔT = Temperature raise of supply air (°C)

To avoid pyrolysis of dust, the supply air (after the heat exchanger) should not be heated more than 30 K (Feist, 2006b). The available power for space heating is calculated as follows:

$30 \text{ m}^3\text{/h,pers} \cdot 0.33 \text{ Wh/m}^3\text{K} \cdot 30 \text{ K} = 300 \text{ W/pers}$

$30\text{m}^2\text{/ pers} \rightarrow$ **10 W/m²**

By using a ventilation flow based on volume per person, the air change rate in a building varies depending on the living area each person has access to but also the ceiling height in the building. In Figure 9.1 the resulting air change rate (ach) for a ventilation rate of 30 m^3/h per person is shown as a function of the living area per person for two different ceiling heights; 2.5 and 3 m.

Figure 9.1 shows that a living area of 30 m^2 per person corresponds to 0.3 – 0.4 ach at a ceiling height of 2.5 – 3 m as recommended by the German Passive House Institute. The ventilation rate of 0.5 ach is needed if each person has a living area of 24 m^2 at a ceiling height of 2.5 m or if the ceiling height is raised to 3 m and each person has a living area of 20 m^2. The calculated possible power load of 10 W/m^2 in the supply air for space heating at an air change rate of 0.3 ach is increased by approximately 20% when the air change rate increases to 0.5 ach.

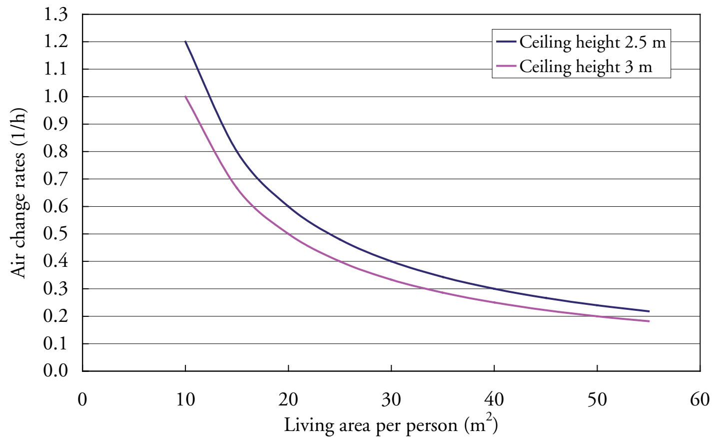


Figure 9.1 *Air change rates per person with a ceiling height of 2.5 and 3 m and an air change rate of 30 m³/h per person.*

The living area of 30 m^2 used in the German passive house definition is not the general living area per person in Sweden. According to Swedish statistics the average living area in Sweden varies with the type of building. For rental apartments the average living area was 36 m^2/pers, for single family houses 41 m^2/pers and for co-operative flats 49 m^2/pers (Sandberg, 2009). In the German passive house definition, the living area of 30 m^2

gave a possible power distributed in the supply air of 10 W/ m^2. If the average living area in Sweden is used, the power distributed in the supply air varies from 6.1 W/m^2 to 8.3 W/m^2.

Using the Swedish required ventilation rate of 0.35 l/s m^2 (approximately 0.5 ach) and the statistics on living area in different types of dwellings, the ventilation rates vary between 45.4 m^3/h per person to 61.7 m^3/h per person, depending on the type of residential building as presented in Table 9.3. The possible power distribution in the supply air is calculated to 12.5 W/m^2 at the higher air change rate.

Table 9.3 Ventilation rates in dwellings in Sweden based on living area statistics.

	Rental apartments	Single family houses	Co-operative flats
Living area (m^2/person)	36	41	49
Required ventilation rate (m^3/h,person)	45.4	51.7	61.7

9.3.2 Power for space heating distributed with the supply air at different outdoor temperatures

The maximum power for space heating distributed by the supply air is calculated according to Equation 9.3 and dependent on the outdoor temperature by the factor ΔT.

$$P\ (W/m^2) = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \qquad \text{Equation 9.3}$$

Where

P = available space heating power (W/m²)
$\dot{V}$ = ventilated air flow (m^3/s)
ρ = density of air (kg/m^3)
c_p = heat capacity of air (J/kgK)
ΔT = Temperature rise of supply air (°C)

In many countries the maximum value of the supply air temperature in low energy buildings is set to 52°C (Thullner, 2010) as in the Swedish passive house recommendations (FEBY, 2009). The reason for this limit is to avoid pyrolysis of dust (Feist, 2006b). As presented earlier, in the basic passive house criteria the supply air (after heat exchanger) should not be heated more than 30 K (Feist, 2006b). The temperature rise of the supply air is actually the difference between the supply air temperature after the heat exchanger and the maximum allowed temperature of the supply air (Equation 9.4). When the maximum supply air temperature of 52 °C is used in the calculation of power consumption, a static temperature raise of the supply air (ΔT) of 30 K will only give an approximate calculation of the possible heating power distributed by the supply air.

$$P = \dot{V} \cdot \rho \cdot c_p \cdot \Delta T \quad (W/m^2)$$
$$= \dot{V} \cdot \rho \cdot c_p \cdot (52 - T_{after\ heat\ exchanger}) \qquad \text{Equation 9.4}$$

The supply air temperature after the heat exchanger depends on the outdoor temperature, the indoor temperature and the efficiency of the heat exchanger as calculated in Equation 9.5.

$$T_{after\ heat\ exchanger} = T_{outdoor,dim} + \eta \cdot (T_{indoor} - T_{outdoor,dim}) \qquad \text{Equation 9.5}$$

The available space heating power at different outdoor temperatures varies as presented in Figure 9.2, using Equations 9.4 and 9.5 with a ceiling height of 2.5 m, an indoor temperature of 20 °C, a heat exchanger efficiency of 80% and an air change rate of 0.5 ach.

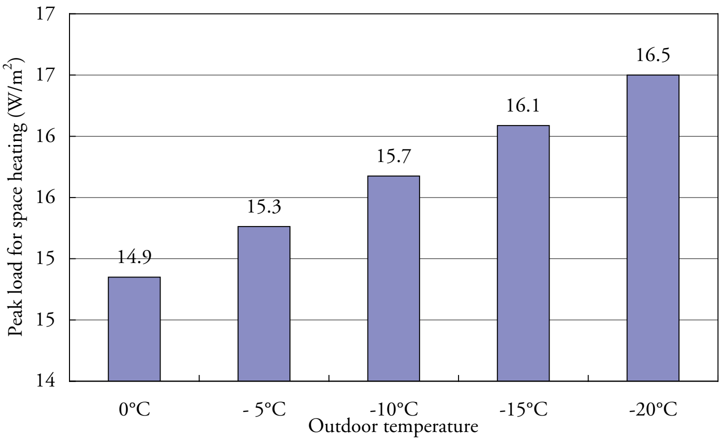


Figure 9.2 *Possible space heating power in the supply air at different outdoor temperatures with an indoor temperature of 20° C and an air change rate of 0.5 with 80% recovery on the heat exchanger, ceiling height 2.5 m.*

Using the same input data, but also varying the ventilation rates from 0.3 ach to 0.5 ach, the peak load for space heating carried within the air at an outdoor temperature of -20 ° C varies from 9.9 W/m^2 at an air change rate of 0.3 ach to 16.5 W/m^2 at an air change rate of 0.5 ach. The available peak load for space heating at different outdoor temperatures and ventilation rates, with a ceiling height of 2.5 m, is calculated in Figure 9.3.

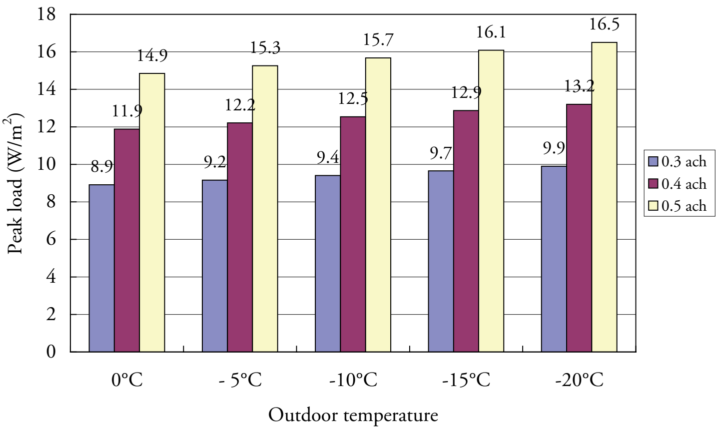


Figure 9.3 *Possible heating power in the supply air at different outdoor temperatures and different air change rates with 80% heat recovery of the heat exchanger and an indoor temperature of 20° C, with a ceiling height of 2.5m.*

9.3.3 Variable air change rates and the influence of ventilation losses

The overall heat loss coefficient for space heating (P_{tot}) depends on transmission losses (P_t) and ventilation losses (P_v) (Equation 9.6). A variation of air change rates will influence the ventilation losses and thereby the peak load and energy demand for space heating.

$$P_{tot} = P_t + P_v \quad \text{(W)} \qquad \text{Equation 9.6}$$

The losses due to ventilation depend on mechanical ventilation and air infiltration/ exfiltration losses through the building. To limit the infiltration losses, requirements on the airtightness of the climate shell are always regulated in the available passive house criteria (Thullner, 2010). An airtight building also ensures a high efficiency of the heat exchanger when all supply and exhaust air passes through the heat exchanger on its way in or out of the building. The variation of the mechanical ventilation rates according to national building regulations will influence both the peak load for space heating and levels of the energy demand for space heating. The ventilation losses are calculated according to Equation 9.7.

$$P_v = \rho \cdot c_p \cdot q_{mechanical} \cdot (1-\eta) + \rho \cdot c_p \cdot q_{infiltration}$$

Equation 9.7

Where

ρ = density of air (kg/m^3)
c_p = heat capacity of air (J/kgK)
$q_{mechanical}$ = mechanical ventilation rate (m^3/h)
η = efficiency of the heat exchanger (%)
$q_{infiltration}$ = ventilation losses due to air infiltration/ exfiltration (m^3/h)

The energy demand for space heating is calculated according to Equation 9.8:

$$Q_{tot} = P_{tot} \cdot \int (T_{supply} - T_{outdoor})\, dt$$

Equation 9.8

Where

P_{tot} = the total power demand for space heating (W)
T_{supply} = the supply air temperature (°C)
$T_{outdoor}$ = the outdoor air temperature (°C)

The outdoor climate strongly affects the transmissions losses of the building but also the energy use in the ventilation system. According to research made at the German Passive House Institute, the peak load level for space heating of 10 W/m^2 is equal to an energy use for space heating of 15 kWh/m^2a; a result from both simulations and measurements (Feist, 2006b). To reach the energy level of 15 kWh/m^2a, a Central European climate was used. The energy level for space heating in passive houses is shown in that study to vary between approximately 20 kWh/m^2a in Stockholm and 10 kWh/m^2a in Rome, depending on the different climates.

The influence of different air change rates on peak load and annual energy demand for space heating was studied using the simulation program DEROB – LTH v1.0 (Kvist, 2006). The two demonstration passive house projects in Frillesås and Värnamo were simulated in the program at different ventilation rates. The ventilation rates were varied between 0 ach and 1.0 ach. Other data used in the simulations were not varied and are as presented in Chapters 3 and 4.

In Frillesås, at an air change rate of 0.5 ach, the calculated value of the peak load for space heating was 10.8 W/m^2 and the energy demand for space heating was 14.8 kWh/m^{2}a. When the air change rates increased from 0.3 ach to 0.5 ach, the peak load for space heating increased by 10%. The energy demand for space heating increased by 16% when the air change rates increased from 0.3 ach to 0.5 ach (Figure 9.4).

Looking at the apartment buildings in Värnamo, the calculated peak load for space heating was 8.1 W/m^2 at an air change rate of 0.5 ach and the energy demand for space heating was calculated to 9.8 kWh/m^{2}a. The peak load for space heating increased by 14 % when the air change rate increased from 0.3 ach to 0.5 ach and the energy demand increased by 29 % when the ventilation rates increased from 0.3 ach to 0.5 ach (Figure 9.5).

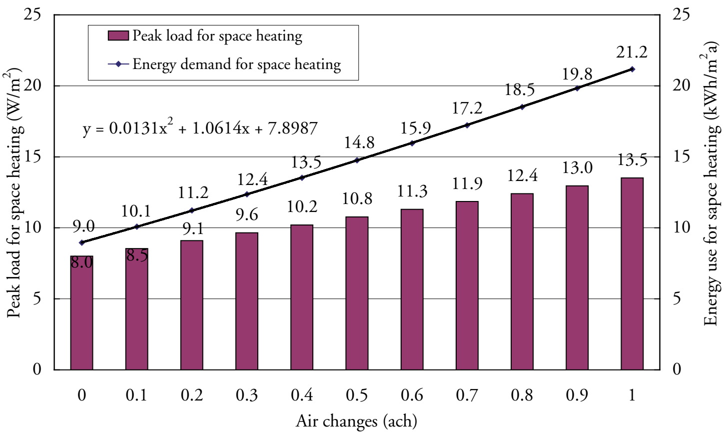


Figure 9.4 *Energy demand and peak load for space heating in the passive house project in Frillesås at different air change rates using climate data for Göteborg (with solar radiation).*

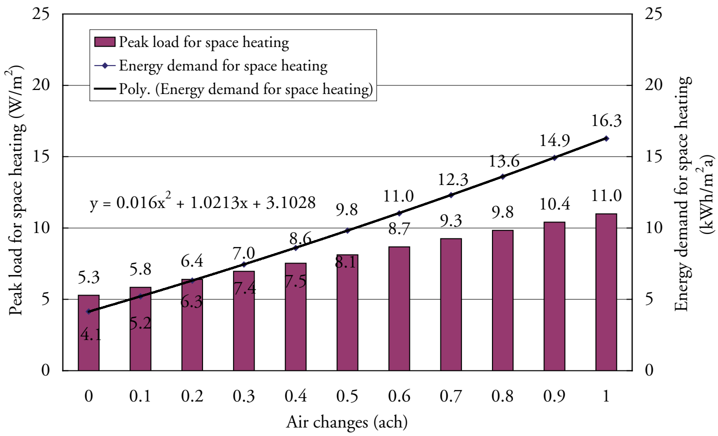


Figure 9.5 *Energy demand and peak load for space heating in Värnamo at different air change rates using climate data for Jönköping (with solar radiation).*

9.4 Fan electricity

The fans installed in the mechanical ventilation system require electricity all year round. There are fans on the market with a low electricity use, and these should be used to keep the overall energy use for the building as low as possible. The Specific Fan Power (SFP) should be low and is therefore regulated in the building standards in many countries (Thullner, 2010). In Swedish and Norwegian passive houses it is recommended to keep the SFP value below or equal to 1.5 kW/m^{3}s. The specific fan power is calculated according to Equation 9.9 (SIS, 2007b).

$$P_{SFP} = P/\dot{V}_v = \Delta P/\eta_{tot} \qquad \text{Equation 9.9}$$

Where

P_{SFP} = the specific fan power (W/m^{3}s)
P = the input power of the motor for the fan (W)
$\dot{V}_v$ = the design air flow through the fan (m^3/s)
Δp = the total pressure difference across the fan (Pa)
η_{tot} = the overall efficiency of the fan (-)

It can be seen in Equation 9.9 that if the ventilation rate increases, the load on the fans in the ventilation system will increase, and they will use more electricity. The different ventilation rates recommended in each country's building regulations will therefore influence the fan electricity use in the system and thus the total energy use of the building.

If the fan energy is limited by the SFP, the energy needed for the fans is calculated according to Equation 9.10.

$$Q_{fan} = SFP \cdot \dot{V} \cdot t / A \qquad \text{Equation 9.10}$$

Where

Q_{fan} = the energy use for the fan (kWh/m^2a)
$\dot{V}$ = the ventilation air flow (m^3/s)
t = hours per year (h)
A = heated area (m^2)

Regulations regarding the maximum energy use for the fans in the ventilation unit can also be given in other ways than by the SFP. According to the German Passive House Institute (PHI), the electrical efficiency of the ventilation system should be lower than 0.45 Wh/m^3 (Passivhaus Institute, 2009).

To see how the annual energy demand for the fans varies at different air change rates the energy use was calculated, using both a limitation on the SFP value and the energy limitation according to the German PHI. Ventilation rates of 0.3 ach, 0.4 ach and 0.5 ach were compared using a ceiling height of 2.5 m.

The results show that the two limiting values of energy use for ventilation fans give a similar annual energy use, as presented in Table 9.4.

Table 9.4 Fan energy demand at different electricity limits and different air change rates.

Air change rate (ach)	0.3	0.4	0.5
Supply air ($m^3/h,m^2$)	0.75	1.0	1.25
Fan energy demand with a fan electricity limit <0.45 Wh/m^3 ($kWh/m^2,a$)	3	3.9	4.9
Fan energy demand with a fan electricity limit SFP <1.5 $kW/(m^3/s)$ (kWh/m^2a)	2.7	3.7	4.6

The additional energy use for the fans when the air change rate is increased from 0.3 ach to 0.5, both if the fan energy was limited to 0.45 Wh/m^3 or if the SFP value was set to 1.5 kW/(m^3,s) was calculated to 1.9 kWh/m^2a.

9.5 Discussion and conclusions

Not much research is available in the area of residential buildings and indoor climate. The studies made indicate, however, that low ventilation rates (below 0.5 ach) increase the concentration of emissions from materials, the moisture content, mouldy odours and the concentration of phthalates in the indoor air. The higher concentrations increase the risk of illness among children. In order to remove the pollutants known at present from the indoor air in residential buildings, an air change rate of 0.5 ach seems according to available research to be sufficient to achieve a good indoor air quality. Since extensive research is still needed to be carried out within the area of indoor pollutants and their effect on health, low emitting materials should be used.

To be able to keep the air change rate at these required levels, a mechanical ventilation system is needed with a heat exchanger of high efficiency in the ventilation unit to decrease the energy use. The fans mounted in the ventilation unit should have a low specific fan power (SFP) to keep the overall energy use in the system at a low level.

It is seen here to be difficult to link requirements on ventilation rates with the number of persons in a residential building, especially when related to a fixed living area. A required air change rate based on air changes of indoor air per hour seems to be the best way to regulate ventilation rates. A variation of air change rate in the ventilation system will affect the available power in the supply air for space heating but also affect the ventilation losses in the building and the fan electricity needed in the ventilation unit.

By simulating the two demonstration projects in Frillesås and Värnamo, the difference in energy demand for space heating and fan electricity at the air change rates 0.3 ach and 0.5 ach and an SFP of 1.5 kW/(m^3/s) was studied using DEROB – LTH and showed that the energy use increased by a total of 4.3 kWh/m^2a. In an apartment of 60 m^2 the annual energy use would, through having a ventilation air change rate of 0.5 ach instead of 0.3 ach, increase by 258 kWh per year in both Frillesås and Värnamo.

As earlier stated, a ventilation air change rate of 0.5 ach has in previous research seemed to be necessary in order to achieve a good indoor air quality. The small increase in energy use when the ventilation rate is increased to 0.5 ach from 0.3 ach must not be a reason to turn down the ventilation rate.

10 Discussion and conclusions

Energy use in the building sector is at an unnecessary high level and needs to be reduced drastically. The energy demand for space heating in passive houses is much lower than in traditional buildings and also ensures a good indoor climate for the tenants. The main purpose of this research was to see what knowledge and components that were needed to achieve a wide spread deployment of passive houses in Sweden. By participating in four demonstration projects knowledge has been gained about the total building process but also about building management among the clients and the tenants' needs and experiences.

The development of passive houses in Sweden, and the interest in these, has increased rapidly during the period of this research. In 2005 there were two known passive house projects in Sweden; Lindås and Glumslöv, and in 2010 there are over 1000 passive house apartments built and many more planned all over Sweden (Passivhuscentrum, 2010). The increase is due to many factors but increasing energy prices in Sweden together with a growing awareness of global warming and the need of energy saving measures are probably the most important factors. Also, the Energy Performance of Buildings Directive issued by the European Union has put requirements on both new and existing buildings, which has enlightened local authorities and made them aware of the energy saving potential in buildings and that buildings in the future need to be more energy efficient. Another reason that can not be neglected is the experience spread from these demonstration projects. All projects have gained much attention and have been visited regularly by both national and international groups and also been frequently reported about in both newspapers and on television. This shows the importance of full scale demonstration projects that both inspire visitors to build their own passive houses and where experiences are gained to use in future projects.

The wide spread deployment of passive houses wished for as a result of this PhD study has in some sense already started during the period of research. More and more carpenters have become familiar with airtight constructions, and this has reduced the additional time needed to build passive houses. Traditional building materials are used in passive houses as seen in these four demonstration projects. However, some not traditionally used products are needed to make the building overall energy efficient, for instance doors and windows with very low U-values. When more products suitable for energy efficient buildings are easily available on the market the projects can be carried out at a lower cost. This lower cost in future projects has already been seen by some of the clients in this study who have continued after the demonstration project with new passive house projects.

In this chapter the knowledge gained from the work on the four demonstration projects will be discussed together with suggestions for the development of products and processes seen to be needed, using these projects as a base. Some development of both products and processes mentioned has slowly started but some are still needed to be initiated and evolved.

10.1 Introduction

Some initial questions were raised in the beginning of this research such as was it at all possible to build passive houses in a Swedish climate? Was it possible to renovate using passive house principles and did it work to build a single family passive house and get a good indoor climate? What products were needed to be developed? What were the key factors for a passive house project with a successful final result? What are the experiences of the tenants of living in a passive house? The outcome was said to be not project specific but generally usable for passive house projects.

A residential building is not an energy saving system; it is a place for living, and the wellbeing of the tenant should always be in major focus. The design of the building should be optimized according to many factors; aesthetic, functional and economic, and it should always conform to national building regulations. To achieve a building with a low energy demand should be a natural part of the design process.

The passive house concept is a good way to build energy efficient buildings with a high indoor comfort. Due to differences in national building regulations and outdoor climate it is however difficult to have one common required level for energy use for space heating for passive houses in different countries. However, the passive house principle can be used all over the world.

10.2 The planning process

Experiences from the planning process in these four demonstration projects have shown that the client needs to know very well what a passive house is and must specify what the desired final result of the finished building should be. Explicit requirements set up by the client for the final result make it easy for the persons planning the project to know what targets to fulfil and for the client to check what has been planned. Also the contractor knows what to aim for and when the work is actually finished. To order a passive house might be something the client has never done before. To know what important factors are needed to be put into focus to achieve a well functioning passive house building, support could be received from an expert or from a colleague who has the knowledge needed.

Another factor for a successful energy efficient building project is a committed project leader who works in a firm way, steers the project in the right way and with a democratic way of leadership. It is important that the project leader is well aware of the targets set up by the client and always makes sure that these are fulfilled. Experiences from these four projects show that it is a great disadvantage to change the project leader in an ongoing project. Much knowledge and informal information and decisions are lost and the planning process might be extended when many items need to be repeated.

The planning process should preferably be performed in an iterative circle, not as more traditionally in a straight line where the baton is handed over from the architect to the designer to the HVAC consultant like a relay race. A much better way to get a good final result is for the architect to start, hand over the initial plans to the designer to have a look at the construction and after that the HVAC consultant takes a close look to see if the energy performance of the building is sufficient for a passive house. Then the project goes back to the architect who makes the necessary changes and the circle starts again. In this way, all participants' consultants learn from each other and hopefully feel that they are satisfied with the building design. When the specified requirements from the client are fulfilled, the circle is finished and the building process can start. However, it is very important not to make the solutions too theoretical. Carpenters must be continuously asked if the drawn up designs are practically feasible before the plans are finished and the work on site starts. If the planning process had formed a mediocre basis of construction, it would strongly affect the building process. It is very difficult for the contractors to come up on site with a sustainable solution for a construction they never tried before and even more difficult to know what was actually ordered by the client. The best solutions are finished in the planning "circle" with major inputs from the contractors.

Within the planning group it is highly recommended to have someone responsible for the energy aspects of the project, who makes sure that the energy aspects are considered in all decisions taken. A holistic approach during the planning process should however be kept by all participating consultants. It is important to understand what side effects a change made by one consultant might give rise to in the other disciplines. If one consultant makes a change to the original design of e.g. the outer wall construction it might not cause such a big difference to the calculated energy demand. Nor if the architect increases the window area of the building. But these two changes added together could cause a large difference to the energy demand for space heating of the building. It is important for each discipline not to compare their designs individually with the original design but to take all changes into consideration and cooperate between disciplines. To ease this in the planning process, all changes should be discussed with the person responsible for energy issues in the project before changes in the design are approved.

These four projects were initiated by one extraordinary driving force; one in each project. Both here and earlier it seemed to be necessary, in this initial phase of building passive houses in Sweden, to actually make the passive house project real. In this research it has become clear that the driving force also needs a partner who knows all about the technical aspects and can translate the visions made by the driving force into reality. Otherwise, the good intentions seem to fade away somewhere halfway and the initial demands and the finished project do not correspond well.

10.3 The building process

The carpenters in these four demonstration projects have been very proud of their work, which is a very nice side effect that the passive houses have achieved. The high quality final result handed over to the client by the contractors is due to many different aspects, but one important factor was that the carpenters had more time available in the building process in all four projects than in regular projects, since building passive houses was something new for all involved and the time needed to be finished was uncertain. Especially the time needed for making the building airtight was an uncertain parameter. The longer available time was appreciated by the carpenters who did not have to rush through the project and had time to finish the constructions with a high accuracy.

Another key factor for the high quality result was said by the carpenters to have been the weekly meetings held in some of the projects, where all contractors discussed the work that had been put down during the week and where the opportunity was given to suggest improvements to building processes. When these improvements were used later in the project the contractors described that they got a great feeling of participation in the project, and that what they had done really made a difference. This feeling of commitment both improved the pleasure taken by the carpenters in their work and the quality of the final product.

An installation layer has been included in all outer wall constructions in these four projects but must also be remembered in the ceiling in the roof construction in future projects.

The U-value of the windows in all four projects was below 1.0 W/m^{2}K. Due to the low U-value, there is a risk of condensation on the outer pane of the windows on nights with a clear sky. In the interviews, none of the tenants answered that outdoor condensation of the energy efficient windows has caused any inconvenience and it had only been noticed by three households of the total 23 interviewed households.

To get a well functioning final result, all contractors need to think beyond the traditional boundaries of their contract. The mistakes detected in these four projects during the building process were most commonly found at the interfaces between different contractors where information was lost or when both contractors thought the other one was responsible for the construction.

10.4 Measurements

According to the European Building Directive, occupants should be able to regulate their own use of energy for space heating and domestic hot water, as far as such measurements are cost effective (European parliament, 2010 f). The need of measurements is also regulated in the Swedish building code where it is said that the energy use in the building should be followed continuously by measurements in order to be able to read the energy use of the building for a certain period of time (Boverket, 2009a). It is also recommended in the building code that if the building is heated by electricity, the use of electricity for space heating should be measured separately. The tenant should have easy access to the measured values of energy use. To visualize the energy use for the tenants and give them an opportunity to have an influence on their energy use is an important purpose of the measurements of energy use. But the measurements should also be used to simplify the clients' control of the distribution systems for the apartments. By regular controls of the measured energy use it is easy for the caretaker to see if something is not functioning properly.

Experiences from this research project show that the measuring system is often quite expensive but if the measured results can be used by the client in practice, the cost is usually not a problem. Both private owners and the public housing companies need to see an additional value in the measured results. Within these demonstration projects, there was a great difference in the way the results from the measurements were used. It could be seen that in the apartment projects in Värnamo and Frillesås, the clients were familiar with how to use the measurements. The results were used for debiting the energy costs from the tenants but were also continuously supervised, in order to make sure the systems were well functioning. When the measurements are practically used like this by the client, measurements become a natural part of the building project and save money for the client when the results are used as part of the daily management of the buildings. In the renovation project, measurements were made but no one in the organization of the client took the advantage of using the received data and the responsibility for the measured data was uncertain between the energy company who performed the measurements and the client.

The measurements of actual energy use should be made by someone who is committed about the results of the measured figures and uses them in the daily work of maintenance of the buildings. If the measurements are made by someone else than the client, the measurements need to be collected and sent to the client regularly in order to have control of the systems in the building. A measuring system should be used where the data are easy to access and assemble so that the control of the system does not take an unnecessarily long time for the client.

The results of the measurement could have a great usability in apartment buildings but the question of measurements is more complex in single family houses. An investment in building a house is often just what a family can bear financially. Employing measuring companies with a high need of profits might be difficult to achieve for single family house buyers. Measurements for single family houses need to be made in a cost effective way and where the house owner can see that the measurements are usable and worth paying for. A basic low cost measuring method should be developed, including measurement of airtightness, energy use and indoor comfort, which could be used in single family houses. Maybe these controls could be made by the local authorities.

Measurements of a finished building might show too high a measured value of e.g. annual energy use for space heating. It is important to have it explained in the planning process who is responsible if the measurements show too high values and who then has the responsibility to take measures. If this is included in the guarantee from the building company in single family house projects it is most important that the measurements are made by a neutral party so that the single family house owner receives accurate values. The energy use varies a lot according to tenants' living behaviour and outdoor climate compared to a normal year, which needs to be taken into consideration when the measured values are compared to the specified requirements.

10.5 Results from the measurements

10.5.1 Energy use

One of the major questions raised in this research was to see what levels of the peak load and energy use for space heating were reached in these four demonstration projects. The measured figures could be used as a guideline for future passive house projects. The peak load for space heating and annual energy use for space heating in the four projects were first simulated in DEROB – LTH v.1.0 during the planning process and measured after the buildings were finalized and the tenants had moved in.

The measured peak load for space heating and the calculated figures are presented in Table 10.1 together with maximum peak load for space heating as set by FEBY (FEBY, 2009).

Table 10.1 Measured and calculated peak load for space heating.

	Measured peak load for space heating (W/m^2)	Calculated values for space heating at an indoor temperature of 20°C (W/m^2)	Requirements by FEBY (W/m^2) (FEBY, 2009)
Värnamo	10.9	8.3	10
Frillesås	11.3	10.8	10
Lidköping	20	12.6	12
Alingsås	14	8.8	-

The goals regarding energy use in the demonstration buildings for space heating and domestic hot water were initially set to 25 – 50 % of the energy used in similar buildings built according to the current Swedish building code. These goals were measured to have been fulfilled in all four projects as presented in Subsection 7.1.5. The measured energy use for space heating revised to a normal year was in the two apartment building projects below 15 kWh/m^{2}a (measurements made after correction of one ventilation unit in Frillesås), in the renovation project 27 kWh/m^{2}a and in the single family house 34 kWh/m^{2}a.

The measured values of energy demand for space heating are compared with the recommended values of total energy use in Swedish passive houses set by FEBY to see how well they correlate. All four projects are situated in Climate zone 3 (Boverket, 2009a). The weighted levels of total measured annual energy use in Swedish Passive houses as recommended by FEBY should be below 60 kWh/m^{2}a in Climate zone 3, using Equation 10.1. The area used is $A_{temp+garage}$. The total energy use includes energy for space heating, domestic hot water and common electricity.

$$Q_{weighted} = \Sigma(e_{el}\cdot Q_{el}+e_{dh}\cdot Q_{dh}+e_{bp}\cdot Q_{bp}+e_{s,w}\cdot Q_{s,w}) \leq$$
$$\leq Q_{requirement}\ (kWh_{weighted}/m^2a) \qquad \text{Equation 10.1}$$

Where

Q_{el}, e_{el} = delivered energy (kWh/m^{2}a) and energy correction factor, electricity
Q_{fv}, e_{dh} = delivered energy (kWh/m^{2}a) and energy correction factor, district heating
Q_{bp}, e_{bp} = delivered energy (kWh/m^{2}a) and energy correction factor, bio fuels
$Q_{s,w}$,$e_{s,w}$ = delivered energy (kWh/m^{2}a) and energy correction factor by solar systems or wind power plants

There are no national Swedish energy correction factors. It is recommended by FEBY to use energy correction factors that correlate to the factors for Climate Zone 3 according to the Swedish building code BBR 16 (Boverket, 2009a) which are:

e_{el} = 2
e_{dh} = e_{bp} = 1
$e_{s,w}$ = 0

The measured energy use in the four demonstration projects is weighted according to Equation 10.1. The results are presented in Table 10.2. Looking at the weighted energy use in Table 10.2, the use of electricity for common areas has a great impact on the total energy use. In Värnamo, the electricity was produced by a wind power plant. The wind power plant was not placed on the property of the apartment buildings in Oxtorget, which is necessary to be able to subtract the energy bought from the wind power plant from the measured total energy use. None of the projects has a weighted energy use below the required level of 60 kWh/m^{2}a.

Table 10.2 Annual mean weighted measured energy use.

Energy use (kWh/m^{2}a)	Space heating revised to a normal year	DHW heating	Electricity common areas	Total weighted bought energy
Frillesås	18.8	15	33.4	67.2
Lidköping	34	17	13.2	63.9
Värnamo	18	29	22.4	69.4
Alingsås	26.6	16.1	46.4	89.1

An alternative requirement for non weighted annual bought energy is set by FEBY to 50 kWh/m^{2}a, or 30 kWh/m^{2}a if the energy for space heating is electricity. The measured total energy use in the four demonstration projects is presented in Table 10.3.

Table 10.3 Annual mean measured energy use.

Energy use (kWh/m^{2}a)	Space heating revised to a normal year	DHW heating	Electricity common areas	Total weighted bought energy
Frillesås	18.8 (14.3)	15	16.7	50.5 (45.1)
Lidköping	34	17	6.6	57.3
Värnamo	9	14.5	11.2	34.7
Alingsås	26.6	16.1	23.2	65.9

The energy source in Frillesås is district heating and when looking at the measured annual energy use for the four projects in Table 10.3, the project in Frillesås almost manages to pass the limit of 50 kWh/m^{2}a. If the use of energy for space heating in Frillesås is changed to 14.3 kWh/m^{2}a, which was measured after the temperature correction had been made in one ventilation unit; the total energy use would be 45.1 kWh/m^{2}a.

The project in Värnamo has the lowest amount of total bought energy, 34.7 kWh/m^{2}a, but since the building uses electricity as energy source for space heating and domestic hot water, the project should be below 30 kWh/m^{2}a to be a passive house according to the proposed levels by FEBY. It should be noted that these recommended values are from the latest version of the Swedish passive house criteria (FEBY, 2009), which did not exist when the above studied buildings were designed.

As can be seen in both Table 10.1 and Table 10.2, the total energy use in the buildings is very much dependent on the energy use for domestic hot water. The energy use for domestic hot water is very much influenced by the tenants' behaviour and because of this varies a lot between different apartments. The mean value of the domestic hot water use was measured in all four projects to be lower than the average use in Sweden. These measured results were confirmed in the interviews when all tenants answered that since they paid for their own use of domestic hot water, they have been more concerned of their use. To decrease the energy use in future projects, this seems to be a good model to copy; to let the tenants pay for their own domestic hot water. It can be questioned why the energy use for domestic hot water is included in the energy use for a building as decided in the Swedish building code. The domestic hot water use has a great variation amongst different users and has a great influence on the measured annual energy use, even though it says nothing about the energy performance of the building. The energy use for domestic hot water should naturally be kept on a level as low as possible but the regulations regarding energy use for domestic hot water could be separated from those regarding the energy use for space heating and common electricity of the building, so that the energy performance of the building construction may be defined.

It was seen in the measurements that the total energy use varied a lot between different tenants, especially the energy use for domestic hot water and household electricity. Looking at the measured results of total energy use in the four projects, the major part was used for household electricity, varying from 23% in one project to 40 – 52% in the other three projects. Some electricity was used in the fans in the ventilation units, as included in the measurement of household electricity, but in the Värnamo project where the electricity for the fans was measured separately the use of household electricity was still very high. The high use of household electricity did not vary much over the year and no correlation was found between high use of electricity and high energy demand for space heating. As a result of the answers from the interviews the high use of household electricity can be explained by a high number of computers, flat screen televisions and video games.

The energy use for space heating in the projects is also highly dependent on the behaviour of the tenants. This is especially clear in the Frillesås project where the total number of apartments is quite low and the high energy use for space heating in one apartment dominates the annual energy demand of the project and, when the recommendations set up by FEBY are used, actually makes the difference whether or not the project is a defined as a passive house project.

Looking at the correlation between the measured figures and the calculated figures in the four projects for both peak load for space heating and energy demand for space heating revised to a normal year, there is no clear agreement. The figures are close but not exactly right in any of the projects. It was seen in some projects that specific thermal bridges needed to be added to get a high agreement between calculated and measured figures but in others this was giving too high an energy demand compared to measured levels. The values of the calculated thermal bridges vary a lot depending on what dimensions are input in the simulations. A common method needs to be used for calculating thermal bridges to be able to add the Ψ-values properly in the energy simulations and to be able to compare Ψ-values in constructions using the same base. Available templates with Ψ-values for different types of constructions are not suitable for well insulated constructions. Existing templates should be enlarged with Ψ-values for energy efficient constructions to make the work on adding thermal bridges in the energy simulations easier. This uncertainty in the correlation between measured figures and simulated figures shows the importance of making measurements of the energy performance of the building and not rely on simulations.

In both simulations and measurements made of solar radiation in different Swedish cities, it can be seen that the solar gains can not be utilized to decrease the peak load for space heating. Simulations also show a great difference in energy demand for space heating at different geographical locations. The different climates and differences in solar gains make it difficult to have one national standard on peak load for space heating and energy demand for space heating in Sweden.

The measured bought energy for space heating varies a lot between the four projects but they all work according to the passive house principle; the energy demand for space heating is on such a low level that it can be distributed within the supply air anyway needed. The peak load for space heating is measured to be somewhat higher than the required 10 W/m^2 (12 W/m^2 in the single family house) but the annual energy demand for space heating is much influenced by the tenants' behaviour and it seems to be difficult to set one specific energy figure on the passive house criteria.

The measured energy use for space heating in one single family passive house is especially difficult to value; is it a family that uses an exceptional amount of energy or a family that has a very low annual energy use, and what do the measured figures show of the energy efficiency of the building? A national database for passive houses could be a good idea to collect the energy use for different projects and in that way enable smaller projects to be put in a wider context. To be able to compare houses in a reliable way, a method needs to be developed to normalize the measured results in order to decrease the influence of the tenants' behaviour on the measured energy performance of the building. It needs to be easy for the client to know what the measured figures actually say about the quality of the finished project. One way could be in future projects to complement the measurement of energy use with measurements of indoor temperature. A template should then be developed where the measured indoor temperatures together with the energy use for space heating could be normalized to an estimated energy demand for space heating at an indoor temperature of 20 °C. These normalized figures could be used more easily to compare the energy use for space heating in different projects.

10.5.2 Indoor temperature

The measured indoor temperatures in the projects were at desired levels most of the time. Measurement of indoor air temperatures has been found to be a valuable tool for the client to gain information about the status of the indoor climate in the apartments. The measured operative temperature in one apartment Frillesås differs a lot from the measured indoor air temperature in the same apartment. The measured indoor temperature was very constant compared to the operative indoor temperature that fluctuated widely. This difference might explain why the measured indoor temperature in all four projects does not always correlate with the tenants' experiences of their indoor temperature, which might be more like the operative temperature.

To avoid too high indoor temperatures it is very important to include solar shades in the design of the building. The solar shades could also protect the outer window panes from condensation. Operable windows should be installed to make it possible for the tenant to air the apartment as much and as often as desired.

To be able to reach the indoor temperature desired by the tenant, the heating batteries or heating coils installed need to have the power to make this possible. In one of the demonstration projects, the installed heating power was used to 100% and the indoor temperature still did not reach 20°C in some of these apartments. The installed power should be higher than the design peak load for space heating to ensure a good indoor comfort for all tenants. Currently, the available heating batteries on the market are set at different power levels with quite big differences between them. More flexible power levels are needed in the heating batteries to make it easy to install a suitable battery and not need to buy an oversized battery at a high cost just because the smaller size is a few watts too low.

10.5.3 Efficiency of heat exchanger

The efficiency of the heat exchanger in the projects was said by the producers to be on a certain level. It has in this research seemed to be difficult to measure the actual efficiency of the units installed in the projects. The measurement of the efficiency must in future projects be easier to carry out when the units are mounted, in order to exclude this parameter if the energy use in the building is higher than required by the client or if the indoor temperature is too low, and the building is searched for faults.

10.5.4 Ventilation system

All tenants who were interviewed said that they were very pleased with the quality of their indoor air and some said they experienced their indoor air to be so fresh that no airing of their apartment was necessary. This indicates that the mechanical ventilation system is well functioning in the buildings and a good solution to choose for ventilation of residential buildings to get a good indoor climate.

The importance of a well planned ventilation system, in order to achieve a perfectly functioning passive house, has become obvious in these demonstration projects. Ventilation issues need to be early included in the design process and someone must take full responsibility for the ventilation system all the way through the building process; if the baton is handed over somewhere in the project, important information might get lost. The person who plans and the person who mounts the ventilation system must be experienced and have good knowledge of how the system should work and if it is supposed to be used as the heating system, according to air flow rates, ventilation supply units, insulated duct work and placement of the supply and exhaust air devices.

The measurement of the sound levels caused by the ventilation unit in the single-family house showed initially too high values and had to be attended to. This was the only comment from any tenant in the four projects about disturbance from internally generated sound from the ventilation units. The apartments were said to be very quiet.

The family in the single-family house also experienced a temperature difference of approximately 3 °C in the indoor air on the first storey between floor and ceiling, which might be caused by the placement of the supply air devices. In the apartments in Alingsås, the interviewed tenants experienced that the small bedrooms were the warmest rooms and that the indoor temperature in the living rooms was somewhat too low. The bedrooms had the same ventilation air flow as the living rooms even though the living rooms had twice the living area. These are examples of experiences which show that the ventilation system when used as heating distribution system can not be planned as it has always been done. If the building is heated with the ventilation air, the heated air should reach where it is needed according to the space heating demand. It must also be remembered during the planning of the building to think of the possible need for insulation of the ducts and the siting of supply air terminals.

It is shown in this study that there is only a slight difference in electricity used by the fans in the ventilation units when ventilating the building with an air change rate of 0.5 ach compared with 0.3 ach and only a small amount of additional energy is needed for heating the larger volume of air, if energy efficient fans and a heat exchanger with a high efficiency are used. This small increase may not be a reason to turn down the ventilation rate.

10.6 Products

A major question in this research was to see if there was a lack of products needed for passive houses on the market, which should be developed in a near future in order to make it easier to build passive houses. The lack of products was seen to be most obvious in the single-family house project but also detected in the apartment buildings.

The airtightness of the building was a time consuming stage in all four projects. By thinking of prefabrication of components early in the planning process, the time needed for the airtightness could be reduced and the quality and life of the seal could be increased. One good example is prefabricated plastic foil corners, suitable to mount in the window openings. The airtightness in the window openings was said by the carpenters to take much time and that it was difficult to know when it was airtight enough. The prefabricated plastic foil corners are made with specific angles and are mounted in one piece which will both decrease the time for sealing the corners and make it easy for the carpenters to know when the seal is completed. Another good example is prefabrication of the bushing for ventilation ducts. By adding a metal plate on both sides of the duct pulled through the hole in the wall, the sealing tape of the plastic foil only needs to be mounted in straight lines with a much better adhesion than when the tape is placed around the duct in a circle.

The ventilation units must be easier to use for the tenants. A development of the display in the units is necessary to get a large scale use of these products. On the display it should be obvious how to raise or lower the indoor temperature, what the current indoor temperature is, how much energy has been used for a certain period of time, if the by pass is running or if the heating coil is switched on, if the fans are running at a high or low speed or if the filters need to be changed. The efficiency of the unit and the use of electricity for the fans must all be tested using the same standard so the client can compare products. It is most important that the products fulfil what is promised in the tests, when used in real projects and of course equipped with a heating coil that communicates with the connected energy source.

The supply air devices need to be developed to be usable for both low and high supply air temperatures at the low ventilation rates required in residential buildings. It would be very nice if the ventilation devices were designed to look good and made to be easy to clean for the tenants. The air inlets mounted in the façade should be developed so that they are not blocked by white frost in winter.

The measured use of common electricity is quite high in the demonstration projects. One of the high electricity consuming devices was discovered to be the pump for circulating water. A development of even more energy efficient pumps or a new way of avoiding Legionnaires' disease is needed. Also the fans in the ventilation units have a significant high use of electricity. The development towards units with more energy efficient fans has started and there are units on the market today with lower electricity use for the fans than presented in this research. It is however important to remember to order the units with the efficient fans, since this electricity use strongly influences the total energy use of the building.

The energy losses in distribution pipes in the ground need to be avoided by using pipes with added insulation. The insulated pipes available on the market have only a limited insulation thickness and better insulated pipes need to be developed.

Entrance doors with a low U-value at normal cost are another product needed as seen both in the single family house and in the apartment buildings. In the apartment buildings, airtight apartment doors were another product needed but hard to find on the Swedish market. So were also well insulated airtight roof hatches that need to be developed for future projects.

To be able to use district heating in single family houses that use less energy than a normal house, a development of subcentres suitable for lower energy consumption should be developed. Communication from these subcentres to the heating coils in ventilation units must be possible.

Affordable pellets burners in combination with a solar panel system need to be developed for single-family houses. The internal gains from the pellet burner need to be designed to be kept at a low level to avoid too high indoor temperatures.

Woodburning stoves available on the market for single-family houses have a power outlet to the room that is much too high to be able to be used in passive houses. Woodburning stoves with a power to the room of 1 – 3 kW are asked for by many persons who want to build a passive house but keep the living quality that a fireplace provides.

10.7 The tenants

The tenants should always be in mind and in the very centre of a building project. Residential buildings are made for someone to live there, not to save energy.

Information must be given to the tenants on how a passive house works and how they should operate their heating system. In these four projects, a file with information has been placed by the client in all apartments with information about passive houses, the installed machines and white goods and special things to think about for the tenants to get a good indoor climate.

When a building is renovated it is important for the tenants who move back to see the improvements made. This is especially important when the rent has been raised, to realize what the additional money pays for.

After the project is finished, the client should take the opportunity to take a cup of coffee with the tenants. To discuss their living situation in a relaxed way solves any small dissatisfactions there might be in the apartments and gives the client indispensable information about how the project is working and what improvements could be made in future projects.

The caretakers of the apartment buildings have a very important role in making the tenants feel at home. Time should be available for the caretakers to regularly visit the tenants, sit down for half an hour and listen to their experiences. The caretaker can answer the questions from the tenants regarding the apartment or about passive houses, fix minor problems and early reveal if something is wrong with the building or distribution system. The tenants will in this way establish a good relationship with the caretaker and hopefully this could also result in fewer emergency calls from the tenants and therefore save money for the client by decreasing the number of callouts. The caretaker could also take the opportunity to discuss the tenants' behaviour regarding energy use and help the tenants to reduce their energy bill.

Many of the tenants have in their interviews discussed the rent of the apartments, especially tenants living in single households and elderly persons. Some described how they did their best to save energy to get a lower monthly bill and that they were afraid they might need to move to be able to make ends meet. The wish for a lower rent is not something unique for renting an apartment in a passive house building but needs to be taken into consideration. Passive houses were developed to have a low energy use and a high indoor comfort in order to achieve a low living cost, so that a good indoor climate should be affordable for everyone. Passive houses must not be turned into something that could only be afforded by persons with a high income and the energy savings only come to be used by the owner of the building and not the tenants.

10.8 Other experiences

The three clients of the apartment buildings have all continued with building new passive houses or renovating according to the passive house definition after their demonstration project. Further development of the concept has been made, like using photovoltaics for electricity and heat exchanger on the grey water in order to use even less energy.

It is here proven that it is possible to build single family passive houses in a Swedish climate. Unfortunately, the single-family house producers seem to be afraid of changing their traditional concept of construction and space heating distribution, since the costumer would then be unable to compare their product with other similar products on the market. By adding for instance a mechanical ventilation heating system not used by the other producers is seen as a great risk, since it might confuse the costumers. For single-family houses, more impartial support is needed during the design and construction phase. Often the family is in the hands of the single-family house producers, and do not know what they could ask for or demand of their building. The support could with advantage be connected to the already existing "Energy adviser" that is mandatory in all local communities. By giving impartial information to persons who want to build a single-family house, the demands on the single-family house producers might be to produce more energy efficient buildings and therefore try new solutions. If sufficiently many persons ask for an energy efficient home, the producers of single family houses might start to make changes in their original concepts.

All tenants experienced their apartments to be very quiet according to sound from outside, which might make passive houses suitable to build where low indoor sound levels are required, and where noisy outdoor environments govern (e.g. in cities).

In all the demonstration buildings studied here, an initial meeting has been held with information about passive houses and discussions on building designs. These meetings have been very much appreciated by all participants and affected the project positively. It might however be a good idea to also have a meeting when it is time to hand over the project to the client. The major purpose of such a meeting should be for the client and the caretakers to know how the building actually works and how they could ensure the best possible indoor comfort for the tenants. The contractors could at the meeting explain to the caretakers what they have built, how it should work, what is needed to be checked regularly, what can be the reason if something appears to be wrong with the building, who is in charge at different contractors of the project and should answer questions etc.

10.9 Future research

The energy use for space heating in the project in Värnamo was lower than the similar project in Frillesås. One explanation of the higher energy use in Frillesås could be that the heating coil is not a direct heating system and needs some time to get started before heat is distributed to the supply air. The project in Värnamo used electrical heating batteries that switched on and off whenever needed with no delay. The measured energy use in the heating coil might be higher since it includes the water flow in the start up. In future research it would be interesting to measure the time and the water flow in this start up time to see how long time it actually takes before the heating coil has its required temperature and to estimate the losses in the system.

More tenants in Värnamo said they had experienced too low indoor temperatures than in Frillesås, but the measured annual indoor temperatures were quite similar. One explanation of the experienced lower indoor temperature in the project in Värnamo could be the somewhat higher U-values on the windows in this project, something that might affect the indoor comfort. To be able to know the difference in indoor comfort due to differences in U-values in window constructions it would be interesting to study different constructions in detail, using e.g. a thermal camera and make detailed interviews with the tenants. This study, together with measurements of peak load and energy use for space heating, could be used to determine what U-value should be required for windows in future passive houses.

In the Brogården project, early input from the renovation of the buildings following the demonstration building has shown a good indoor climate when a system with a central ventilation unit is used, with almost no complains from the tenants. In future research, the use of a central ventilation unit should be studied in order that the fan electricity needed, use of energy for space heating, maintenance costs and measurements of indoor comfort may be compared with experiences from apartments with separate ventilation units.

In the measurements it was seen that when the operative indoor temperature was measured it differed from the indoor air temperature. Looking at the projects where only the indoor air temperature was measured, the answers of the tenants regarding the indoor temperature were sometimes different from the actual measured results. It seems that the operative temperature is the one experienced by the tenants. This needs to be studied in other projects to ensure a reliable and affordable measurement of indoor temperature. By having a continuous measurement of the indoor temperature it is easy for the client to supervise the indoor comfort in the apartments and also to answer the tenants concerning their indoor temperature if they claim it is too low or too high.

The four demonstration buildings are all heated by air. There were many points of view of the heating system among the tenants; many positive but also negative. It might be considered to use radiators as heating source, in those projects where that could be afforded, together with a central ventilation system. Since a passive house is so well insulated, the radiator could be placed anywhere and is not needed to be placed right under a window. In future research, differences in indoor comfort in passive houses with radiators should be compared with passive houses heated by air, complemented with interviews with the tenants.

Not much research is available in the area of residential buildings and indoor climate. Further research is needed regarding ventilation rates and indoor pollutants when the major focus should be to look for the unexpected to try to solve the question regarding increasing allergy symptoms, especially among children, and if there is a connection to something in the indoor air and air change rates.

The renovation project in Brogården shows an impressive decrease in the energy use after renovation. It is clearly possible to make very energy efficient renovations in a Swedish climate. Still, not many housing companies take the opportunity to take energy efficient measures when renovation is carried out. Often the cost of such an extensive renovation as made in Brogården has showed to have a deterrent effect on visiting housing companies. This is an interesting and very important question that needs to be further investigated. Detailed cost analysis of energy efficient renovations needs to be made in future research in order to detect how to make energy improving measures affordable for all house owners.

Summary

The use of energy is a major global issue both according to climate changes but also in the aspect of national safety tied to the trade with energy sources. The energy use and consequently the greenhouse gas emissions need to decrease dramatically in the following years to put a break on global warming. Of the total energy use in the member states of the European Union, about 40% is used in residential and commercial buildings, which makes the building sector responsible for approximately 36% of the Union's total carbon dioxide emissions. To decrease the energy use in buildings, directions from the European parliament have been published in the European Building Directive (EPBD) on what measures that need to be taken for all member states to build nearly-zero energy buildings by December 31, 2020. The directive also says that national political decisions should be taken to stimulate that when buildings are renovated, this should include increasing the energy performance of the building to nearly-zero energy buildings. According to the environmental target "A good built environment" set by the Swedish Government, the energy use per heated area of dwellings and premises in Sweden should be decreased by 20% by 2020 and 50% by 2050 with reference to the energy use in 1995.

Passive houses are one way to drastically reduce the energy use in buildings and at the same time keep a good indoor comfort. The basic idea of the passive house concept is to have well insulated and air tight climate shell together with a mechanical ventilation system. When the building envelope is so well insulated that the indoor surface temperatures get close to the indoor air temperature, thermal indoor comfort is achieved without the need to place radiators on external walls and below windows. In passive houses, an air-to-air heat exchanger is used in the mechanical ventilation system to extract the energy from the exhaust air and use it to heat the supply air; however recirculation of air is not used. The combination of a well insulated and airtight climate shell and the heat recovery in the ventilation system makes it possible to provide space heating by the ventilation system alone, distributed with the hygienic air flow rates, needed in any case for a good indoor air quality.

Within this research, four Swedish passive house projects are studied; three apartment building projects and one single-family house. The research was funded by the Swedish Energy Agency and has been a five year project. The main purpose with the study was to see how energy efficient residential buildings, mainly passive houses, can be built in Sweden and on a more widespread scale than before. The passive house projects have been followed from the early planning stage to evaluation of the actual buildings. Support has been given to consultants, contractors and clients. Simulations of the energy demand of the buildings have been made as a part of the planning process. Interviews made with the participants in the building process and with the tenants after moving in, together with measurements made of the energy performance of the buildings, have given a wide overall knowledge of the projects.

In Värnamo (latitude 57°12'12 N), the public housing company Finnvedsbostäder has built 40 apartments in five buildings according to the passive house principles. The apartments are heated by the supply air and each apartment has its own mechanical ventilation unit with an air-to-air heat exchanger. There are solar panels on the roof of the buildings for domestic hot water production. Additional heat for domestic hot water and space heating is supplied by electricity from a wind power plant. The measured energy use in the apartments shows of a mean value of the total annual energy use for space heating, domestic hot water and common electricity of 36 kWh/m^2a, when the energy demand for space heating is revised to a normal year. This should be compared to the level of annual energy use of 110 kWh/m^2a, as required in the current Swedish Building code. The mean value of the peak load for space heating in the apartments was measured to 10.9 W/ m^2.

The second passive house project within this study was built in Frillesås (57°19'0"N) by the public housing company Eksta Bostads AB. Twelve apartments are situated in three buildings with four apartments in each building. Each apartment has its own mechanical ventilation unit with an air-to-air heat exchanger. The space heating is supplied by air. Solar panels mounted on a separate building produce domestic hot water. Additional heat for space heating and domestic hot water is supplied by district heating. The measured energy use in the 12 apartments varies much and a few high energy consumers strongly affect on the mean value of the measured annual total bought energy of the area. The total annual energy use, including energy for space heating, domestic hot water and common electricity, was measured to 50.5 kWh/m^2a (space heating revised to a normal year). The mean value of the peak load for space heating in the apartments was measured to 11.3 W/ m^2.

The single-family house Villa Malmborg was built in Lidköping (58°27'55"N) according to the passive house principles. The prefabricated house was built in two storeys with a total living area of 171 m^2. The house has a mechanical ventilation unit with an air-to-air heat exchanger and is heated by the supply air. The domestic hot water and additional heat for space heating is supplied by district heating. The measured annual bought energy for space heating and domestic hot water was 51 kWh/m^2a (space heating revised to a normal year). The peak load for space heating was calculated by ATON Teknikkonsult based on the measured figures to 20 W/m^2.

In Alingsås (latitude 57°55'48 N) an area of a total 300 apartments are renovated using the passive house principles. One building in the area with 18 apartments (16 after renovation) was a part of this research. The existing concrete load bearing construction was kept in the renovation and completed with new outer walls, new balconies and a new ventilation system together with improvements to make the area more suitable for elderly and disabled persons. Each apartment in this first renovated building has its own mechanical ventilation unit with an air-to-air heat exchanger and the apartments are heated by the supply air. Heat for domestic hot water and for additional space heating is supplied by district heating. The measured mean value of the total annual energy use in the renovated apartments was 65.7 kWh/m^2a, revised according to a normal year, or 86.2 kWh/m^2a including household electricity. The total energy use before renovation (2004) was 215 kWh/m^2a including household electricity. The decrease in total energy use including energy for space heating, domestic hot water, common electricity and household electricity before and after renovation was approximately 60%.

Experiences from the planning process in these four demonstration projects have shown that the client needs to set up explicit requirements for the final result to make it easy for the persons planning the project to know what targets to fulfil and for the contractor to know what to aim for and when the work is actually finished. The carpenters in these four demonstration projects have been very proud of their work, which is a very nice side effect that the passive houses have achieved. The planning process should preferably be performed in an iterative circle, where the architect start, hand over the initial plans to the designer to have a look at the construction and after that the HVAC consultant takes a close look to see if the energy performance of the building is sufficient for a passive house. Then the project goes back to the architect who makes the necessary changes and the circle starts again. In this way, all participants learn from each other and hopefully feel that they are satisfied with the final building design.

There is a great variation of the energy use in the four projects and also between different tenants' energy use in the projects, especially of domestic hot water use and use of household electricity. The measured use of domestic hot water in all projects, with an average use of almost half of the statistical average use in Swedish multi family houses, could be explained with the low-energy taps installed in all projects but also in answers from the interviews where many tenants said to have great awareness of their use of domestic hot water since it was seen on the rental bill and paid for by themselves. Looking at the measured results of total energy use in the four projects, the major part was used for household electricity, varying from 23% in one project to 40 – 52% in the other three projects.

The tenants should always be in mind and in the very centre of a building project. Information must be given to the tenants on how a passive house works and how they should operate their heating system. After the project is finished, the client should take the opportunity to take a cup of coffee with the tenants. To discuss their living situation in a relaxed way solves any small dissatisfactions there might be in the apartments and gives the client indispensable information about how the project is working and what improvements could be made in future projects.

In this study, totally 23 households or 32 tenants were interviewed about their experiences of living in a passive house. The tenants have all moved in to the passive house apartments for different reasons but the main reason given for moving was that they liked the location of the apartments. No one answered that they explicitly moved into the apartments because they were passive houses. The experiences of the living situation in the apartments vary a lot between the tenants. However, they all agreed that the apartments were very quiet. Another mutual experience expressed by the tenants in all projects was the indoor air quality; always very fresh air and never a feeling of stuffiness. Some tenants said that the indoor air felt so fresh that they never needed to air their apartment.

In the interviews the rent was mentioned to be high, but many tenants also said that they were paying for high service and high comfort, which made the level of the rent fully acceptable. They said that their awareness of their energy use had increased when the energy use was explicitly presented on the rental bill.

In three of the interviewed apartments, condensation had appeared on the outer pane of the windows. The condensation had appeared during morning hours but at different seasons in the different apartments, according to the interviewed tenants. No one said the condensation had been a problem since it had been only for a few hours at a time.

The experienced indoor temperature varied between the projects and sometimes within the projects. The different answers between the projects might be explained by the different seasons at the time of the interviews. Most tenants who experienced an excessive indoor temperature also had a high use of household electricity with many appliances used at the same time and at a long period of time every day; computers, flat-screen television sets etc. The tenants who experienced an inadequate indoor temperature were mostly sedentary. The desired indoor temperature varied between 20 - 23 °C and most tenants answered that they wanted to have an indoor temperature of 22 - 23 °C.

To be able to investigate the importance of the solar radiation contribution for the energy demand for space heating in passive houses built in a climate with less solar radiation, three different analysis were made. First measurements of the global and diffuse solar radiation made in the Frillesås project were analyzed using an evaluation graph, earlier used within the IEA – SHC Task 28. Secondly, the three new built projects were simulated in DEROB-LTH to see how the orientation of the building influenced on the annual energy demand and peak load for space heating. Thirdly, simulations were made in DEROB-LTH of the new built apartment buildings using climate data for different Swedish cities, to see how the differences in the outdoor climate and the available solar radiation influence on the annual energy demand and peak load for space heating. The results in these three studies all show that in a Swedish climate, solar radiation can not be utilized for space heating when it is actually needed on cold days. Still, orienting the larger windows facing south seem to have a positive influence on the annual energy demand for space heating in the apartment buildings, with a variation up to 20% in the Värnamo project. The differences in outdoor climate make it difficult to set one national limiting value on the peak load for space heating in Swedish passive houses. To get one limiting value, the ventilation and transmission losses need to be reduced even more in some areas, which could be difficult and hard to accomplish both economically and technically.

It is of major importance to have a well functioning ventilation system in all buildings to ensure a good indoor air quality. In passive houses, the ventilation system plays a key role in many different respects. If it is decided to heat the building by air, a high ventilation rate will increase the possible space heating power distributed by air. Raising the ventilation rate will on the other hand cause higher thermal energy losses from the ventilation system and a higher use of electricity by the fans in the ventilation unit. According to the Swedish Building Code the ventilation rate in residential buildings should be minimum 0.35 l/s,m^2 when people are at home, which often correlates with an air change rate of 0.5 ach. Previous research shows that a ventilation air change rate of 0.5 ach seems to be necessary in order to achieve a good indoor air quality. Simulations made in this research shows that not much energy is saved by decreasing the ventilation rate below 0.5 ach, since the heat recovery is high and the SFP-value of the fans are low, and should be avoided to assure a good indoor comfort.

Some products have been detected to be in need of development to ease the building of passive houses in the future. The ventilation units must be easier to use for the tenants. The supply air devices need to be developed to be usable for both low and high supply air temperatures at the low ventilation rates required in residential buildings. Entrance doors and windows with a low U-value needs to be available and at a normal cost. To be able to use district heating in energy efficient single family houses, a development of subcentres suitable for lower energy use should be developed. Communication from these subcentres to the heating coils in ventilation units must be possible. Woodburning stoves with a power to the room of 1 – 3 kW are asked for by many persons who want to build a passive house but keep the living quality that a fireplace provides.

The goals regarding energy use in the demonstration buildings for space heating and domestic hot water were initially set to 25 – 50 % of the energy used in similar buildings built according to the current Swedish building code. These goals were measured to have been fulfilled in all four projects. The measured bought energy for space heating varies a lot between the four projects but they all work according to the passive house principle; the energy demand for space heating is on such a low level that it can be distributed within the supply air anyway needed. The peak load for space heating is measured to be somewhat higher than the required 10 W/m^2 (12 W/m^2 required in the single family house). The annual energy demand for space heating is much influenced by the tenants' behaviour and it seems to be difficult to set an energy criterion on the passive house principles.

The development of passive houses in Sweden, and the interest in these, has increased rapidly during the period of this research. All projects within this study have gained much attention and have been visited regularly by both national and international groups and also been frequently reported about in both newspapers and on television. This shows the importance of full scale demonstration projects that both inspire visitors to build their own passive houses and where experiences are gained to use in future projects.

The renovation project in Brogården shows an impressive decrease in the energy use after renovation. It is clearly possible to make very energy efficient renovations in a Swedish climate. Still, not many housing companies take the opportunity to take energy efficient measures when renovation is carried out. Often the cost of such an extensive renovation as made in Brogården has showed to have a deterrent effect on visiting housing companies. This is an interesting and very important question that needs to be further investigated. Detailed cost analysis of energy efficient renovations needs to be made in future research in order to detect how to make energy improving measures affordable for all house owners.

The cost for the new built demonstration projects within this study was seen to be somewhat higher than new buildings built in a traditional way. There were some additional costs in these demonstration projects for e.g. education, air-tight solutions and more expensive products. These costs can be decreased in future projects when more suitable products are available on the market and when the knowledge and experience of how to plan and build energy efficient buildings is natural and well spread among carpenters and consultants. An indication of this development is that the three clients of the apartment buildings have all continued with building new passive houses or renovating according to the passive house principles after their demonstration project was finished. In these projects it can be seen that the development towards lower costs has already started.

Sammanfattning

Energianvändningen i världen måste minska drastiskt inom en snar framtid för att därmed minska utsläppen av växthusgaser och bromsa klimatförändringarna. Energi och handlande med energikällor har även blivit nationella säkerhetsfrågor. Inom Europeiska Unionen används ungefär 40% av den totala energianvändningen i byggnader, vilket innebär ungefär 36% av det totala koldioxidutsläppet i unionen. Genom att minska energianvändningen i byggnader kan stora förbättringar uppnås. EU har nyligen beslutat att år 2020 ska alla byggnader i alla medlemsländer ha en energianvändning som är nära noll och när byggnader renoveras ska energiförbättrande åtgärder ingå.

Det är väldigt viktigt att en lägre energianvändning i en byggnad inte försämrar inomhuskomforten. Ett bra sätt att lyckas med detta är att bygga passivhus. Grundtanken med passivhus är att göra klimatskalet så välisolerat och lufttätt att den värme som behövs till huset kan tillföras med den ventilationsluft som ändå behövs. För att minska behovet av tillförd energi värms den inkommande kalla, friska luften av värmen i den utgående varma, begagnade luften i en värmeväxlare. In i huset kommer frisk och värmd tilluft. På vintern behöver tilluften värmas extra med till exempel en vattenburen värmeslinga för att huset ska ha rätt inomhustemperatur.

Att värma med luft är inget måste men det ska vara en möjlighet. Om byggnaden är konstruerad så att den maximalt behöver 10 – 16 W/m^2 för uppvärmning den kallaste dagen är det möjligt att värma med tilluften. (Jämför med en hårtork som ofta har en effekt runt 2000W!) Detta motsvarar ett väldigt lågt energibehov för uppvärmning. Genom att ha en tät byggnad och att tillföra uppvärmd luft minskar också risken för att uppleva drag inomhus.

I denna forskningsstudie har fyra svenska passivhusprojekt följts från start till färdig byggnad med det huvudsakliga målet att se hur fler passivhus kan byggas i Sverige. Genom att praktiskt delta i de fyra projekten från start till färdig byggnad med kunskapsstöd, beräkningar och samtal med entreprenörer har kunskap erhållits från alla steg i byggprocessen. Efter att hyresgästerna flyttat in har de blivit intervjuade om hur det är att bo i passivhus. Faktisk energianvändning och inomhustemperaturer har mätts och sammanställts i alla projekten.

Finnvedsbostäders hyresrätter i Värnamo var det första projektet som färdigställdes; de 40 lägenheterna var klara för inflyttning under sommaren 2006. Den årliga energianvändningen för värme, varmvatten och fastighetsel (till exempel fläktar, pumpar och utomhusbelysning) mättes till 36 kWh/m^{2}a (normalårskorrigerat). Det andra projektet som blev klart byggdes av Eksta Bostads AB som hyresrätter i Frillesås. Dessa 12 lägenheter hade en årlig mätt energianvändning för värme, varmvatten och fastighetsel på 50.5 kWh/m^{2}a (normalårskorrigerat). Det tredje projektet som blev klart var en villa som byggdes i Lidköping. Villan är på 171 m^2 och hade en årlig mätt energianvändning för värme och varmvatten på 51 kWh/m^{2}a (normalårskorrigerat). Enligt gällande regler från Boverket ska en nybyggd bostad max använda 110 kWh/m^{2}år. De uppmätta resultaten från dessa projekt visar tydligt att det går att bygga bostäder med mycket lägre energianvändning, med vanliga snickare, vanliga material och vanliga hyresgäster.

Det fjärde projektet blev färdigställt i februari 2009 och var en renovering av ett befintligt hyreshus från 1970 med 18 lägenheter (16 lägenheter efter renovering). Energianvändningen efter renovering för värme, varmvatten och fastighetsel var 65.7 kWh/m^{2}a (normalårskorrigerat) eller 86.2 kWh/m^{2}a inklusive hushållsel. Före renovering var energibehovet 215 kWh/m^{2}a, inklusive hushållsel. Det finns inga regler om hur mycket energi en renoverad byggnad maximalt får använda efter renovering men detta resultat visar att det är möjligt att sänka energianvändningen i en befintlig byggnad med 60%.

Alla fyra projekten har uppnått det initialt satta målet att använda 25 – 50% av tillåten energinivå enligt Boverkets byggregler. Att bygga passivhus verkar vara ett bra sätt att drastiskt minska energianvändningen i samhället, både vid renovering och vid nybyggnad utan att göra avkall på inomhuskomfort. För att underlätta i framtida projekt skulle det behövas en produktutveckling av till exempel lättmanövrerade ventilationsaggregat för småhus, kaminer anpassade för bostäder med lågt uppvärmningsbehov och estetiskt tilltalande tilluftsdon som fungerar för både höga och låga flöden och varierande temperaturer på den luft som blåses in i rummet.

De tre fastighetsägarna till hyreslägenheterna i denna studie har alla fortsatt att bygga fler passivhus eller renovera enligt passivhusprinciperna, då de varit mycket nöjda med de resultat som uppmätts i projekten.

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Appendix A

Questions used in the interviews with the tenants

(Boström et al, 2003)

1. Household composition; who lives in the apartment? What age are they?
2. Occupation. What do you work with?
3. For how long have you lived in the apartment? When did you move in?
4. Where did you live before you moved here? What type of dwelling was that?
5. What was positive with your previous living place (the area and the building)?
6. What was negative with your previous living place (the area and the building)?
7. What was the reason for moving from your old living place?
8. If we move back to the time when you were looking for a new place to live. What kind of information did you use to get knowledge about what apartments/houses that were available? Did you look in newspapers or on the internet? Do you remember how you first got information about the new apartments in Värnamo/Frillesås/Alingsås?
9. What made you want to have a close look at these apartments/single family houses? What was especially attractive?
10. Did you look at other apartments/ single family houses at the same time? Which? Where?
11. What information did you get about your new apartment/ single family house? By who? Was it enough information to be able to make a decision to move?

12. Did you ask anyone else for information? Who gave you advice?
13. What questions did you have about the new apartments/ single family house? What was important to get answers about? (For instance about the space heating and the indoor temperature).
14. How was it that you finally decided to move here? Was it important that it was rental apartments/single family house?
15. What importance was it for you that the apartment/single family house was energy efficient and did not have a radiator heating system?
16. Do you remember what expectations you had before you moved to your new apartment / single family house?
17. You have now been living here for a while. What do you think is positive with this area?
18. What is negative with the area?
19. What is positive with this apartment/single family house?
20. What is negative with this apartment/single family house?
21. Is it something you think is missing in the apartment/ single family house? Something that could have been designed differently? Why?
22. At what time during weekdays are you usually at home?
23. How varies the indoor temperature during different seasons?
24. How is the indoor temperature when you wake up in the morning? Have you considered if any room has a lower temperature then the others? How do the floors feel? Is there a difference depending on season?
25. When you spend a longer period of time at home, how do you experience the indoor temperature? If there are many people spending time in the apartment/ in the house, how do you experience the indoor air quality?
26. If the house has been empty for a long period of time (one week or one day), how is the indoor temperature when you come back? Is there a difference between the seasons?
27. Desire/ acceptance: What indoor temperature do you preferably have at home? Do you usually have that?
28. If the indoor temperature gets too high, how do you do to decrease it?

29. How do you raise the indoor temperature if it feels too cold? Do you remember how much you used your heating battery in the supply air during the last winter?

30. Have you received any suggestions on how to act to get at an even and comfortable indoor temperature? What kind of tips was that? Who gave them to you?

31. Have you experienced draught at any place in the apartment/house?

32. Have you experienced the indoor air to be humid during the last year?

33. Have you experienced the indoor air to be dry during the last year?

34. Have you experienced any static electricity in the dwelling? At what season was that?

35. Have you experienced any funny smell anywhere in the dwelling, for instance in the morning or when the apartment/house has been empty for a longer period of time? Any special season?

36. How often do you air your apartment/house? Why? For how long? Which windows do you use? Why do you use these windows? Do you air your apartment differently during different seasons?

37. How do you experience the sound environment in the apartment/house?

38. Have you experienced any noise (inconvenient sound) in the apartment/house?

39. How do you experience the light situation in the apartment/house? Does any room feel brighter than others? Is there a difference between seasons?

40. If you compare this new apartment/house with your earlier living place, can you mention any difference regarding the indoor temperature? The sound environment? The light environment? Is there a difference in how you feel compared to your old living place?

41. How often do you use your washing machine? Do you iron your laundry? How often do you use your tumble dryer? How often do you use the vacuum cleaner?

42. How often do you cook a warm meal at home? Which devices do you use for cooking? Toaster? Microwave oven? Stove? Coffeemaker?

43. How often do you use the dishwashing machine?

44. What other electrical devices do you have and how much do you use them? (Television, computers etc.)
45. Do you have a bathtub or a shower? Approximately how often do you take a shower/bath? How long is a normal shower for you? At what time during the day do you most often take a shower?
46. Does anyone in the household work from home?
47. Does it happen that you run many electrical devices at the same time, like the tumble dryer, the dishwasher and many lamps? Do you then feel any difference in the indoor temperature? Does this happen often in your household?
48. What type of lighting do you usually have at home? Do you use low energy light bulbs?
49. Is there any of these activities that we now have discussed that you do differently in this new apartment/house compared to your previous living?
50. What kind of white goods do you have? Were you able to choose them by yourself? Is there a difference in the type and in the number of white goods in this new apartment/house compared to your old living?
51. Do you know how much household electricity you use? Is there a difference compared to your old living?
52. What electrical company are you connected to? Have you changed, or considered changing it, since you moved here?
53. Is there anything considering the energy use in the house; space heating, electricity use, ventilation system, which you would have wanted to be designed/planned differently?
54. Were you committed to environmental questions before you moved here? Was there any specific question that you were engaged with? In what way did you express your commitment?
55. Have your interest in energy issues increased since you moved here?
56. Have you learnt something about the use of energy in the household since you moved here? How did you learn?
57. What do you know about the solar panels? What do you think about the appearance of the solar panels? Have you received any information about the solar system?

58. Is there any difference between the windows in this apartment/house compared to your old living? In what way? What is positive with these windows? Is there anything negative with these windows? What kind of windows would you like to have if you could choose freely? Is the skylight window working satisfactorily? Have you thought of any improvements?
59. Do you know anything about the ventilation system? Do you think you have received good information about how the ventilation system works? How does it work with the change of filters?
60. Do you have any additional comments or ideas? Can I come back again if I have further questions?




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