Energy use in multi-family dwellings : measurements and methods of analysis

Bagge, Hans

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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Measurements and Methods of Analysis

Hans Bagge

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Licentiate Dissertation

Building Physics LTH
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

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Abstract

In 2001, multi-family dwellings were built at nine properties in Västra hamnen, Malmö, Sweden. Several well known Swedish architects were involved in designing the buildings, hence they reflect modern architecture. Prior to the inauguration, the buildings were displayed at the international housing exhibition Bo01. The housing exhibition had an ecological and sustainability focus. Regarding energy use, all buildings were restricted to use no more than 105 kWh/m² annually including space heating, domestic hot water heating, common electricity and household electricity. Different building techniques and technical systems were used at the different properties. A measurement program including hourly measurements of district heating, common electricity and household electricity was set up to monitor the energy use of the buildings. The aim of the research project presented in this licentiate dissertation has been to study the energy use at these properties based on the measurements. Use of district heating, use of domestic hot water heating, assimilation of solar heat gains, use of common electricity and use of household electricity were all studied in detail. Power signatures were used to make corrections regarding differences in the outdoor climate between the different years and to study the energy use during different conditions. Methods were developed and used to study parameters that were not measured directly and to study variations in use during the day and during the year. All properties, except one, used more energy than restricted. The variations in total energy use between the different properties were large. There was a factor of almost three between the lowest and largest use. Solar heat gains were assimilated to different extents at the different properties due to different window areas, orientation of the window areas and the technical systems used. The variations during the year and during the day in use of household electricity and domestic hot water heating was considerable and this should be taken into account when measured energy use during shorter periods are compared and when energy simulations are done. Key values are presented that can be used to critically examine different designs, systems and results from energy calculations.

Keywords: multi-family dwellings, energy use, district heating, space heating, domestic hot water heating, common electricity, household electricity, solar heat gains.

Contents

1 Introduction

1.1 Background

During 2001, the international housing exhibition Bo01 was held in Västra hamnen, in Malmö, in the south of Sweden. This housing exhibition had an ecological and sustainability focus and the area was supposed to be self supporting regarding energy with 100 percent locally produced renewable energy and there was supposed to be an annual balance of energy production and energy use at the area (Lövehed, 2005).

Multi-family dwellings were built at 14 properties. Several well known Swedish architects were involved in designing the buildings, hence they reflect modern architecture.

Regarding the energy supply systems, heat is mainly generated by a heat pump, which takes heat from an aquifer and from the sea. Solar collectors placed on several of the buildings provide some additional heat. Electricity is primarily generated by a wind turbine with additional electricity provided by solar electric photovoltaic panels. The heat and electricity production systems in the area are connected to the public grids through which the buildings get their heat and electricity. By connecting the heating and electricity production systems to the public supply systems, it is possible to use heating and electricity from these systems during days when the energy use of the area is larger than production. For days when production is higher than use, it is possible to deliver heat and electricity to the public supply systems.

To achieve the balance between energy used and produced in the area, all buildings were designed to use a maximum of 105 kWh/m² energy annually including space heating, domestic hot water, common electricity, and household electricity (Quality Programme Bo01, 1999). The developers used different techniques to achieve the restrictions regarding energy use. Before getting a building permit, the developers had to present calculations that proved that their building's energy use fulfilled the demand of 105 kWh/m². The quality program demanded that the energy used at the properties was measured during two years after inauguration.

A measurement program was set up to monitor the energy use of the buildings. Since the buildings were taken into use, use of district heating, common electricity and household electricity have been measured and stored every hour. Nilsson (2003) studied the energy use during the first year of operation and concluded that the energy use was higher than the demand at all properties except one.

In this report, the energy use has been followed up after Nilsson's study to make it possible to see trends and statistics regarding energy use in modern multi-family dwellings. This licentiate dissertation presents results from the analysis of the energy use during the first four years after inauguration.

1.2 Objectives

The objective of this research project is to study the measured energy use in the multi-family dwellings built for the housing exhibition Bo01. This shows whether or not the different properties fulfilled the demand regarding energy in the quality program after the first years of use. The key values concerning energy use provided can be used to critically examine different designs and systems, and results from calculations. Energy use for space heating, domestic hot water, assimilation of solar heat gains, common electricity and household electricity is presented to give input that helps designers of buildings to fulfil demands concerning low energy use.

1.3 Methods

When energy use is to be analysed, the only method with reasonable accuracy is measurements of the physical parameters in a positivistic research approach. It would be interesting to combine these measurements with a hermeneutic approach with for example interviews and questionnaires for the building users, but in this research project, the focus has been limited to measurements.

Before this research project was formed, the energy use measurements were outlined. The energy use data have been collected hourly by E.ON. The resolution has been 1 kWh. To analyse the measured data, outdoor climate data have been used from Heleneholm's weather station in Malmö, which is located about four kilometres away from Västra Hamnen. Outdoor temperature and global radiation was collected every hour.

To be able to analyze the energy use, a number of models and assumptions based on other studies and theories were used. They are presented in each subchapter. Data about the buildings, their construction and technical systems, have been collected from the developers.

1.4 Limitations

From the 14 properties of residential units built, due to different circumstances, only 9 properties were included in this study. The energy use at two other properties in the area was studied by Haryd (2006).

The energy use during 2006 was not included since the energy meters were replaced and a new measurement system was installed. Hence, this study includes the energy use during 2002, 2003, 2004 and 2005.

Energy use was measured at the property level. If there was more than one building on each property, it was not possible to separate the energy used in the different buildings.

1.5 The examined properties

The building techniques and the characteristics of the buildings at the examined properties have been described by Nilsson (2003) and Nilsson (2006). At seven of the properties, there were both high rise buildings and terraced houses. At two of the properties there were only high rise buildings. Table 1.1 presents key data of the buildings at the examined properties regarding number of apartments and floor area, Table 1.2 presents key data regarding heating, ventilation and heat recovery systems.

Table 1.1 Data regarding the number of apartments in the buildings and different floor area of interest is presented for each property respectively.

	Apartments in the high-risebuilding	Apartments in the terraced house	Total area /m²	Heated floor area excluding garage /m²	Apartment area /m²
Entréhuset	37	4	7550	5463	4001
Friheten	9	2	1570	1445	1242
Havshuset	16	7	4749	3546	2002
Havslunden	15	5	4075	2623	1657
Kajplats 01	23	-	6251	3115	2656
Sundsblick	8	3	1750	1739	1309
Tango	27	-	4322	3467	2667
Tegelborgen	21	1	3772	2437	2686
Vitruvius	13	5	3366	2390	1621

Entréhuset, Kajplats 01 and Tegelborgen had commercial space. At Entréhuset there were two clothiers, at Kajplats 01 a coffee house and at Tegelborgen two restaurants and a clothier.

Table 1.2 Characteristics regarding heat distribution system, ventilation system and ventilation heat recovery is presented for each property respectively. Electrical heaters in bathrooms can be towel driers and/ or underfloor heating.

	Heat distribution system			Ventilation system		Ventilation heat recovery	
	Hydronic radiators	Hydronic underfloor heating	Electrical heaters in bathrooms	Mechanical exhaust air	Mechanical supply and exhaust air	Exhaust air heat pump, space heating	Exhaust air heat pump, domestic hot water
Entréhuset	x		x	x		x	
Friheten	x		x		x	x	x
Havshuset	x		x	x		x	
Havslunden	x		x	x			
Kajplats 01		x	x	x		x	
Sundsblick	x		x		x	x	x
Tango	x	x		x			
Tegelborgen		x		x			
Vitruvius	x		x	x			

At Friheten and Sundsblick, each apartment has its own air handling unit consisting of supply- and exhaust air fans and a heat pump. The heat pump prior heating the domestic hot water and secondary heats the supply air. At Havslunden and Vitruvius, the supply air to the garage is the extract air from the apartments.

1.6 Dissertation structure

Chapters 2 through 7 present different parts of the energy use of the examined buildings. In each chapter, methods and limitations in question for that specific part is presented and a discussion concludes each part in a way that it is possible to read them separately. Chapter 2 presents the use of district heating. Chapter 3 presents energy use for heating the domestic hot water. Assimilation of solar heat gains is studied in Chapter 4. Chapter 5 presents use of common electricity and Chapter 6 presents the usage of household electricity. The results from these chapters are discussed in Chapter 7 and conclusions are given in Chapter 8.

2 Use of district heating

This chapter presents the use of district heating at the different properties during four years, from 2002 through 2005. Power signatures were made and the use of district heating was corrected for differences in the outdoor climate. The use at the different properties and for the area as whole is discussed.

2.1 Method

Measured energy data is presented as power signatures for each year and property respectively. The power signatures were used to correct the energy use for differences in the outdoor climate.

2.1.1 The power signature

The power signature describes the relationship between the heating power and the outdoor temperature. The power signature gives a graphical description of how the building works during different conditions and is obtained by plotting the average heating power as a function of the corresponding mean outdoor temperature for a chosen time span as seen in Figure 2.1 where a power signature is made from daily data. Other time spans can be used, for example hourly, weekly, or monthly data.

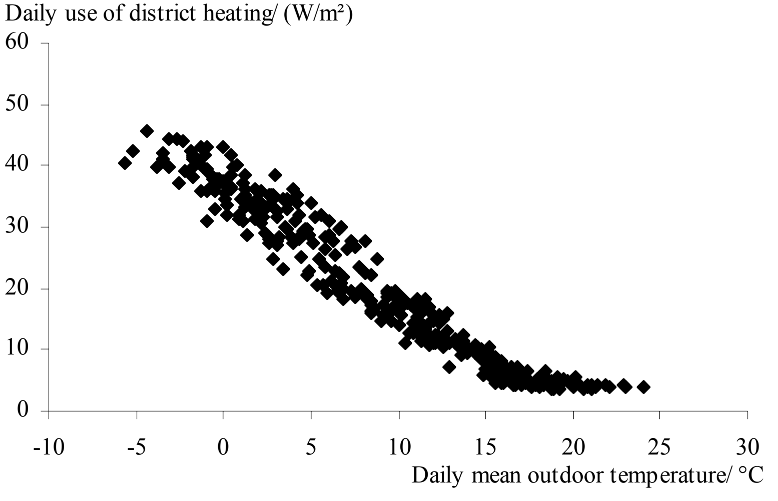

Figure 2.1. An example of a power signature based on the daily average district heating power and the daily mean outdoor temperature for one year.

Physically, it would be more correct to plot the average heating power as a function of the temperature difference between indoors and outdoors as this temperature difference determines the heat loss. However, often there are no measurements of the indoor temperature and, based on the assumption that the indoor temperature is relatively constant during the heating season, the outdoor temperature is only used. The power signature describes how the building and its technical systems work as whole in cooperation with its occupants.

If the buildings’ energy use depended only on the outdoor temperature, there would be no scatter in the signature except for measurement errors. In a real building the energy use would also depend on other weather parameters such as wind and sun. Additionally, the indoor temperature will most likely not be constant for all weather conditions. The occupants will affect the energy use depending on how many people live in the building, their attendance, how much household electricity and domestic hot water they use and what indoor temperature they want. The occupants will also affect the energy use depending on how much they ventilate the apartment through open windows and how solar shading is used. This could be called energy related behaviour. Use of domestic hot water heating and use of household electricity are studied in other chapters in this report. The scatter in the signature might indicate how sensitive the building is to climatic factors besides outdoor temperature and the occupants’ energy related behaviour. The scatter’s relationship to global radiation is studied in the Chapter 4.

At a certain outdoor temperature, called the balance temperature, the internal heat gains balance the heat losses and there should not be a demand for space heating at temperatures higher than the balance temperature. However, if the measured power is used for both space heating and domestic hot water heating, a heating demand will be visible for outdoor temperatures higher than the balance temperature due to use of domestic hot water. This use should be more or less constant in relation to the outdoor temperature.

By using the values in the power signature, it is possible to make two lines based on the least square method. These lines are called performance lines. The first line, P_1 in Figure 2.2 shows the relationship between district heating power for heating, including both space heating and domestic hot water heating, and outdoor temperature. The slope of the regression line P_1 indicates the loss factor, that is how much the heating power changes for a change in the outdoor temperature. The second line, P_2 in Figure 2.2, represents a constant value of energy use during times when the district heating only heats the domestic hot water. The balance temperature, $T_{balance}$, is defined as the intersection between the performance lines P_1 and P_2.

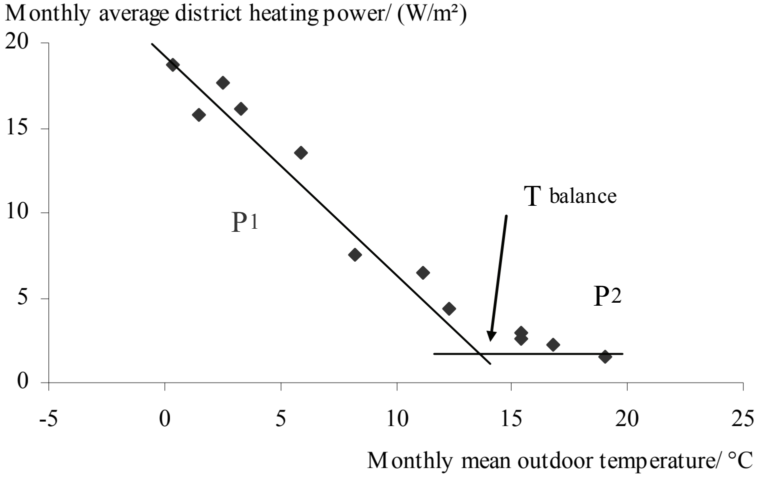

Figure 2.2 An example of a power signature based on monthly average district heating power and the corresponding monthly mean temperatures outdoors. The regression lines P_1 and P_2 and the balance temperature, $T_{balance}$, are presented in the figure.

The power signature can be used to make meteorological corrections of the energy use. When using the power signature, there is no need for assumptions on, for example, the balance temperature that would have been necessary if the degree day method was used. The correction of the energy use, with respect to outdoor temperature, is executed by calculating the energy use according to the performance lines and sum up over the desired time interval (Schulz, 2003). For each temperature, the average power is determined based on the performance lines and the energy used during the time interval is calculated. If daily average temperatures are used, this is executed for all 365 days of the year and if monthly average temperatures are used, this is executed for all 12 months of the year, to obtain the annual energy use for heating.

2.1.2 Presentation of measured data and meteorological correction

For each property, power signatures are presented based on monthly average district heating power and monthly mean outdoor temperature for the years 2002, 2003, 2004 and 2005 respectively. Based on the values in the signatures, the lines P_1 and P_2 were determined and the balance temperature, $T_{balance}$, calculated for each year respectively. The temperature corrected annual use of district heating was calculated for the different years. For the year 2005, a power signature based on daily values is presented for each property.

The performance line P_1 is based on months with monthly mean temperature below 10 °C and the performance line P_2 is based on months with monthly mean temperature more than 18 °C. $T_{balance}$ is calculated as the temperature at the intersection of P_1 and P_2.

The annual use of district heating was calculated based on P_1, P_2 and $T_{balance}$ using daily average temperatures during a statistical "normal year", according to SMHI, based on temperatures from 1969 to 1990, see Figure 2.3.

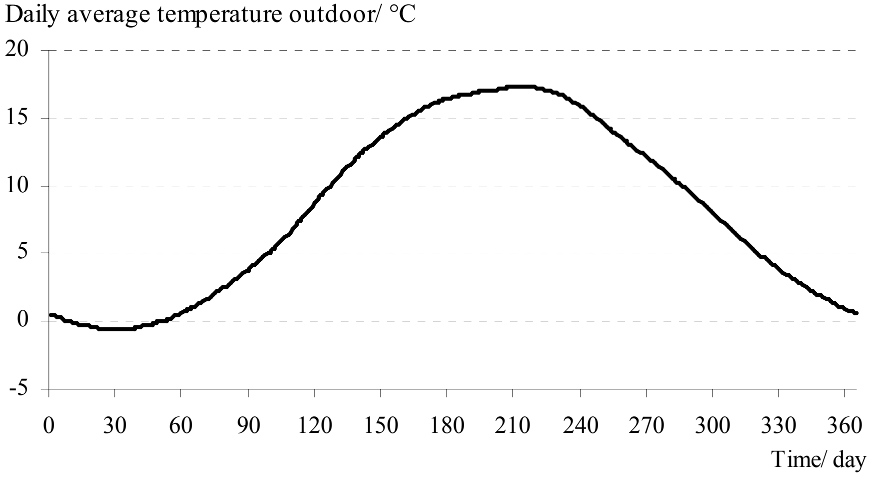

Figure 2.3. Daily mean temperatures based on the daily mean temperatures from 1969 to 1990.

2.2 Limitations

The correction for differences in outdoor climate only includes the outdoor temperature although wind and sun also might affect the energy use. All properties do not have measured data from 2002. For most properties district heating is used for both space heating and domestic hot water heating. In the measured data, it was not possible to separate the use of district heating for domestic hot water heating.

2.3 Results

2.3.1 Monthly average outdoor temperature

Figure 2.4 presents the monthly average outdoor temperatures during 2002 through 2005 and the monthly average outdoor temperatures during a normal year. For a majority of the months the average temperature was higher compared to the normal year. Because of this, the corrections of the energy use with respect to outdoor temperature should give somewhat higher energy use compared to the measured.

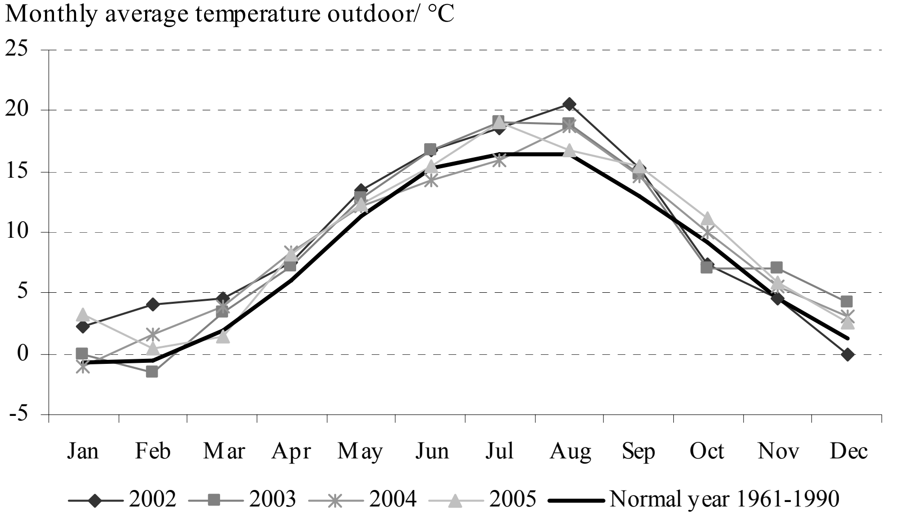

Figure 2.4 Monthly mean outdoor temperatures during 2002 through 2005 and the monthly average outdoor temperatures during a normal year.

2.3.2 Entréhuset

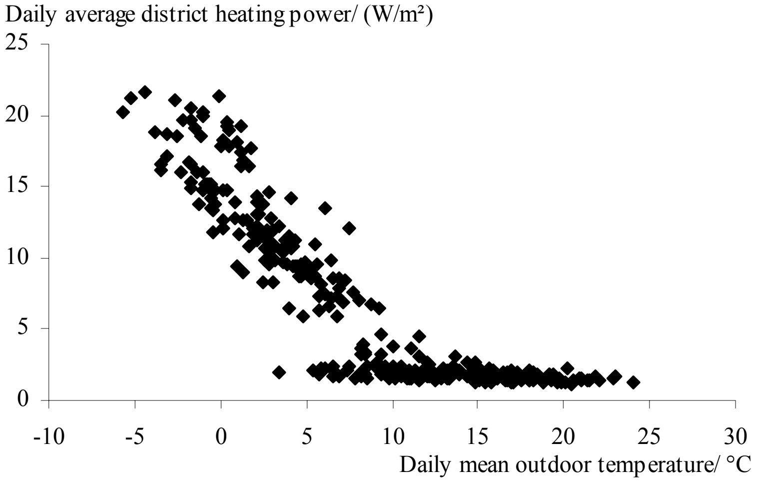

Figure 2.5 Entréhuset. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

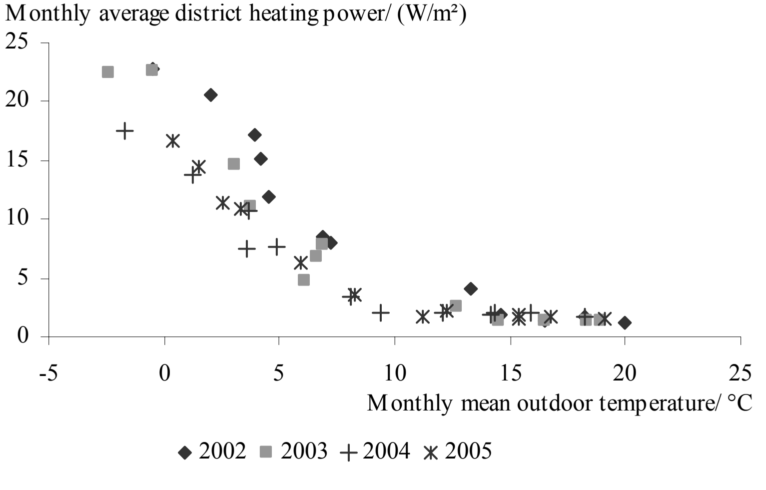

Figure 2.6 Entréhuset. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2002 to 2005 respectively.

Table 2.1 Entréhuset. Equations for the regression lines P_1 and P_2 in the form of $P_1 = k \cdot T + m$ and the corresponding R^2 values, $P_2 = n$, the balance temperature $T_{balance}$ and the annual use of district heating (DH) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2002	-2.1	23.2	0.93	1.4	10.5	87
2003	-2.0	19.5	0.93	1.3	9.3	70
2004	-1.4	14.9	0.96	1.7	9.3	57
2005	-1.7	16.6	0.98	1.5	9.1	61

The use of district heating has decreased since 2002. During 2005 the energy use was 30% less than 2002. The energy use in 2005 was slightly higher than 2004. The overall loss factor has varied between 1.4 and 2.1 The energy use during off heating season was lowest in 2003, 1.3 W/m², and highest in 2004, 1.7 W/m². The balance temperature has decreased from 10.5 °C in 2002 to 9.1 °C in 2005. The constants of the regression lines have changed between the years and this is visualized in Figure 2.6. It is especially during outdoor temperatures below 5 °C that the use has differed between the years.

The power signature in Figure 2.5 shows that during a number of days with the daily mean outdoor temperatures down to 5 °C, no more heat was used than during off heating season. When the daily energy use during 2005 is studied, it seems as the heat produced by the heat pump has made up for the energy losses during these days and hence no district heating has been needed for space heating. During the heating season there is a considerable amount of scatter in the signature. The scatter has almost the same amplitude for all outdoor temperatures.

2.3.3 Friheten

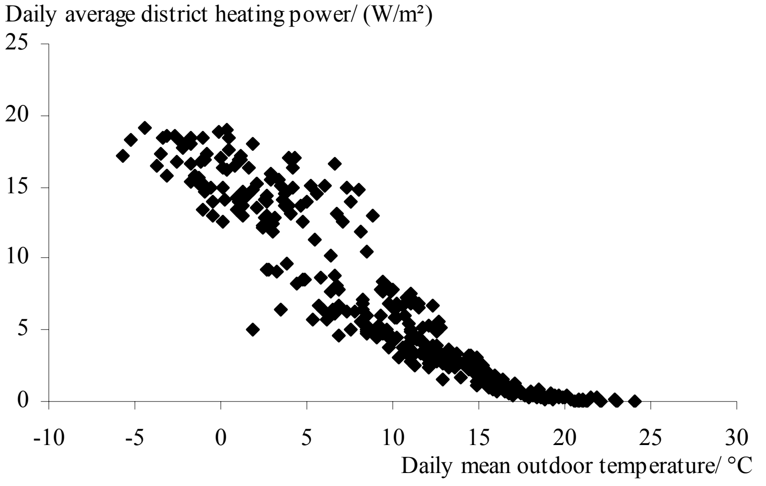

Figure 2.7 Friheten. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

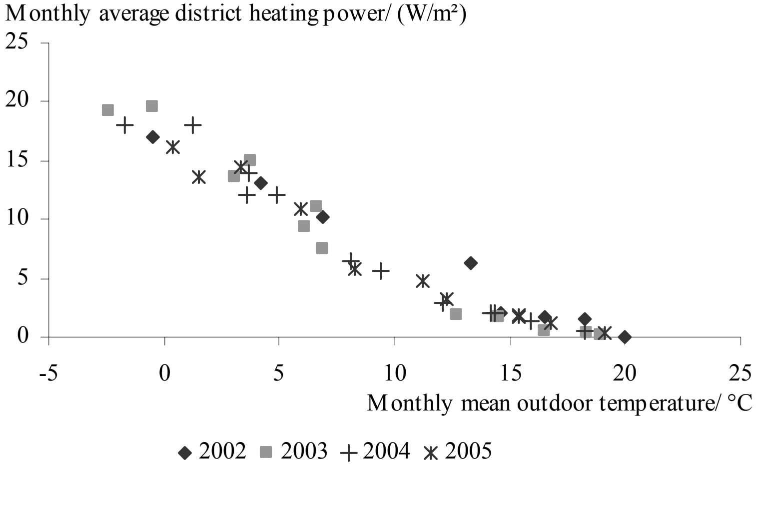

Figure 2.8 Friheten. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2002 to 2005 respectively.

Table 2.2 Friheten. Equations for the regression lines P_1 and P_2 in the form of $P_1=k{\cdot}T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2002	-1.1	19.8	1.00	0.9	17.4	79
2003	-1.5	21.1	0.90	0.4	14.3	73
2004	-1.5	20.9	0.93	0.5	13.6	71
2005	-1.4	19.9	0.89	0.4	13.9	68

In the power signatures for Friheten, Figure 2.7 and 2.8, the garage area was included. The numbers in Table 2.2 were recalculated to refer to heated floor area excluding the garage area.

The use of district heating has decreased since 2002. During 2005 the use was 14% less than 2002. The use has decreased every year. The overall loss factor has varied from 1.1 W/(°C·m²) to 1.5 W/(°C·m²). The use during the off heating season was very low because the district heating was not used to heat the domestic hot water. Although there should not be a demand for district heating at outdoor temperatures higher than $T_{balance}$, the use was 0.4 W/m² during 2005. This might be due to standby heat losses in the heat exchanger. The balance temperature in 2002 was high, 17.4 °C, but has decreased to 13.9 °C during 2005. Since the heat pump in each apartment pre-heats the supply air, district heating was not the only heat source for space heating. The heat pumps are supported by household electricity and hence some of the household electricity was actually energy for space heating.

As seen in Figure 2.7, there is a considerable amount of scatter in the signature during the heating season. The scatter is most spread when the outdoor temperature is around 5 °C. This indicates that there is a break point at about 5 °C where there seems to be a jump in the use. This might be due to the fact that the heating system uses different control parameters at different temperatures at different times of year.

2.3.4 Havshuset

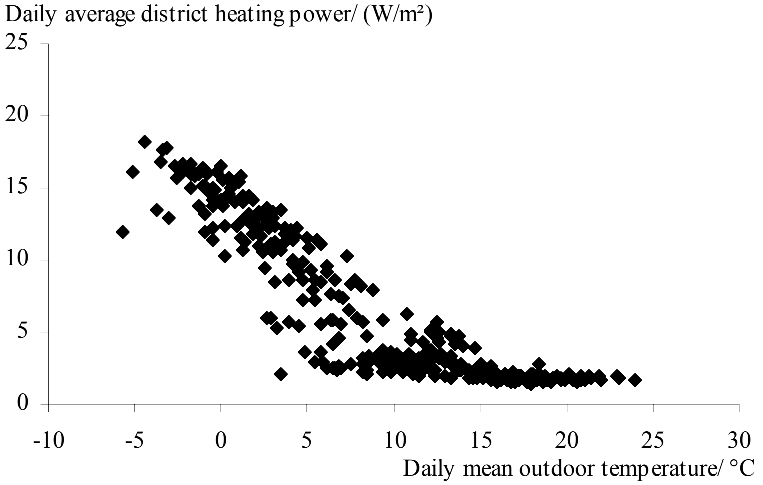

Figure 2.9 Havshuset. Power signature based on daily use of district heating and daily mean outdoor temperature 2005.

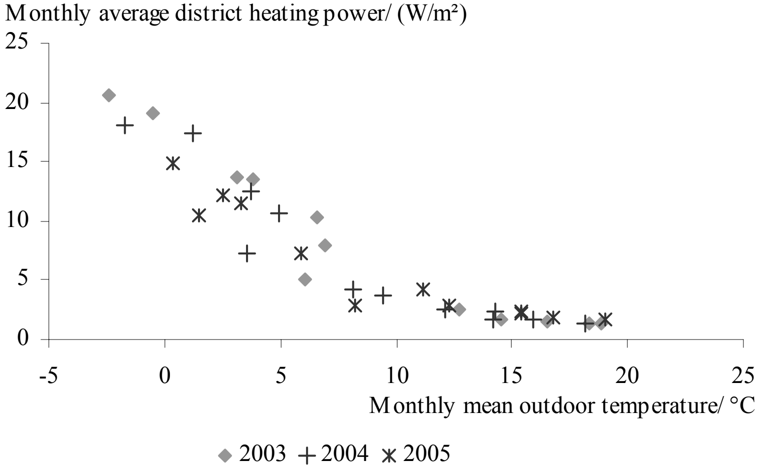

Figure 2.10 Havshuset. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2003 to 2005 respectively.

Table 2.3 Havshuset. Equations for the regression lines P_1 and P_2 in the form of $P_1=k\cdot T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2003	-1.5	17.8	0.89	1.4	11.2	70
2004	-1.4	16.5	0.86	1.4	10.6	65
2005	-1.4	14.8	0.90	1.7	9.6	58

During 2002, measured energy data only exists for a few months and therefore energy use during this year has not been calculated.

The use of district heating has decreased since 2003. During 2005, the energy use was 17 % less than in 2003. The use has decreased every year. The overall loss factor has decreased from 1.5 W/(°C·m²) in 2003 to 1.4 W/(°C·m²) in 2005. The use during off heating season has increased from 1.4 to 1.7 W/m². The balance temperature has decreased from 11.2 °C to 9.6 °C. Although the use during off heating season has increased the annual use has decreased due to the decreased loss factor and reduced balance temperature. The constants of the regression lines have changed between the years as seen in Figure 2.10.

The power signature in Figure 2.9 shows that during a number of days with daily mean outdoor temperatures down to 5 °C, no more heat than during off heating season has been used. When the daily use during 2005 is studied, it seems that the heat produced by the heat pump has made up for the energy losses during these days and hence no district heating has been needed for space heating. During the heating season there is a considerable amount of scatter in the signature.

2.3.5 Havslunden

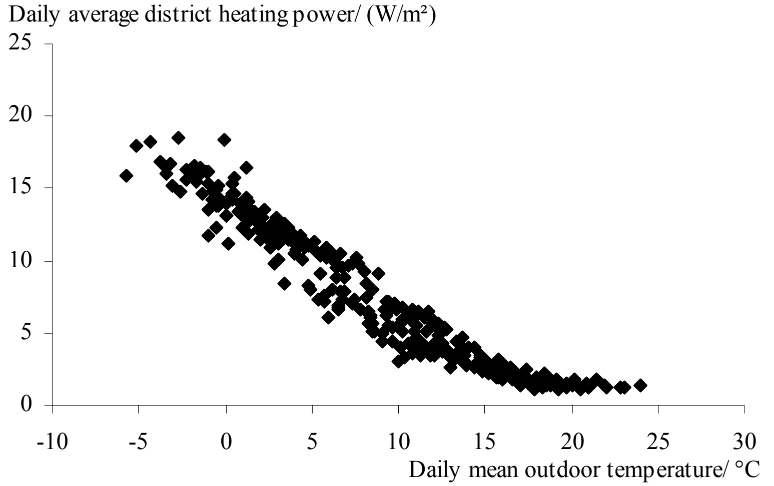

Figure 2.11 Havslunden. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

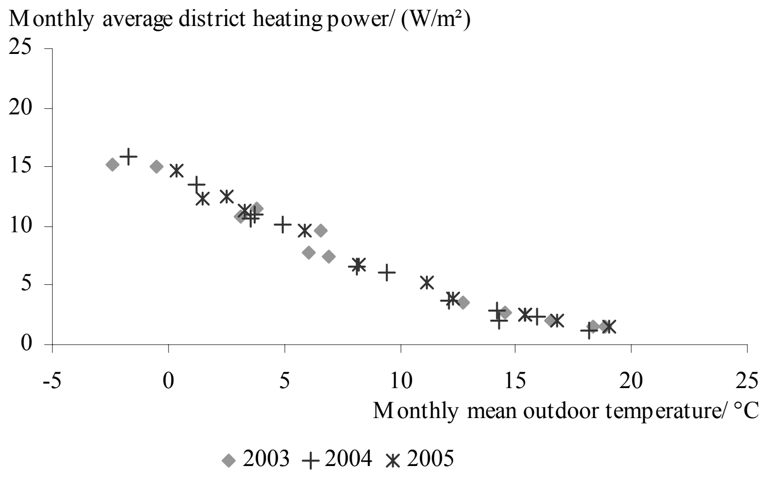

Figure 2.12 Havslunden. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2003 to 2005 respectively.

Tabel 2.4 Havslunden. Equations for the regression lines P_1 and P_2 in the form of $P_1=k \cdot T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	$k/(W/(m^2 \cdot °C))$	$m/(W/m^2)$	R^2	$n/(W/m^2)$	/°C	$/(kWh/m^2)$
2003	-1.0	16.9	0.92	1.8	14.8	64
2004	-1.1	17.5	0.99	1.5	14.3	64
2005	-1.1	17.8	0.96	1.8	14.2	66

During 2002 measured energy data only exists for a few months and therefore energy use during this year has not been calculated. In the power signatures, Figure 2.10 and 2.11, the garage area is included. The numbers in Table 2.4 have been recalculated to refer to heated floor area excluding the garage area.

The use of district heating has increased slightly since 2003. During 2005, the energy use was 3 % higher than in 2003. The overall loss factor has increased from 1.0 $W/(°C \cdot m^2)$ in 2003 to 1.1 $W/(°C \cdot m^2)$ in 2005. The use during the off heating season was more or less the same during 2003 and 2005, 1.8 $W/(°C \cdot m^2)$ and a bit lower during 2004, 1.5 $W/(°C \cdot m^2)$. The balance temperature has decreased slightly from 14.8 to 14.2 °C. The energy use and the constants of the regression lines have been about the same during the years. This is seen in Figure 2.12 where the plotted data from the different years almost superpose.

According to Figure 2.11 the scatter during the heating season is moderate. The amplitude of the scatter seems to have almost the same amplitude for all outdoor temperatures during the heating season.

2.3.6 Kajplats 01

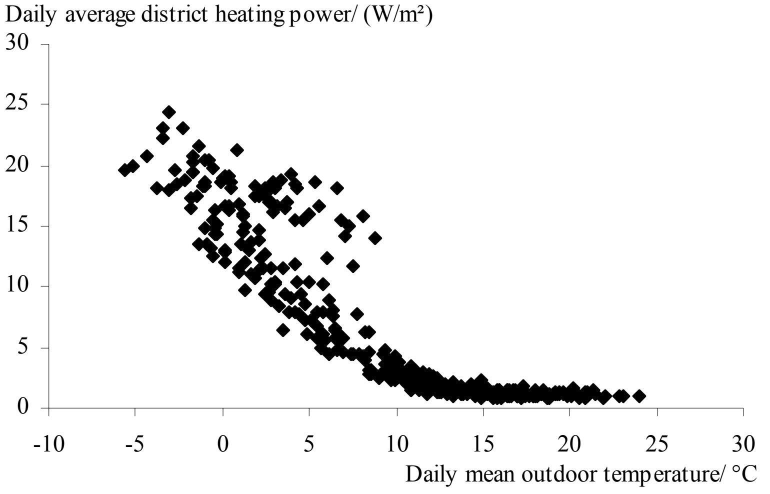

Figure 2.13 Kajplats 01. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

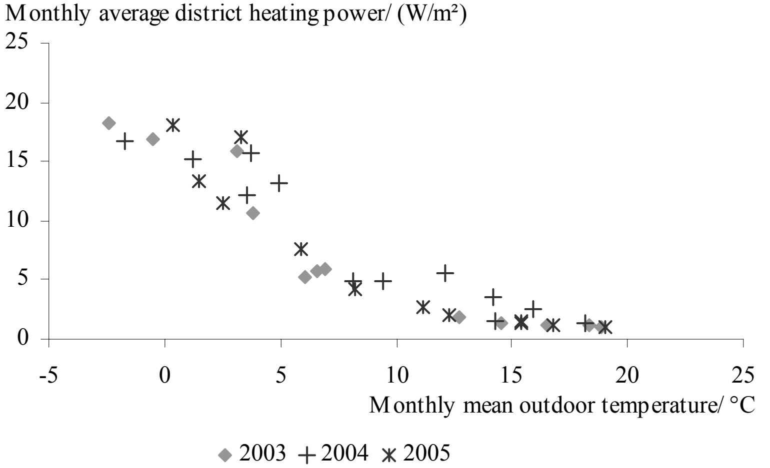

Figure 2.14 Kajplats 01. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2003 to 2005 respectively.

Table 2.5 Kajplats 01. Equations for the regression lines P_1 and P_2 in the form of $P_1=k \cdot T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2003	-2.4	26.6	0.87	1.8	10.2	113
2004	-1.9	27.5	0.82	2.1	13.1	116
2005	-2.6	29.3	0.78	1.7	10.4	108

During 2002 measured energy data only exists for a few months and therefore energy use during this year has not been calculated. In the power signatures for Kajplats 01, Figure 2.13 and 2.14, the garage area is included. The numbers in Table 2.5 have been corrected to refer to heated floor area excluding the garage area.

The use of district heating has decreased slightly since 2003. During 2005, the use was 4 % lower than in 2003. The overall loss factor has increased from 2.4 W/(K·m²) in 2003 to 2.6 W/(°C·m²) in 2005. The energy use during the heating season was lowest, 1.7 W/(°C·m²), during 2005 and highest, 2.1 W/(°C·m²), during 2004. The balance temperature was the same during 2003 and 2005, 10.4 °C. During 2004, the balance temperature was almost 3 °C higher. The energy use and the constants of the regression lines have varied during the years. This is seen in Figure 2.14. Although the loss factor was considerably lower during 2004 compared to 2005, the annual use was lower during 2005 due to the lower balance temperature and off heating season use.

The power signature in Figure 2.13 shows that during a number of days with daily mean outdoor temperatures between 0 and 10 °C, the use was higher and deviates from the linear behaviour. These data refer to January 2005. Malfunctioning of the heat pump might be one reason. During the heating season there is a considerable amount of scatter in the signature. If the above mentioned peculiarity is neglected it seems as if the amplitude of the scatter increases with decreasing outdoor temperature.

2.3.7 Sundsblick

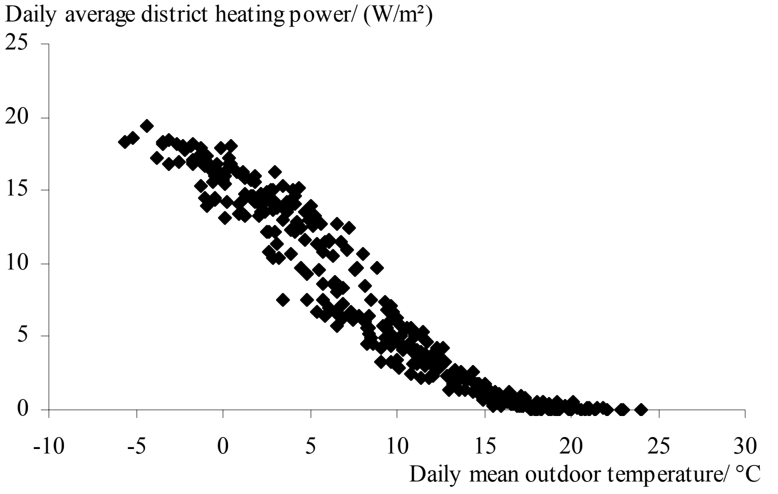

Figure 2.15 Sundsblick. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

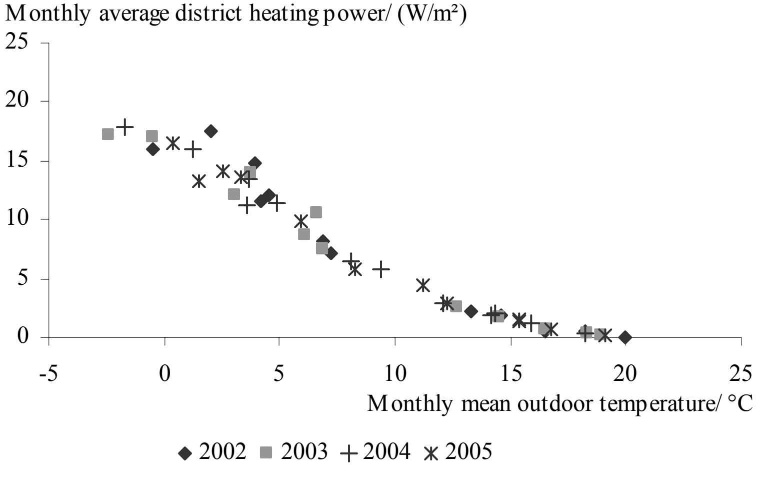

Figure 2.16 Sundsblick. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2002 to 2005 respectively.

Table 2.6 Sundsblick. Equations for the regression lines P_1 and P_2 in the form of $P_1=k{\cdot}T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2002	-1.3	17.6	0.79	0.3	13.6	70
2003	-1.0	15.8	0.88	0.3	15.6	68
2004	-1.2	16.6	0.96	0.3	14.1	68
2005	-1.3	16.7	0.94	0.2	13.2	65

The use of district heating has decreased slightly since 2002. During 2005, the use was 7 % lower than in 2002. The overall loss factor has varied between 1.0 and 1.3 W/(°C·m²). The energy use during off heating season was lowest, 0.2 W/m², during 2005 and highest, 0.3 W/m², during 2003 and 2004. The energy use during off heating season was low because district heating was not used to heat the domestic hot water. Although there should not be any demand for district heating during the off heating season, the use was 0.2 W/m² during 2005. This might be due to standby heat losses in the heat exchanger. The balance temperature has varied between 13.2 and 15.6 °C. Since the heat pumps in each apartment pre heats the supply air, district heating was not the only heat source for space heating. The heat pumps are supported by household electricity and hence some of the household electricity was actually energy for heating.

The power signature in Figure 2.15 shows that during the heating season there is a certain amount of scatter in the signature. The scatter is most spread when the outdoor temperature is around 5 °C. The power signature in Figure 2.15 indicates that there is a break point at about 5 °C where there seems to be a jump in the use. This might be due to that the heating system uses different control parameters at different temperatures or different time of year. However, this is not as explicit at this property as for some of the other properties.

2.3.8 Tango

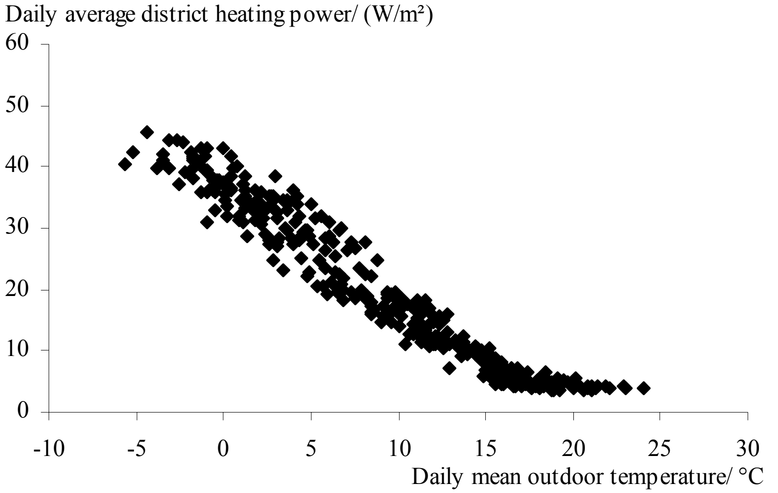

Figure 2.17 Tango. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

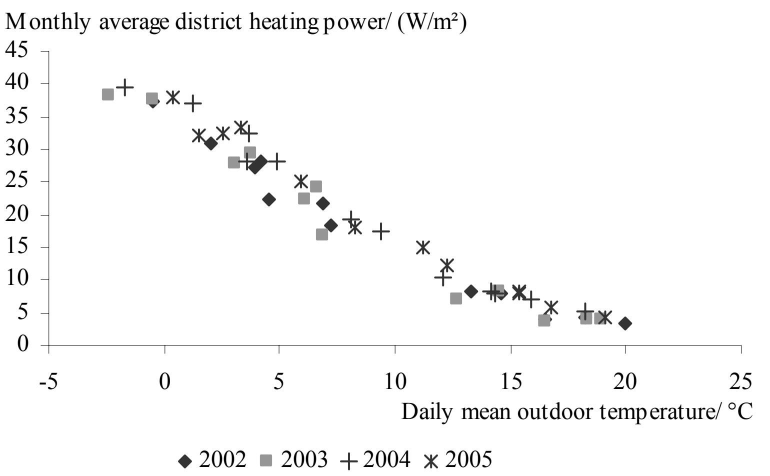

Figure 2.18 Tango. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2002 to 2005 respectively.

Table 2.7 Tango. Equations for the regression lines P_1 and P_2 in the form of $P_1=k\cdot T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2002	-2.3	35.8	0.93	3.9	13.9	160
2003	-2.1	35.0	0.91	4.0	15.0	163
2004	-2.1	37.9	0.95	5.1	15.3	182
2005	-2.3	38.4	0.93	4.3	14.6	177

The use of district heating has increased since 2002. During 2005, the energy use was 10 % higher than 2002. The energy use was highest during 2004. The overall loss factor has varied between 2.1 W/(°C·m²) and 2.3 W/(°C·m²). The use during off heating season was lowest during 2002, 3.9 W/m², and highest, 5.1 W/m², during 2004. The balance temperature has varied between 13.9 and 15.3 °C. The constants of the regression lines have been almost the same through the years during the heating season while the off heating season energy use and balance temperature has varied.

During the heating season there is a considerable amount of scatter in the signature, as seen in the power signature in Figure 2.17. The scatter has largest amplitude between 2 °C and 7 °C.

2.3.9 Tegelborgen

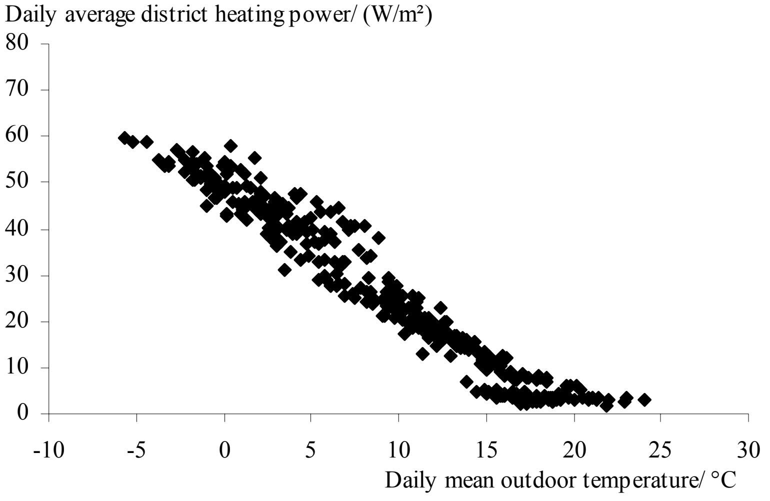

Figure 2.19 Tegelborgen. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

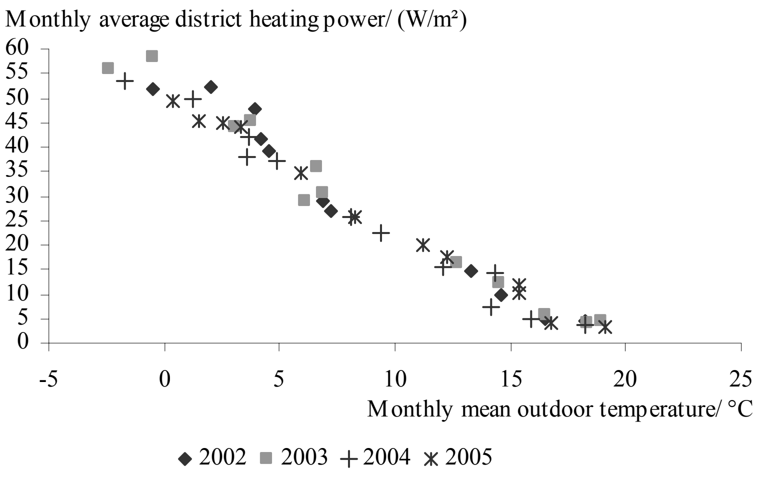

Figure 2.20 Tegelborgen. Power signatures based on monthly use off district heating and monthly mean outdoor temperature during 2002 to 2005 respectively.

Table 2.8 Tegelborgen. Equations for the regression lines P_1 and P_2 in the form of $P_1=k\cdot T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2002	-3.5	55.4	0.85	4.3	14.5	245
2003	-3.0	52.8	0.89	4.2	16.3	249
2004	-3.0	50.7	0.97	3.7	15.9	234
2005	-3.0	51.4	0.97	3.3	16.2	234

The use of district heating has decreased slightly since 2002. During 2005, the energy use was 4 % lower than 2002. The energy use was highest during 2003. The overall loss factor was 3.5 W/(°C·m²) during 2002 and decreased to 3.0 W/(°C·m²) in 2003. The energy use during off heating season has decreased from 4.3 W/m² in 2002 to 3.3 W/m² during 2005. The balance temperature has varied between 14.5 and 16.3 °C. As seen in Figure 2.20, the energy use at outdoor temperatures between 7 and 13 °C was more or less the same during the years, while the use at higher and lower temperatures has differed between the years.

During the heating season there is a considerable amount of scatter in the signature, as seen in the power signature in Figure 2.19. The scatter has largest amplitude between 2 and 8 °C.

2.3.10 Vitruvius

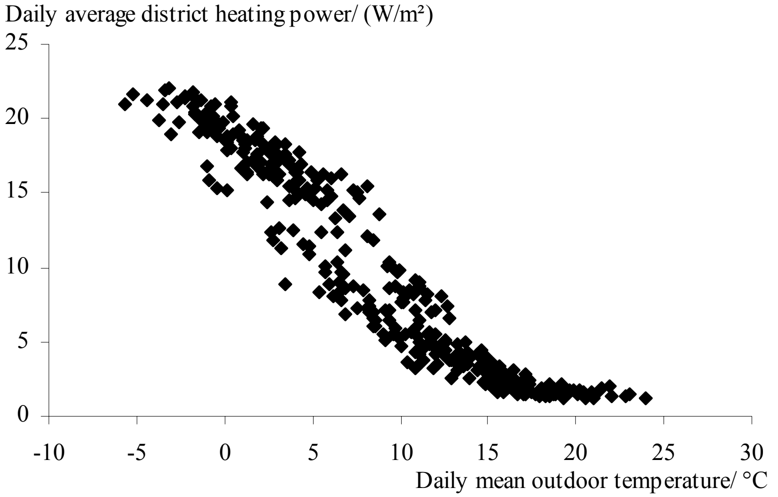

Figure 2.21 Vitruvius. Power signature based on daily use of district heating and daily means outdoor temperature 2005.

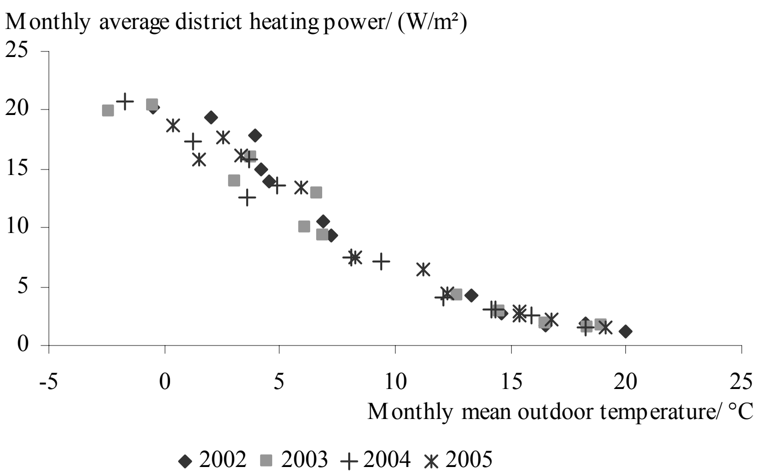

Figure 2.22 Vitruvius. Power signatures based on monthly use of district heating and monthly mean outdoor temperature during 2002 to 2005 respectively.

Table 2.9 Vitruvius. Equations for the regression lines P_1 and P_2 in the form of $P_1=k\cdot T+m$ and the corresponding R^2 values, $P_2=n$, the balance temperature $T_{balance}$ and the annual use of district heating (D.H) for the different years respectively.

	P_1			P_2	$T_{balance}$	Annual use of DH
	k/(W/(m²·°C))	m/(W/m²)	R^2	n/(W/m²)	/°C	/(kWh/m²)
2002	-1.8	25.4	0.89	1.8	13.2	106
2003	-1.4	22.1	0.87	1.9	14.9	100
2004	-1.5	22.5	0.95	1.9	13.5	97
2005	-1.5	23.4	0.87	1.8	14.1	102

In the power signatures for Vitruvius, Figure 2.21 and 2.22, the garage area is included. The equations in Table 2.9 have been corrected to refer to heated floor area excluding the garage area.

The use of district heating has decreased slightly since 2002. During 2005, the energy use was 4 % lower than 2002. The energy use was highest during 2002 and lowest during 2004. The overall loss factor has varied between 1.4 W/(°C·m²) and 1.8 W/(°C·m²). The energy use during off heating season has varied between 1.9 W/m² and 1.8 W/m². The balance temperature has varied between 13.2 and 14.9 °C. At outdoor temperatures below 7 °C, the use differs between the years while the use at outdoor temperatures over 7 °C is about the same during the years, as seen in Figure 2.22.

The power signature in Figure 2.21 indicates that there is a break point at about 5 °C where there seems to be a jump in the use. This might be due to the fact that the heating system uses different control parameters at different temperatures or different time of year.

2.3.11 Comparisons between the properties

Figure 2.23 presents the measured annual use of district heating corrected for differences in outdoor temperature and by the developers predicted annual use.

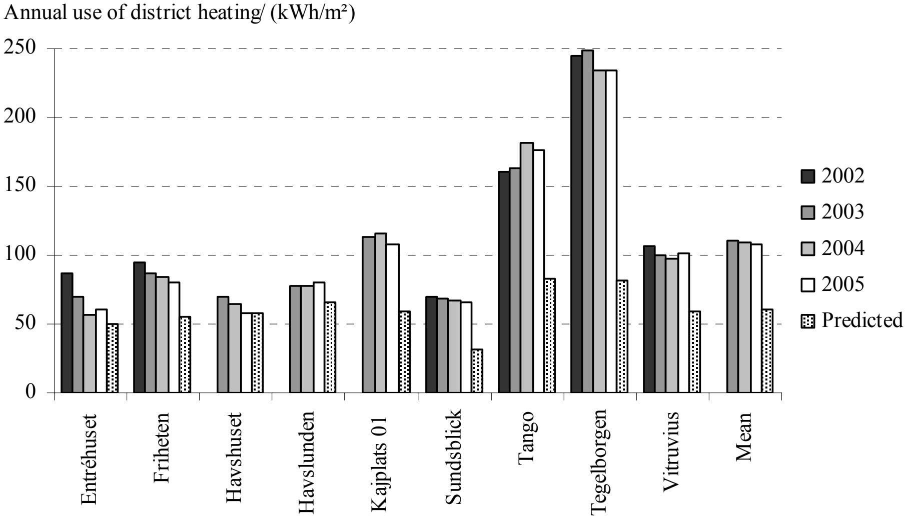

Figure 2.23 Measured annual use of district heating from 2002 to 2005 corrected for differences in outdoor temperature and by the developers predicted annual use. The use is presented as use per heated floor area, garage excluded.

The mean annual energy use including all properties has decreased from 111 kWh/m² during 2003, to 104 kWh/m² during 2005. The energy use during 2005 was lowest at Havshuset, 58 kWh/m², and highest at Tegelborgen, 234 kWh/m². The mean, by the developers, predicted annual energy use including all properties was 60 kWh/m². The measured and outdoor temperature corrected use was on average 73 % higher than the predicted. If the energy use during 2005 is compared to the energy use during 2002, the energy use decreased at seven out of nine properties. At most properties, the use of district heating decreases from year to year. At individual properties, the energy use might first have increased where after it has decreased. The energy use has decreased the most, 30 %, at Entréhuset and increased the most, 10 %, at Tango.

The result shows a great span in the use of district heating between the different properties. There is a factor four between the highest and the lowest use of district heating during 2005. Tegelborgen and Tango used significantly more district heating than the other buildings.

The properties that have low use of district heating typically have some kind of ventilation heat recovery. However, Havslunden had relatively low use without having any kind of heat recovery and Kajplats 01 had relatively high use despite having a heat pump.

The buildings at the properties Kajplats 01, Tango and Tegelborgen, were the only that used underfloor heating as primarily heat distribution system. The average use of district heating at properties with underfloor heating as primarily heat distribution system was 173 kWh/m². The average use of district heating at properties with radiators as primarily heat distribution system was 70 kWh/m², note that two of these properties did not use district heating for domestic hot water heating.

The average overall loss factor during 2005 was 1.8 W/(°C·m²) and varied between 1.1 W/(°C·m²) and 3.0 W/(°C·m²) at the different properties. At properties without any kind of heat recovery, the average overall loss factor was 2.0 W/(°C·m²). At properties with exhaust air heat pumps the average overall loss factor was 1.7 W/(°C·m²).

The average balance temperature was 12.8 °C and varied between 9.1 °C and 16.2 °C. At properties with heat pumps, the average balance temperature was 11.2 °C. At properties with central heat pumps the average balance temperature was 9.7 °C. At properties without any heat recovery the average balance temperature was 14.8 °C.

2.4 Discussion and conclusions

For most properties, the use of district heating has decreased during the years. Although the use decreased, most properties, still during 2005, used more heat than what the developers predicted. On average, the use of district heating was more than 70 % higher than predicted by the developers.

The use of district heating was higher at properties with underfloor heating as primarily heat distribution system compared to the use of district heating at properties with radiators as primarily heat distribution system.

At all properties except Friheten and Sundsblick, district heating was used for domestic hot water heating. In Chapter 3, the use of district heating is split into space heating and domestic hot water.

Lindén (2006) studied the energy use at a housing area built in 2001 in Stockholm, Sweden. The buildings were designed to use no more than 60 kWh/m² annually including all electricity. The average use of district heating during 2005 was 91 kWh/m². Note that it is not clear if garage area is included or not. The building with the lowest use used 47 kWh/m² and the highest was 153 kWh/m². The buildings that had relatively low use of heat typically had some kind of ventilation heat recovery. However, none of the buildings fulfilled the restrictions regarding energy use. Lindén concludes that the energy restriction set to 60 kWh/m² was impulsive and not based on what could be achieved in reality. During 2004 the use decreased significantly in most buildings. This is assumed to be due to the drying out of concrete and adjustments of the heating and ventilation systems. These results are similar to the results from this study. In both cases the variations are great between the highest and the lowest use, the average use is much higher than predicted and the use decreases during the first years after the inauguration. In the Stockholm case, the average district heating use alone was more than 50 % higher than the total energy restriction which implies that the measured use of district heating was very much higher than the predicted use of district heating.

A report from SABO (2006) presents the use of space heating and domestic hot water heating in newly built multi-family dwellings with different types of ventilation systems. The use refers to data from 75 properties and reported use from the property owners. The use is presented per area to let which should give slightly higher values compared to if the heated floor area excluding the garage area was used. The average use of heat at properties with mechanical exhaust air was 146 kWh/m² At properties with mechanical supply and exhaust air and heat exchanger, the average use was 134 kWh/m² and at properties with mechanical exhaust air and exhaust air heat pump, the use was 53 kWh/m². The average use at Bo01 properties with mechanical exhaust ventilation was 140 kWh/m², which is slightly lower compared to the reported average. The average use at Bo01 properties that includes exhaust air heat pumps was 72 kWh/m², which is much higher compared to the reported average.

According to Statistics Sweden (2006) the average use of district heating in residential buildings was 153 kWh/m² during 2005, in temperature zone 4 which includes Malmö. This was 50 % higher than the average use of district heating at the Bo01 properties.

In buildings with exterior walls made from lightweight concrete, initial moisture will increase the heat transfer. Bagge et al (2004) studied the energy use in an energy efficient lightweight concrete house and found that the energy use was higher than predicted since the moisture content in the lightweight concrete caused higher transmission losses. The buildings at the property Friheten and Kajplats 01 have lightweight concrete exterior walls and the decrease in use during the years might be due to drying concrete.

The Swedish building regulations from 2006 state that predicted energy use shall be confirmed by measurements in the actual building. To assure that the actual use will align with the calculated use, it is recommended that safety factors are used in the calculations. No guidelines regarding the safety factors are given. The energy predictions for the Bo01 properties have been executed by consultants that make energy predictions on a regular basis. Yet the actual use of district heating was on average more than 70 % higher than predicted. If the Bo01 case is representative regarding differences between predicted and actual use of heating, a safety factor of about two should be appropriate to assure energy use that not exceeds predictions. However, a safety factor that high would be unrealistic and a declaration of incapacity of the designers and the simulation tools or the construction workers. It is of greatest concern to have energy simulations made carefully and with suitable input data and critical examination of the results to get realistic predictions of use of heating. The construction work needs to be carefully done so the buildings different constructions and technical systems match design data.

3 Use of domestic hot water heating

This chapter presents the use of district heating for heating the domestic hot water. The use of domestic hot water has not been measured separately, neither the volume used nor the energy used for domestic hot water heating. However, during the summer there should not be any need for space heating and thus the use of district heating should be used solely for heating the domestic hot water. Use of district heating during July and August has been studied at 7 properties during 2005. Hourly readings allow the analysis of the variation during the day.

3.1 Method

It was assumed that during the summer the district heating was used solely for heating the domestic hot water. To test the assumption, the relationship between use and outdoor temperature was checked. For each property, power signatures were made based on the daily average district heating power and the daily mean outdoor temperatures during July and August respectively. A regression line that describes the use of district heating, based on the least square method, was applied. If the district heating power was not correlated to the outdoor temperature, the regression line should be horizontal.

Annual use of energy for heating the domestic hot water was calculated based on the use of district heating during July and the variation in use during the year presented by Aronsson (1996). The variations in use over the day during July and August are presented. The variations over the day are presented as hourly power per daily average power.

3.2 Limitations

The use of district heating was measured at the property level, which means that the measured values are the sum of the use in all the apartments at the property. The individual inhabitants' behavior will have a greater affect on the total use at properties with fewer apartments. At properties that include premises and restaurants, the use of these are included and it has not been possible to separate from the use in the apartments. In addition, it was not possible to separate the use for domestic hot water when there was a demand for space heating. Since the measurements are from the summer months when people typically have vacation, the use patterns during the day might be different from the rest of the year.

3.3 Results

3.3.1 Use of district heating during July and August

The properties Havslunden, Havshuset, Tango and Vitruvius consist of apartments and the properties Entréhuset, Kajplats 01 and Tegelborgen consist of both apartments and commercial space.

Figure 3.1 presents an example of a power signature based on daily average district heating power and daily mean outdoor temperature during July. The regression line and its equation are presented in the figure.

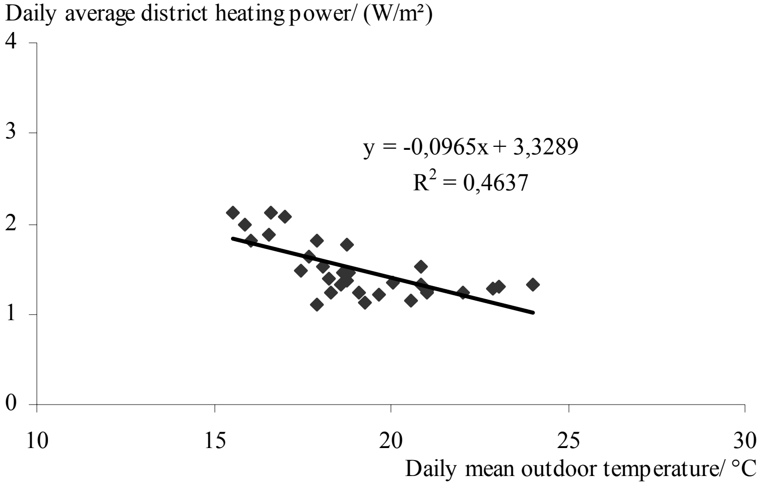

Figure 3.1 An example of a power signature based on daily average district heating power and daily mean outdoor temperature during July.

Table 3.1 presents the slope, k, of the regression lines, defined in Figure 3.1, for the different properties.

Table 3.1 The slope of the regression line and the corresponding R^2 value.

	July		August	
	k/(W/(m²·°C))	R^2	k/(W(/m²·°C))	R^2
Entréhuset	-0.011	0.036	-0.050	0.167
Havshuset	0.003	0.002	-0.030	0.079
Havslunden	-0.097	0.464	-0.160	0.613
Kajplats 01	0.010	0.026	0.032	0.114
Tango	-0.132	0.246	-0.522	0.245
Tegelborgen	-0.071	0.146	-0.228	0.566
Vitruvius	-0.058	0.388	-0.123	0.215

The slope of the regression line indicates how much the heating power changes for a change in the outdoor temperature. Compared to the inclination during the heating season, presented in Chapter 2, the district heating power is much less correlated to the outdoor temperature during both July and August for all properties. However, at all properties, the use is more correlated to the outdoor temperature during August compared to July. During 2005 the mean temperature during August was 16.8 °C which is 2.3 °C less than the mean temperature during July, as seen in Figure 2.4 in Chapter 2. For a couple of days during August, the daily mean temperature dropped below 15 °C, which is close to the average balance temperature at the properties without any kind of heat recovery ventilation. It is likely that district heating was used for heating the buildings during cold days in August. Hence the use during August was more correlated to the outdoor temperature than the use during July. At the properties Tango and Tegelborgen, district heating was used for underfloor heating and towel dryers in bathrooms and since these are also used during off heating season the use at these properties during July and August was most likely not solely for domestic hot water.

The use of district heating during July and August is presented in Table 3.2

Table 3.2 Measured use of district heating during July and August presented as monthly use, daily use per heated floor area and use per apartment.

	Monthly use/ kWh		Average daily use/ (Wh/m²)		Average daily use/ (kWh/apartment)	
	July	August	July	August	July	August
Entréhuset	6090	6945	36	41	5.2	5.9
Havshuset	4536	4925	48	52	6.7	7.2
Havslunden	3528	4968	43	61	5.7	8.0
Kajplats 01	3877	4539	40	47	5.4	6.4
Tango	11030	15280	103	142	13.2	18.3
Tegelborgen	5892	7704	78	102	9.1	11.8
Vitruvius	3267	4724	44	64	6.2	9.0

The average use during July was 56 Wh/m² and varied between 36 and 104 Wh/m² at the different properties. The average use during August was 73 Wh/m² and varied between 41 and 142 Wh/m². If properties that use district heating for underfloor heating and towel dryers are excluded the average use during July was 43 Wh/m² and during August 54 Wh/m².

The use is higher during August compared to July for all properties. On average the use was 30 % higher during August compared to July. If properties that use district heating for underfloor heating and towel dryers are excluded the average use was 27 % higher. The higher use during August was probably not only because of higher use for domestic hot water heating but also due to space heating during a couple of days with daily average temperatures close to the balance temperature. There was no major difference in use between weekdays and weekends.

3.3.2 Annual use of domestic hot water

The annual use of domestic hot water was calculated based on the use of district heating during July and the variation in use during the year presented by Aronsson (1996), see Figure 3.2. Aronsson studied use of district heating at

50 properties in Sweden and presented the variation in use of domestic hot water heating during the year. Hultström at al (2006) observed equal variations in use during the year as Aronsson when use of domestic hot water was studied in four multi-family dwellings in Sweden.

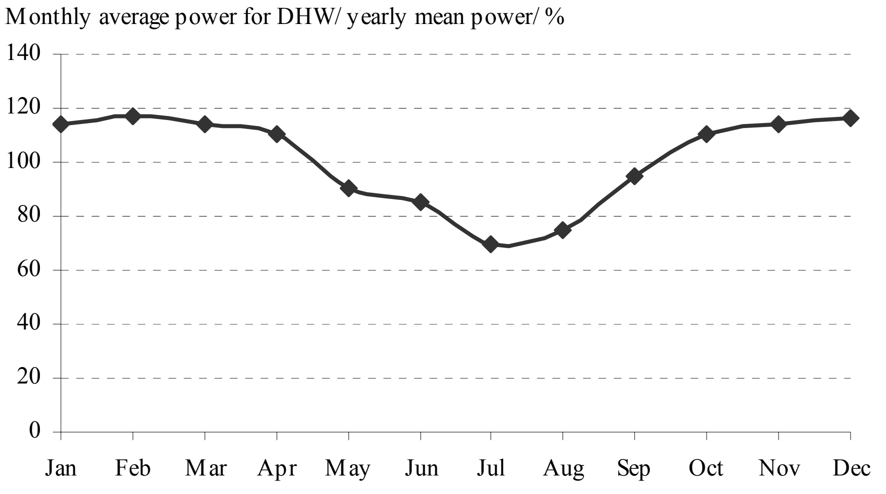

Figure 3.2 The monthly average power for domestic hot water as part of the yearly average power according to Aronsson (1996).

Table 3.3 presents calculated annual use of domestic hot water heating and the developers assumed use of domestic hot water heating.

Table 3.3 The measured annual use of domestic hot water heating and the developers' assumed use. At properties that do not have commercial spacel, the measured annual use* of domestic hot water heating is presented as use per apartment. It was not possible to measure the use at Tango and Tegelborgen.*

	Measured* annual use			Assumed annual use	
	/kWh	/(kWh/m²)	/(kWh/ap.)	/(kWh/m²)	/(kWh/apt.)
Entréhuset	105270	19.3		28.2	4056
Havshuset	78408	25.5	3564	31.5	4396
Havslunden	60984	23.3	3049	29.3	3838
Kajplats 01	67017	21.5		31.3	4238
Tango				35.4	4542
Tegelborgen				43.1	5006
Vitruvius	56472	23.6	3322	29.6	4164

** Measured annual use of domestic hot water heating is calculated based on the measured use during July.*

The average measured annual use of domestic hot water heating at the properties, Tango and Tegelborgen excluded, was 23 kWh/m². At properties that do not have any commercial space, Havshuset, Havslunden and Vitruvius, the average annual use per apartment was 3310 kWh. The average by the developers assumed annual use including all properties was 33 kWh/m² or 4320 kWh per apartment. The average assumed use per apartment was 30 % higher than the measured use at properties that did not have commercial space, the assumed use per m² was 35 % higher.

Figure 3.3 presents measured use of district heating, as presented in Chapter 2, split into use of space heating and use of domestic hot water heating. Use of space heating is calculated as the difference between the annual use of district heating and the measured use of domestic hot water heating.

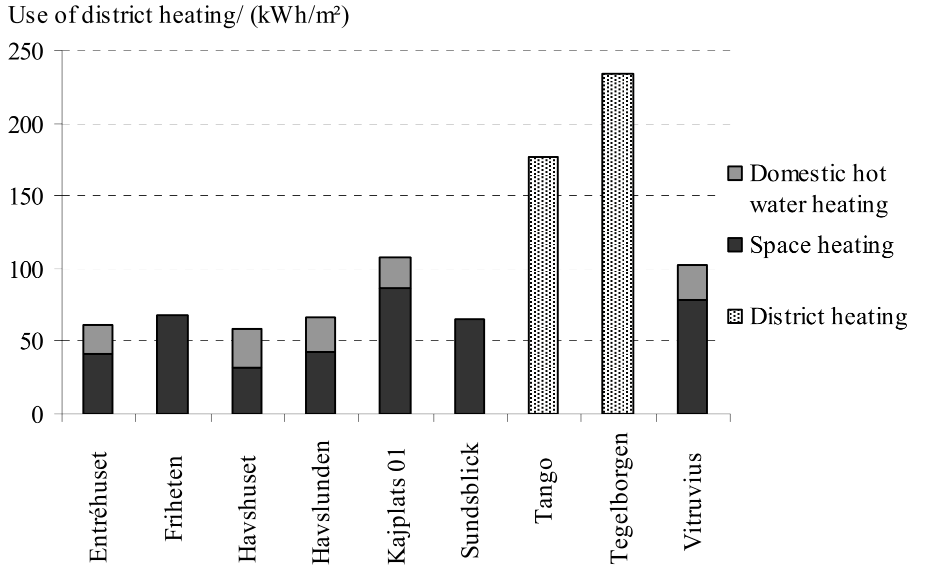

Figure 3.3 Measured annual use of district heating split into use of space heating and domestic hot water heating during 2005. For the properties Tango and Tegelborgen it was not possible to measure the use of domestic hot water. At the properties Friheten and Sundsblick domestic hot water was not heated by district heating.

At properties that used district heating to heat the domestic hot water, it was on average 31 % of the total use of district heating, Tango and Tegelborgen excluded, and at properties that do not include commercial space, 34 %.

3.3.3 Variations during the day

In Figure 3.4 through 3.10, the variations over the day are presented as hourly power per daily average power. The presented profiles are mean values of all days during July and August 2005. The variation during weekdays and weekends are presented respectively.

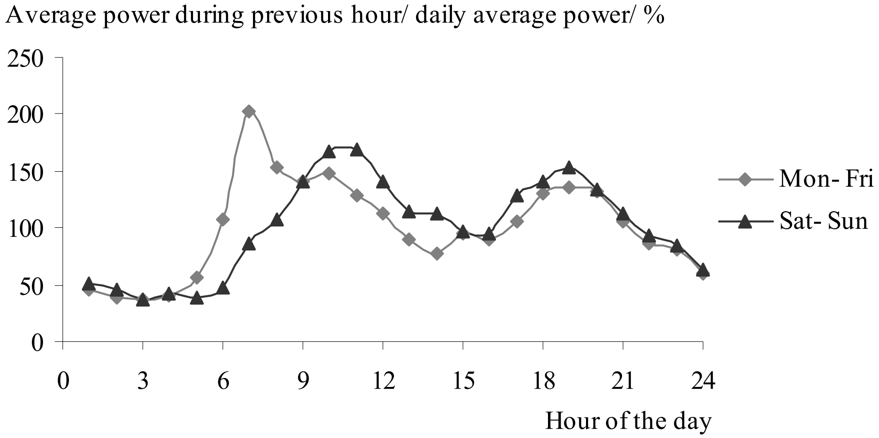

Figure 3.4 Entréhuset. Variations during the day in the use of district heating during July and August.

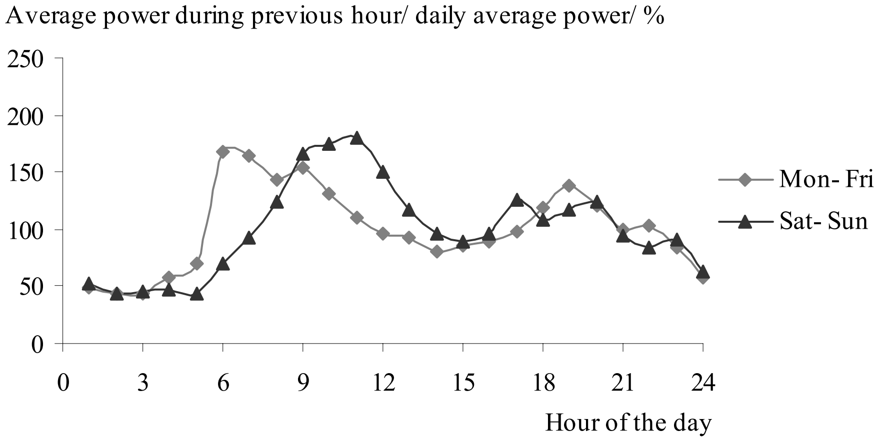

Figure 3.5 Havshuset. Variations during the day in the use of district heating during July and August.

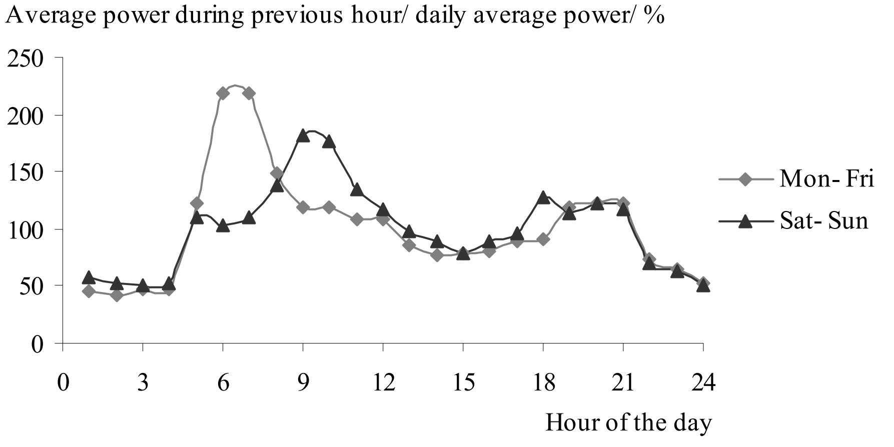

Figure 3.6 Havslunden. Variations during the day in the use of district heating during July and August.

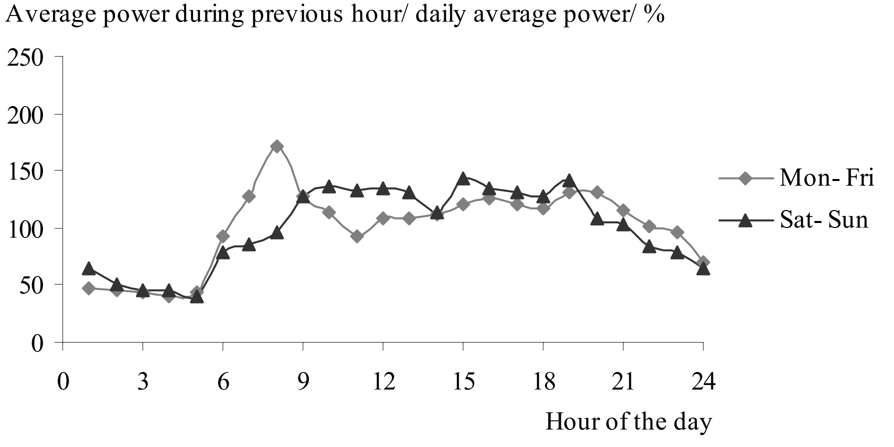

Figure 3.7 Kajplats 01. Variations during the day in the use of district heating during July and August.

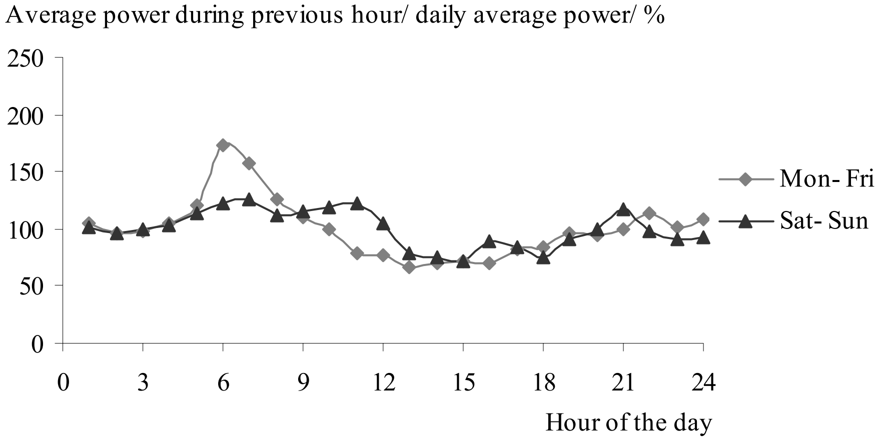

Figure 3.8 Tango. Variations during the day in the use of district heating during July and August.

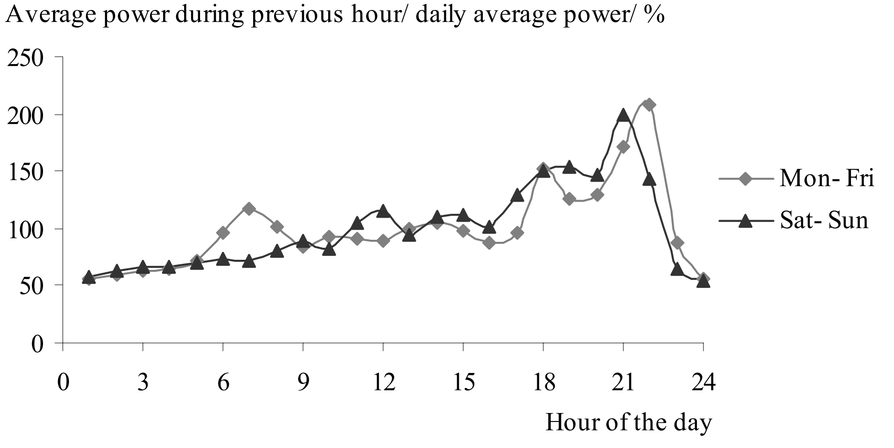

Figure 3.9 Tegelborgen. Variations during the day in the use of district heating during July and August.

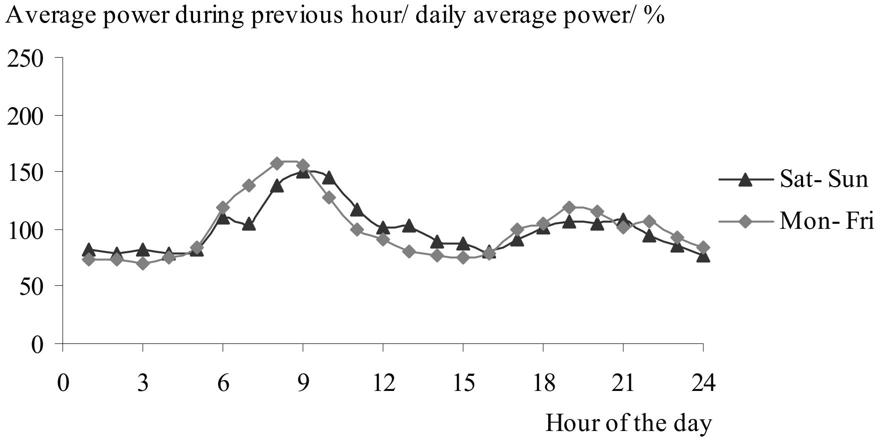

Figure 3.10 Vitruvius. Variations during the day in the use of district heating during July and August.

Typically, during weekdays all properties have two peaks during the day. For most properties this was also the case during weekends. However, during weekends these peeks were not as distinct as during weekdays. The first peak occurred during morning and the second peak during the evening. The peak during the morning occurs earlier during weekdays compared weekends while the peak during the evening occurs at about the same time during both weekdays and weekends. For all properties except Tegelborgen, the peak during the morning was greater than the peak during the evening. At all properties except Tango, the use was least during the night.

The amplitude of the variation in power during the day was about the same at most properties. It varied between 50 and 200 % relative to the average daily power. At Kajplats 01, Tango, and Vitruvius the amplitude was smaller and varied between 75 and 150%.

At the properties Tango and Tegelborgen, that used underfloor heating and towel dryers supported by district heating in bathrooms, the peaks are less pronounced. At Tegelborgen there was two restaurants and at Kajplats 01 there was a coffee house. The use of domestic hot water heating in these has probably affected the daily use patterns at these properties.

3.4 Discussion and conclusions

The annual use was, on average, 23 kWh/m² and varied between 19 and 25 kWh/m². On average the energy used for domestic hot water heating was 30 % of the total use of district heating during 2005. The variations during the day in use of domestic hot water heating typically showed two peaks during the day, one during the morning and one during the evening.

Zmeureanu and Marceau (1999) found that electricity use for domestic hot water heating was higher during weekends than during weekdays, 10–30 kWh/day compared to 20–40 kWh/day, in a monitored single family house in Montreal, Canada. The annual electricity use for domestic hot water heating was 82.8 kWh/m². This is much higher than the average use at the Bo01 properties, 23 kWh/m². At the Bo01 properties there was no major difference in use between weekdays and weekends.

Bagge et al (2005) studied energy use in an energy efficient single family house in Malmö, Sweden. The annual use of domestic hot water heating was 2000 kWh. This was thought to be low. The low use was explained by the occupants' habits and that circulation was not used. The use was much lower compared to the average use at the Bo01 properties that did not include premises, 3310 kWh/ apartment.

Bøhm and Danig (2004) monitored the energy use in a district heated apartment building in Copenhagen and found that the gross domestic hot water heating was 3600 kWh per apartment, while the net domestic hot water heating was 1275 kWh per apartment which shows that the heat loss from the boiler and the pipes were major. The measurements showed higher energy use for domestic hot water heating during the winter compared to the summer. The gross domestic hot water heating was almost the same as the average use at the Bo01 properties that did not include commercial space, 3310 kWh per apartment during 2005.

Papakostas et al (1995) monitored domestic hot water heating in four apartment buildings in a Solar Village in Greece. The use was higher during weekends than during weekdays. The use during different seasons was studied and it was found that during spring, the use could be 100% higher than during the summer season. This was partly explained by the temperature of the incoming water. Average domestic hot water use patterns by day of the week were analysed. During weekdays, the patterns showed equal characteristics. The highest peak in use was between 20:00 and 22:00 and the second highest peak around 13:00. During weekends the peaks appeared earlier and the use was more uniform. This description of the daily use patterns differs from the use patterns at Bo01, although there are some similarities. In both cases there are two distinctive peaks during the day. However, the peak during the evenings was the highest peak in the Greece case while this peak was the second highest in the Bo01 case. In the Bo01 case the highest peak was during mornings while the Greece case did not have any peak until around 13:00. While the peaks in the Greece case appeared earlier during weekends it was the opposite in the Bo01 case where the peak during mornings appeared later during weekends.

Vine et al (1987) monitored domestic hot water use in four low income apartment buildings in San Francisco. Each building had a solar-assisted domestic hot water system. During a typical day, there was a peak in use during the morning and another peak in the evening. These peaks were related to bathing practice and cooking and dishwashing. Different usage patterns were observed for weekdays and weekends. During weekends a very large peak occurred during the middle of the day. This description of the daily use pattern aligns well with the use patterns at Bo01 although no separate peak during the middle of the day was observed in the Bo01 case.

The Swedish building code demands that calculated energy use shall be verified by measurements in the actual building. It will be important to be able to separate space heating and domestic hot water heating in order to analyse differences between calculated and measured energy use. This study has presented a method for calculating the annual use of domestic hot water based on the use of district heating during summer. However, this method has limitations and it is recommended that energy for heating domestic hot water is measured separately.

When energy calculations are executed, in most cases, energy use for domestic hot water is assumed to be constant during the year. If the energy use for domestic hot water varies during the year as presented by Aronsson (1994) and Hultström et al (2006), the energy use during the winter will be underestimated and the use during summer will be overestimated. This has to be paid attention to if energy use during shorter periods than one year is studied.

4 Assimilation of solar heat gains

This chapter analyses how the heating power and heating energy are affected during days with different amounts of global radiation. A method for calculating the assimilated solar heat gains based on measurements of heating is presented. New buildings and newly built buildings often have an architecture that has large glazed areas. A huge amount of solar heat gains will enter the building through the windows. Even if a certain amount of heat gains enter the building through the windows, it is not clear to what extent it will be assimilated. The objective was to study how much solar heat gain that can actually be assimilated in a building in a given case.

4.1 Method

Measured data were analyzed to display the assimilation of solar heat gains and the effect on the use of district heating. No existing method for analysing the amount of assimilated solar heat gains based on measured use of heat was found in the literature.

The analysis is based on daily global radiation, daily averages of outdoor temperature and use of district heating during 2005. Power signatures based on daily data were made. The signatures are based on days with outdoor temperatures between zero and 10 °C. These temperatures were chosen because the relationship between the use of district heating and outdoor temperature in this interval should be described by a linear function. Also, these temperatures typically appear during spring and autumn when solar heat gains are thought to be utilized.

Two power signatures are presented for each property. The first power signature presents the daily average power during days that had daily outdoor temperatures between zero and 10 °C. In the second signature for each property, the data is grouped based on whether it was a sunny or a cloudy day. In this study, sunny days were defined as days with daily global radiation between 3000 and 5000 Wh/m² while cloudy days were defined as days with global radiation less than 500 Wh/m². Days with global radiation between 500 Wh/m² and 3000 Wh/m² were defined as partly cloudy days. A regression line was fitted for sunny and cloudy days respectively. The equations describing the regression lines and the corresponding R^2-values are presented in the figures.

The difference in district heating power between sunny and cloudy days was calculated for each property for eleven different outdoor temperatures from zero to 10 °C in steps of one °C. From these differences, the mean decrease in district heating power during sunny days compared to cloudy days was calculated.

The annual decrease in use of district heating due to assimilation of solar heat gains was calculated for each property. The calculations were made based on daily mean outdoor temperatures and daily accumulated global radiation during 2005 and the regression lines that describe the use of district heating during sunny respectively cloudy days. The calculations were made for the heating season which was defined as days with a daily mean outdoor temperature below 15 °C.

When the daily accumulated global radiation was less than 500 Wh/m², it was assumed that there was no decrease in district heating power due to solar heat gains. The decrease in district heating power for days with daily accumulated global radiation exceeding 3000 Wh/m² was assumed to be equal to the difference between the heating power during a sunny and cloudy day according to the regression lines. The decrease in district heating power for days with daily accumulated global radiation between 500 and 3000 Wh/m² was assumed to be a linear function of the daily accumulated global radiation. The decrease was then calculated as the difference between the district heating power during a sunny and cloudy day and multiplied by the daily accumulated global radiation exceeding 500 Wh/m² divided by 2500.

4.2 Limitations

The global radiation does not give any information whether it is a day with sunshine from a clear sky or if it is overcast since the global radiation is the sum of direct solar radiation and diffuse sky radiation. By using daily accumulated global radiation some information is lost. For example, during late spring, the day has many more daylight hours compared to a day in December. In December, sunshine from a clear sky during the few hours of daylight might equal the amount of daily accumulated global radiation during an overcast day with more daylight hours. However, the diffuse sky radiation can also be assimilated in the building.

The characteristics of the windows at the different properties, U-value, G-value, coatings, etcetera were not studied.

Days with high global radiation due to direct solar radiation might have high outdoor temperatures during the day while the night might have low outdoor temperatures due to the clear sky. The daily mean values are measured from

00:00 hours to 24:00 hours. This means that heat gained by the building during the day might be doing the building a favour the following day. Another alternative would have been to measure the day from sunrise to sunrise but the time of sunrise changes during the year.

4.3 Window orientation and glazed area

Figure 4.1 presents window area and glazed area at the different properties. The data are from the developers' energy calculations. Window area includes both frame and glazed area.

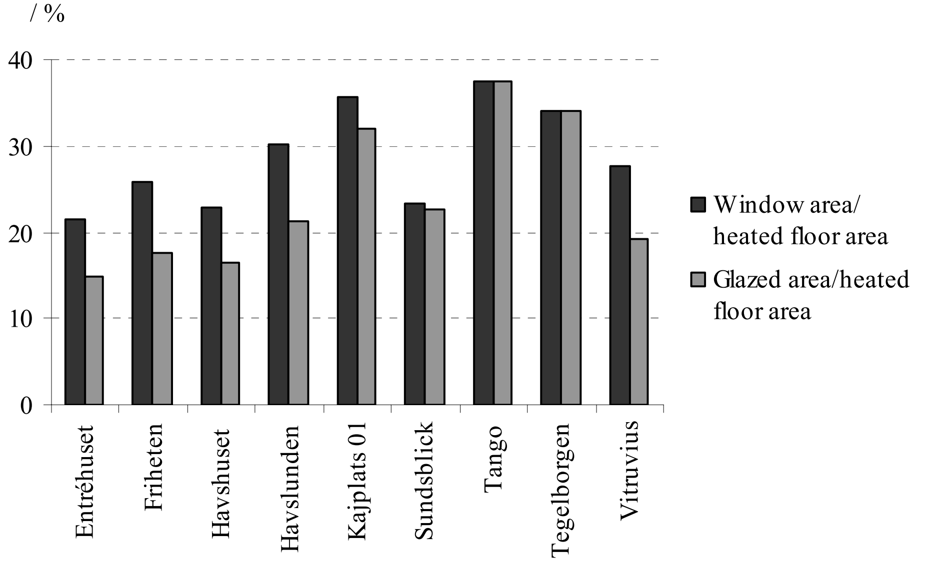

Figure 4.1 Window area and glazed area in relation to heated floor area. The data are from the developers' energy calculations.

Most of the developers assumed a glazed area of about 70 % of the window area. Three of the developers assumed that all, or almost all, window area was glazed. This is unrealistic since all windows have frames. It is possible that the persons who executed the energy calculations did not subtract the frame area when the glazed are was specified.

Figure 4.2 presents the orientation of the glazed area at the different properties. The data are from the developers' energy calculations.

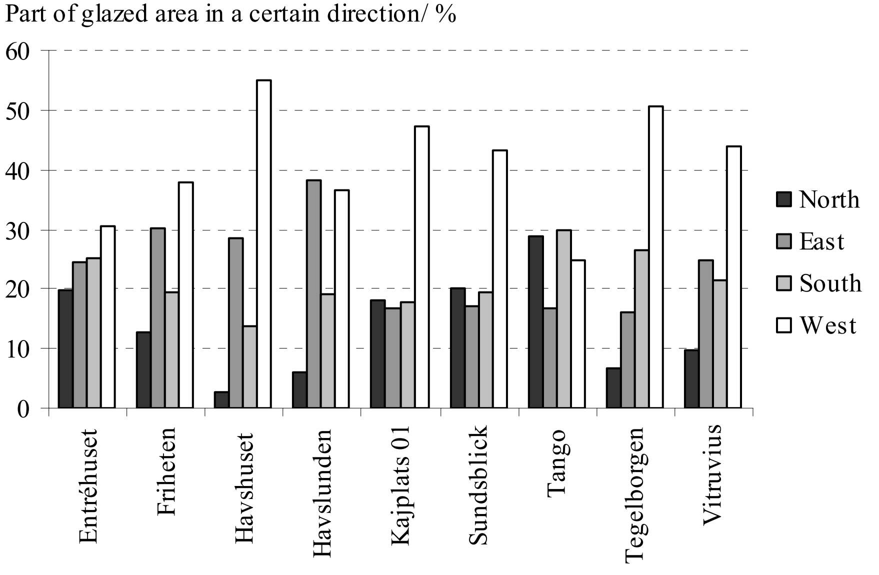

Figure 4.2 Orientation of the glazed area at the properties.

Seven out of nine properties have more glazed area facing west than other directions. At some of the properties, about twice as much glazed area face west than other directions. Properties that have large glazed area facing west are typically placed where they have a view of the sea in that direction. These properties have no buildings or other obstacles in front of their west façades. The properties Havslunden and Tango are placed where they do not have a view of the sea. These properties do not have more glazed area facing west than other directions. Most likely, when the buildings were designed, window orientation was based more on the view and less on heating and cooling aspects.

4.3.1 Global radiation in Malmö during 2005

Figure 4.3 presents the monthly global radiation during 2002 through 2005 measured at the weather station at Heleneholm and the monthly global radiation during a normal year in Malmö, according to SMHI. For a majority of the months, the global radiation was about the same as during the normal year. During June and July 2004 the global radiation was lower than the normal year and during June 2002 the global radiation was higher than the normal year.

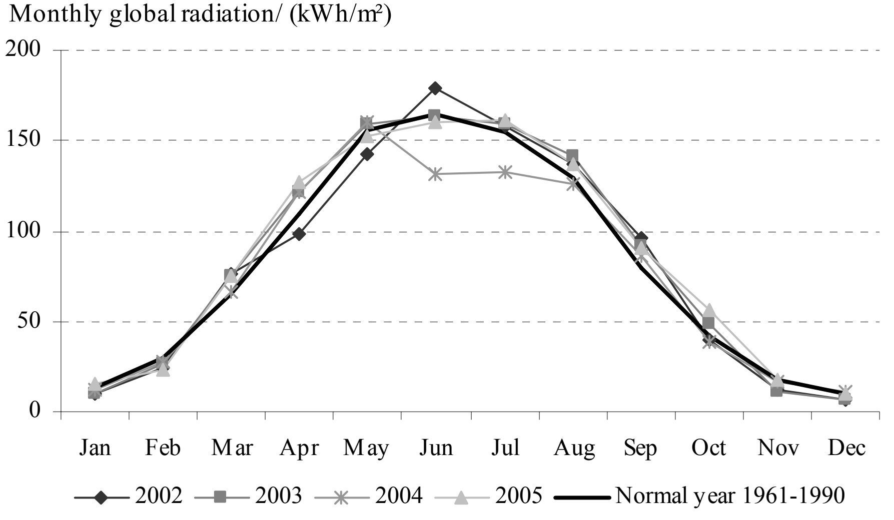

Figure 4,3 Monthly global radiation during 2002 through 2005 and the monthly global radiation during a normal year in Malmö.

Figure 4.4 presents the daily global radiation in Malmö during 2005, measured at the weather station at Heleneholm.

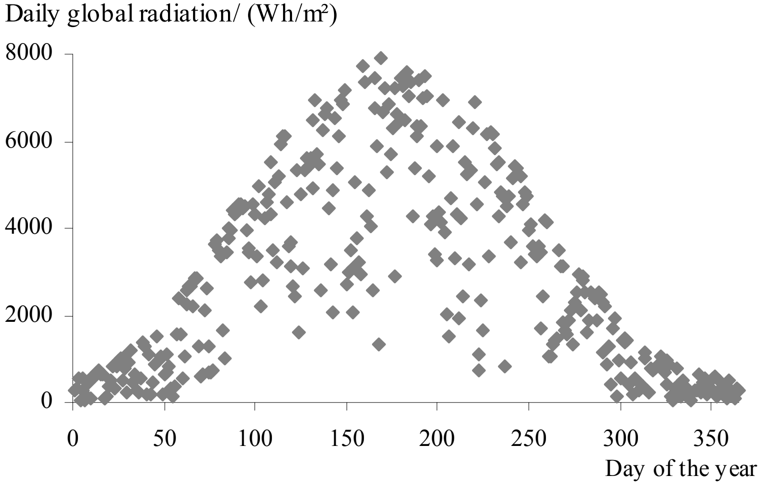

Figure 4.4 Daily global radiation in Malmö during 2005

Figure 4.5 presents the permanence of daily global radiation during 2005 in Malmö. The permanence is presented for all days during the year, for days when the outdoor temperature was below 15 °C, and for days when the outdoor temperature was below 10 °C respectively. The temperature limits, 10 °C and 15 °C, represents a high and a low balance temperature. They were chosen based on the balance temperatures presented in the Chapter 2.

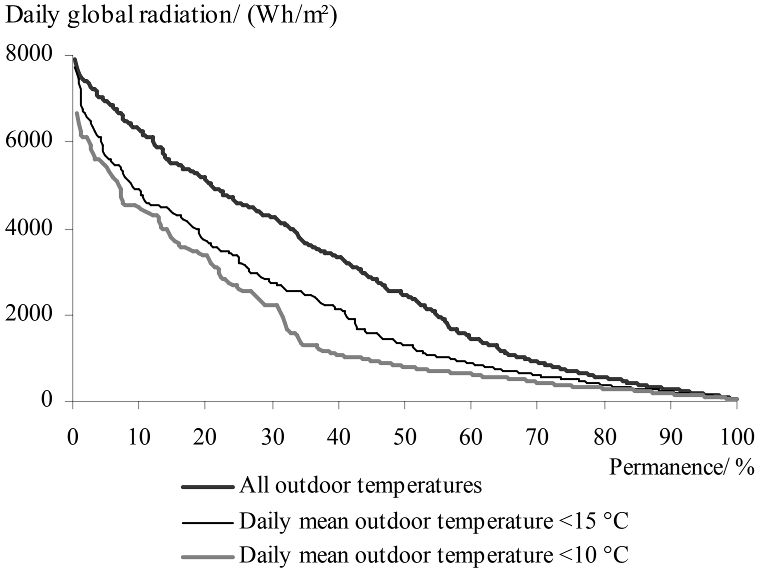

Figure 4.5 Permanence of daily global radiation in Malmö during 2005.

Days when the daily global radiation exceeded 3000 Wh/m² occurred during about 45 % of the year. Many of the days with high global radiation occurred during off heating season when the outdoor temperature was high and there was no heating demand. During days with outdoor temperatures below 15 °C, 26 % had daily global radiation exceeding 3000 Wh/m² and 25 % had daily global radiation less than 500 Wh/m². During days with outdoor temperatures below 10 °C, 22 % had daily global radiation exceeding 3000 Wh/m² and 33 % had daily global radiation less than 500 Wh/m².

4.4 Result

In Figure 4.6 to 4.23, the power signatures for the different properties are presented.

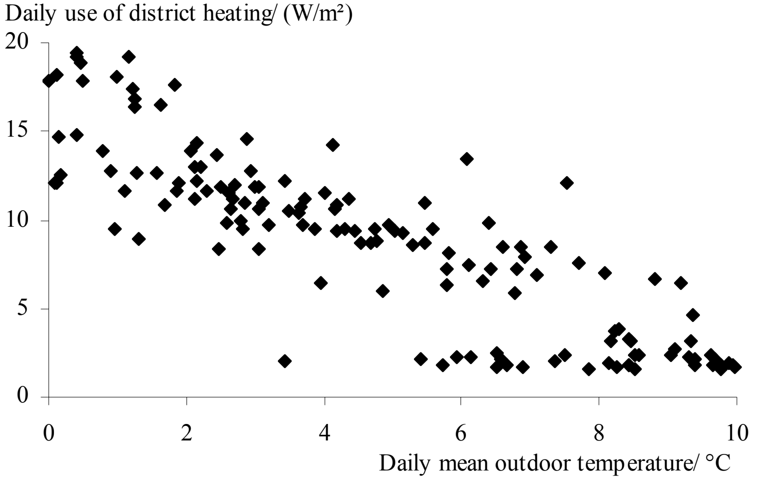

Figure 4.6 Entréhuset. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

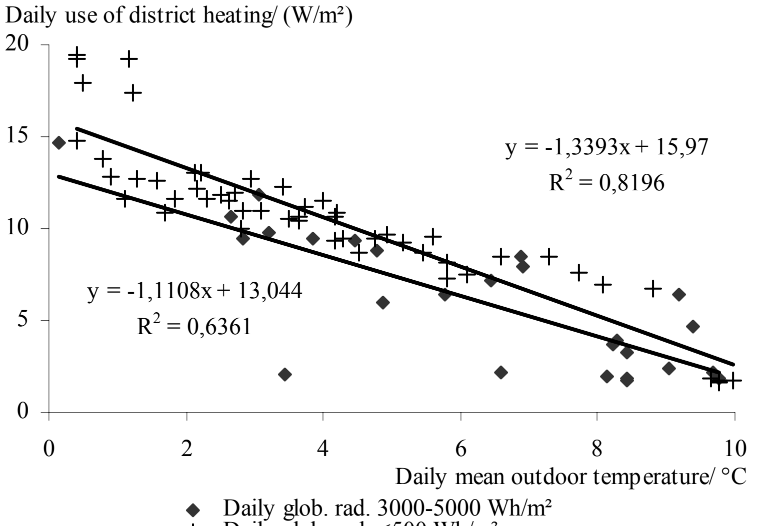

Figure 4.7 Entréhuset. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

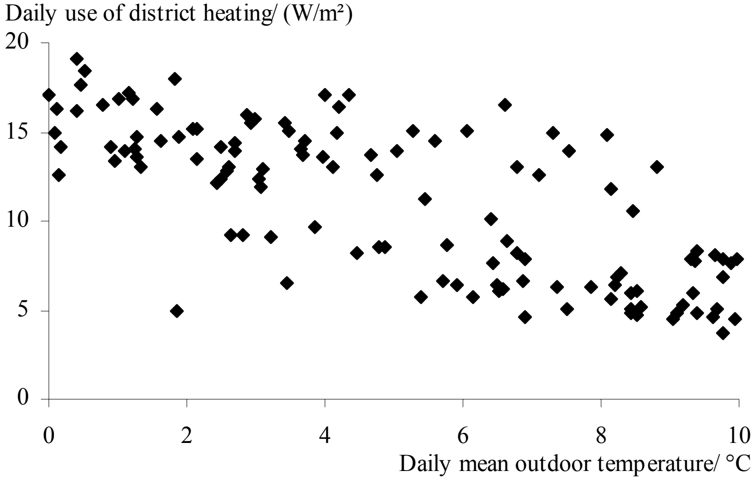

Figure 4.8 *Friheten. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.*

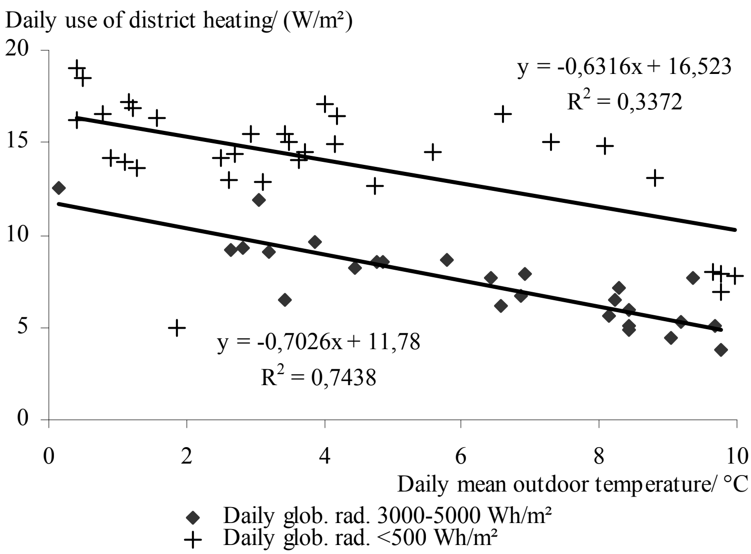

Figure 4.9 *Friheten. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.*

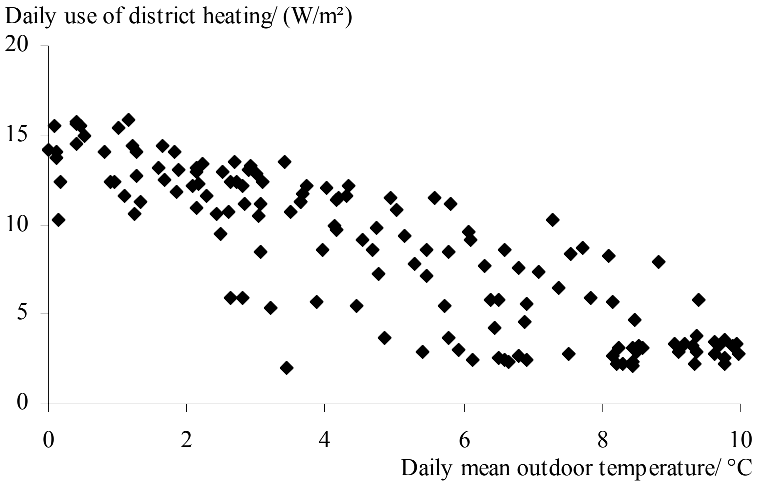

Figure 4.10 Havshuset. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

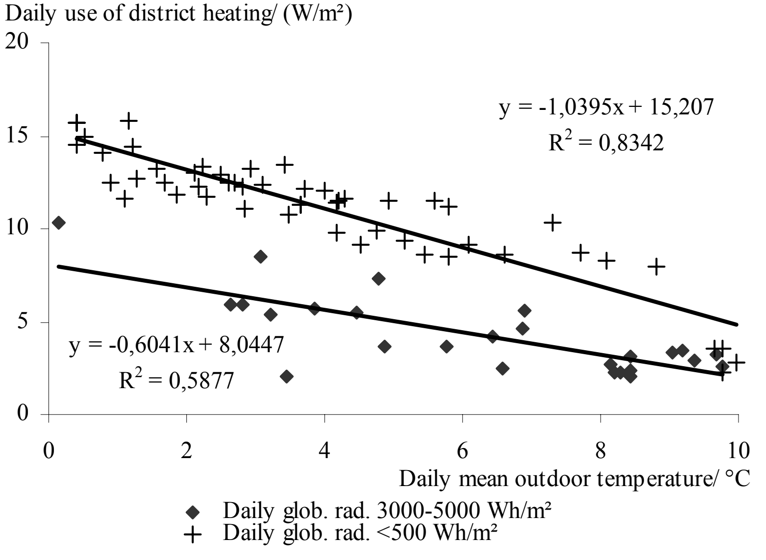

Figure 4.11 Havshuset. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

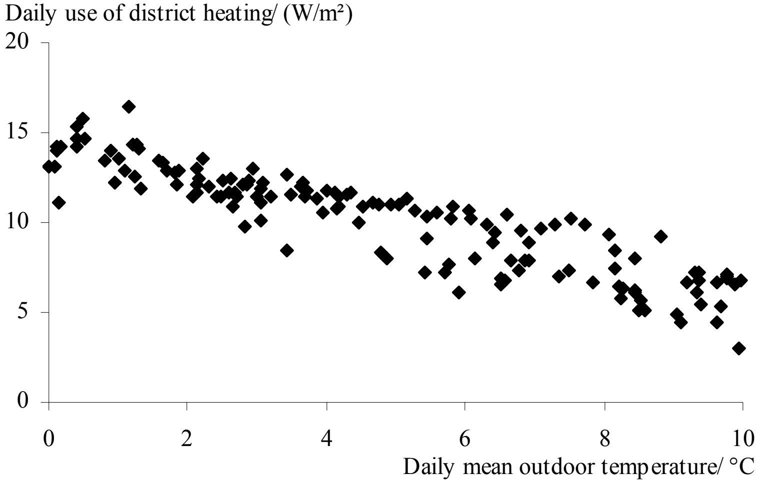

Figure 4.12 Havslunden. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

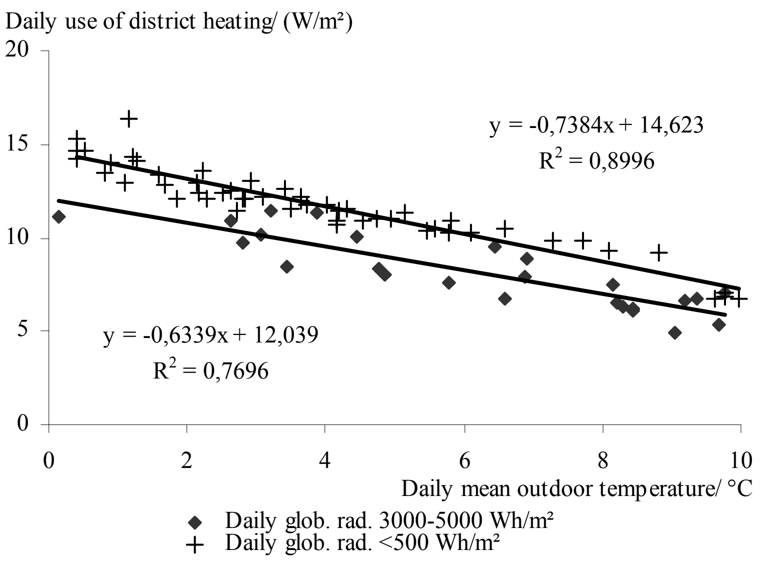

Figure 4.13 Havslunden. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

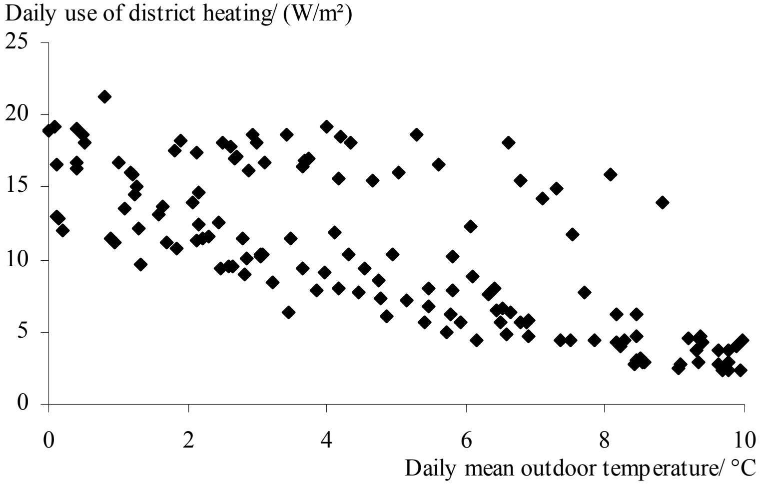

Figure 4.14 Kajplats 01. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

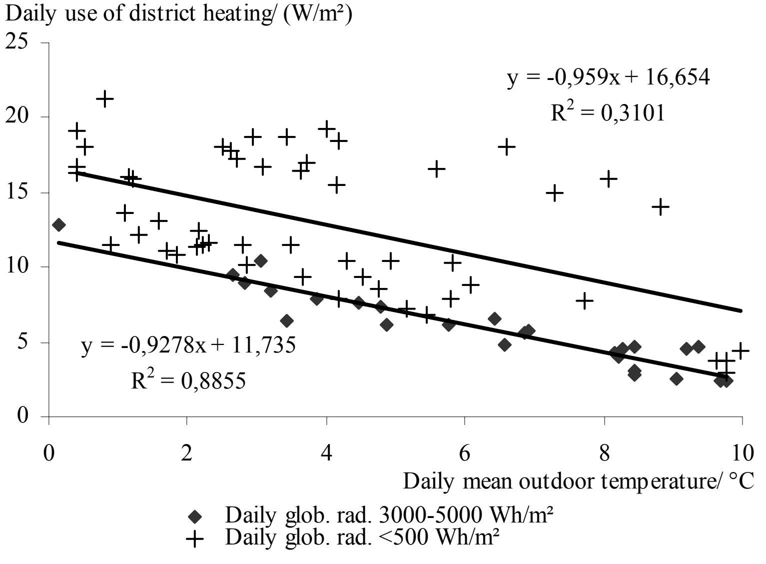

Figure 4.15 Kajplats 01. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

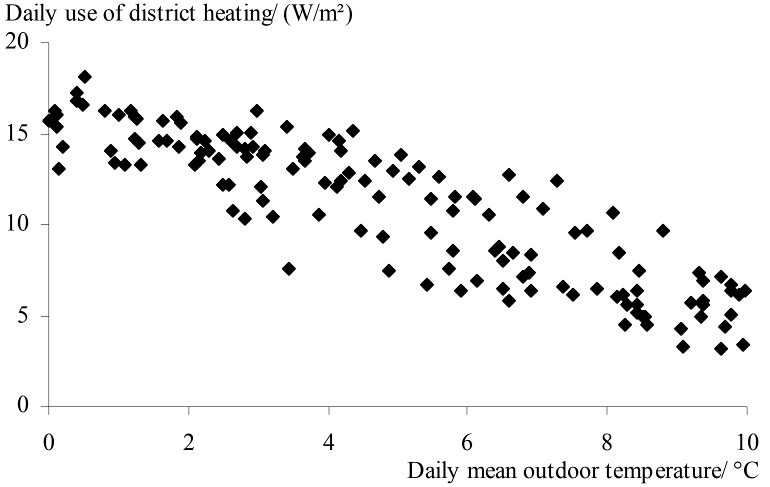

Figure 4.16 Sundsblick. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

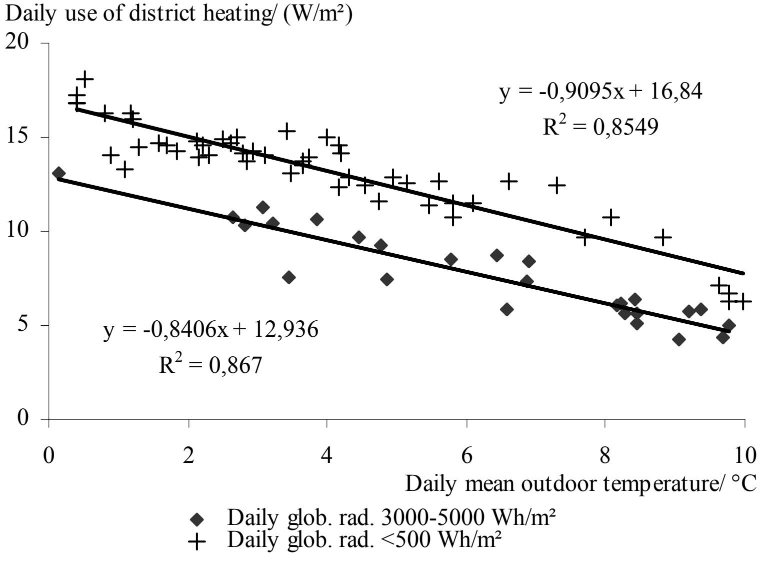

Figure 4.17 Sundsblick. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

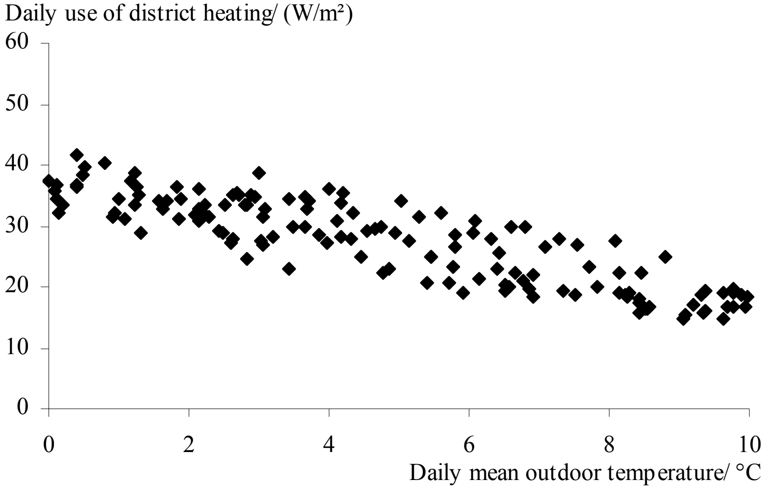

Figure 4.18 Tango. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

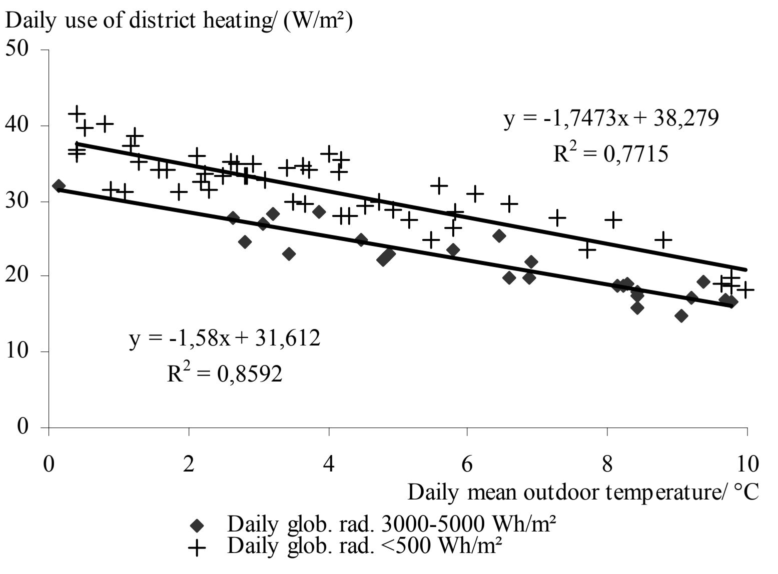

Figure 4.19 Tango. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

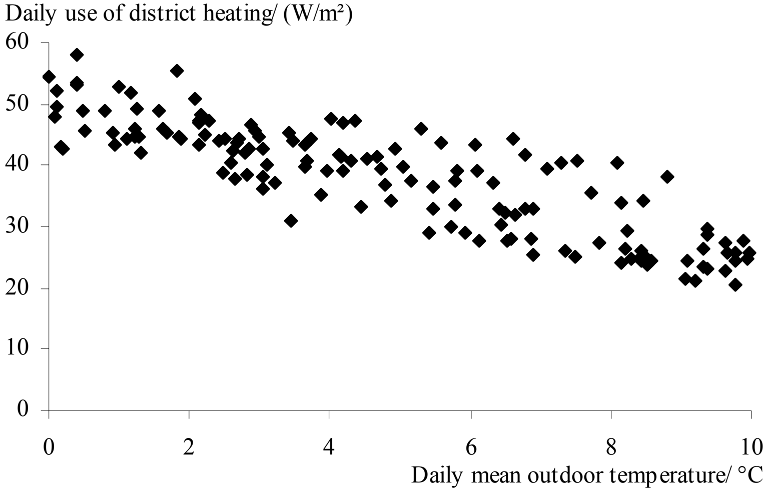

Figure 4.20 Tegelborgen. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

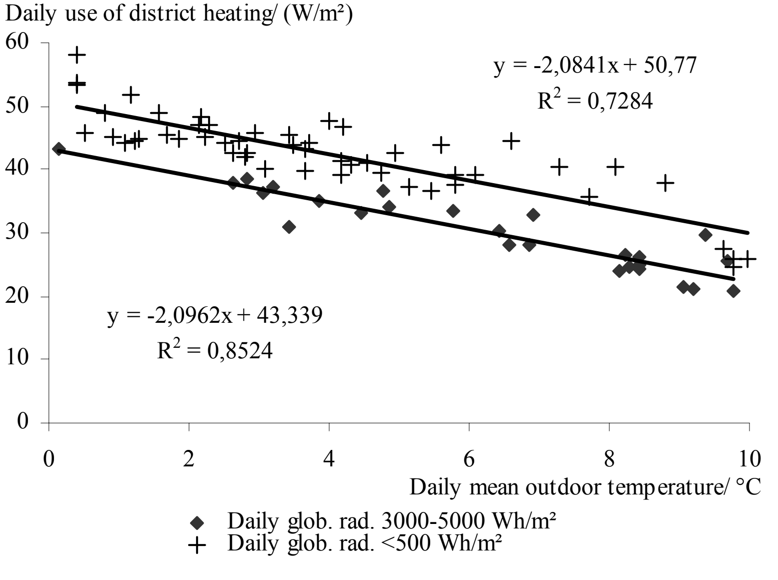

Figure 4.21 Tegelborgen. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

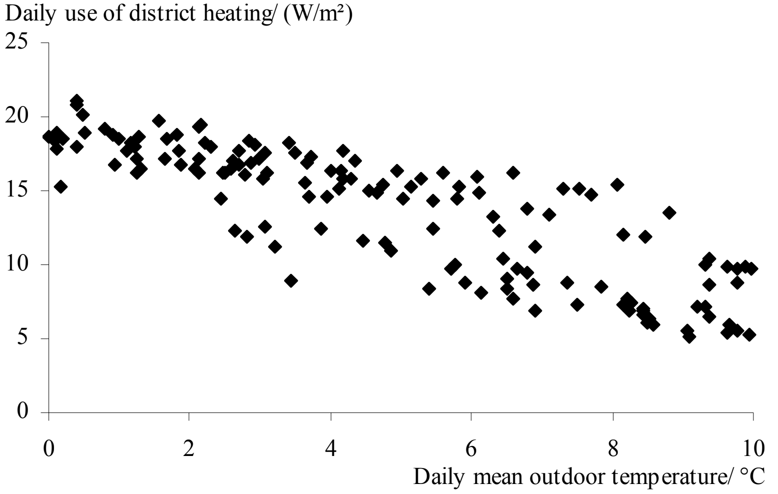

Figure 4.22 Vitruvius. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C.

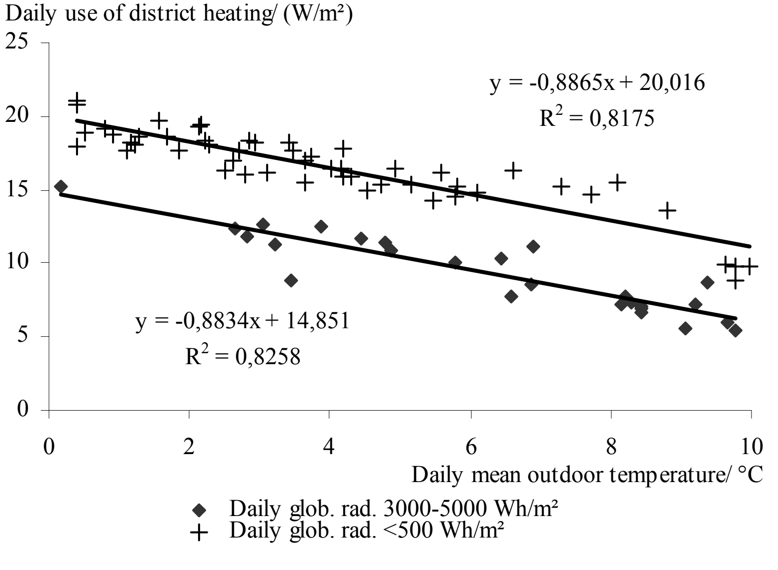

Figure 4.23 Vitruvius. Power signature, based on daily use of district heating and daily mean outdoor temperature during 2005, for daily mean outdoor temperatures between 0 °C and 10 °C, and daily global radiation less than 500 Wh/m² and between 3000 and 5000 Wh/m² respectively.

According to the regression lines that describe the district heating power during cloudy respective sunny days, all properties used less district heating during days when the global radiation exceeded 3000 Wh/m² compared to days when the daily global radiation was less than 500 Wh/m².

The decrease for each property expressed as decrease in district heating power, decrease in energy use and energy decrease/ heated floor area is presented in Table 4.1.

Table 4.1 The mean decrease in the use of district heating during sunny days compared to cloudy days as decrease in power and energy and the decrease in energy use/ use of space heating.

	Power decrease/ (W/m²)	Energy decrease/ (kWh/m²)	Energy decrease/ use of space heating/ %
Entréhuset	1.8	3.1	7
Friheten	6.1	18.2	23
Havshuset	5.0	10.0	31
Havslunden	2.5	6.0	11
Kajplats	7.8	21.9	25
Sundsblick	3.6	9.5	15
Tango	5.8	15.1	10
Tegelborgen	7.5	21.5	10
Vitruvius	6.2	17.6	22

The average assimilated solar heat gain power was 5 W/m² and varied between 1.8 W/m² and 7.8 W/m² at the different properties. The calculated annual assimilation of solar heat gains was on average 13.7 kWh/m² and varied between 3 kWh/m² and 22 kWh/m² at the different properties. On average, the assimilated solar heat gains was 17 % of the annual use of space heating.

Figure 4.24 presents the annual assimilated solar heat gains as part of the annual use of space heating, as function of the window area as part of heated floor area.

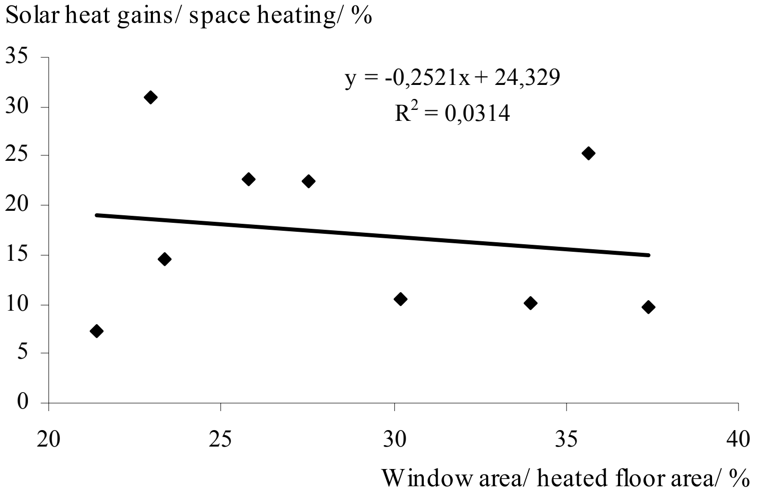

Figure 4.24 Annual decrease in energy use as part of the space heating.

At the five properties that have a window area less than 30 % of the heated floor area, the annual decrease was on average 20 % of the space heating. At the four properties that have a window area more than 30 %, the annual decrease was on average 14 % of the space heating. The regression line in Figure 4.24 indicates that when the window area increases, the heat losses increase more than the assimilated solar heat gains.

4.5 Discussion and conclusions

The result shows that if there is a very sunny day and there is a heating demand, the use of district heating can be reduced to a great extent. However, the very sunny days are relatively few compared to days with less sunshine with less or no decrease in energy use. During the winter, when there are only few hours of daylight, most of the day, no solar heat gains are available and the windows will act like a poorly insulated transparent wall. On average, at the nine properties, the annual decrease in use of heating due to assimilated solar heat gains was 14 kWh/m² and varied between 3 kWh/m² and 22 kWh/m².

Bagge et al (2004) studied energy use in a low energy houses. The measured assimilated solar heat gains was 11 kWh/(m²·year). This was slightly less compared to the average decrease in this study. However, the studied house had a majority of its windows facing north.

When residential buildings have architecture that have a large window area, as is common in modern buildings, the aspect of solar heat gains is important both from an energy and indoor climate perspective. Assimilation of solar heat gains might lead to reduced need for heating but might also result in high indoor temperatures and the need for cooling. If the building is well designed, it should make efficient use of solar heat gains to reduce energy use for heating and at the same time avoid too much solar heat gain that results in high indoor temperatures.

Bagge et al (2006 a) studied indoor temperatures in one apartment at Sundsblick. Already during February, very high indoor temperatures were observed when there were sunny days. Radiator thermostats were placed close to the floor in vicinity of French doors. When the occupants aired the apartment to lower the high indoor temperature, cold air passed the thermostats and the radiator was not turned off despite the high indoor temperature. This counteracted the possibility to utilize solar heat gains effectively. It is of greatest concern that these kinds of design errors are avoided.

The decrease in use during sunny days should be compared to the increased transmission losses that a higher percentage of window area results in. More energy can probably be saved by a restricted window area compared to what can be saved by assimilation of solar heat gains through a higher percentage of window area.

5 Use of common electricity

In this study, use of common electricity includes electricity for operating the building's technical systems such as fans and pumps, exterior and staircase lightning, equipment in community laundry rooms, elevators and heat recovery. Common electricity bills are paid by the property owner. Common electricity is the difference between the total electricity use and household electricity use. The energy restriction in the Swedish building code BBR12 includes use of common electricity and use of heating. In the future, use of common electricity use needs to be measured in all buildings to verify that it meets the restriction set in the building code.

5.1 Method

The annual use of common electricity use has been measured at seven properties. At the properties Entréhuset and Havshuset, only the total electricity use, including both household and common electricity, was measured. The total electricity use at these properties is presented in Chapter 6

The annual use is presented for the years 2002 through 2005 for each property respectively as energy use per heated floor area excluding garage area.

5.2 Result

The measured annual use of common electricity during the first four years after inauguration is presented in Figure 5.1.

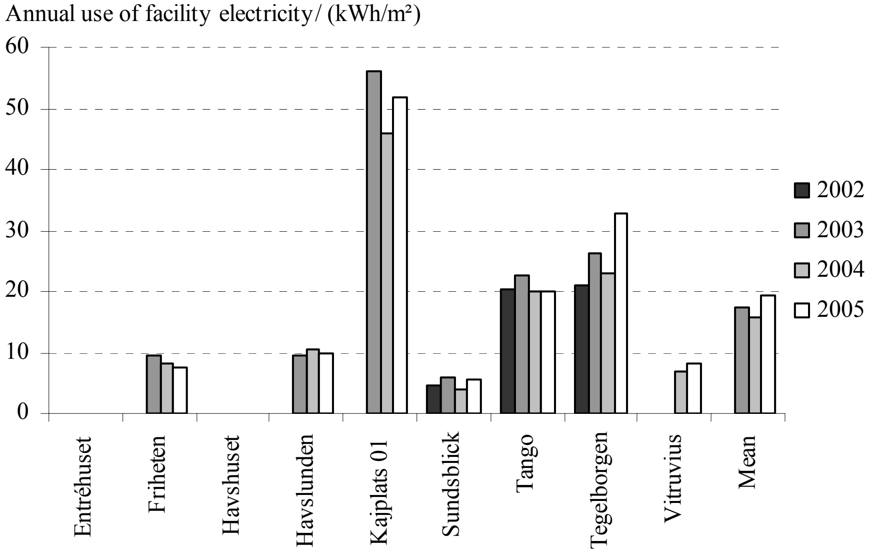

Figure 5.1 Annual use of common electricity per heated floor area, garage area excluded. Use of common electricity was not measured separately at Entréhuset and Havshuset.

The use at the different properties varied to different extents during the years. There is no general trend for all properties. The use during 2005 was, on average, 19.5 kWh/m². The highest use of common electricity was 52 kWh/m². and the lowest 6 kWh/m². In the following text, data refers to the energy use during 2005.

The differences in use of common electricity between the properties are large. There was almost a factor of nine between the highest and the lowest use.

The average use at properties with mechanical exhaust air, Havslunden, Tango, Tegelborgen and Vitruvius was 18 kWh/m².

At the properties Friheten and Sundsblick, each apartment had its own ventilation system including an air handling unit with fans for supply- and exhaust air. A heat pump recovers heat from the exhaust air and heats the supply air and the domestic hot water. The fans and the heat pumps were run with household electricity from the apartment. Because of this, the use of common electricity at these properties did not include electricity for fans and heat pumps. The average use at properties where fans and heat pumps are supported by household electricity, Friheten and Sundsblick, was 6.5 kWh/m². Both these properties included a garage.

Kajplats 01 has mechanical exhaust ventilation with central fans and a heat pump. The garage has a separate ventilation system consisting of mechanical supply and exhaust air and a heat exchanger. The high use of common electricity might be partly due to the two separate ventilation and heat recovery systems. The use of common electricity is divided by the heated floor area excluding garage area which means that all electricity used in the garage is allocated to the heated floor area excluding garage area.

5.3 Discussion and conclusions

The use of common electricity at the different properties varies between 6 and 52 kWh/m². This variation can be because of the type of ventilation system used, whether or not heat recovery is used, if a garage exists, who pays the bill etc. Since the energy use includes different systems at the different properties, the energy use can not be directly compared. A qualitative marking is necessary before comparisons can be made.

Havslunden and Vitruvius have a relatively low use of common electricity. This was expected since these buildings have mechanical exhaust ventilation supported by central fans and no heat recovery. At Tango and Tegelborgen that also has mechanical exhaust ventilation and no heat recovery, low use of common electricity would be expected. However, the use at these properties was relatively high.

A higher use of common electricity due to heat recovery should lead to lower heat use, also higher use of common electricity due to use of laundry rooms should lead to lower use of household electricity. This demonstrates that it is of greatest concern to study the building as a system and only studying single parameters might give results that are hard to interpret or are even misleading.

If fans and other technical systems such as heat recovery are supported by household electricity, this energy use should be measured and it should be possible to separate it from the total use of household electricity since this use is part of the energy needed for operating the building. This is important since the Swedish building regulations, BBR12, states that energy use including electricity for operating the building shall be measured in the building during operation.

If a building has a garage, the electricity used in the garage is allocated to heated floor area excluding garage area. This means that a property that includes a garage will have higher use per heated floor area excluding garage area compared to an identical building without a garage.

Energirådgivningen (2007) reports that the use of common electricity usually is within an interval between 5 och 55 kWh/m^2 heated floor area. This agrees quite well the measured use at Bo01.

The MEBY-project studied the use of common electricity in buildings built during the 1990s (Sandberg, 2006). The use was, on average, 16 kWh/m². In a further study of 22 properties built between 1997 and 2002, the use of common electricity was, on average, 15 kWh/m². None of the studied properties used any kind of exhaust air heat recovery. The use of common electricity at the studied properties varied between 4 and 37 kWh/m². These values are lower than at Bo01, which is to be expected since the properties studied in the MEBY-project did not use any kind of exhaust air heat recovery.

According to Dalenbäck (2006), property owners estimate the use of common electricity to be about 20 kWh/m². Dalenbäck presents results from the database E-nyckeln which gives an average use of common electricity of 37 kWh/m². The average use estimated by the property owners agrees, almost exactly, with the average use at Bo01 while the average from E-nyckeln is much higher than the average at Bo01.

Sandberg (2006) studied the use of common electricity at the properties of four big property owners in Sweden and found that the average use for the different owners varied between 17 and 27 kWh/m². There is no information to what extent different ventilation systems were used. However, the average use at Bo01 falls within these reported averages.

A report from SABO (2006) presents use of common electricity at properties with different types of ventilation systems. The energy use refers to data from 75 properties and reported energy use from the property owners. The energy use is presented per area to let, which should give slightly higher values compared to if heated floor area excluding garage area was used. The use of common electricity at properties with mechanical exhaust air was 17 kWh/m². At properties with mechanical supply and exhaust air with a heat exchanger, the use was 36 kWh/m² and at properties with mechanical exhaust air and exhaust air heat pump, the use was 50 kWh/m². The use at the Bo01 properties with mechanical exhaust ventilation was slightly higher. The use at Kajplats 01 was 52 kWh/m², which agrees quite well with the reported average use at the properties with exhaust air heat pump. However, Kajplats 01 also includes a large garage that uses mechanical supply and exhaust air and heat exchanger.

The use of common electricity at the Bo01 properties was in the range of what is normally found in Swedish buildings. The use of common electricity might vary to a great extent between different properties. In order to rate whether the use is high or low, a qualitative judgment is necessary. It might not be appropriate to compare the use of common electricity at different properties without, at the same time, studying the use of heat and household electricity. A higher use of common electricity should, in many cases, result in lower use of heating and household electricity while a lower use of common electricity might result in higher use of heating and household electricity.

6 Use of household electricity

This chapter presents the use of household electricity at the different properties during 2002 through 2005. In this study, use of household electricity includes all electricity that was used in the apartments. The household electricity bill is paid by the occupants. The variation in use during the year and during the day was studied. The objective was to present characteristics of the use of household electricity that enables comparisons and give references. As buildings become more and more energy efficient, the use of household electricity will become a greater part of the total energy use. Hence it is important to have detailed knowledge of the characteristics of the household electricity use in order to make estimates of energy use, especially since modern low energy buildings are designed to make efficient use of excess heat from household electricity.

6.1 Method

The household electricity use was measured at 7 properties, containing 145 apartments. In addition, total electricity use was measured at 2 properties, containing 55 apartments. Hourly readings were used to analyse the variation in use during the day and monthly averages was used to analyse the variation during the year.

The annual use of household electricity is presented for the years 2002, 2003, 2004 and 2005 for each property respectively. The use is presented as annual use per heated floor area excluding garage area, annual use per apartment and annual use per apartment area.

The variation in use during the year was studied. The variation is presented as the monthly mean power in percentage of the yearly mean power. This means that the differences in absolute use between the properties are not shown. Instead, the relative amplitude of the variation in use during the year will be directly comparable between the properties.

The variation in use during the day was studied. Due to the variation in use during the year, the daily use will be different at different times of the year. The relative variation during the day was equal during the year despite the variations during the year. The variations during the day are presented as hourly power for each hour of the day compared to that day’s average power, expressed as percentage of the daily mean power. This means that the differences in absolute use between the properties are not shown. Instead, the relative amplitude of the variation in use during the day will be directly comparable between the properties. The presented profiles are mean values of all days during 2005. The variations during Monday to Friday and Saturday to Sunday are presented respectively.

6.2 Limitations

The use was measured at property level which means that the measured values are the sum of the use in the apartments at the property. The individual inhabitants' behaviour will have a greater affect on the total use at properties with fewer apartments. At the properties Entréhuset and Havshuset the total use of electricity was measured, including both household electricity and common electricity. The use at these properties is presented as use per heated floor area excluding garage area only. No respect was taken to holidays that occur on a week-day.

6.3 Result

6.3.1 Annual use of household electricity

Figure 6.1 presents the annual use of household electricity per heated floor area during the first four years after inauguration. At Havshuset and Entréhuset, the presented use is total use of electricity since only total electricity use was monitored at these properties.

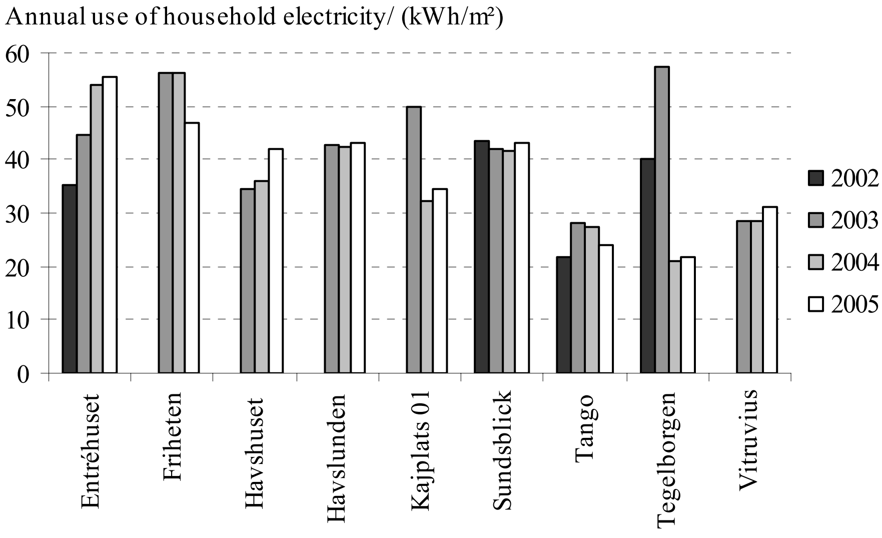

Figure 6.1. Annual use of household electricity per heated floor area, garage area excluded. The use at Entréhuset and Havshuset is the total use of electricity.

The use at the different properties has varied to different extents during the years. At Tegelborgen, the use was very high during 2003 compared to the use during 2004 and 2005. This was due to heaters in some apartments where construction work was going on.

The use during 2005 was on average 35 kWh/m², Entréhuset and Havshuset excluded. The highest use was 47 kWh/m² and the lowest was 22 kWh/m².

Figure 6.2 presents the annual use per apartment during 2003 through 2005.

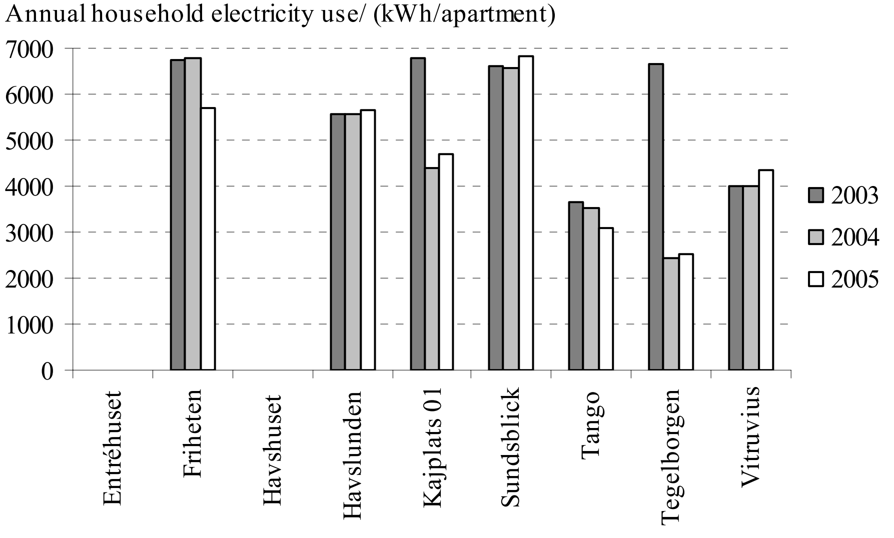

Figure 6.2 Annual use of household electricity per apartment.

The average annual use per apartment during 2005 was 4680 kWh/apartment. The highest use was 6815 kWh/apartment and the lowest was 2520 kWh/apartment.

The properties Kajplats 01, Tango and Tegelborgen consists of rentable flats. In Figure 6.3 the use per apartment at these properties has been corrected with respect to the number of vacant apartments. It is assumed that there was no use of household electricity in the vacant apartments. The exclusion gives higher use per apartment. The exclusion of vacant apartments should give a better value on household electricity use per apartment. At the other properties, the apartments were owned (co-operative flats) and vacant apartments were not filed.

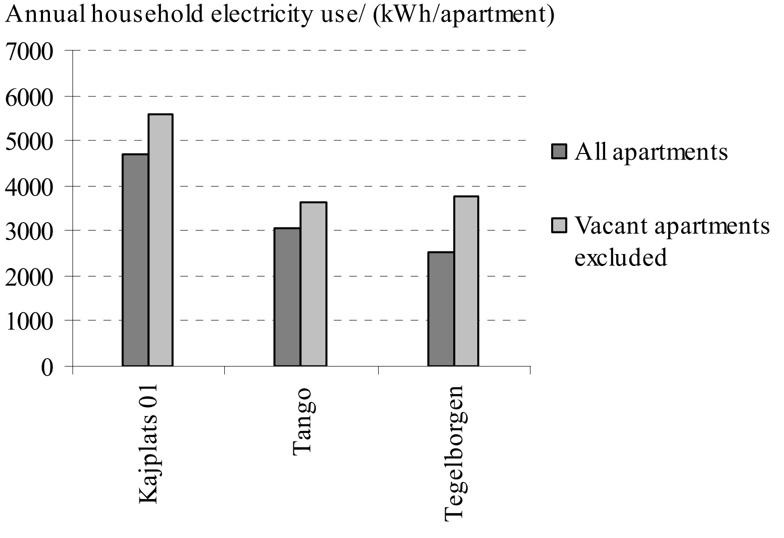

Figure 6.3 Annual use of household electricity during 2005 with and without respect to the number of vacant apartments.

Figure 6.4 presents the annual use of household electricity per apartment area. This means that the use is divided by the area where it was actually used.

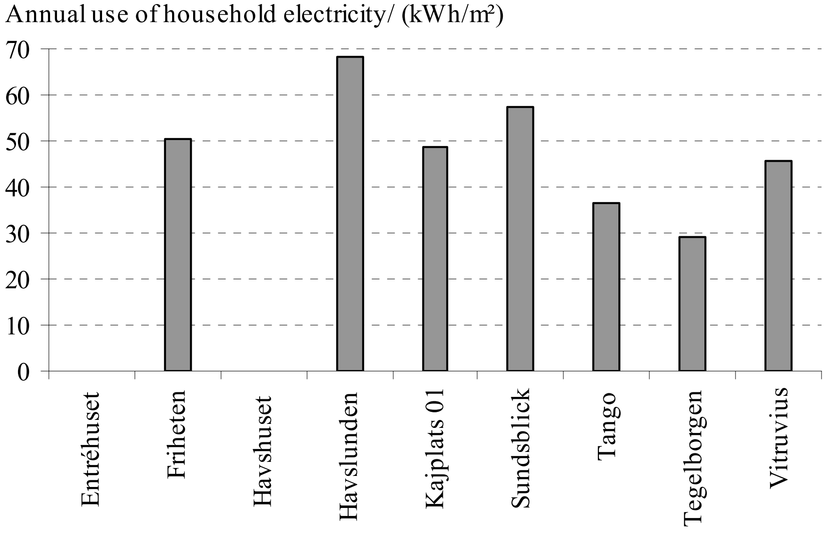

Figure 6.4 Annual use of household electricity per apartment area during 2005.

The average annual use per apartment area during 2005 was 47 kWh/m². The highest use was 68 kWh/m² and the lowest 28 kWh/m².

At the properties Friheten and Sundsblick, each apartment had its own ventilation system including an air handling unit with fans for supply- and exhaust air. A heat pump recovers heat from the exhaust air and heats the supply air and the domestic hot water. The fans and the heat pumps were run with household electricity from the apartment. Since the need for heating the supply air depends on the outdoor temperature, the household electricity use in these buildings should depend on the outdoor climate. The inclusion of fans and heat pumps in the household electricity in multi-family dwellings is not common practice in Sweden. Instead these are typically run with common electricity.

Depending on whether heaters in bathrooms, towel driers and underfloor heating, and air handling units were run by household electricity, the use of household electricity varied.

At properties that had heaters in bathrooms, run by household electricity, Havslunden Kajplats 01 and Vitruvius, the use during 2005 was on average 36 kWh/m² or 4900 kWh per apartment.

At properties that had heaters bathrooms, run by district heating, Tango and Tegelborgen, the use during 2005 was on average 23 kWh/m² or 2800 kWh per apartment.

At properties that had air handling units and heat pumps run by household electricity, Friheten and Sundsblick that also used electrical heaters in bathrooms, the use during 2005 was on average 45 kWh/m² or, 6200 kWh per apartment.

6.3.2 Variations in use during the year

Figure 6.5 presents the variation in use during the year at all properties respectively and the mean variation based on all properties.

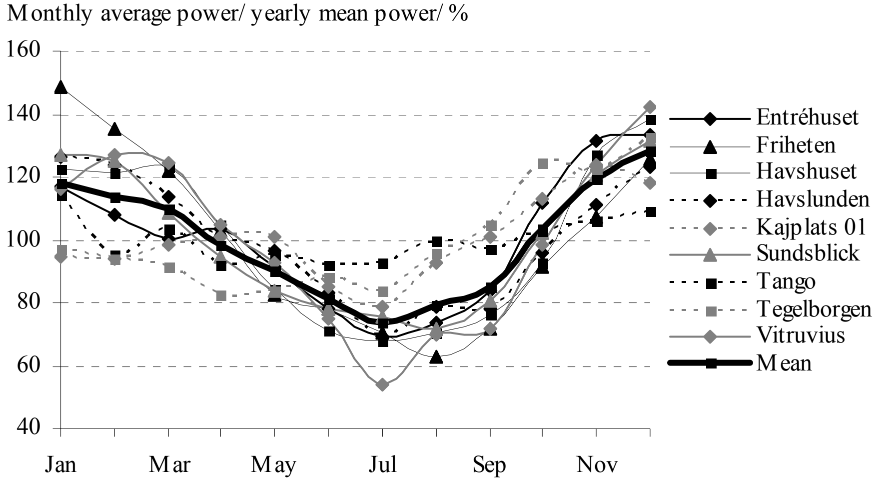

Figure 6.5 The monthly variations in the use of household electricity at the different properties and the mean variation.

At all properties, the household electricity use was higher during the winter compared to the use during the summer. According to the mean variation based on all properties, the use varied between 75 and 130 % of the yearly mean power. Other studies have found similar variations (Norén, 1998; Sandberg, 2005). The variations in use differ to some extent between the properties. This can partly be explained by different technical solutions. For example, household electricity is used for fans and heat pumps in the individual apartments at Friheten and Sundsblick, and at Havshuset and Entrehuset, the use includes common electricity.

6.3.3 Variation in use during the day

Due to the yearly variations in use, presented in Figure 6.5, the daily use will differ at different times of the year. Figure 6.6 presents the monthly mean power for each hour of the day, for the months February and August during 2005. At each hour, the power is about twice as high during February compared to August.

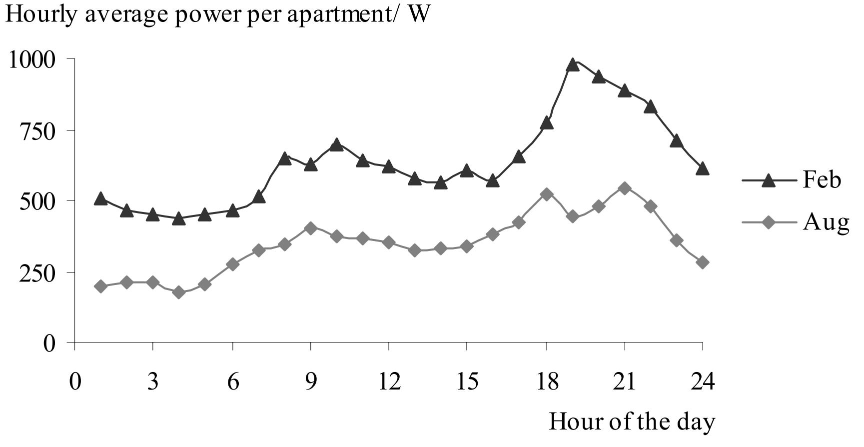

Figure 6.6. Vitruvius. The daily variations in the use of household electricity presented for February and August respectively.

Figure 6.7 presents the relative variation in use. The power at each hour of the day is compared to that day's mean power and expressed as percentage of the daily mean power for February and August during 2005.

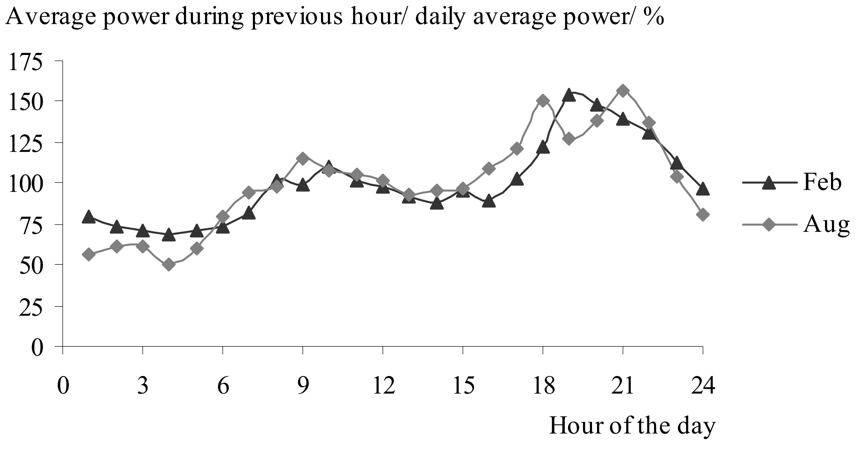

Figure 6.7 Vitruvius. The daily variations in the use of household electricity presented for February and August respectively.

Despite the large differences in the use of household electricity during the year, the daily variations are the same relative to the daily use all year around. This applies for all investigated properties.

In Figure 6.8 through 6.16, the daily variations are presented for the different properties during weekdays and weekends respectively.

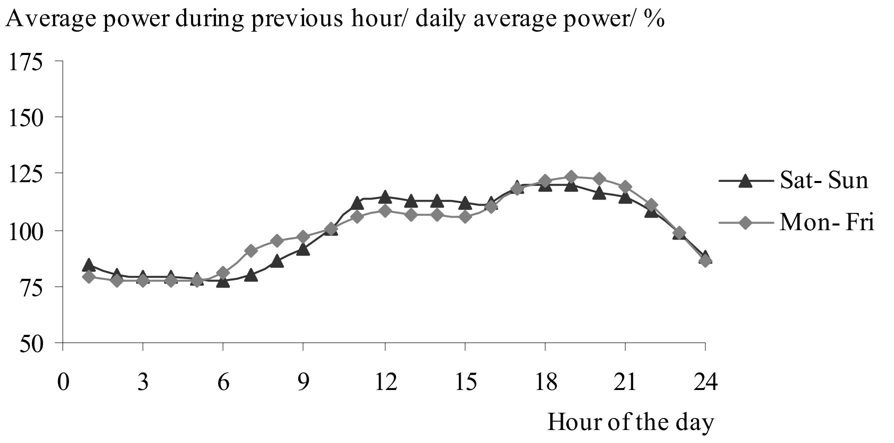

Figure 6.8 Entréhuset. The variation in use of electricity, including household electricity, electricity used at premises and common electricity, during the day, presented for Monday to Friday and Saturday to Sunday respectively.

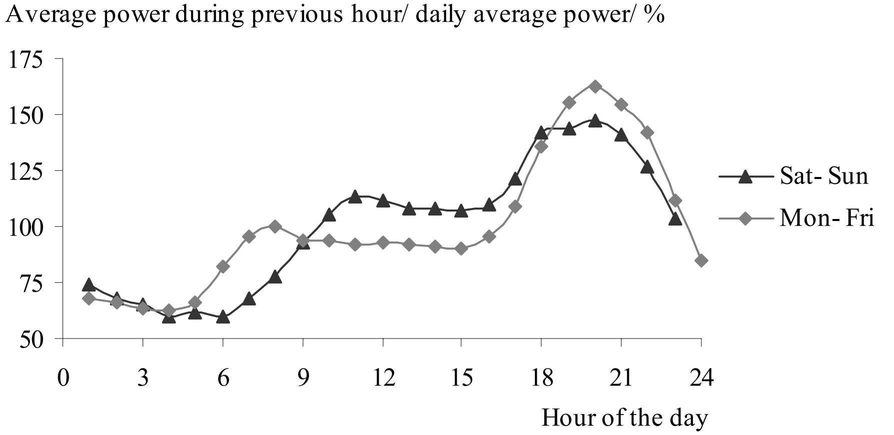

Figure 6.9 Havslunden. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

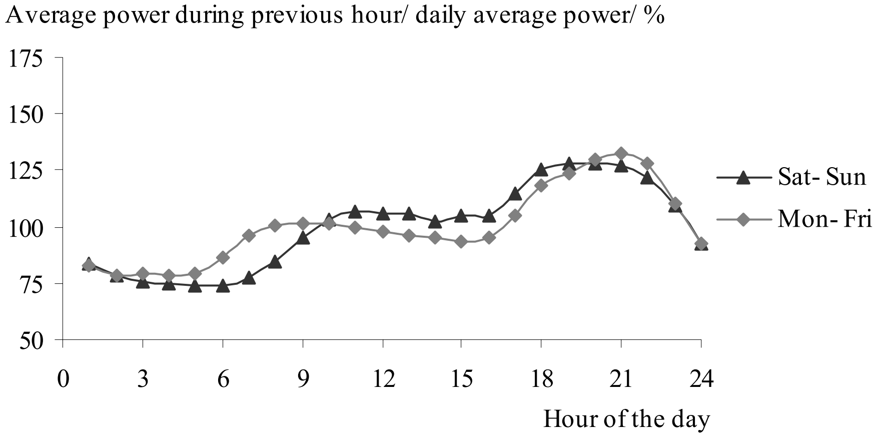

Figure 6.10 Havshuset. The variation in use of electricity, including household electricity and common electricity, during the day, presented for Monday to Friday and Saturday to Sunday respectively.

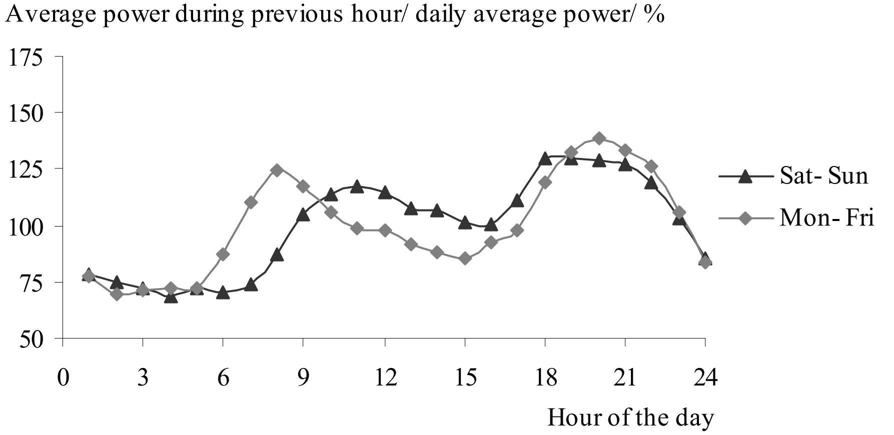

Figure 6.11 Friheten. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

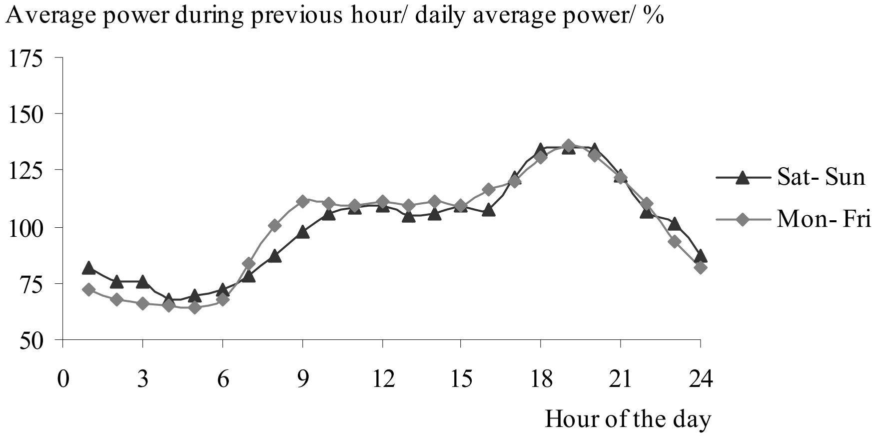

Figure 6.12 Kajplats 01. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

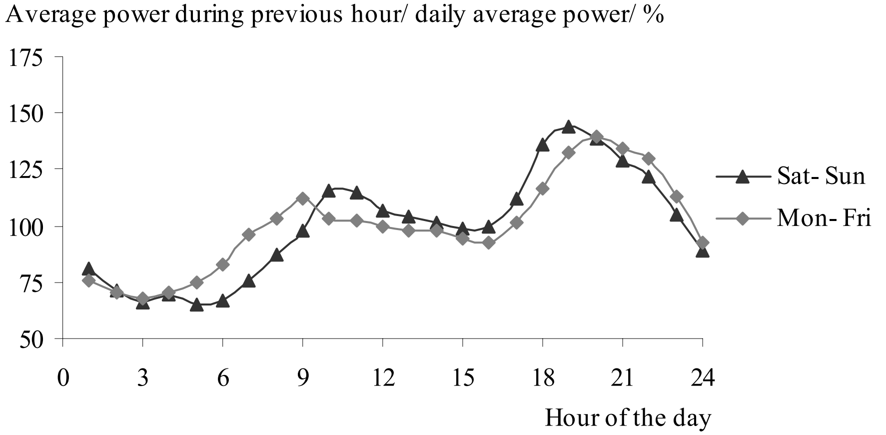

Figure 6.13 Sundsblick. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

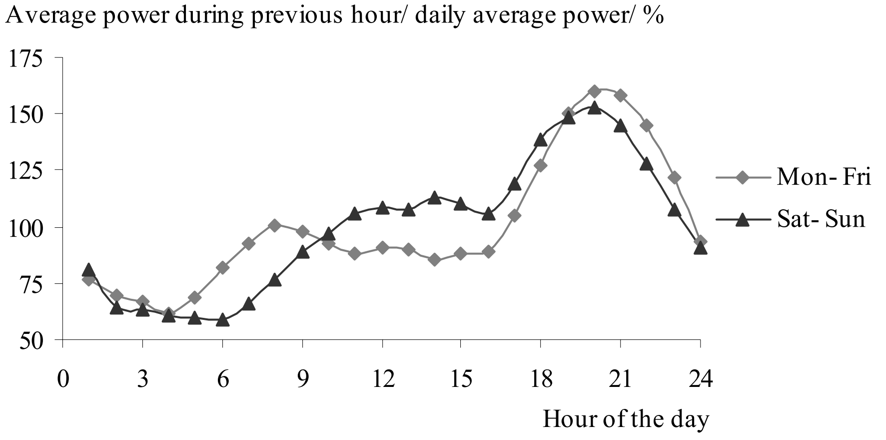

Figure 6.14 Tango. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

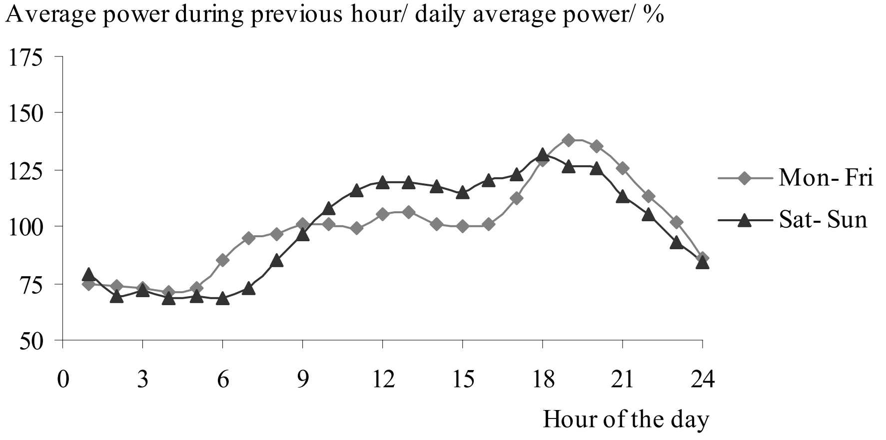

Figure 6.15 Tegelborgen. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

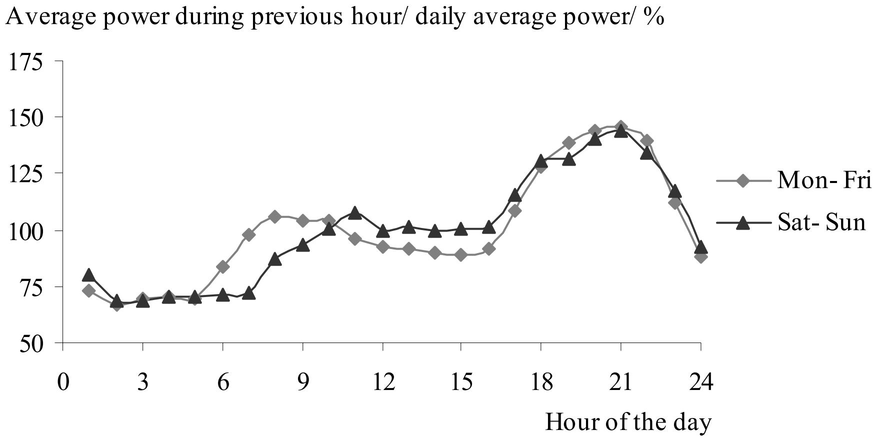

Figure 6.16 Vitruvius. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively.

Most of the properties had daily household electricity profiles with common characteristics, although that there were differences in the amplitude of the variation during the day at the different properties:

- the use was least during the night
- increased during the morning where there was also a small peak
- was about constant during the day and afternoon
- increased during late afternoon
- reached a maximum at eight or nine

During weekends, the use increased later during the morning compared to weekdays. The use was higher during the afternoon during weekends compared to weekdays.

Altough the use at Entréhuset and Havshuset was total use of electricity, these properties had equal variation in use during the day as the other properties.

At Friheten, the peak during mornings is more accentuated than at the other properties. This might be due to that the domestic hot water was heated by a heat pump in each apartment, run with household electricity. Sundsblick has the same system but the peak during the mornings was not as high.

6.4 Discussion and conclusions

The use of household electricity will have different values depending on how it is distributed. If the use was divided by heated floor area excluding garage area, the average annual use during 2005 was 35 kWh/m². The use per heated floor area was highest at Friheten and lowest at Tegelborgen. If the use was divided by the number of apartments at the properties, the average use per apartment during 2005 was 4680 kWh. The use per apartment was highest at Sundsblick and lowest at Tegelborgen. If the use per apartment is corrected for vacant apartments, the use was lowest at Tango. If the use is divided by apartment area, the average annual use during 2005 was 48 kWh/m². The use was highest at Havslunden and lowest at Tegelborgen. These examples illustrates the importance of a carefully chosen area when energy use at different properties or buildings are compared in order to give a fair rating.

The variation in use over the year was high. During December, the household electricity power was almost twice as high compared to the power during July. The variations during the day are also high with a smaller peak during mornings and a large peak during evenings.

Bagge et al (2005) studied energy use in an energy efficient house in Sweden. The measured use of household electricity was 4150 kWh or 30 kWh/m². During the planning phase, the use was assumed to be 22 kWh/m² or 28% less compared to the measured use.

Wall (2006) studied energy use in energy-efficient terrace houses. The measured use of household electricity was 31.8 kWh/m². During the planning phase of these houses, the use was assumed to be 23.8 kWh/m² or 25% less compared to the measured use.

Lindén (2006) studied the energy use at a housing area built in 2001 in Stockholm, Sweden. The buildings had a restriction to use no more than 20 kWh/m² electricity annually, including all electricity. The average use of household electricity during 2005 was 27 kWh/m². It is not clear if garage area was included or not.

Compared to the result from these three studies, the average use per heated floor area at Bo01, 35 kWh/m², was higher.

Persson (2005) reported that electrical heaters in bathrooms could increase the use of household electricity by 2000 kWh annually per apartment. The difference between average annual use of household electricity at the Bo01 properties with and without electrical heaters in bathrooms run by household electricity was 2100 kWh per apartment. At properties with air handling units run by household electricity and electrical heaters in bathrooms, the annual use was on average 1300 kWh higher per apartment compared to the average use at properties with electrical heaters in bathrooms.

Tso and Yau (2003) studied the daily consumption patterns of household electricity in about 1500 households in Hong Kong. The use was about the same during the whole day except for a large peak in the evening. No noticeable difference was found between the patterns for weekdays and weekends. The use was higher during summer compared to winter due to the use of air-conditioning to cool the apartments.

Riddell and Manson (1995) studied power usage patterns of domestic consumers in New Zealand. It was found that universal for the different patterns was mid morning and early evening peaks.

Capasso et al (1994) monitored the electricity use during 22 working days in 95 households in Milan. The daily average load profile showed a smaller peak at eight o'clock in the morning and a bigger peak at eight o'clock in the evening. The use was least around 5 o'clock in the morning. After the morning peak the use stayed at a higher level compared to the use during the night.

Paatero and Lund (2006) monitored use of household electricity in 702 households in Finland and presented the variations in use of household electricity during the year and during the day. The variation over the year has about the same amplitude as the mean variation at Bo01. The variations during the day have a large peak around eight o'clock in the evening during both weekdays and weekends. The use increased during the morning but there was no peak. Between mornings and evenings, the use was higher during weekends compared to weekdays.

The daily use patterns presented in these studies showed equal characteristics as the variations in use during the day at the Bo01 properties.

The variations in use over the year calls out for caution when household electricity use measured at different times of the year are compared. If no respect is taken to the variations over the year, there might be large errors if household electricity measured during a shorter period is used for estimating the annual use.

To make accurate energy calculations, the variation in use of household electricity, during the day and the year should be taken into account. Especially when modern low energy buildings are designed since these are thought to make efficient use of excess heat from household electricity.

Bagge et al (2006 b) interviewed consultants who ran energy simulations of buildings. The consultants seldom simulated the variations in use of household electricity over the day and the year although they were aware that there were variations. This was because no data regarding the variation was available and most energy simulation programs for buildings were not adapted for input data that varied during the day and the year.

Bagge et al (2006 c) simulated energy use in buildings. The use of household electricity was assumed to vary over the year. The variation was about the same as the mean variation over the year presented in Figure 6.5. The result showed that the calculated heating demand was reduced about 10% in well insulated buildings if the household electricity was assumed to vary compared to if a constant use was assumed.

7 Discussion

7.1 Measurements

The energy use measurements included the use of district heating, the use of common electricity and use of household electricity. The division of the energy use into these posts agrees with the different types of energy (heat and electricity) and who is billed. Usually, the property owner pays the heat and common electricity bill while each apartment holder pays the household electricity bill. At most properties in Sweden, the energy use is measured divided into the above uses. However, the use is seldom monitored hourly. Another problem is that the use of household electricity is not usually available.

From an energy analysis perspective, it would have been very useful if the energy use had been divided into end uses and if the energy use had been measured at building level instead of property level. Measurements of district heating gives information on the buildings' total use of heating, but heating is, in most cases, both space heating and domestic hot water heating. If the buildings performance is to be determined, it is necessary to separate use for space heating and domestic hot water since the use of domestic hot water is mainly related to user behaviour and space heating is mainly related to the building construction and the outdoor climate.

District heating might not be the only heating source. If electric towel driers and floor heating is used in bathrooms, some of the household electricity is also used for heating purpose. If heat pumps are used to generate heat, the compressor is run by electricity. If it is a central heat pump, it is probably run by common electricity and if the heat pumps are located in individual apartments, they might be run by household electricity. Furthermore, the heat pumps might deliver heat to space heating as well as domestic hot water or both. To enable an accurate analysis of a buildings heat use, electricity used for heating purpose or for generating heat, should be measured separately to avoid the assumptions that otherwise has to be performed. These measurements are also necessary to enable an accurate analysis of the household electricity and common electricity use. If cooling is present, it is also necessary to split electricity for the chillers from other electricity to analyse the building regarding the cooling need.

To summarize, it should be possible to measure all energy used for space heating, domestic hot water heating, ventilation and cooling separately, independent of energy source and who is paying the bill. It is also a hypothesis that the division of the different energies into different bills influences the energy use itself.

The analyses of energy use in this study would have been better had there been separate measurements of:

- space heating and domestic hot water heating
- the amount of water and domestic hot water used
- electricity used to run fans, pumps and heat pumps
- electricity used for underfloor heating and towel dryers

If these energy posts would have been measured, several more energy meters would have had to be installed at the properties. When new buildings are built, a suitable amount of energy meters should be installed to facilitate verification of the energy used during operation.

7.2 Methods

Since the use of heating depends a lot on the outdoor climate, which varies from year to year, differences in energy use during different years might depend on the outdoor climate and not on the building and its heating system. The power signature method was used for corrections regarding differences in the outdoor climate between different years. This correction should normalize the use of heating regarding differences in the outdoor climate. If there are still differences in the corrected use of heating for different years, they should not depend on the outdoor climate. For example, rebuilding, change in occupants, and malfunctioning heating and ventilation systems can result in differences in use during different years.

The power signature gives a graphical explanation of the energy use during different conditions. The power signature method has advantages when energy use at different buildings or properties are compared since it gives more information than just the annual energy use. For example it gives information on the balance temperature, the loss factor and the use during off heating season. The graphical description of the use of heating in the signature is pedagogical and facilitates comparisons between the use at different cases or during different times. The power signature method implies that use of heating is measured at a regular basis during different times of the year in order to give accurate result.

Since only the total use of district heating was measured and the domestic hot water was heated by district heating at all properties, with the exception of two, a method for calculating the annual use of domestic hot water heating from use of district heating was used in Chapter 3. The annual use of domestic hot water heating was calculated based on the use of district heating during July and assumptions on how the use of domestic hot water heating varied during the year. If the assumed variations are representative, this method should give a better estimate of the use of domestic hot water heating than assumptions of a constant use during the year. However, it would have been an advantage if the use of domestic hot water heating was measured separately. This method is not accurate if towel driers and floor heating in bathrooms are run by district heating since these might be used during summer for comfort reasons.

When energy efficient buildings are designed, it is important to have accurately simulated internal heat gains as these are aimed to balance the heat losses during a large part of the year. The heat gains vary during the day and the year and these variations should be taken into account when energy efficient buildings are designed. The variation during the day in use of household electricity and district heating for heating the domestic hot water is presented as hourly average power for each hour of the day divided by that day's average power. This means that the differences in absolute use between the properties are not shown. Instead, the relative amplitude of the variation in use during the day will be comparable between the properties. Despite large differences in absolute use of household electricity at different times of the year, the relative variation in use during the day was about the same. The variation in use of household electricity during the year was studied with the same method. The variation is presented as monthly mean power for each month of the year divided by that year's average power. This method is useful when variations are studied over time.

The examined buildings had a high percentage of windows in relation to heated floor area and estimated solar heat gains represented a large part in the energy balances calculated by the developers. It is of interest to be able to analyse how much solar heat gains actually affect the energy use in the buildings. A method for calculating how much the assimilation of solar heat gains decreases the use of space heating is presented in Chapter 4. This method is based on analysis of the distribution in the power signature. The decrease in energy use is calculated based on measurements of daily use of heating, accumulated global radiation and average outdoor temperature. No method for calculating the assimilation of solar heat gains based on measurements of the use of heating was found in the literature. The presented method can be used to verify whether a building assimilates solar heat gains in accordance with estimations or simulations. A divergence calls for an investigation clarifying whether the estimated solar heat gains were erroneous or if the buildings technical systems were not working correctly.

7.3 Analysis

7.3.1 Total energy use during 2005

The total energy use during 2005 is presented in Figure X.1. The energy use is divided into

- use of space heating, presented in Chapters 2 and 3
- use of domestic hot water, presented in Chapter 3
- use of common electricity, presented in Chapter 6
- use of household electricity, presented in Chapter 5

In Figure 7.1, the assimilated solar heat gains, presented in Chapter 4, is also included as negative bars to enable it to be shown in the same graph.

At the properties Tango and Tegelborgen, it was not possible to calculate the use of domestic hot water heating. Hence, the total use of district heating is presented and includes both space heating and domestic hot water, as presented in Chapter 2.

At the properties where household electricity and common electricity were not measured separately, the total electricity use is presented, as presented in Chapter 5.

All the developers designed the buildings to achieve the same goal concerning energy use. It is remarkably to find out that the measured total energy use varied by almost a factor three between the lowest and the highest use during operation and that the average does not correspond at all with the estimations. Only one out of nine properties, Havshuset, fulfilled the demand in the Quality programme, with total annual energy use below 105 kWh/m².

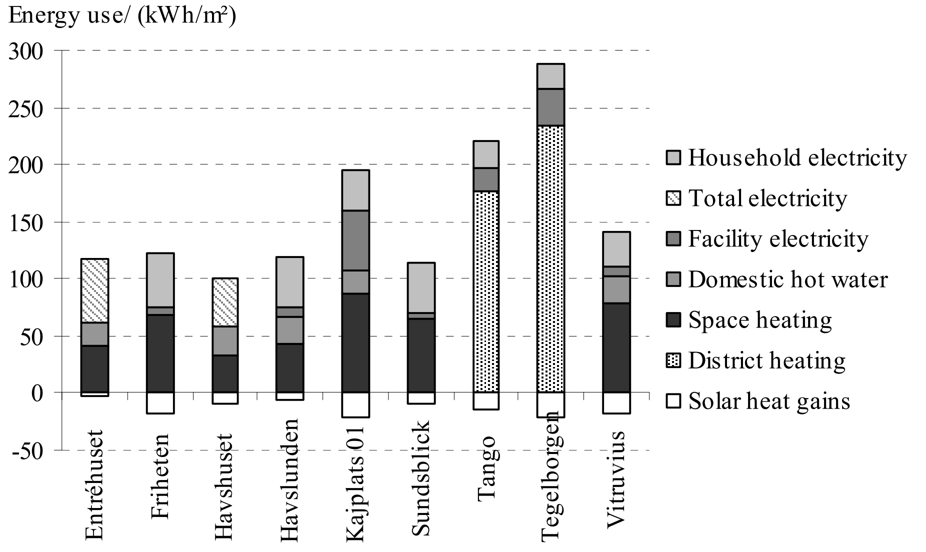

Figure 7.1 Energy use during 2005 at the different properties. Electricity use in commercial space is not included except for Entréhuset. Solar heat gain, that is not a bought energy, is presented as negative bars to allow it in the same graph.

Three properties used more than 190 kWh/m², five properties used between 110 kWh/m² and 140 kWh/m² and one used 100 kWh/m². The total average annual energy use, including all properties, was 157 kWh/m² during 2005. If the properties with underfloor heating as the primarily heat distribution system, Kajplats 01, Tango and Tegelborgen, were excluded, the total average annual energy use was 119 kWh/m².

7.3.2 Solar heat gains and windows

The three properties that had the highest total energy use, Kajplats 01, Tango and Tegelborgen, have three particular features. They were the three properties with the highest window area in relation to heated floor area of all properties, they all had underfloor heating as primarily heat distribution system and they had the highest use of district heating. A large part of the windows were facing west and the calculated assimilated solar heat gains are relatively high at these properties.

The property Havlsunden had much lower total energy use even if it had very large window area in relation to heated floor area, 30 %, and a majority of the windows faced east and west. Despite the large window area and its orientation, the assimilated solar heat gains were very low, which can be caused by the fact that the windows facing west at Havslunden are shaded by buildings at the properties that face the sea. Despite low assimilation of solar heat gains and the large window area, the use of space heating was about the same as the space heating at the properties Entréhuset and Havshuset that used exhaust air heat pumps. One reason for this might be that the buildings at Havslunden have better insulated walls and roofs compared to most of the other buildings.

Havslunden exemplifies that low use of space heating can be achieved with a large window area. The buildings at Havslunden used radiators as a primary heat distribution system while the buildings at the properties Kajplats 01, Tango and Tegelborgen used underfloor heating as primary heat distribution system. These three properties were the only in the area that used underfloor heating as a primary heat distribution. This implies that the high use of space heating at these three properties might be due to the heat distribution system and not the large window area alone. Furthermore, it might be the large window area in combination with underfloor heating that resulted in high use of space heating.

7.3.3 Heat recovery and thermal insulation

The buildings at the properties Havslunden and Vitruvius are the only buildings that fulfilled the demand regarding thermal insulation in the building code that was valid at the time. However, the U-values were not extremely low. The total energy use at Havslunden was as low as in buildings that used exhaust air heat recovery and the use of space heating was the second lowest of all properties. This stresses the importance of a well insulated building envelope to achieve low energy use.

The two properties that had the highest use of heat, Tango and Tegelborgen, did not have any kind of exhaust air heat recovery. These properties had the highest and the third highest window area in relation to heated floor area and underfloor heating as the primarily heat distribution system. This indicates that a combination of these three characteristics might be unfavorable from an energy use perspective.

Kajplats 01 used an exhaust air heat pump that produced space heating and a ventilation heat exchanger in the garage. Considering that, the use of space heating was high. The use of space heating is slightly higher than the use of space heating at Vitruvius that did not use any kind of ventilation heat recovery. The use of common electricity is high at Kajplats 01, perhaps because of the exhaust air heat pump and the inclusion of a large garage.

At the properties that used exhaust air heat recovery, the use of district heating was, in most cases, lower compared to properties where no exhaust air heat recovery was used. However, at properties that used exhaust air heat recovery, the total energy use was not necessarily lower compared to properties that did not use any kind of exhaust air heat recovery.

7.3.4 Different use at different times

At places where the outdoor climate varies during the year, the use of space heating will vary too since it depends on the outdoor temperature. In the Swedish outdoor climate, this means that the use of space heating will be largest during the winter and lowest during the summer. Other energy posts such as use of household electricity and use of domestic hot water will also be different at different times of the year. The use of household electricity and domestic hot water should both be largest during the winter and lowest during the summer. When energy simulations are made, the use of domestic hot water and household electricity are in most cases assumed to be constant during the year. Assuming a constant use of household electricity during the year should result in incorrectly calculated space heating since excess heat from the household electricity is an important internal heat gain. The space heating will be overestimated during the winter while the domestic hot water heating will be underestimated during the winter and overestimated during the summer.

The use of household electricity and domestic hot water does not only vary during the year, but also during the day. The daily variations in use of household electricity and domestic hot water have equal characteristics. There are peaks at the same times during mornings and evenings. However, the peak during morning is larger for domestic hot water and the peak during evening is larger for household electricity. These variations in use should be taken into account, when energy use is simulated, in order to give a better estimation of the energy use.

7.3.5 Same function, different system

A building that appears to have a low use of heating might have that because the domestic hot water was heated by, for example, electricity. This is the case at Friheten and Sundsblick where the domestic hot water was heated by an exhaust air heat pump run by household electricity. These properties also had relatively low use of common electricity since each apartment had its own air handling unit run with household electricity.

At the properties Tango and Tegelborgen, towel dryers and floor heating in bathrooms were heated by district heating. At the other properties, towel dryers and underfloor heating in bathrooms were run by household electricity. This may explain the higher use of district heating at the properties Tango and Tegelborgen and why these properties have considerable lower use of household electricity compared to the other properties.

Therefore, the entire picture of the different types of energy is needed. When it comes to money and environmental impact, different types of energy is also usually valued differently. It is apparent that it is not possible to rate a building with only one parameter regarding energy use.

7.4 Future work

A continuous study during several years of the energy use at these properties should give information on how the energy use varies over time. Does the energy use stabilize and how large variations can be expected between different years?

Studies of the indoor temperature with hourly measurements during a one year time span should be used to analyse how different outdoor climate conditions affect indoor temperature, what the "normal" indoor temperature is and if the control for the heating system works correctly.

A thorough survey of the technical systems in the buildings, such as radiator thermostats, fans and heat pumps would facilitate detailed studies of the energy uses.

It is valuable to study the air tightness and thermal bridging. A method for measuring air tightness in apartments in multi-family dwellings should be developed.

The continuation of this project will focus on input data to provide the industry with better energy use estimations. Particularly, internal heat gains such as household electricity, attendance rate and assimilation of solar heat gains are parts that are often important but uncertain when energy use is estimated.

8 Conclusions

To enable a detailed analysis of a buildings energy use and to find reasons for deviations between calculated and measured energy use, the measurements of energy use need to have a high time resolution and they need to be divided into suitable end uses of energy. This was partly done at the examined properties but not enough. It was, for example, not possible to split domestic hot water from space heating, and in many cases, common electricity or household electricity was apparently a part of the heating system without separate meters.

The result stresses the importance of a detailed analysis of the energy use in order to rate a building or a property. Studying just a single parameter, for example use of heating, might result in an inappropriate rating of the energy use.

A certain goal concerning total energy use in the newly built multi-family dwellings in Västra Hamnen in Malmö resulted in a spread by almost a factor three between the lowest and the highest total energy use during operation and only one property out of nine that fulfilled the goal. This result stresses the importance of higher quality of energy predictions to enable design of buildings that fulfils demands for low energy use, regardless whether the deviation is due to insufficient usage of energy use simulation tools, unqualified users or imperfect construction work.

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