Solar Heating in Norwegian Passive Houses

A Case Study of two Passive Houses Heated by Solar Collectors and Heat Pump

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Master Thesis
in fulfillment of the degree of
MASTER OF SCIENCE
in Materials, Energy and Nanotechnology

UiO : Department of Physics
University of Oslo

August 21, 2013

Contents

Nomenclature

ach	Air change rate (of total building volume) [s^{-1}]
A_H	Heated area [m^2]
COP	Coefficient of Performance
C_P	Specific Heat Capacity [Wh/liter]
DHW	Domestic hot water
EL	Electricity [Wh or kWh]
E	Energy [Wh or kWh]
F_V	Volume Flow [liter/s]
G	Solar irradiance incident on collector surface [W/m^2]
K_1	loss coefficient of collector efficiency [W/m^2K]
K_2	loss coefficient of collector efficiency [W/m^2K^2]
P	Power [W]
Q	Heat [Wh or kWh]
t	Time [s]
T	Temperature [°C]
T_0	Ambient temperature [°C]
T_B	Base temperature [°C]
ΔT	Temperature difference [K]
ΔT_D	Temperature difference between T_{Indoor} and T_B [K]
T_{CW}	Temperature of cold water [°C]
T_{DHW}	Temperature of DHW [°C]
T_W	Mean temperature of solar collector heat carrier [°C]
TEK10	Current Norwegian building regulations
TFA	Treated Floor Area [m^2]
U	U-value [$W/(m^2K)$]
V	Volume [liter]
V_{DHW}	DHW consumption [liter]

Greek letters

η	efficiency [%]
η_0	efficiency for $T_W = T_0$
η_{HP}	Theoretical efficiency of heat pump
λ	Thermal conductivity [W/(mK)]
θ_{ym}	Annual mean temperature [°C]

Abstract

Two similar, newly erected passive houses in Oslo were monitored in order to see how well they performed. One was heated with solar thermal energy, the other with a heat pump. Estimations of the houses' energy consumption had been done in advance. Measured delivered energy for space heating and domestic hot water was significantly higher than estimated, violating the demands set by the passive house standard. Unforeseen events made it difficult to compare solar energy with the heat pump system as intended, but the solar heating system performed well compared to the estimated consumptions except not being active during winter months.

Preface

The amount of data collected in this project allows for many thesis, and this one only utilized a small portion of it. Several detailed analysis could be done of domestic heat water consumption, the solar heating system and also the functioning of the heat pump. Even though not the main scope of the thesis, some analysis were done regarding heat pump efficiency, and results were displayed in the Result chapter not directly applicable for this thesis, but which might be of some general interest.

For questions regarding this work, please contact the author

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or his supervisor Michaela Meir.

Acknowledgments

The Acknowledgments will be given in the language of whom to they are meant.

Jeg vil takke mine to veiledere, John Bernhard Rekstad og Michaela Georgine Meir, for muligheten til å jobbe med prosjektet. Takk til John for inspirasjon og takk til Michaela for samarbeidet og konstruktiv hjelp på slutten, selv over telefon fra ferie på Korsika.

Ich würde gerne Dr. Andreas Hermelink und vom Passivhaus Institut, Dr. Jürgen Schnieders für die Erlaubnis ihre Figuren verwenden danken.

Jeg vil takke beboerne i Hus A og B, som har måttet tåle jevnlige besøk fra ivrige akademikere. En spesiell takk til Herr T i Hus A for nyttige tilbakemeldinger vedrørende solfangeranlegget og husets funksjon.

Kristin Tyldum Kjøglum fran Oslo kommunes vann- og avløpsetat var meget behjelpelig med kaldtvannstemperaturer, og for det ønsker jeg å takke henne. Jeg vil også takke Signe Kroken ved Universitetet for miljø- og biovitenskap, som sendte meg meteorologiske data fra Ås.

Takk til mine studiekamerater. Takk Aylin, for nyttige diskusjoner og latex-innspill. Tack Lenny, för luncher och samtal. Takk til Hans, for kaffe. Takk til Gro for tanker rundt felles skjebne.

En liten beklagelse til Øyvind Aardal og økonomiavdelingen ved Øyafestivalen for min fraværenhet og takk for deres overbærenhet med denne og for en god festival.

En liten beklagelse går også til venner og familie, som ikke har fått mye av min oppmerksomhet de siste årene. Takk til Mamma, Pappa og Pål for støtte.

Takk til Jon-Kristian for gode diskusjoner under treningsøkter på Hasle, og omtanke i innspurten av oppgaven. Takk også til Stein, Christoffer, Øystein og Pejman for omtanke.

Takk til Anette Mathisen for gjennomlesning og innspill.

Takk til Fysisk institutt.

Takk til Realistforeningen og Gildestyret.

Takk til Lillefy og alle menneskene der.

Thanks to the people at SAFE. Especially Eda and Sunniva S for encouragement and support towards the end.

Den største takken fortjener kjæresten min, Anne-Lene, hvis hjelp var uvurdelig. Uten henne ville det ikke ha eksistert noen oppgave verdt å forsvare. OG la meg sitere frøkna: “Jeg tuller ikke!”

Chapter 1

Introduction

The Norwegian government have in their white paper from 2012, about Norwegian Climate Policies (Miljøverndepartementet, 2012), indicated that building regulations will require passive house standard on all new buildings from 2015. The low amount of delivered energy allowed for passive houses makes it difficult to heat these buildings with conventional electric heating. There are several ways to heat a house more efficiently and the use of a heat pump is one. Heat pumps have become very popular in Norway with 750 000 units sold so far (NOVAP, 2013). This thesis will investigate the use of a less common alternative for reducing the need for delivered energy, namely solar thermal heating.

The market for solar thermal energy is small but growing in Norway. In 2011, flat plate solar collectors with a capacity of 2 MW thermal energy were installed in Norway, reaching a total installed capacity of 10.1 MW. This is quite modest compared to Sweden which, with similar solar conditions, by 2011 had installed flat plate collectors with a a total capacity of 179.2 MW thermal energy. China has by far the largest installed capacity of solar thermal energy in the world with more than 150 000 MW of flat plate collectors and evacuated tube collectors, which are popular in China. The installed capacity per capita corresponds to 2 W, 19 W and 114 W for Norway, Sweden and China respectively, showing the potential for growth in Norway (Mauthner & Weiss, 2013).

As a consequence of the new energy conserving regulations soon to be imposed by the Norwegian government, more and more passive house construction projects are being initiated. To optimize the energy saving potential of passive houses and solar collectors, it is important to study already realized projects. Prior to housing projects being implemented, calculations and estimations are performed concerning their energy saving potential. Such calculations have little value if not seen to match with reality.

This thesis will present a case study of a newly erected house satisfying the Norwegian passive house criteria, with solar thermal energy contributing to space heating and heating of domestic hot water. This house will be compared to a nearly identical neighboring house, using an air-to-water heat pump. The houses' need for delivered energy and their consumption of energy were in advance estimated by the contractor and this thesis will compare this estimation to measured values. Aspects of the heat pump will be looked at, but the yield of the solar heating system and its functioning through the year will be the main focus of the thesis.

Chapter 2

Theoretical Background

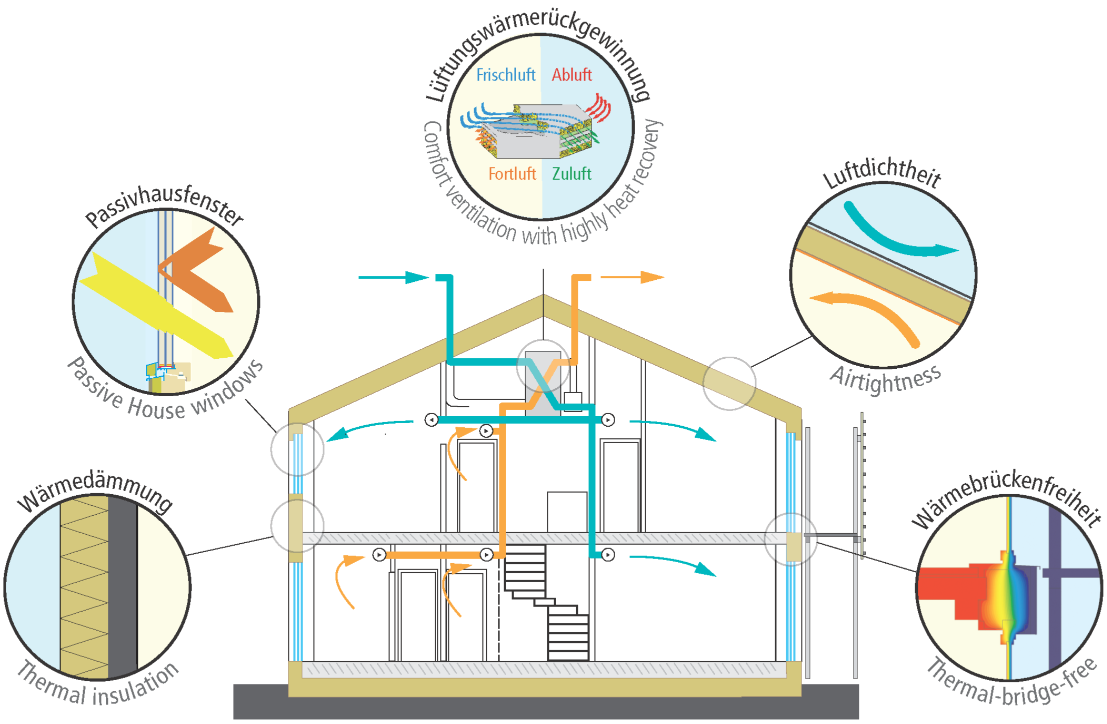


Figure 2.1: *Most important parts of a Passive House*
With permission from the Passivhaus Institut (2013)

2.1 Buildings and Energy Consumption

When analyzing energy consumption in buildings, it is important to distinguish between *delivered* energy and *consumed* energy. Heat pumps and solar thermal heating can yield more energy in the form of heat than they consume in electricity. A building's expected energy *consumption* for space heating is calculated based on its properties and assumptions of user behavior. Heat pumps and solar thermal heating are then means with which one can reduce the need of *delivered* energy.

2.1.1 Passive Houses

The passive house concept originates from a conversation in 1988 between Swedish Professor Bo Adamson and Professor Wolfgang Feist, the German founder of the Passivhaus Institut in Darmstadt, where the first passive house was built in 1990 (Passivhaus Institut, 2013). The main idea behind the concept is to drastically reduce the need for space heating, using means such as highly insulated envelopes and ventilation with high heat recovery. The key features of passive houses can be seen in Figure 2.1. This was meant to make the passive houses energy efficient, comfortable and affordable. One of the ways passive houses were to become affordable, was the low maximum space heating load of 10 W/m^2. Such a load could be facilitated using the ventilation system, thus removing the need for a regular space heating system and hence reducing the investment costs (Schnieders & Hermelink, 2006).

The criteria for passive houses vary from country to country, as climates are not the same in all locations. The Norwegian criteria are given in the standard NS 3700, and can be summarized as follows:

- Annual energy delivered for space heating less than 15 kWh/m^2
- Maximal space heating demand of 10 W/m^2
- Utilization of the sun by southward facing windows
- As compact a building envelope as possible
- Well thermally insulated building envelope with U-values below 0.15 W/(m^{2}K), preferably down towards 0.10 W/(m^{2}K)
- Building envelope preferably without thermal bridges
- Well insulated windows with overall U-values of 0.80 W/m^{2}K or less
- Airtightness corresponding to a leakage of less than 0.6 of total house volume per hour, during an excess pressure of 50 Pa
- Balanced ventilation with heat recovery of at least 80 %
- Specific fan power must be less than 1.5 kW/(m^3/s)
- Total amount of annual delivered energy less than 80 kWh/m^2

(SINTEF Byggforsk, 2013)

Table 2.1: *Norwegian criteria for passive houses, depending upon annual mean temperature θ_{ym} and heated area A_H. (Standard Norge, 2010)*

θ_{ym}	**Maximum calculated demand for space heating** [kWh/(m^{2}a)]	
	Building where $A_H < 250m^2$	Building where $A_H \geq 250m^2$
≥ 6.3	$15 + 5.4 \times \frac{(250-A_H)}{100}$	15
< 6.3	$15 + 5.4 \times \frac{250-A_H}{100} + \left(2.1 + 0.59 \times \frac{250-A_H}{100}\right) \times (6.3 - \theta_{ym})$	$15 + 2.1 \times (6.3 - \theta_{ym})$

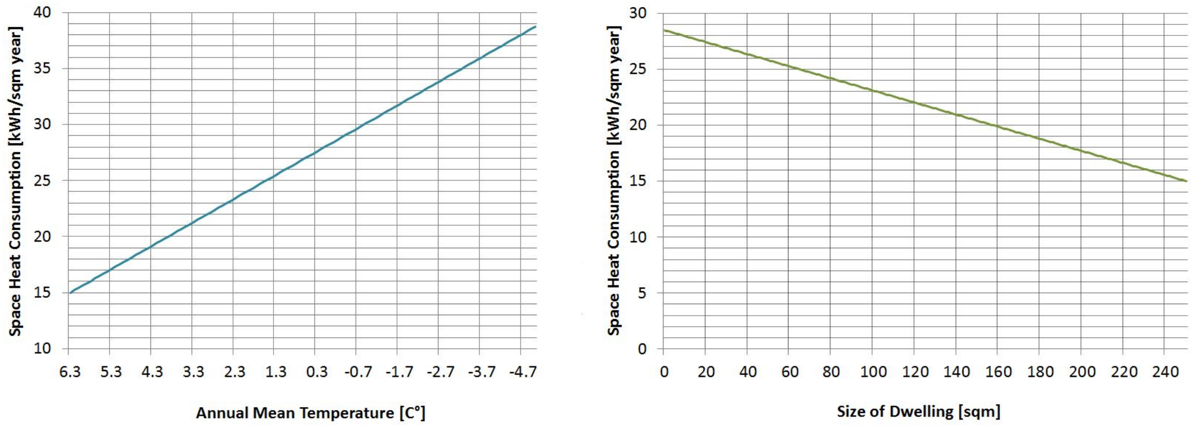


Figure 2.2: *Graphical view of the criteria in Table 2.1.* ***Left:*** *Maximum space heating demand per* m^2 *for buildings larger than 250* m^2*, as a function of average ambient temperature.* ***Right:*** *Maximum space heating demand per* m^2 *for a climate of* 6.3 °C *mean ambient temperature or more, as a function of building size.*

2.1.2 U-value

The U-value is a characteristic of walls, windows, doors and other surfaces, and describe how large the energy flow through a surface will be, depending on the surrounding temperatures. The unit for U-value is $W/(m^2K)$. The U-values of walls depend on how much and what sort of thermal insulation is used, in addition to the structure of the wall. U-values are obtained by dividing the thermal conductivity (λ) by the depth (or thickness) of the material. To find the overall U-value of a wall or other composite structures, the U-values of the different parts are added together as shown in Equation (2.1). A common insulation for walls in buildings is mineral wool with a thermal conductivity, λ of 0.035 W/(mK). In Chapter 3, Table 3.1 displays various U-values needed for passive houses in different climates.

$$\frac{1}{\mathrm{U}} = \frac{1}{\mathrm{U}_1} + \frac{1}{\mathrm{U}_2} + \frac{1}{\mathrm{U}_n} + ... \tag{2.1}$$

2.1.3 Internal Gains

In every building occupied by people either working or living, there will be consumption of energy. Most of this energy will be converted into heat, whether it comes from appliances, lighting or cooking. Domestic hot water also releases heat either through the warm water itself or through heat losses from the boiler. This energy consumption reduces the demand for space heating, and is called internal gain. The German Passive House Institute operates with an internal gain of 2.1 W/m^2 when calculating the need for space heating in passive houses. As will be mentioned in Section 3.2.1, Dokka & Andresen (2006) argues that for Norway, 4.0 W/m^2 would be a more realistic value.

2.1.4 Passive Solar Gains

Glass is close to transparent for solar radiation, but almost opaque to thermal radiation. As in a solar collector, this leads to heat being absorbed through the windows of a house. This effect is exploited in passive houses in order to reduce the need for space heating, and as much of the window area as possible should be facing south and as little as possible should face north. One challenge is overheating in summer, and shading is commonly used to prevent this. Windows with lower transmission are also used. Passive solar gain is sometimes referred to as direct gain (Duffie & Beckman, 2006, p. 556), or just solar gain. To avoid confusion with solar gain from the solar collector, this thesis will use the term passive solar gain.

2.1.5 Heating Degree Days

"Heating degree days" is often used in order to estimate a building's need for heating. If one excludes bathrooms which are often warmer than other rooms, a house needs heating only up to a certain temperature, since internal gains will contribute to heating. This temperature is called the base temperature and varies depending on climate and latitude. A common value for the base temperature in Norway is 17 ℃. To calculate annual heating degree days, the difference between the chosen base temperature, T_{Base}, and the daily mean outside temperature, T_{Day}, is summed, as in Equation (2.2), disregarding the negative values.

$$\sum_{\text{Jan 1}}^{\text{Dec 31}} \left(T_{\text{Base}} - T_{\text{Day Average}}\right) \tag{2.2}$$

Either temperatures from a specific period can be recorded or statistical values from meteorological institutions can be used. In this way one can compare specific years to a meteorological normal, and it also makes it possible to compare places with different climates. The base temperature will depend on the building's heat loss, internal gain and inside temperature as follows:

$$T_{\text{Base}} = T_{\text{Inside}} - \frac{\text{Internal Gain [W/m}^2\text{]}}{\text{Heat Loss [W/(m}^2\text{K)]}} \tag{2.3}$$

In the report *Heating degree days, Cooling degree days and precipitation in Europe* (2008), Rasmus E. Benestad gives the average heating degree days in Oslo in the period 1961 to 1990 for a T_{Base} of 17 °C to be 4404.

Less heat loss and higher internal gain will decrease the base temperature, and hence the heating degree days. Though not very relevant for Nordic climates, the term cooling degree days is also used, which is the number of days and degrees a building needs to be cooled. Here, internal gain is counterproductive and will lower the base temperature, which is negative for cooling degree days (Carbon Trust, 2007).

2.1.6 Current Building Regulations

Norway's current building regulations named TEK10, were introduced in the summer of 2010. For different parts of a building, TEK10 demands the following:

- U-values of exterior walls less or equal to 0.18 $\text{W/m}^2\text{K}$
- U-values of roof less or equal to 0.13 $\text{W/(m}^2\text{K)}$
- U-values of floor less or equal to 0.15 $\text{W/(m}^2\text{K)}$
- U-values of windows and doors, including frames, less or equal to 1.2 $\text{W/(m}^2\text{K)}$
- Heat recovery in ventilation must be larger than or equal to 70 percent

- Specific fan power must be less than 2.5 kW/(m^3/s)
- Airtightness should be better than or equal to 2.5 ach at a pressure difference of 50 Pa
- Total energy need for a house should not exceed

$$120\,\mathrm{kWh/(m^2a)} + \frac{1600}{\mathrm{m^2}}\ \mathrm{kWh/(m^2a)}$$

Here m^2 is the house's heated area. Ach or air change rate describes how much of the total air volume in the house is circulated per hour. In this case less than 2.5 times the house volume of air is leaking per hour. (Kommunal og regionaldepartementet, 2010) The Norwegian Government has announced that building regulations will demand passive house standard for all new houses from 2015, moving towards zero energy buildings in 2020 (Miljøverndepartementet, 2012).

2.2 Heat Pumps

Heat pumps can transfer energy in the form of heat from a cold reservoir to a warm reservoir, with the use of auxiliary energy. In this way the heat pump can give back more energy in the form of heat, than the amount of electric energy it consumes. (Young & Freedman, 2004)

Working Principles

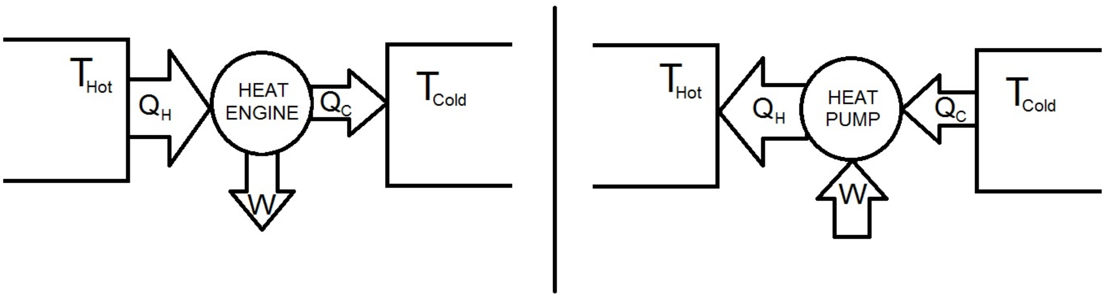


Figure 2.3: *Schematic overview of a heat engine and a heat pump.*

A heat pump is a heat engine in reverse. A heat engine takes heat from a hot reservoir, converts some of this to work and delivers the residual heat to a cold reservoir. The theoretical efficiency of a heat engine, that is the percentage of heat being converted to work, depends on the temperature of the hot and the cold reservoir as

$$\eta_{\mathrm{HE}} \leq \frac{T_{Hot} - T_{Cold}}{T_{Hot}} \tag{2.4}$$

In a heat pump, work is performed to transport heat from the cold reservoir to the hot reservoir. Its theoretical efficiency is the inverse of the heat engine:

$$\eta_{\mathrm{HP}} \leq \frac{T_{Hot}}{T_{Hot} - T_{Cold}} \tag{2.5}$$

As can be seen from the above, the efficiency of a heat pump increases with smaller temperature differences while the heat engine functions better with greater temperature differences. The efficiency of a heat pump, often called the Coefficient of Performance (COP), can be significantly higher than 1. Depending on outside temperature, one can theoretically get 6 – 20 times more energy out than invested. In practice these numbers are more often in the range 2 – 6.

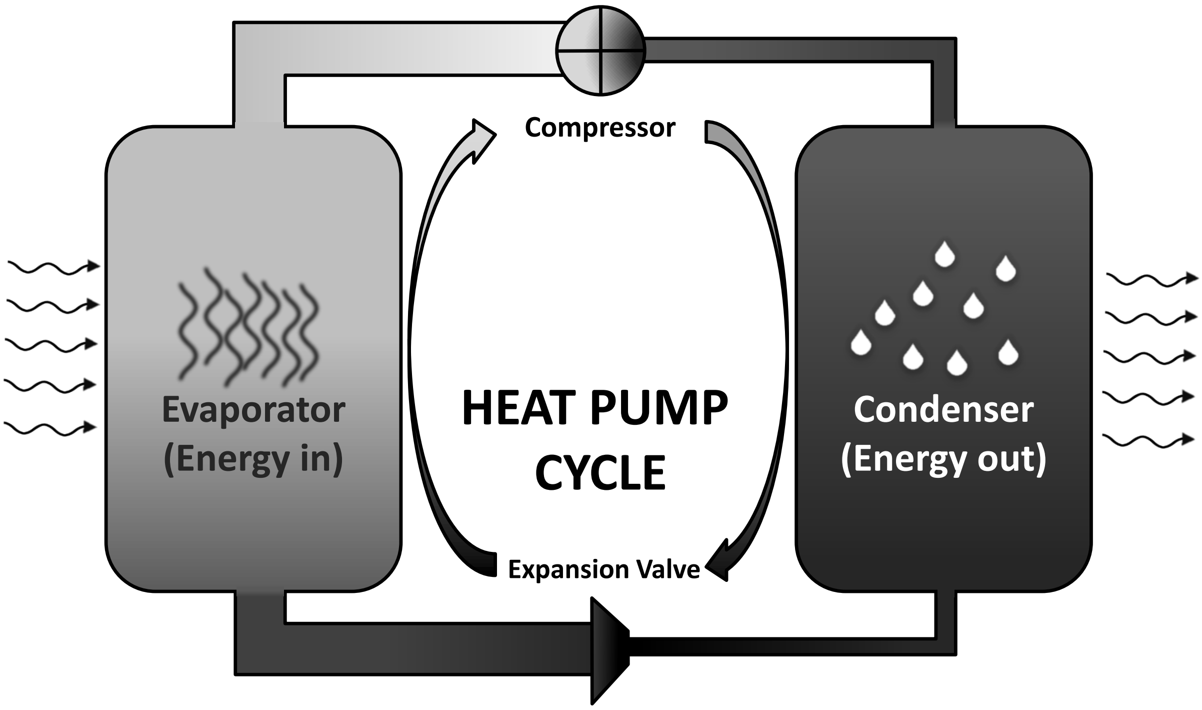


Figure 2.4: *A Diagram of a heat pump's cycle. A refrigerant is transported in the direction of the arrows. Darker color indicates higher pressure.*

A typical heat pump cycle consists of four important parts: Expansion, evaporation, compression and condensation, which can be seen in Figure 2.4. It works as follows: The medium, or refrigerant, go through the expansion valve and into the evaporator. Here the pressure is low, allowing the medium to evaporate at a lower temperature. The evaporation process demands energy, and this is taken from the ambient of the evaporator and stored in the medium as latent heat. The evaporator of a heat pump is situated at the heat source which could be the outside air, ground water, a nearby lake or something else. In Equation (2.5), T_{Cold} is the temperature of the heat source. After evaporation the medium is compressed into the condenser where higher pressure forces the medium to condense. The process of condensation releases the latent heat, enabling the heat pump to transfer energy from the heat source to the heat sink, typically a heat store, even though the temperature of the heat source is lower than the temperature of the heat store. In general, the temperature of a gas is proportional to its pressure. Therefore, a low pressure in the evaporator makes it possible for the gaseous part of the medium to receive energy from its surroundings, if the low pressure has lowered its temperature to one lower than the temperature of the heat source. Typical heat pump media are ammonia, hydrocarbon and other chemical mixtures, often containing fluorides.

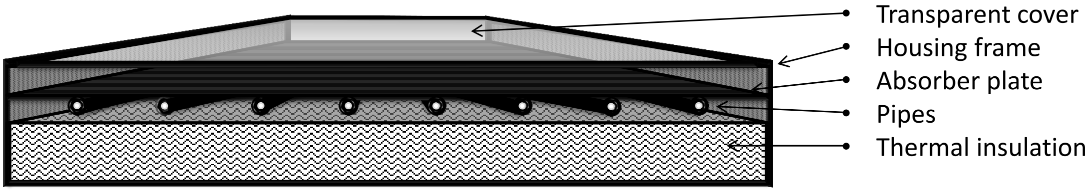


Figure 2.5: *A cross section of a typical flat plate solar collector*

2.3 Solar Collectors

Applications for direct utilization of solar energy come in two varieties: Photovoltaic cells, in which photons are converted directly into electricity, and solar thermal. Some thermal technologies convert heat into electricity while others facilitate the use of heat. The focus of the next section will be the latter, specifically so called flat plate collectors.

2.3.1 Working Principles

The objective of solar collectors is to absorb solar energy and transport the resultant heat into a heat store. This is most commonly done by having water or another medium flow through pipes or through the collector itself, collecting the heat and releasing it into the heat store. The absorber is usually black and often made of metal in order to maximize thermal conductivity. Losses are dominated by thermal losses from the absorber to the ambient, especially radiative losses. By adding a cover sheet(s), radiative losses are reduced since it is nearly transparent to radiation with solar wavelengths, but near opaque to radiation with infrared wavelengths. It also reduces conductive losses by insulating the absorber (Rekstad & Meir, 2012). It has the adverse side effect of reducing the transmittance of the collector, thereby lowering the amount of radiation hitting the absorber. A cross section of a typical flat plate collector can be seen in Figure 2.5.

The absorptance of the absorber is related to the wavelength of the incoming radiation, but is in the order of 0.95. The reflectance from the cover sheet(s) is dependent upon the incident angle and the materials refractive index.

$$\eta = \eta_0 - K_1 \frac{(T_W - T_0)}{G} - K_2 \frac{(T_W - T_0)^2}{G} \tag{2.6}$$

Equation (2.6) gives the efficiency η, as a function of η_0, that is the efficiency when the ambient temperature of the solar collector, T_0 is equal to the mean temperature of the heat medium, T_W. K_1 is in the order of $2\,\mathrm{W/(m^2K)}$ to $6\,\mathrm{W/(m^2K)}$ and K_2 in the order of $0.03\,\mathrm{W/(m^2K^2)}$. G is solar irradiance in $\mathrm{W/m^2}$, and a low G reduce the efficiency of the collector.

As can be seen in the equation, a low T_W reduces losses. It is thus beneficial if the medium going into the collector, often taken from the bottom of a heat store, is as cold as possible. A heat store with stratified temperatures, colder in the bottom and warmer at the top, is therefore desired. But even if stratification exists before collector activity, it is hard to maintain with relatively large flow rates. Heat store stratification is also advantageous when it comes to the use of heat, since energy is easier to extract from warmer sources.

2.3.2 Measuring Solar Gain

Heat Flow Method

One way to estimate the performance of a solar collector is to measure the temperature of the medium flowing into the collector (forward flow) and the medium flowing out (return flow), as well as the flow rate of the medium. Using Equation (2.7) the energy collected per second or the power, $P_{Energy\ Gained}$, is obtained. Here F_V is volume flow and C_P is the volume specific heat capacity of the medium. As can be seen in Appendix D, the volume specific heat capacity of water, which is the most common medium in solar collectors together with a mixture of water and glycol, differs about two percent in the relevant range of temperatures.

$$P_{Energy\ Gained} = (T_{out} - T_{in}) \times C_P \times F_V \tag{2.7}$$

With the heat flow method one can see the instant energy gain from the collector and it is also independent from the rest of the system. To determine the energy gathered over a period, one has to integrate over the period of interest. (Rekstad & Meir, 2012)

Calorimetric Method

Calorimetry means to measure heat. The method is explained in more detail by Imenes (1999). The temperature of the heat store is measured before and after activity by the solar collector. Taking the heat loss from the heat store into consideration, as well as heat withdrawn from the heat store and energy consumed by the solar heating system, *EL*, the energy collected by the solar collector during operation is obtained.

$$Q_{\text{Energy Gained}} = (T_{after} - T_{before}) \times C_P \times V + Q_{\text{Heat Loss}} + Q_{\text{Heat Withdrawn}} - EL \tag{2.8}$$

In Equation (2.8) V is the volume of the heat store. $Q_{\text{Heat Loss}}$ is heat lost from the heat store to the ambient during solar collector operation. $Q_{\text{Heat Withdrawn}}$ is energy removed from the heat store during solar collector operation and *EL* is energy consumed by the solar heating system. The latter is removed as it adds heat to the heat store. For the calculation to be correct one has to have a correct mean temperature for the heat store, since the heat store is often layered with warmer water at the top. One either has to mix the water or measure at several places to obtain the correct temperature. Mixing the water will have the side effect of reducing the collector efficiency, since this depends on inlet temperature. The calorimetric method includes heat loss from the pipes in the system in addition to heat received from the pumps, and could therefore be said to be a measure of solar heating system efficiency.

Chapter 3

Previous Studies

This chapter will review methods and results from earlier research on the topic of energy consumptions in passive houses, and will look closer at CEPHEUS, a large European project measuring energy consumption and temperatures in more than 200 erected passive homes and a report from SINTEF Byggforsk, the Norwegian institute for building technology, concerning passive houses in Scandinavia.

3.1 Passive Houses in Europe

A project meant to launch the idea and assess the viability of passive houses in Europe, CEPHEUS consisted of 14 different housing projects in five European countries, each with between 1 and 40 dwelling units first occupied between 2000 and 2001. Their goal was to prove the concept "passive house" by demonstrating that it significantly lowered the need for space heating, that

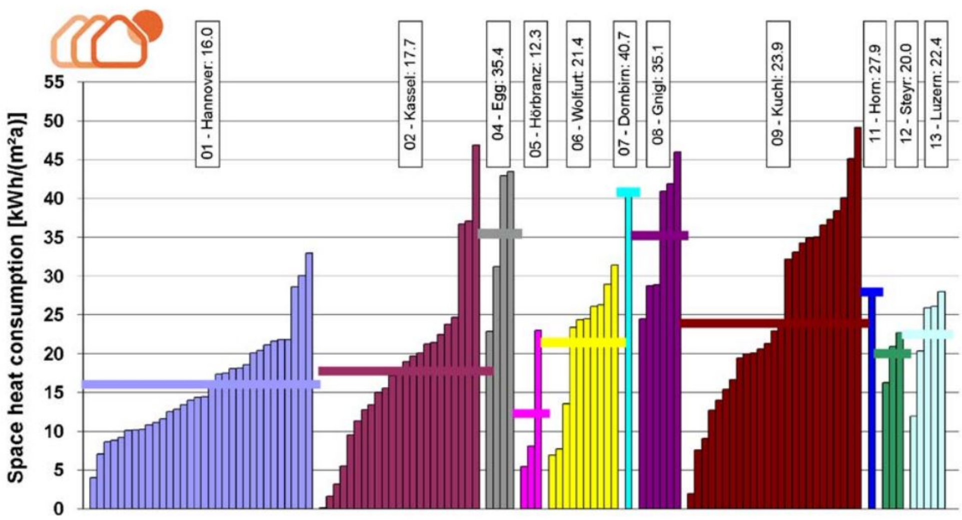


Figure 3.1: *Measured space heating consumption for some of the CEPHEUS projects, in kWh per square meter TFA per annum. Where data from a whole year was not available, the numbers have been extrapolated. (Schnieders & Hermelink, 2006)*

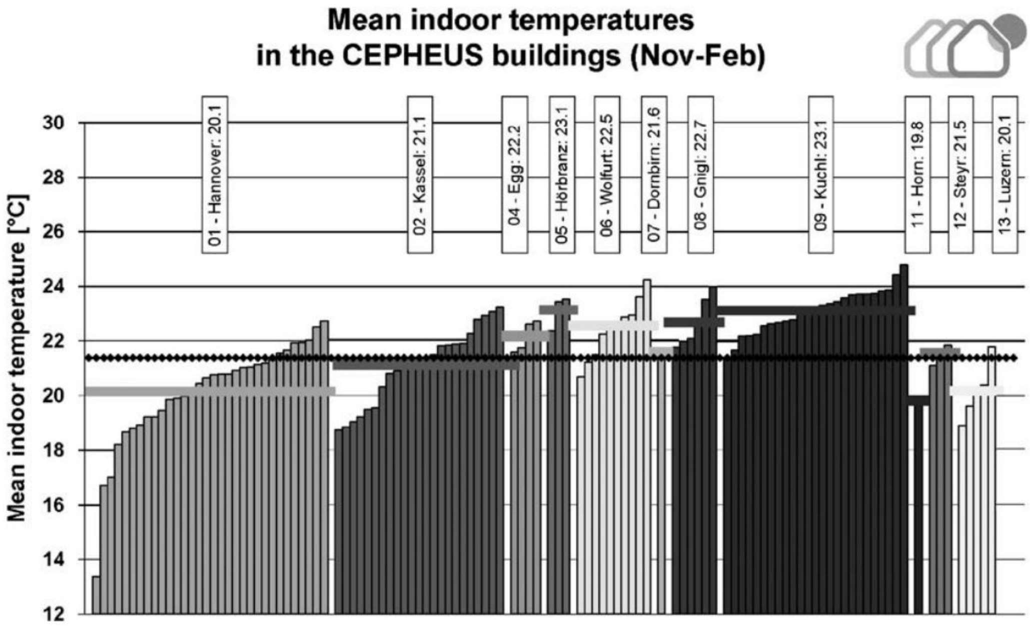


Figure 3.2: Measured mean temperature for the months November to February for selected CEPHEUS projects. Black line indicate overall average. (Schnieders & Hermelink, 2006)

it would not be too costly and that a high level of comfort could be achieved. For all projects energy consumption, hot water consumption and indoor temperatures were measured. For one of the projects, a survey was done among the residents.

Main Results

For the CEPHEUS project, a reduced need for space heating was the most important objective. Figure 3.1 shows the measured consumption of space heating for individual dwelling units, as well as the mean consumption for each project. The numbers are in kWh per square meter TFA per year. TFA stands for treated floor area, and comprise all residential area within the building envelope, and half the area of utility rooms.

We can see that the dispersion of consumption in each project is large. This is partly because some of the apartments were not moved into, but mostly due to different user behavior and number of inhabitants occupying each dwelling. Quite few of the individual units managed to use less than 15 kWh/(m^2a) for space heating, and all but one of the projects had higher mean values, some as high as 35 kWh/(m^2a). This was partly due to erroneous construction (poor airtightness, thermal bridges), but also because indoor temperatures were kept higher than expected. A value of 20 °C is often used when calculating energy consumption, but looking at Figure 3.2 it is observed that the mean indoor temperature for all projects during winter is 21.5 °C. Project 01 and 02 are the largest projects with a fairly low temperature, and these are also the only large projects to come close to the goal of 15 kWh/(m^2a), showing the dependence of indoor temperature on space heating consumption. Even if space heating consumption was higher than expected, for most projects it was still much lower than current building regulation demands, and so it was shown that energy consumption, at least for space heating, could be significantly reduced.

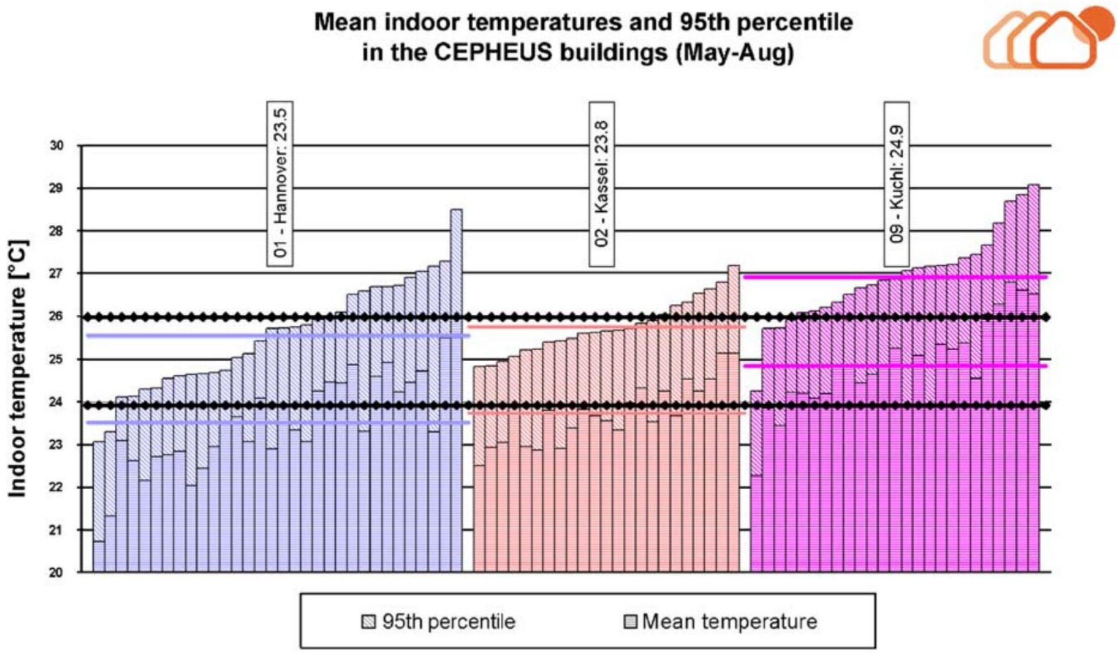


Figure 3.3: *Measured mean temperature and 95th percentile temperature for the months May to August for three of the CEPHEUS projects. Lower black line indicate overall average and the upper its 95th percentile. (Schnieders & Hermelink, 2006)*

Winter indoor temperatures are an important factor in estimating heating consumption, but for such well insulated homes there is a concern that they will become to warm in summer. For CEPHEUS it was important to show that inhabitants could enjoy comfortable indoor temperatures during summer as well. Figure 3.3 shows mean temperatures from May to August for three of the projects. The upper, lighter part of each bar indicate what value the temperature is kept below 95 percent at the time. The average temperature for all three projects was 24 °C, while the temperature was kept below 26 °C 95 percent of the time, which can be said to be a comfortable temperature during summer.

As keeping or improving the degree of comfort was one of the main objectives, a side project called *User-Oriented Design of Passive Houses* funded by the *Deutsche Bundesstiftung Umwelt* looked into residents experience of living in passive house apartments. The project in question (Kassel, 02) included two buildings with 40 dwelling units built for low-income tenants, by the city of Kassel. As can be seen in Figure 3.4, on average the residents experienced an enlarged comfort. When asked why they moved into this project, the fact that there were new buildings with balconies was important, whilst the fact that they were passive houses was the least important factor.

Schnieders and Hermelink conclude that the CEPHEUS project managed to prove the viability of the passive house concept and showed that for a relatively small extra cost, the demand for space heating can be drastically reduced whilst keeping a high level of comfort. The authors go on to say that to further spread the concept, political support is needed and public awareness of passive houses will have to be increased. It was concluded that the lifetime costs of houses and not only investment costs, should be implemented in the asking price when houses are sold.

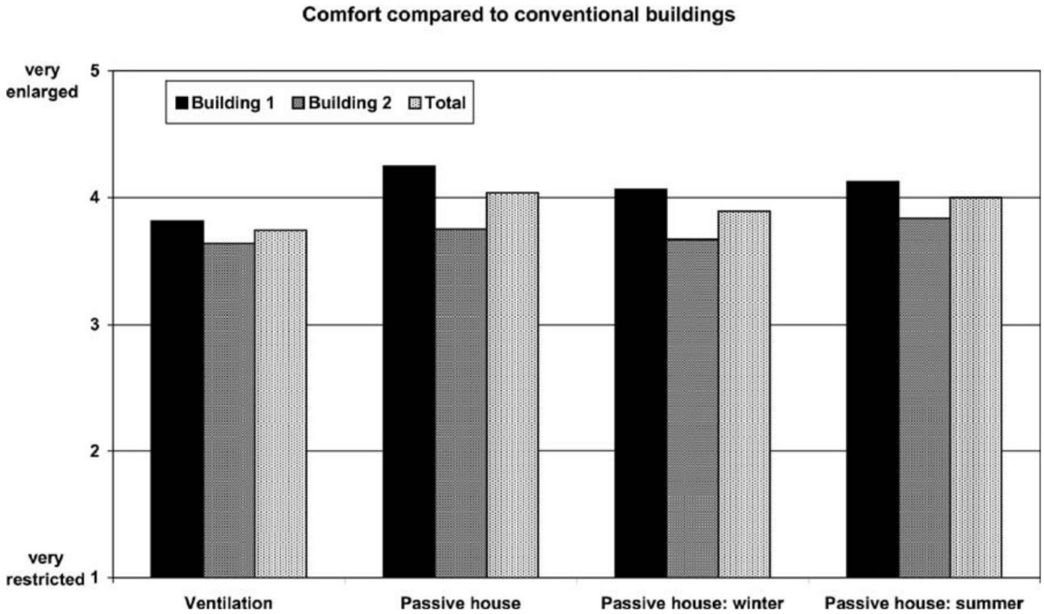


Figure 3.4: *Average rating by tenants in the Kassel buildings when asked to compare different aspects of living in a passive house with their former home. (Schnieders & Hermelink, 2006)*

3.2 Passive Houses in Scandinavnia

3.2.1 Simulations

At the 10th Passive House Conference, Dokka & Andresen (2006) presented some simulations on passive houses in a diverse variety of Norwegian climates. This was done for an apartment building, a series of row houses and a detached house. The detached house was characterized by these parameters: A heated floor area of 160 m^2, external wall area of 180 m^2, roof and floor area of 80.5 m^2 and a window area of 35 m^2, of which half was on the south façade. An indoor temperature of 20 °C and air change rate of 0.45 ach was assumed.

Table 3.1 shows what U-values are needed to meet the passive house standard in different climates, and also an estimate for the thermal insulation needed. It can be seen that it would be difficult to achieve the objectives in Karasjok, where 80 centimeter of insulation is needed, windows with U-values of 0.35 $W/(m^2K)$ and a ventilation system with a heat recovery of 99 percent. The passive house standard would be less demanding in Oslo and Lillehammer, but still a step up from Zürich, which has typical Central-European values.

Dokka & Andresen argue that the commonly used level for internal gain, 2.1 W/m^2, is too low for Norway where historically, low prices for electricity have increased the consumption. The authors suggest 4.0 W/m^2 as a more reasonable value. According to the authors this gives the detached house in Oslo an annual space heating demand of 9 $kWh/(m^2a)$, which is comparable to raising the mean temperature with 5 K. Increasing the internal gain from 2.1 W/m^2 to 4.0 W/m^2 is comparable to moving the house from Oslo to Zürich. They conclude that with the increase in internal gain, the passive house concept will be viable in climates comparable to Oslo and Lillehammer, but not yet for colder climates such as in Karasjok.

Table 3.1: *Building standards necessary to meet the passive house requirement of 15 kWh/m²a for a 160 m² detached house different climates. Thermal insulation thickness based on average thermal conductivity of 0.04 W/m K, taking constructive elements into account. (Dokka & Andresen, 2006)*

Climate	Oslo	Lillehammer	Karasjok	Zürich
Roof construction (nom. insulation thickness)	U = 0.07 W/m^{2}K (~550 mm insul.)	U = 0.07 W/m^{2}K (~550 mm insul.)	U = 0.05 W/m^{2}K (~800 mm insul.)	U = 0.10 W/m^{2}K (~400 mm insul.)
External wall, main façade	U = 0.09 W/m^{2}K (~450 mm insul.)	U = 0.08 W/m^{2}K (~450 mm insul.)	U = 0.05 W/m^{2}K (~800 mm insul.)	U = 0.12 W/m^{2}K (~350 mm insul.)
External wall, gable wall	U = 0.09 W/m^{2}K (~450 mm insul.)	U = 0.08 W/m^{2}K (~450 mm insul.)	U = 0.05 W/m^{2}K (~800 mm insul.)	U = 0.12 W/m^{2}K (~350 mm insul.)
Floor	U = 0.07 W/m^{2}K (~450 mm insul.)	U = 0.07 W/m^{2}K (~450 mm insul.)	U = 0.05 W/m^{2}K (~650 mm insul.)	U = 0.10 W/m^{2}K (~300 mm insul.)
Windows (solar heat gain coefficient)	U = 0.65 W/m^{2}K (g = 0.46)	U = 0.54 W/m^{2}K (g = 0.46)	U = 0.35 W/m^{2}K (g = 0.35)	U = 0.80 W/m^{2}K (g = 0.46)
Ventilation per m^2 (heat recovery)	0.99 m^3/hm^2 (η = 87%)	0.99 m^3/hm^2 (η = 92%)	0.99 m^3/hm^2 (η = 99%)	0.99 m^3/hm^2 (η = 80%)
Air tightness	N50 = 0.45 ach	N50 = 0.45 ach	N50 = 0.3 ach	N50 = 0.6 ach
Specific heat loss	0.38 W/m^{2}K	0.33 W/m^{2}K	0.20 W/m^{2}K	0.51 W/m^{2}K
Annual space heating demand	15.1 kWh/m^{2}a	15.1 kWh/m^{2}a	15.0 kWh/m^{2}a	14.9 kWh/m^{2}a
Peak heat load	10.9 W/m^2	11.5 W/m^2	10.2 W/m^2	12.0 W/m^2

3.2.2 Measurements

The Norwegian institute for building technology, SINTEF Byggforsk, published a report in 2012 aggregating existing experiences and research on passive houses in Norway and other countries.

The Lindås Project

Klinski, Thomsen, Hauge, Jerkø, and Dokka (2012) refer to the first Swedish passive house project of Lindås near Gothenburg, where 20 row houses divided between four buildings were erected. Half of the calculated energy needed for domestic hot water was to be supplied by a solar thermal system with 5 m^2 solar collectors, but the measured values were 37 percent (8.9 kWh/(m^{2}a)). Table 3.2 shows simulated and measured mean consumption for the Lindås project. Measured consumption was slightly larger than simulated. This was mostly due to indoor temperatures being higher than expected. Simulations showed that a temperature of 26 °C compared to 20 °C, tripled the energy consumption for space heating.

In her paper, Wall (2006) mentions passive solar gains, that is, heating of the dwelling from solar radiation coming through the windows, see Section 2.1.4. In the simulations, passive solar gain covers 47 and 38 percent of space heating demand respectively for the 20 °C and 23 °C scenarios.

Table 3.2: *Simulated and measured delivered energy consumption for the Lindås passive house project in Sweden. All numbers in* kWh/(m^{2}a). *(Wall, 2006)*

	Design Stage 20 °C	Design Stage 23 °C	Monitored
Space Heating	6.5	11.1	14.3
DHW	12.4	12.4	15.2
Fans and Pumps	6.2	6.2	6.7
Total	48.9	53.5	68.0

Värnamo, Frillesås, Alingsås and Villa Malmborg

Klinski et al. (2012) go on to mention a project of 40 apartments in Värnamo, in southern Sweden. The annual space heating demand was calculated to 9.8 kWh/(m^{2}a) with an average indoor temperature of 20 °C, increasing to 12.8 kWh/(m^{2}a) for 22 °C. The degree day corrected delivered energy consumption, see Section 2.2, for space heating was measured to 9 kWh/(m^{2}a). The energy consumption for domestic hot water was measured to 25 kWh/(m^{2}a) of which 42 percent was covered by thermal solar heating. Total energy consumption for the project was 63 kWh/(m^{2}a).

Frillesås consists of three buildings, each with four apartments. The estimated need for space heating was 14.8 kWh/(m^{2}a) with an indoor temperature of 20 °C and 18.9 kWh/(m^{2}a) for a temperature of 22 °C. Degree day corrected delivered energy for space heating ended up being 18.8 kWh/(m^{2}a). Of a total energy consumption for domestic hot water of 30 kWh/(m^{2}a), 50 percent was covered with solar collectors. Total amount of delivered energy was 92 kWh/(m^{2}a).

The Alingsås project was a complete renovation of 300 apartments, with a need of delivered energy for space heating of 115 kWh/(m^{2}a) prior to restoration. Renewed heating levels were estimated to 23 kWh/(m^{2}a) for a temperature of 20 °C and 28 kWh/(m^{2}a) for a temperature of 22 °C. Degree day corrected values of 26.6 kWh/(m^{2}a) were measured, while delivered energy for domestic hot water, fans and appliances respectively, were 16 kWh/(m^{2}a), 37 kWh/(m^{2}a) and 43 kWh/(m^{2}a). Total amount of delivered energy is around 86 kWh/(m^{2}a).

Villa Malmborg is a detached house of 171 m^2 over two floors situated in Lidköping, with a stipulated need for space heating of 24.9 kWh/(m^{2}a) at 20 °C, increasing to 31 kWh/(m^{2}a) at 22 °C. Degree day corrected delivered energy for space heating was 33 kWh/(m^{2}a), with a energy consumption for domestic hot water of 18 kWh/(m^{2}a). Delivered energy for fan (ventilation) and appliances were 10 kWh/(m^{2}a) and 30 kWh/(m^{2}a) respectively, giving an overall delivered energy consumption of about 90 kWh/(m^{2}a).

In the projects above, the estimated consumption of delivered energy for space heating is consistent with the measured values. Space heating constitute between 15 and 37 percent of total energy consumption in these projects.

Chapter 4

The Project

The Norwegian housing association OBOS had planned 17 detached passive houses built under the name of Rudshagen, situated at Mortensrud outside of Oslo. To meet the standard for passive houses, all houses would have an air-to-water heat pump. Towards the end of the planning period it was decided that one of the houses should instead have a solar heating system. It was also decided to measure the use of energy in this house, House A, and a neighboring house heated with a heat pump, House B, which to a large extent was identical to House A.

Two similar families of two adults and a small child, moved into the two houses in question in late January 2012. Aventa AS, the supplier of the solar collectors, and the Energy Physics group at the University of Oslo planned the experiment and organized the setup. The project was financed by the Norwegian Research Council through the project SILVER and project partners University of Oslo, Aventa AS and OBOS. The measurements were meant to go on for a whole year, and April 2012 till March 2013 was chosen as the project period. This choice and its implication are discussed in Section 8.1.

4.1 Rudshagen

As mentioned, the housing society of Rudshagen consists of 17 detached houses labeled 101 to 117 in Figure 4.1. OBOS Nye Hjem AS is the developer, and the Rudshagen housing society is a member of the Housing association OBOS. The houses where designed by SPOR Architects and built by Mesterhus AS.

Figure 4.1: *Overview of Rudshagen housing society. (OBOS, 2013)*

Figure 4.2: *The Houses A & B seen with surrounding scenery. (OBOS, 2013)*

An important difference between House A and House B is that they are rotated 90 degrees in relation to each other. House A's balcony and large windows face west while the balcony and large windows of House B face south. This is just possible to make out in Figure 4.1 and 4.2. In Figure 4.2 the immediate surroundings of House A and B can be seen. Worth noting is the buildings and hill on the south side of House A, which cast shadows on the solar collector for parts of the year.

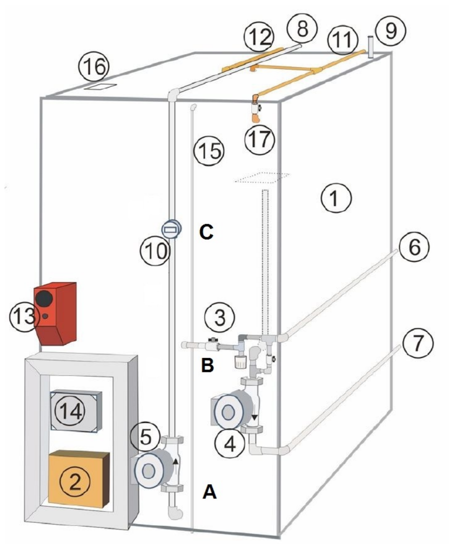
4.2 House A

House A is the house heated by a solar thermal system. It has a gross living area of 116 m^2. It has a closed shed outside of the entrance, since the open storage room found on the other houses was altered in order to make space for the heat store and other systems related to the solar collector. This room will hereafter be referred to as the *technical room*. As can be seen from the floor plan in Figure 4.6, the ground floor includes an entrance, a bath, a combined living room and kitchen, as well as stairs with a closet beneath. The second floor has three bedrooms, a bathroom, a closet and a small hallway. During the project period a family consisting of two adults and an infant child lived in the house.

4.2.1 Heating and Domestic Hot Water System

House A has hydronic floor heating[1] in the two bathrooms, in the entrance and in the hallway on the second floor, in addition to a fan coil in the living room. The fan coil consists of a coil of hot water from the heat store and a fan converting hot water to warm air. All four of the heated floors and the fan coil can be adjusted separately by the users, with a control system delivered by Aventa. The water for space heating comes from the heat store in the technical room. The heat store consists of a thermally insulated steel tank of 800 liter, which is 80 cm wide, 80 cm deep and 125 cm tall. On the sides and top it is isolated with 10 cm of polyurethane foam, and it

[1] Warm water flowing through pipes in the floor, dissipating heat.



1. Heat Store, 800 liter
2. Regulator, uc:symphony
3. Mixing Valve for Hydronic System
4. Pump for Hydronic System
5. Pump for Solar Collector
6. Forward Hydronic System
7. Return Hydronic System
8. Forward Solar Collector
9. Return Solar Collector
10. Flowmeter connected to Datalogger 2
11. Cold Water Supply for Preheating Tank
12. Preheated Water from Preheating Tank
13. Electric Heating Element, 3 kW
14. Terminal box for electrical connections
15. Overflow Pipe
16. Level Monitor
17. Tap for Refilling Heat Store

Figure 4.3: *The heat store and a list of its components. The letters A, B and C mark the approximate placement of the sensors T Tank Bottom, Middle and Top. (Aventa AS, 2012)*

stands on top of 5 cm of styrofoam. An overview of the tank can be seen in Figure 4.3. The heat store is heated by the solar collector and a heating element of 3 kW. 38 cm up from the bottom of the heat store a horizontal steel plate is installed to further enhance the effect of stratified temperatures in the tank. It is perforated to allow flow, but prevent mixing. House A's heating system is outlined in Figure 4.4.

The heat store has room for 800 liter of water, but cannot hold this much as an overflow pipe is situated 5 cm from the top, leaving the heat store with a capacity of around 768 liter. In addition water expands when heated, and at 70 °C which is about the highest temperature achieved, about 751 kg is left, corresponding to 752 liter of 20 °C water. It will be assumed that the heat store has a capacity for 750 kg of water and that every liter measured by a flow meter corresponds to 1 kg of water.

A smaller tank of 96 liter is immersed into the main tank, see Figure 4.4. It is a pressurized steel tank which preheats water for the domestic hot water boiler, from now simply referred to as the DHW boiler, situated in the bathroom on the first floor. The DHW boiler is a 76 liter boiler with a 2 kW heating element, serving the taps in the kitchen and bathrooms. Upon leaving the DHW boiler, the domestic hot water enters a thermostatic mixing valve which is supposed to cool down the 75 °C water to 50 °C, by mixing it with preheated water. Warmer preheated water means less water from the DHW boiler. Of course, when the preheated water exceeds 50 °C this will be the minimum temperature and in theory no water from the DHW boiler should then be used. As later chapters will show, this was not the case.

4.2.2 The Solar Collector

The solar collector is situated on the top half of the south façade, as can be seen in Figure 4.5. It consists of 13 panels 60 cm wide and 300 cm high. The mid panel is passive and only present for aesthetic reasons and it will therefore not be considered a part of the solar collector. Each panel has a 3 cm frame on both sides, a 7.5 cm frame covering the top and a 1.5 cm inactive part at the bottom. This gives gross and active areas of:

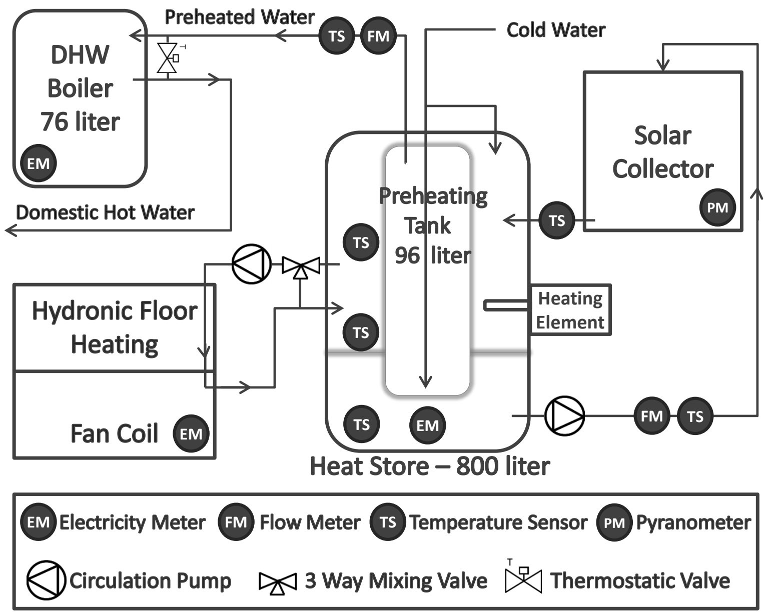


Figure 4.4: *Overview of the solar thermal heating system and its most important elements. Also shown are some of the sensors used in this project.*

$$\text{Gross Area} = 12 \times 0.60\,\text{m} \times 3.00\,\text{m} = 21.6\,\text{m}^2$$

$$\text{Active Area} = 12 \times 0.54\,\text{m} \times 2.91\,\text{m} = 18.9\,\text{m}^2$$

The absorber is made of polyphenylene sulfide (PPS) and has an absorptance of 0.95. The cover sheet is made of polycarbonate (PC) and has a transmittance of 0.85. It is a drain-back collector with pure water as heat carrier. See the data sheet in Appendix C for more details.

The pyranometer measuring solar irradiance, visible in the lower right corner of Figure 4.5, is located next to the lower part of the collector. It will not at all times share the solar conditions of the solar collector, especially not when the sun is low and nearby trees and houses shadow for either the collector or the pyranometer. Even so, it was assumed that the pyranometer had the same solar conditions as the collector, as no easy way to rectify this was found. The pyranometer sends a signal to Datalogger1, which is recorded as a mV signal. To get the wanted units of W/m^2, the signal must be divided by a calibration factor of $0.191\,(\text{m}^2\text{mV})/\text{W}$. The pyranometer was new and had been calibrated by the manufacturer.

As mentioned, the solar collector does not have a free view to the south. In the south-southeast lies a 5-story apartment building. In the southeast and the south lies two houses similar to houses A & B, but on slightly higher ground. To the southwest and south-southwest lies a hill with houses and trees. Because of this and an upward incline southwards with other buildings in some distance, the collector is in shadow from late November till early February, rendering the solar collector idle for about three months. See Figure 4.2.

Figure 4.5: *Solar collector on south wall of House A at Rudshagen.*

4.2.3 Measurements

In House A, two dataloggers from Almemo are situated in the technical room together with the heat store. Datalogger1 measures the temperature in the kitchen on the ground floor and next to the stairs on the second floor. These are measured with in-wall sensors. As mentioned, a pyranometer measuring the solar irradiance is situated on the wall next to the solar collector. A volume meter on the pipe from the preheated tank in the heat store to the DHW boiler measures the consumption of domestic hot water. Energy meters in the fuse box are connected to electric circuits: The fan coil, the DHW boiler and the technical room all have separate electric circuits. The meter connected to the technical room measures the energy use of all electrical equipment, including the pumps, the lights, the dataloggers and the controllers for the heat store. The pump for the floor heating, the pump for the solar collector and the 3 kW heating element draws the most power. Datalogger1 also measures the temperature of the preheated water flowing to the DHW boiler, with a thermocouple attached to the pipe. Another thermocouple was later configured by Aventa to measure the temperature of the solar collector pump, as this had been behaving strangely.

Datalogger2 measures the temperature outside with a sensor on the eastern wall (∼2 meters above ground) and one on the northern wall (∼5 meters above ground). The *T East* sensor is a thermocouple contained in a small, white plastic box for protection. The *T North* sensor thermocouple was encapsulated in a black plastic box. Datalogger2 also measures the temperature inside the technical room. Three thermocouples were fastened on the heat store: one at the bottom, one in the middle and one on top. In Figure 4.3 these are marked with the letters A, B and C respectively. The bottom sensor occasionally gave false values, and was replaced with a thermocouple type K on October 2 2012. The flow through the collector and the temperature of the water going into the collector were measured with a combined flow and temperature sensor, located on the pipe above the collector pump. The flow meter measured flow with the *vortex flow* principle. A sensor attached to the return pipe measured the temperature on the water returning from the collector. A last temperature sensor was used for different measurements, mainly measuring the temperature of the pipe forwarding water to the floor heating system.

See Table 4.1 on page 24 for a list of sensors found in House A. Most sensors are also visible on Figure 4.4. If not stated otherwise, temperatures are measured with thermocouples type T.

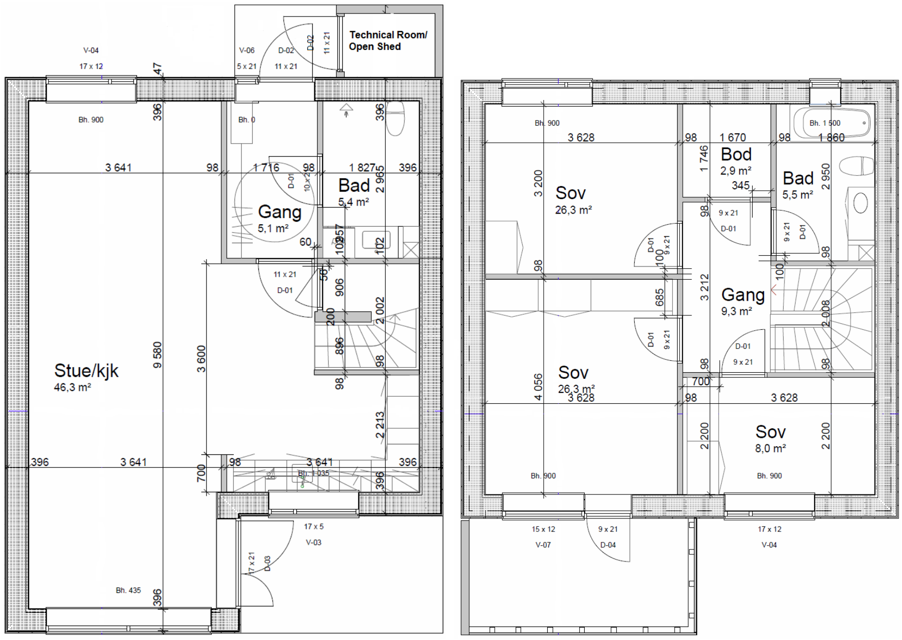


Figure 4.6: *Building plan for ground floor (left) and second floor (right). Both houses share this building plan, but House B is mirrored and has an open shed by the entrance. (Mesterhus, 2013)*

4.3 House B

House B is the house with the heat pump. As House A, it has a gross area of 116 m^2, and except being mirrored, the houses share the same floor plan. A small room for the evaporator of the heat pump, as well as an open shed is found were House A has the technical room. The family living here is similar to that in House A, consisting of a couple with a small child.

4.3.1 Heating and Domestic Hot Water System

In this house, the heating system consists of a Toshiba air-to-water heat pump with an inner and an outer part. In the ground floor bathroom stands a heat store of 300 liter, which is heated by the heat pump but also has the possibility of using a 3 kW heating element. During the project period the water in the boiler was kept in the approximate temperature range 35 °C to 40 °C. The hydronic system is similar to the one in House A. From the heat store, the floors in both bathrooms and the floors in the entrance and the hallway in the second floor are heated. A fan coil is situated in the living room. As in House A, all four of the heated floors and the fan coil can be adjusted separately by the users, but with a different control system than the one found in House A. An overview of the heating system in House B can be seen in Figure 4.7.

A DHW boiler of 76 liter with a 2 kW heating element is situated below the stairs, see Figure 4.6. It gets its water from the heat store. When leaving the DHW boiler, the domestic hot water is mixed with the preheated water in a thermostatic mixing valve to obtain a non-scalding temperature of 50 °C but as the next chapter will show, this does not seem to work properly.

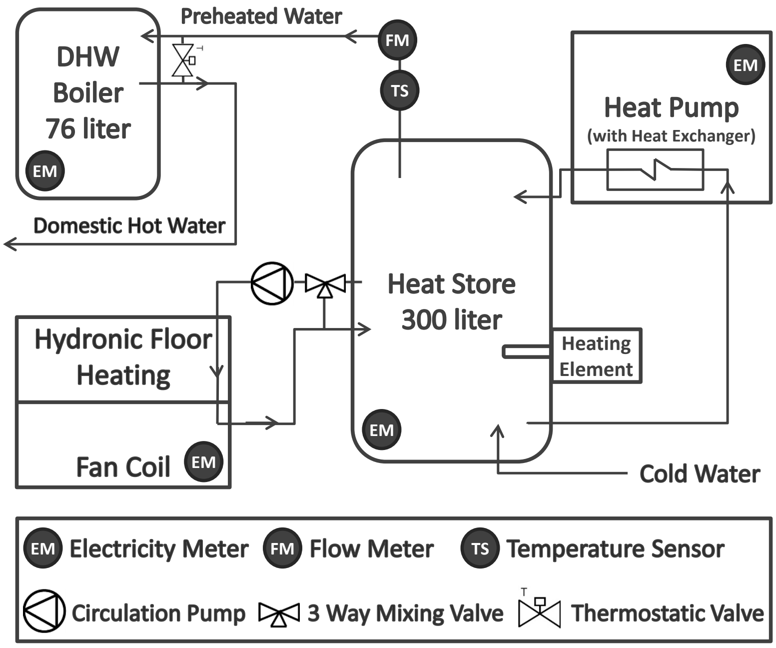


Figure 4.7: *Overview of the heating system in House B and its most important elements. Also shown are some of the sensors used in this project.*

Heat Pump

As mentioned above, the heat pump's evaporator is situated in a little compartment on the backside of the shed by the door. The condenser is found in a compartment underneath the stairs, together with the DHW boiler, while the 300 liter heat store for the heat pump is located in the 1st floor bathroom. Figure 4.7 has merged the evaporator and the condenser part of the heat pump, as their energy is taken from the same circuit and measured by the same electricity meter. Technical specifications for the heat pump is found in Appendix B.

4.3.2 Measurements

In House B an Almemo datalogger, Datalogger3, is located in the compartment below the stairs. It measures the temperature in its immediate vicinity, for estimation of the DHW boiler's heat losses, and the temperature in the kitchen on the ground floor and next to the stairs in the second floor. From March 30 2012 it also measured the temperature of the preheated water flowing from the heat store to the DHW boiler.

All equipment in relation to heating and domestic hot water have separate circuits in the fuse box. An energy meter sends a signal to the datalogger for every 10 watt hour that is used by the heat pump, the heat store, the DHW boiler and by the fan coil. The energy meter connected to the DHW boiler was wrongly installed, but corrected on March 23 2012. We therefore only have the total energy use for this circuit for the period January 25 to March 23, and not the hourly consumption. A volume meter below the stairs measures the use of domestic hot water.

A list of all sensors in House B is found in Table 4.2. Most sensors are shown in Figure 4.7.

4.4 List of Sensors

Table 4.1: *List of sensors, House A*

Sensor Name	Measures	Placement
T Inside 1st	Temperature [°C]	Kitchen 1st floor, next to stairs
T Inside 2nd	Temperature [°C]	2nd floor, next to stairs
Flow DHW	Volume [liter]	On top of heat store
EL Technical room	Electricity use [10 Wh]	Fuse Box, Entrance
EL DHW	Electricity use [10 Wh]	Fuse Box, Entrance
EL Fancoil	Electricity use [10 Wh]	Fuse Box, Entrance
Pyranometer	Solar Irradiance [mV]	South facing wall, next to solar collector
Flow Collector	Flow [liter/min]	Front of heat store
T Collector Forward	Temperature [°C]	On inside of pipe going to solar collector
T Collector Return	Temperature [°C]	On pipe returning from solar collector
T Technical Room	Temperature [°C]	Inside technical room
T Tank Bottom	Temperature [°C]	Front of heat store
T Tank Middle	Temperature [°C]	Front of heat store
T Tank Top	Temperature [°C]	Front of heat store
T East	Temperature [°C]	2 m up on eastern wall
T North	Temperature [°C]	5 m up on northern wall
T Forward DHW	Temperature [°C]	On pipe for preheated water
T Solar Pump	Temperature [°C]	Front of heat store
T Elbox	Temperature [°C]	Front of heat store

Table 4.2: *List of sensors, House B*

Sensor Name	Measures	Placement
T Below Stairs	Temperature [°C]	Under stairs, next to Datalogger3
T Inside 1st	Temperature [°C]	Kitchen 1st floor, next to stairs
T Inside 2nd	Temperature [°C]	2nd floor, next to stairs
Flow DHW	Volume [liter]	Next to Datalogger3
EL Heat Pump	Electricity use [10 Wh]	Fuse Box, Entrance
EL Heat Store	Electricity use [10 Wh]	Fuse Box, Entrance
EL DHW small	Electricity use [10 Wh]	Fuse Box, Entrance
EL Fancoil	Electricity use [10 Wh]	Fuse Box, Entrance
T Forward DHW	Temperature [°C]	On pipe for preheated water, next to Datalogger3

Chapter 5

Methods

5.1 Measurements

With the use of dataloggers, large amounts of data was collected from both House A and B. The data collected from House A was designed to facilitate an in-depth analysis of the solar heating system and the house's energy consumption. In addition, some data were collected from House B as a basis for comparison.

5.1.1 Dataloggers

Data from the dataloggers at Rudshagen were collected at different intervals. Collecting the data took between 5 and 15 minutes for each datalogger, during which time the dataloggers did not record measurements. The total time of non-recording should be less than 0.5 ‰ of a year.

In the beginning the dataloggers logged their values only every half hour, but from January 31 2012 they collected data every 15 minutes. The measured use of electricity and domestic hot water was accumulated over time, recorded every measurement period and then reset. The temperature sensors measured the instant temperature at the time of measurement. The flow meter measuring collector flow and the pyranometer also measured instant values, but were changed during March 2012 to instead record the average measured value over the measurement period of 15 minutes.

5.1.2 Measurements - House A

House A had two dataloggers, Datalogger1 and Datalogger2. For the most part the dataloggers worked well, but at two instances, Datalogger 2's power supply was pulled out and temperature data, outside and from the heat store, are therefore missing for the periods from 02.05.2012 to 08.05.2012 and from 13.09.2012 to 18.09.2012. The average daily outside temperature from these periods could to some extent be reproduced with the help of weather data from the Norwegian University of Life Sciences (Thue-Hansen & Grimenes, 2013).

Figure 5.1 shows a plot of two days of raw data collected from House A. These days were both sunny and the temperature in the heat store, *T Tank Middle*, lies around 65 °C. One can see the temperature in the heat store drop in the morning of May 25, as tens of liter of domestic hot water, *Flow DHW*, is consumed. The temperature sensors outside, *T East* and *T North*, can be seen to show elevated values as they are exposed to direct solar radiation. May 25 2012 was the warmest day of the project period. The family in House A went away on the evening of the 25th, and the house was unoccupied the next day. Hence there was no use of domestic hot water on the 26th.

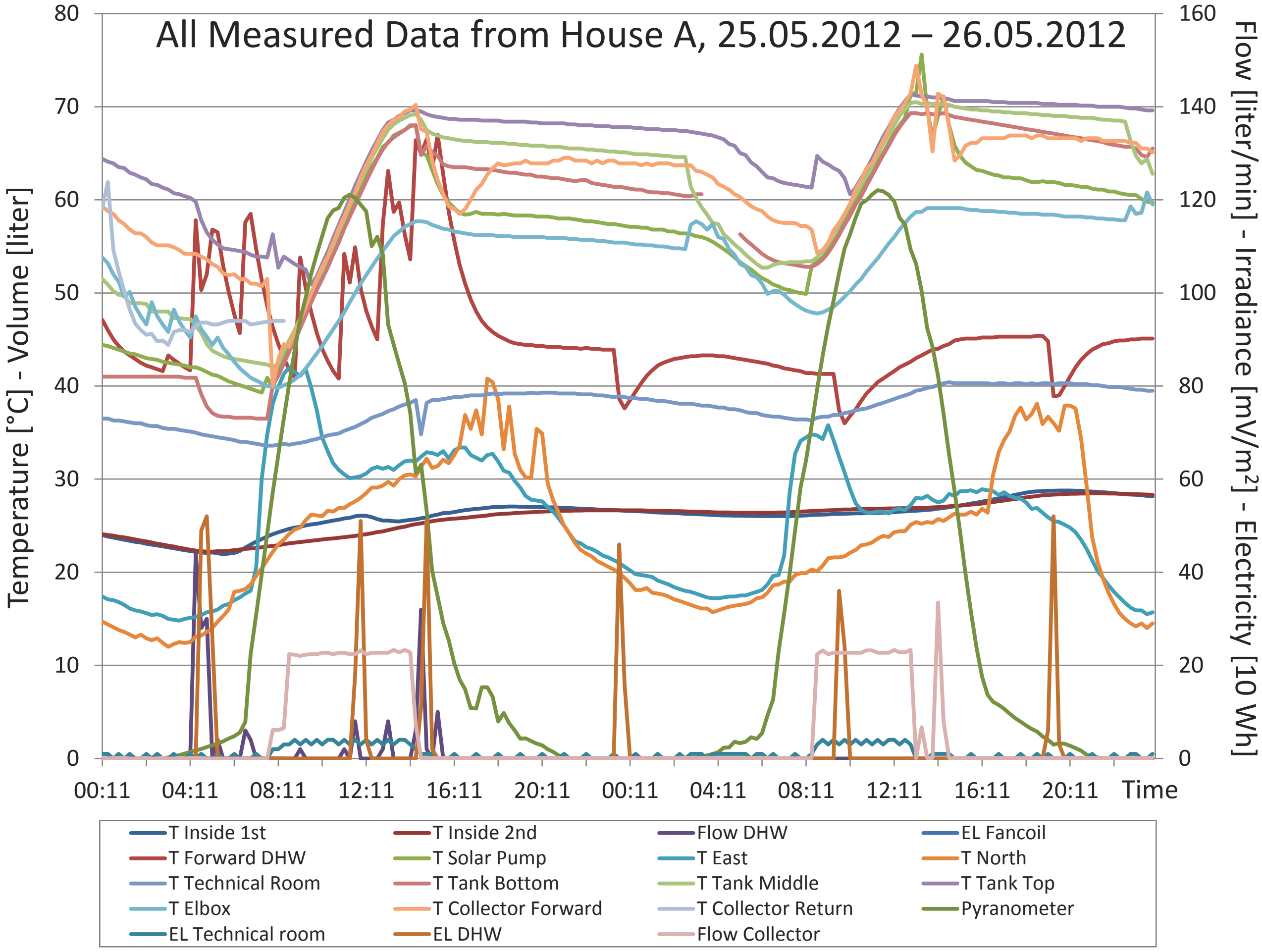


Figure 5.1: *Example of raw data from House A. Measurements from 25.05.2012 to 26.05.2012. Values labeled with T are temperatures, EL is electricity consumption, Flow Collector is liter of water per minute and Flow DHW is consumption of DHW in liter.*

5.1.3 Measurements - House B

House B had one datalogger, Datalogger3. It was attempted to avoid collecting data from House B when the heat pump was active, as this would prevent the energy consumption by the heat pump to be recorded during data collection. However this was not always possible. There were no individual outdoor temperature measurements recorded for House B. Instead measurements from House A were used.

Figure 5.2 shows all data measured from May 25 to May 26 2012 in House B. It is about half the number of variables compared to House A and so the plot is less cluttered. The day was warm so the heat pump, *EL Heat Pump*, was not very active, but if we compare with the outdoor temperature measurements in Figure 5.1, we see that many of its active periods were during relatively cold periods of the day. We see that flow of domestic hot water, *Flow DHW*, often indirectly triggers both the DHW boiler, *EL DHW small*, and the heat pump to start, since the addition of cold water to the heat store and to the DHW boiler lowers the temperature,

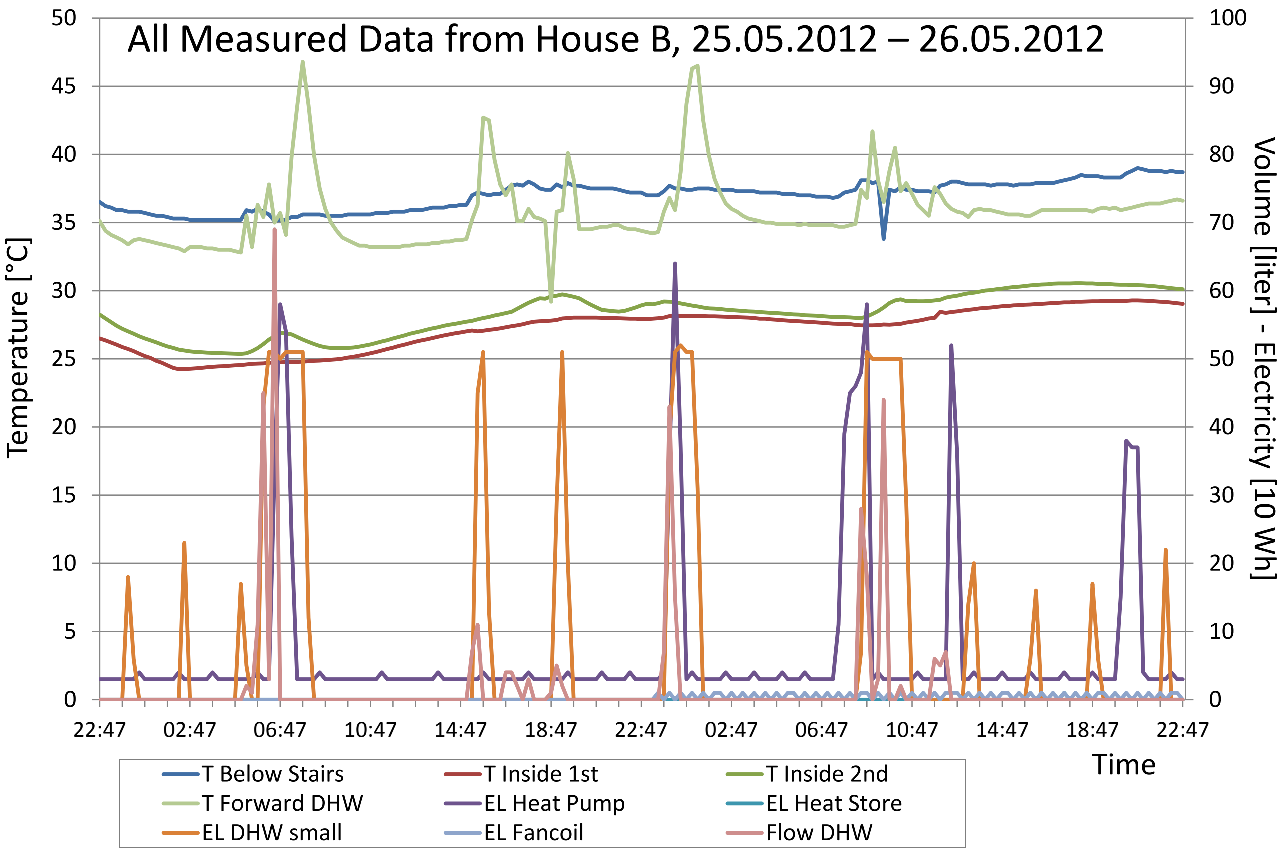


Figure 5.2: *Example of data measured in House B. The prefixes in the sensor names denote the following:* T *for temperature,* EL *for electricity consumption and* Flow *for volume of DHW in liter.*

triggering the thermostats. The thermocouple measuring the temperature of the preheated water, *T Forward DHW*, gets heated by the flow of domestic hot water, then often heated even more by the activity of the DHW boiler. It can be seen that the inside temperature, *T Inside 1st* and *T Inside 2nd*, is in general higher than in House A.

5.2 Methods for Analysis

5.2.1 Sorting Data with Matlab

The data were read out as Excel-files, which were compiled together to one file as they were collected. Several MATLAB-scripts were written in order to sort out the information from the Excel-file which had more than 42 000 lines and more than a million data points. The main script sorted the data into hours, days and weeks. Another script analyzed the heat pump's activity, see section 7.3.2.

5.2.2 Methods for Analyzing Domestic Hot Water

Energy used for Preheating

A considerable amount of the energy consumed by the heat pump and heat store heating element in House B or in the technical room of House A is used for preheating domestic hot water, and not for space heating purposes. When looking at the energy used it is helpful to know for what purpose the energy has been used. Methods for allocating the delivered energy for domestic hot water were developed for both houses.

House A - Domestic Hot Water

The domestic hot water consumption and temperature of the preheated water were measured. Using temperatures obtained from Oslo Water and Sewerage Department (2013) for the cold water entering the heat store, the energy used to preheat the water, was added to get the total amount of delivered energy for domestic hot water by the following formula:

$$E_{\text{DHW-A}} = EL_{\text{BOILER}} + \Delta T\ C_P\ V_{DHW} \tag{5.1}$$

$E_{\text{DHW-A}}$ is the total amount of energy delivered in the form of electricity for domestic hot water to House A. EL_{BOILER} is the energy used by the DHW boiler, ΔT is the temperature difference between the preheated water and cold water in the relevant week, C_P is the specific heat capacity of water, 1.16 Wh/(liter K) and V_{DHW} is the consumption in liter of domestic hot water. The energy then added to the DHW energy consumption was subtracted from the energy used in the technical room. As the heat store retrieved energy from the solar collector there were weeks when the energy used in this room was lower than what was subtracted. When this occurred, all energy delivered to the technical room was allocated to DHW. Any rest energy in the technical room was assigned to space heating.

House B - Domestic Hot Water

In House B the heat pump delivers the majority of heat to the heat store, with a heating element contributing when needed. The formula used for allocating domestic hot water energy consumption was the following:

$$E_{\text{DHW-B}} = EL_{\text{BOILER}} + \frac{\Delta T\ C_P\ V_{DHW}}{\text{COP}} \tag{5.2}$$

$E_{\text{DHW-B}}$ is the total amount of energy delivered for domestic hot water in House B. EL_{BOILER} is energy delivered to the DHW Boiler, ΔT is the temperature difference between the preheated water and cold water for the relevant week, C_P is the specific heat capacity of water 1.16 Wh/(liter K) and V_{DHW} is the consumption of domestic hot water in liter. To achieve an average Coefficient of Performance (COP) of 3 over the year, which was the value assumed, the following equation was used:

$$\text{COP} = \sqrt{\frac{T_{\text{2nd FLOOR}}}{T_{\text{BELOW STAIRS}} - T_{\text{OUTSIDE NORTH}} + 6\,\text{K}}} \tag{5.3}$$

As a real COP, this COP was dependent on outdoor temperature. The COP arrived at in such a manner was probably too high in cold weather and too low in warm weather, but still better than using an average for all weeks in the year.

Temperature of Domestic Hot Water

The temperature of the domestic hot water was not measured, as a thermostatic mixing valve was supposed to keep it fixed at 50 °C. But measurements of preheated water temperatures and DHW boiler consumption showed that this was not the case and a method for estimating this temperature was conceived. It is based on the assumptions that the DHW boiler starts and stops at given temperatures, and that the heat loss from the boiler is constant, and that there is no stratification in the boiler. Energy balance considerations give

$$V_{\mathrm{DHW}}\ C_{\mathrm{P}}\ (T_{\mathrm{DHW}} - T_{\mathrm{preheated}}) + t\ P_{\mathrm{loss}} = E \tag{5.4}$$

In Equation (5.4) V_{DHW} is the volume of consumed domestic hot water and C_{P} the specific heat capacity. P_{loss} is the heat loss from the DHW boiler in watts, t is the time between two withdrawals of domestic hot water and E is the energy used by the DHW boiler in the time period t. As all parameters, including temperature of the preheated water, are measured or can be estimated, the domestic hot water temperature is the only unknown parameter. A reshuffling of the equation gives:

$$T_{\mathrm{DHW}} = \frac{E - t\ P_{\mathrm{loss}} + T_{\mathrm{preheated}}\ C_{\mathrm{P}}\ V_{\mathrm{DHW}}}{C_{\mathrm{P}}\ V_{\mathrm{DHW}}} \tag{5.5}$$

Converting the measured DHW consumption, V_{DHW}, from the found temperature, T_{DHW}, to the anticipated temperature of 50 °C can be done using

$$V_{50\,°\mathrm{C}} = \left(\frac{T_{\mathrm{DHW}} - T_{CW}}{50\,°\mathrm{C} - T_{CW}}\right) \times V_{DHW} \tag{5.6}$$

where T_{CW} is the temperature of the cold water. The equation above was applied on both houses using an value for T_{CW} of 6.6 °C, which was the average over the project period, of the weekly temperatures obtained from Oslo Water and Sewerage Department (2013). As the consumption of domestic hot water is quite stable throughout the year, the error arising from the use of this average is small, compared to other errors.

5.2.3 Methods for Analyzing the Solar Heating System

When analyzing the yield of the solar heating system, two main methods were used, both mentioned in Section 2.3.2: the heat flow method and the calorimetric method.

Heat Flow Method

The heat flow method can calculate the instant power of the solar heating system. The main principles behind heat flow method were presented in Section 2.3.2 and the relevant equation is

$$P_{Energy\ Gained} = (T_{Outlet} - T_{Inlet}) \times F_V \times C_P \tag{5.7}$$

Here, $P_{Energy\ Gained}$ is the power of the solar system, F_V is referring to the volume flow of water through the collector, while C_P is the specific heat capacity of water. T_{Inlet} and T_{Outlet} are the temperatures of the water flowing into and out from the solar collector respectively. In principle, the collector forward temperature sensor, *T Collector Forward*, gives the most accurate values for the inlet temperature. This sensor, which is a combined temperature and flow meter, is situated on the inside of the pipe transporting the water from the heat store to the solar collector. However, the collector return sensor measuring outlet temperature, is fastened to the outside of the return pipe. This placement leads to an underestimation of these temperatures. As can be seen in Equation (5.7), it is the temperature difference that is the important parameter. As the temperature sensor at the bottom of the heat store is located on the outside of the heat store, next to the outlet for the collector, measurements from this sensor were used as inlet temperature.

The heat flow method was used as a quantitative method, applied on several thousand lines in Excel at once. An IF-command in Excel was used to pick out the periods when the solar pump was active, demanding a flow rate higher than 0.6 liter/min as the *Flow Collector* sensor sometimes recorded false values of 0.1 or even negative values when no water was flowing. Temperatures in the bottom of the heat store, collector forward and collector return were sorted out, together with average flow through the collector and the *Pyranometer* measurements.

Calorimetric Method

The average temperature in the heat store was found using the three sensors fastened directly to, and in good contact with the tank. It was assumed that the water in the heat store consisted of three homogeneous layers, each with their corresponding temperature sensor. 240 liter in the bottom, 300 liter in the middle and 210 liter at the top, adding up to 750 liter. The average heat store temperature before startup of the solar thermal system and when the heat store was at its warmest was calculated. Using this temperature difference, ΔT, the energy added to the heat store was found. Energy from other sources going into or leaving the heat store also had to be considered: Heat loss from the heat store, supply of cold water to the preheating tank, energy supplied by pumps or heating element. Heat also left the heat store through the hydronic floor heating system. By averaging the energy used or lost by the heat store before and after activity by the solar collector, correcting for use of domestic hot water, a more correct result for energy added to the heat store was arrived at:

$$Q_{\text{Energy Gained}} = \Delta T \times C_P \times 750\,\text{l} - \text{EL} + DHW_{Preheat} + \text{HEAT} \tag{5.8}$$

EL is electricity consumption in the technical room during solar collector operation and is measured directly. It includes electricity consumption of both heating element and the pump for the solar collector, but also the pump for the hydronic system, a lamp, the dataloggers and the control unit for the solar heating system.

$DHW_{Preheat}$ is energy withdrawn from the heat store during solar collector operation in the form of preheated domestic hot water. This parameter is derived using measured data and corresponds to the second part of Equation (5.1), but here the temperature of the cold water is assumed to be 5.7 °C[1] throughout the year.

HEAT represents the energy used for space heating. It cannot be measured whilst the solar collector is in operation, but has to be estimated by considering the energy used before and after collector activity. It also includes heat losses from the heat store. It was derived at by adding together the change of energy in the heat store due to temperature changes and the energy consumed in the technical room and subtracting the energy used for preheating of domestic hot water.

5.2.4 Corrected Outdoor Temperatures

As mentioned in Chapter 4 the outdoor temperature sensor, *T East*, was encapsulated in a white plastic container for protection against the elements. Measurements showed elevated temperatures during exposure to direct solar radiation. The sensor on the northern façade, *T North*,

[1] Too late to correct, this value was found to be erroneous. But as mentioned in Section 5.3.2, the error caused by this mistake is small.

was exposed to less direct solar radiation, but as it was contained in a black box it also showed elevated temperatures. This can be seen in Figures 5.1 and 6.11, in the morning for the east sensor and in the evening for the north sensor. In general the northern sensor showed slightly lower temperatures than the eastern one, which could be caused by radiative cooling. From the northern façade it was further to neighboring houses and the northern sensor had a larger view of the sky. Figure 6.11 shows that the mean temperature difference between the sensors are small mid day, and larger during nighttime, which support the radiative cooling theory.

Outdoor temperatures are used in several of the analyses and to compensate for the elevated measurements, a routine in EXCEL distinguished the times when a sensor had too high temperatures by comparing the two sensors, as the measured temperature offset between the sensors was quite constant. The routine then corrected the value by replacing it with the average offset of the two sensors ahead of the error, added to the value of the other sensor.

At two instances Datalogger2 did not record measurements. Meteorological data from the Norwegian University of Life Sciences at Ås (Thue-Hansen & Grimenes, 2013) was used to reconstruct daily mean values for those 13 days. These reconstructed mean temperatures were used when calculating yearly and monthly mean temperatures.

5.3 Sources of Error and Error Estimation

5.3.1 Errors in Measurements

The accuracy of the measurements depend on the equipment. In Appendix E the sensors used are listed with their manufacturer and accuracy. As can be seen, a certain error stems from the dataloggers themselves.

The error caused by the sensors on measured electricity consumption is ± 2 percent. In addition, an error arises as the dataloggers do not record consumption while data is collected from them. But the total time used on readout for each datalogger should be less than 5 hours in a year, and therefore insignificant compared to the sensor accuracy. These measurements were probably those with the least errors in the project.

Temperature measurements have several sources of error. Most sensors had an accuracy of ± 0.05 K, but other errors dominate. As seen in the previous section, external sources as solar irradiance could affect the measured temperature. In both houses, the indoor temperature sensors *T Inside*, could be exposed to solar irradiance. In addition, the ventilation system or user behavior could cause the sensors to measure a temperature not representative to the indoor temperature. By looking at the measurements, solar irradiance does not seem to be a problem for the indoor temperature sensors. Other thermocouples, like *T Forward DHW (B) and T Below Stairs* in House B, are in the vicinity of a freezer that occasionally produced heat. The *T Forward DHW (B)* is also affected by the activity of the DHW boiler, which is connected to it with 1 m of brass pipe. All temperature sensors measure an instant temperature every 15 minutes. The measured temperature is not necessarily representative for the last 15 minutes. The *T Tank* sensors attached to the heat store in House A for instance, will during solar collector activity or when many liter of domestic hot water is used experience rapid changes in temperature. On top of all this, errors also arise from calibration uncertainties.

The *Pyranometer* was put in average mode in March 2012, recording the average solar irradiance in the past 15 minutes. It has a ± 3 percent accuracy and its measurements could probably be trusted, but since its placements on the façade is not the same as the solar collector, it will not always measure the same solar irradiance as the irradiance striking the collector. The collector itself is rather large and at times the solar irradiance will vary across it.

The *Flow DHW* sensors in both houses have an accuracy of ± 2 percent, but at low flow rates of 1 liter/min or less, they will underestimate the amount with about 5 percent.

The combined temperature and flow sensor from Ahlborn measured flow with the *vortex method*, which utilize that the rate of vortices created behind a barrier in a pipe is proportional to the flow rate. The *Flow Collector* sensor also measured flow when the water was running back from the collector, confounding the measurements. At times it also measured small values of about 0.1 liter/min, when the flow clearly was zero.

5.3.2 Errors in Analysis

All analysis involving the use of temperatures was affected by the nature of these measurements, described above. The *HEAT FLOW METHOD* was also affected by the errors from the *Flow Collector* sensor, and especially when the solar collector was active for a short period only, the derived values could be negative or several times the value arrived at with the calorimetric method. It could not separate the flow rates measured when the water was running backwards from the normal flow rates, and a slightly delayed temperature sensor could give large errors. When the collector was active and stable for a longer time the heat flow method would normally yield results close to what was derived with the calorimetric method, but often differing with 10 to 25 percent. All in all the heat flow method, as applied in this thesis, did not seem trustworthy.

The *CALORIMETRIC METHOD* for analyzing the solar yield, depended on the accuracy of the temperature measurements from the heat store in House A, as well as on some assumptions. It was assumed that the heat store contained 750 liter of water. This is probably the minimum and it could be up to 18 liter more. The heat capacity of the heat store was not included. It weighed about 100 kg and being mostly of steel, this gives it a heat capacity of around 13.6 Wh, corresponding to around 12 liter of water. Together this adds up to a possible underestimation of 4 percent. The heat store was imagined to be stratified, with each of the three heat store sensors being attached to a layer. Choosing different sizes for the layers, within reasonable limits, could change the temperature ± 2 K, but since the temperature difference was the important parameter this did not have large effects. When taking the flow of domestic hot water into account, a too low mean temperature of the cold water of 5.7 K was used by mistake. On days with large consumption of domestic hot water this could have an effect, but on most days the error caused by this mistake was less than 0.1 percent. The error arising from using an annual average value for the temperature of cold water, and not real temperatures was probably larger, but should not exceed 1 percent on average even though it could be higher at times. Estimating the space heating consumption proved difficult and before and after values were used. But solar days when the solar collector was not active showed that space heating thus could be overestimated with 300 percent at the most, though yielding reasonable values on other days. This could on seldom occasions lead to overestimation of solar collector yield with as much as 15 percent.

Analysis of the domestic hot water was based on measurements from the DHW boilers, temperature sensors and data from the Sewerage Department. Electricity consumption by the DHW boilers was probably about as accurate as stated in the appendix, but measurements from the *T Forward DHW* sensors could be affected by their surroundings. Also, when small amounts of preheated water passed, the sensor would have time to cool down if this happened in the beginning of the 15 minutes period, giving too low temperatures.

The analysis of the heat pump's efficiency used mostly measured raw data and thus it can be said to be quite accurate, but the linear fits did not match up exactly with the data points, and cannot themselves be said to be accurate.

Chapter 6

Results

6.1 Key Results

House A

***Table 6.1: Key Results** - House A*
See text for further explanations.

April 1 2012 to March 31 2013	**House A**
Total delivered energy for space heating and DHW	9670 kWh
Delivered energy for space heating	6215 kWh
Delivered energy for space heating per m^2	53.6 kWh/m^2
Delivered energy to DHW boiler	2294 kWh
Delivered energy for DHW	3454 kWh
Delivered energy for DHW	29.8 kWh/m^2
Total amount of delivered energy per m^2	123 kWh/m^2
DHW consumption	43 113 liter
Average temperature of DHW	67.6 °C
Average indoor temperature	22.5 °C
Days with residents away	56
Average outdoor temperature	6.0 °C
Total insolation on south façade	657 kWh/m^2
Yield of solar collector	2132 kWh
Total energy consumption for heating and DHW	11 802 kWh

Table 6.1 summarizes the energy consumption in House A for 01.04.2012 - 31.03.2013, which is the project period. Total delivered energy for space heating and domestic hot water is the electricity consumption measured by Datalogger1 and used by the fan coil, by the DHW boiler

Table 6.2: Key Results *- House B*
See text for further explanations.

April 1 2012 to March 31 2013	House B
Total delivered energy for heating and DHW	8631 kWh
Delivered energy for space heating	5475 kWh
Delivered energy for space heating per m^2	47.2 kWh/m^2
Delivered energy to DHW boiler	2441 kWh
Delivered energy for DHW	3156 kWh
Delivered energy for DHW per m^2	27.2 kWh/m^2
Total amount of delivered energy per m^2	115 kWh/m^2
DHW consumption	60 904 liter
Average DHW temperature	62.7 °C
Average indoor temperature	23.8 °C
Number of days with residents away	52

and in the technical room. Delivered energy for space heating is measured electricity consumption in the technical room and by the fan coil, but as some of the energy used in the technical room was used to preheat domestic hot water, this was subtracted as explained in Section 5.2.2. Delivered energy for DHW is the electricity consumed by the DHW Boiler in addition to the energy used in the technical room for preheating. Total amount of delivered energy, is based on the average values for electricity consumption found in Section 7.1. The domestic hot water consumption was measured by the volume meter in the technical room, and corresponds to an average of 118 liter/day. If this is converted to the anticipated temperature of 50 °C, it is equivalent to 166 liter/day. The average temperature of the domestic hot water was calculated according to the method described on page 29. Days with residents away include all days with a domestic hot water consumption of less than 10 liter. This limit was set not to include days when residents consumed only a small amount of domestic hot water before going away or after coming back home, and thus were away for most of the day.

The average outdoor temperature for the period is based on corrected temperature data, as described in Section 5.2.4, while the indoor temperature is the average of all measured indoor temperatures in the period, both from the 1st and the 2nd floor. Total insolation includes all irradiance measured by the pyranometer on the south façade in the period, while the yield of the solar collector is based on manual calorimetric calculations from each day the collector was active, except seven active days in the two periods when Datalogger2 was not recording. Total energy consumption for space heating and DHW includes the total delivered energy for space heating and DHW and the yield of the solar collector.

House B

Table 6.2 summarizes the project period for House B. Relevant comments for House A also apply for House B. DHW consumption in House B amounted to an average of 167 liter/day, but if converted to a temperature of 50 °C this corresponds to 216 liter/day, which is 30 percent more than in House A. Note also the higher average indoor temperature, compared to House A.

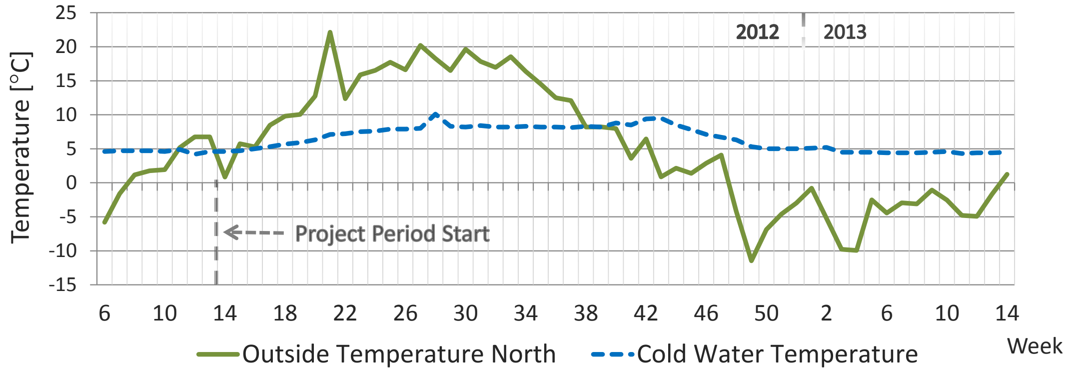


Figure 6.1: *Weekly average outside temperatures and weekly temperatures of the cold water, measured by the Water and Sewerage Department at Bjørndalen Pump Station. (Oslo Water and Sewerage Department, 2013)*

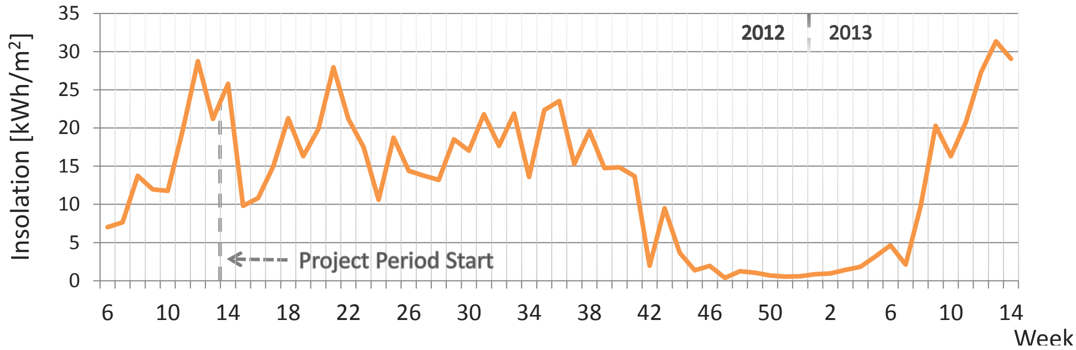


Figure 6.2: *Weekly insolation on the south façade, House A, as measured by the pyranometer.*

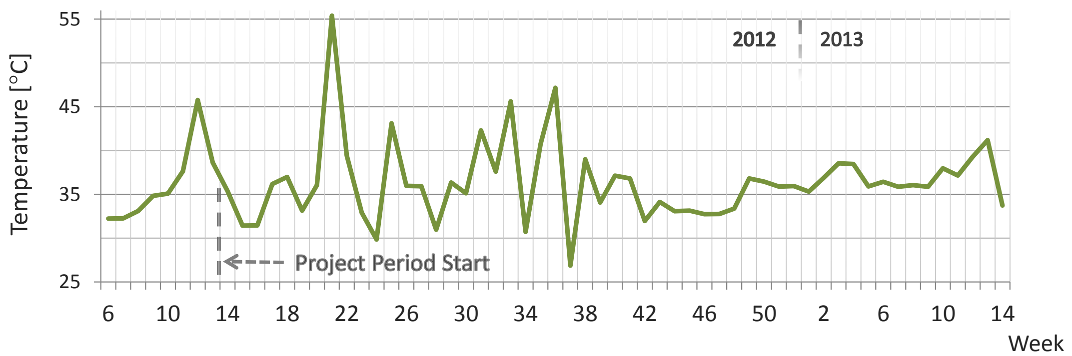


Figure 6.3: *Weekly mean temperature from the middle sensor on the heat store in House A.*

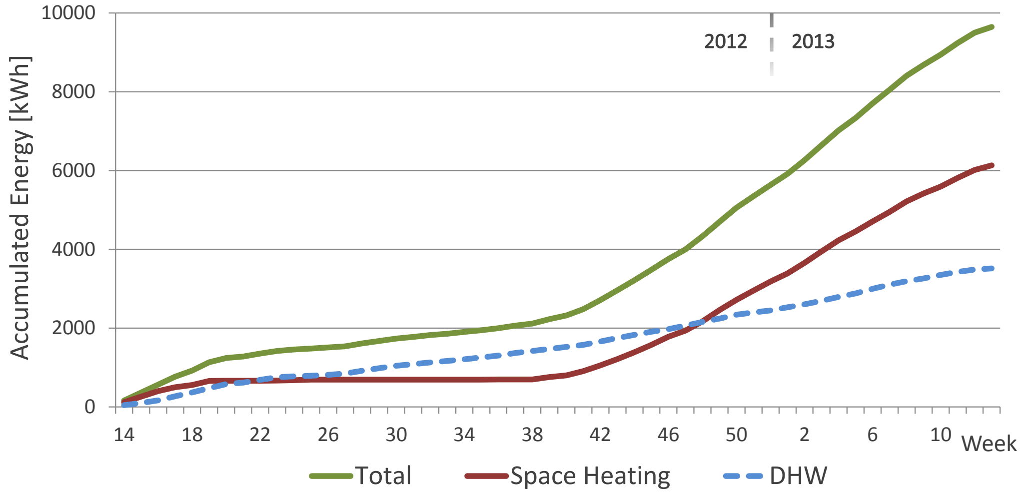


Figure 6.4: *Measurements from HOUSE A: Accumulation of delivered energy from week 14 in 2012 to week 13 in 2013. Energy used in technical room to preheat DHW assigned to DHW in this figure.*

6.2 Weekly Data

Figures 6.1 and 6.3 show how the weekly average temperatures outside and in the heat store of House A vary throughout the year. Also the temperature of the cold water delivered from the water supply is shown. Figure 6.2 shows the total insolation per m^2 for each week, on the south façade of House A where the solar collector is mounted.

Weekly Accumulated Data

Figure 6.4 and 6.5 show how the amount of delivered energy accumulates over the year, starting on week 14, 2012, for House A and B respectively. Both figures display periods of linear consumption. For both houses, domestic hot water energy consumption varies little throughout the period, but a small increase in energy delivered during the winter period can be seen.

For House A a clear increase in delivered energy for space heating can be seen in week 42 when the mean insolation is reduced, shown in Figure 6.2. The amount of delivered energy for domestic hot water is approximately 60 kWh/week, while for space heating the weekly mean varies from about 110 kWh/week early in the period to around 240 kWh/week in the winter period, with nearly zero during the summer period.

House B experiences a change in delivered energy for space heating in week 48, when the average outside temperature drops below zero, see Figure 6.1. Delivered energy for domestic hot water is approximately 60 kWh/week throughout the year, with small variations from summer to winter. Space heating consumption is around 50 kWh/week in the first part of the project period, corresponding to the warmer part of the year, while it is around 180 kWh/week in the colder part of the year.

Figure 6.6 compares the total amount of energy delivered for heating and domestic hot water purposes in the two houses. It can be seen that less energy is delivered to House A than B during summer, but more delivered energy is needed when the insolation decreases closer to winter. In this figure two months before and after the project period are also included. For February and March 2012 only the total amount of energy delivered to the DHW boiler in House B is known,

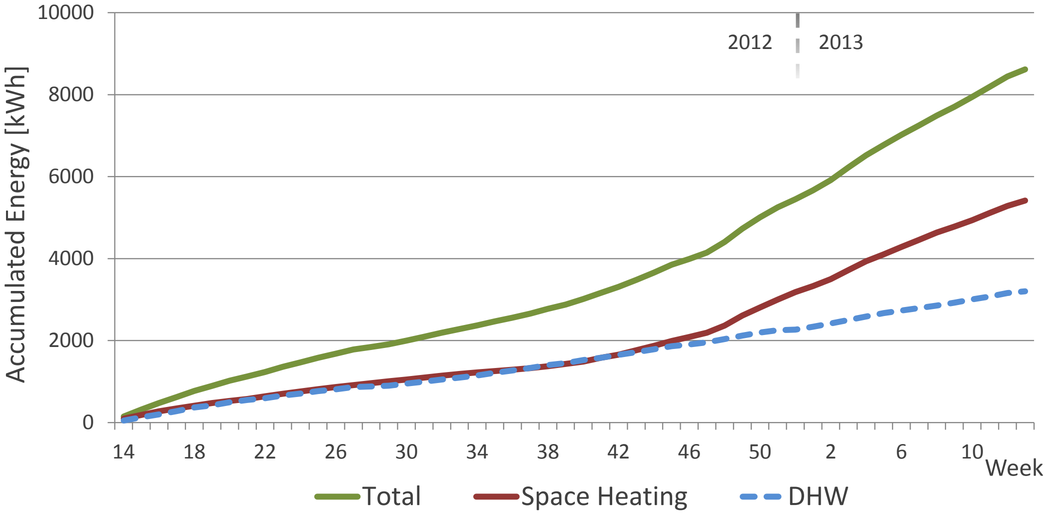


Figure 6.5: *Measurements from HOUSE B: Accumulation of delivered energy from week 14 in 2012 to week 13 in 2013. Energy used by heat pump to preheat DHW, are assigned to DHW in this figure.*

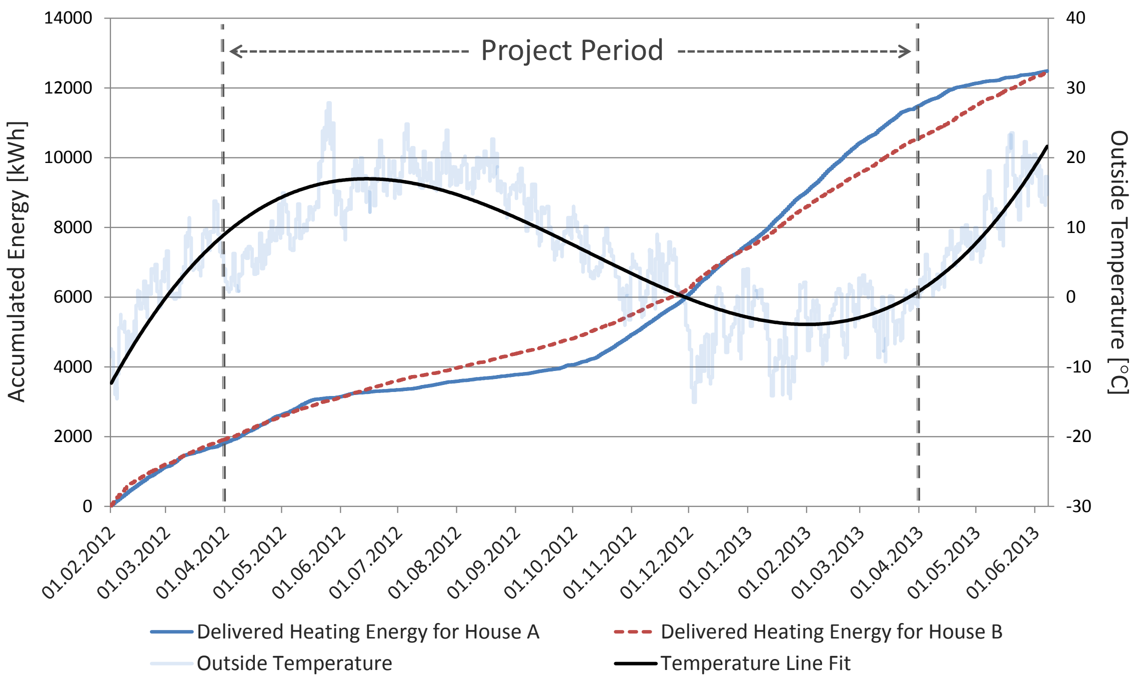


Figure 6.6: *Comparison of accumulated energy for space heating and DHW delivered to House A and B, from February 1 2012 to June 6 2013. Daily outdoor temperatures and a line fit to these are also shown.*

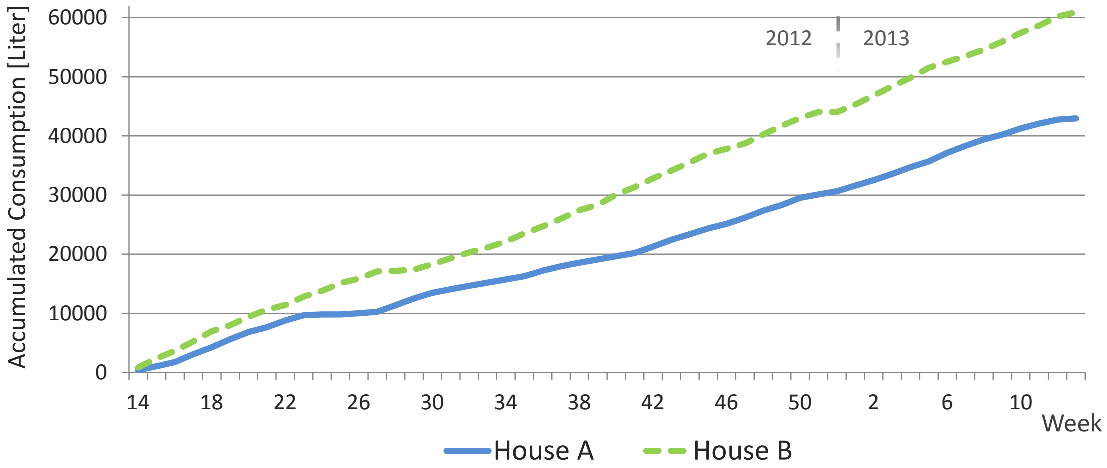


Figure 6.7: *Comparison of accumulated domestic hot water consumption in House A and B, starting in week 14, 2012.*

due to issues with the relevant sensor. This energy has been distributed over the period in which it was used according to consumption of domestic hot water. The mean of the two outdoor temperature sensors as measured at eight o'clock in the morning and evening are also shown together with a line fit.

Figure 6.7 shows the accumulated consumption of domestic hot water throughout the period for both houses. Shorter periods when the residents are away can be seen as intervals with zero slope. The domestic hot water consumption seems fairly constant when looking at a figure with resolution of weeks, and even though the daily consumptions can vary significantly, there seems to be a fairly steady consumption throughout the year, though increasing slightly during winter.

6.3 Daily Profiles

Profiles of the daily development of temperatures and consumption are helpful in revealing consumer habits and for optimizing systems. The following profiles are based on measurements from February 1 2012 to April 7 2013. Matlab was used to sort measured values according to time of day, with a resolution of one hour. And thus it was possible to make an average for a measured parameter of all values in the period measured within an hour. All times are without daylight saving time. This applies to Figure 6.8 till Figure 6.11.

Figure 6.8 shows how, on average, the temperature of the heat store in House A rises during daytime and falls in the nighttime. It can also be seen how the temperature in the upper part of the heat store is higher and sinks more slowly after being heated.

Figure 6.9 shows how the temperatures vary during the day for both houses, and on both floors. These profiles are divided into weekdays, Monday to Friday, and weekends.

Figure 6.10 shows the hourly domestic hot water consumption for both houses, separated into weekdays and weekends. The elevated consumption in House B can be seen, as well as a trend for more concentrated consumption during weekdays for both houses.

The outside temperature is highly dependent upon time of day as can be seen in Figure 6.11. It can also be seen how direct solar radiation gives heightened temperatures in the morning on the eastern sensor and on the evening on the sensor to the north. The figure also shows the mean solar irradiance on the south facing façade with the solar collector.

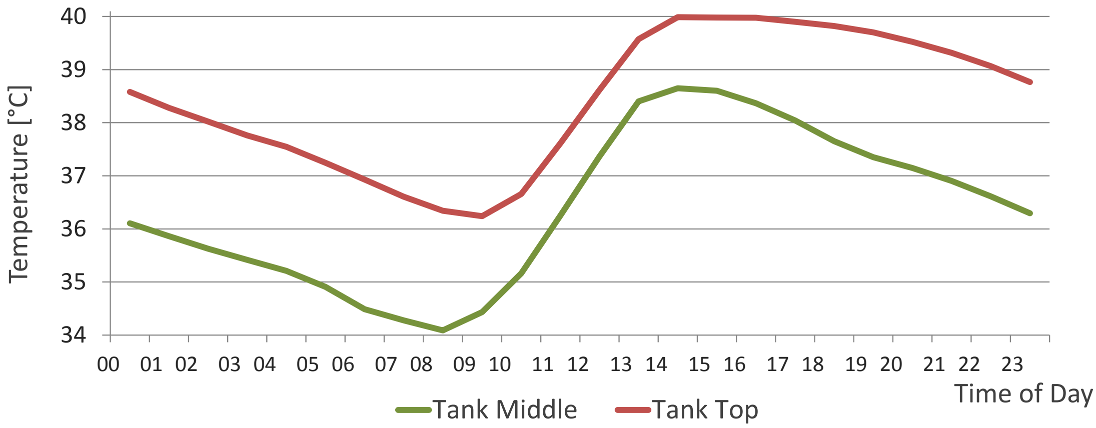


Figure 6.8: *Mean temperature in the top and the middle of the heat store in House A. Time along the x-axis. Averaged values from February 1 2012 to April 6 2013.*

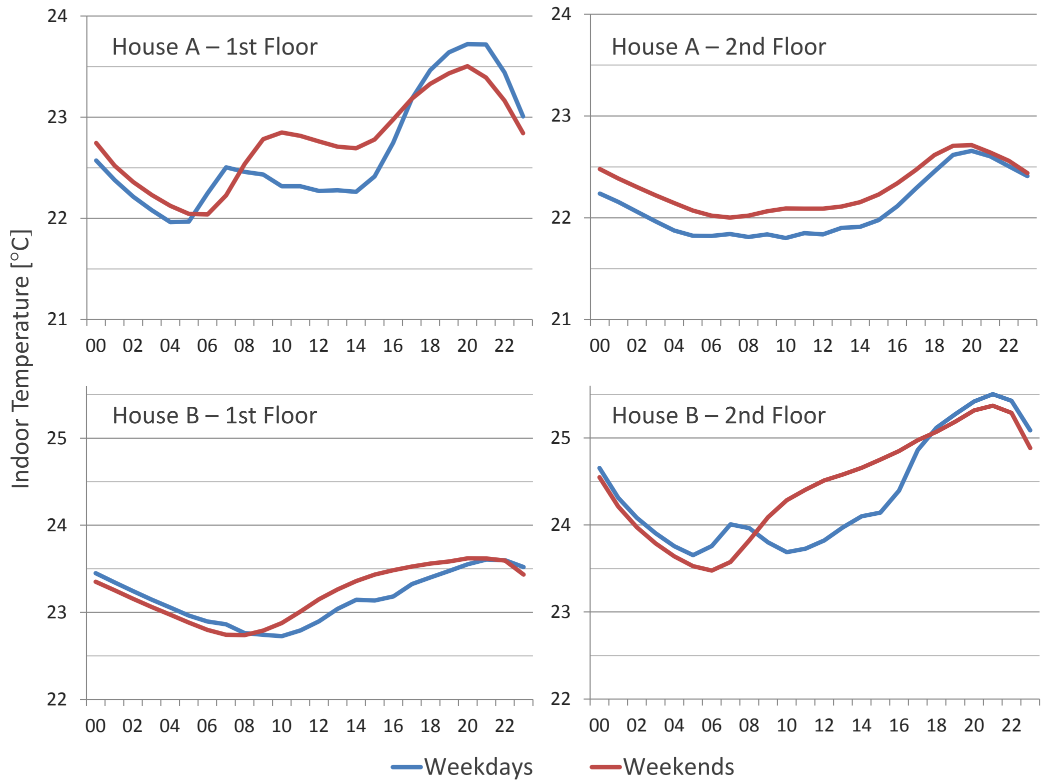


Figure 6.9: *Temperature profiles from House A and B, 1st and 2nd floor, as a function of time of day. Note the different axis for the two houses. Averaged values from February 1 2012 to April 6 2013.*

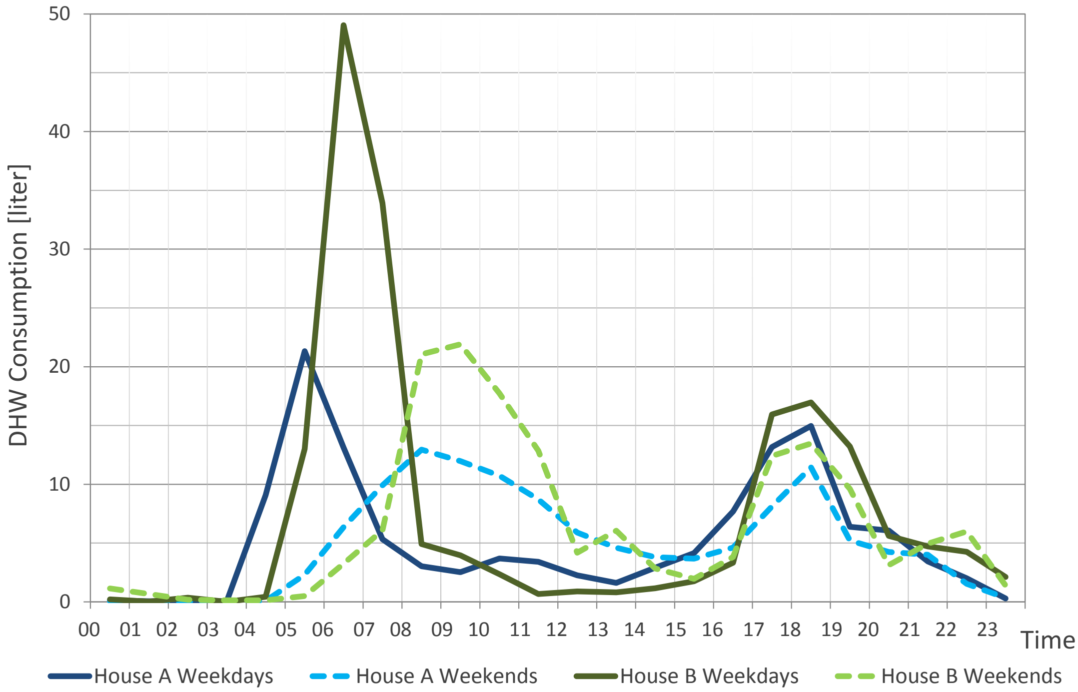


Figure 6.10: *Domestic hot water consumption as a function of time of day. Averaged values from February 1 2012 to April 6 2013.*

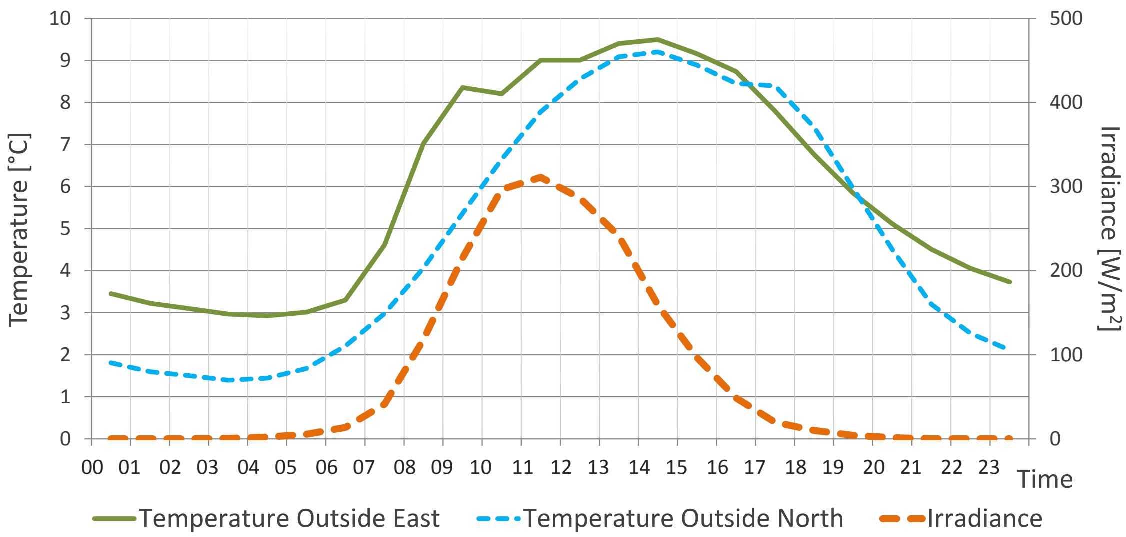


Figure 6.11: *Average measured temperatures in the two outside temperature sensors, and average irradiance as a function of time of day. Averaged values from February 1 2012 to April 6 2013.*

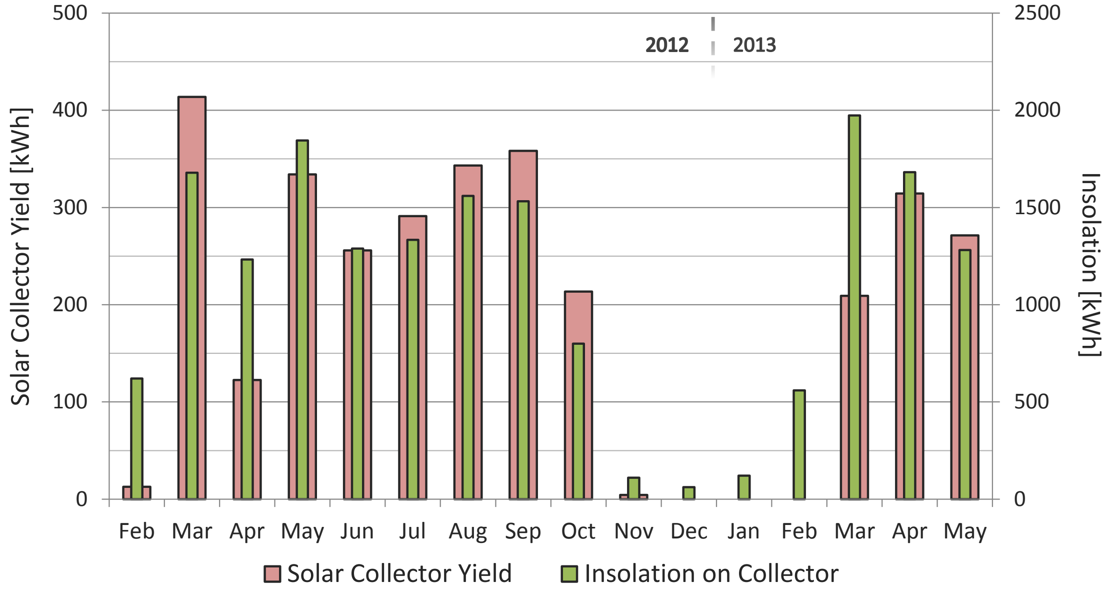


Figure 6.12: *Monthly yield by the solar heating system, as calculated with the calorimetric method. Also shown is the total insolation on the collector for each month, as measured by the pyranometer.*

6.4 Monthly Data

As monthly values are easier to relate to, Table 6.3 displays average outside temperature, average temperature of delivered cold water and average insolation for each month from February 2012 to May 2013.

Figure 6.12 displays the monthly energy delivered by the solar collector, the solar heating system yield, in addition to the monthly insolation on the solar collector. April 2012 and March 2013 stand out as two months when the yield of the solar collector did not correspond to the solar potential. This was because the solar collector was out of function for larger parts of these months. In the project period the solar collector delivered a total of 2132 kWh. From February 2012 till May 2013, 3144 kWh was delivered, and in this period the solar heating system had an average efficiency of 35.6 percent and covered 21.7 percent of the energy consumed for space heating and domestic hot water. Of the 458 days from February 1 2012 till May 31 2013, the solar heating system was active on 220 days with a mean daily yield of 14.6 kWh. Figure 6.13 shows the monthly energy consumption for space heating and domestic hot water and the part of this covered by the solar heating system, the solar fraction, for each month. Figure 6.15 shows the insolation measured by the *Pyranometer* and the estimated solar heating system yield for all days from February 1 2012 till June 6 2013. Several days and longer periods when the solar system should have been active can be seen, especially in March to May of 2012 and March and April of 2013.

Figure 6.14 shows the monthly consumption for both houses. Notice though that in this figure, energy for domestic hot water is only the DHW boiler, while heating compromises the rest without regarding energy used to preheat the domestic hot water. Outside temperature is included to show the space heating consumption's dependence on this.

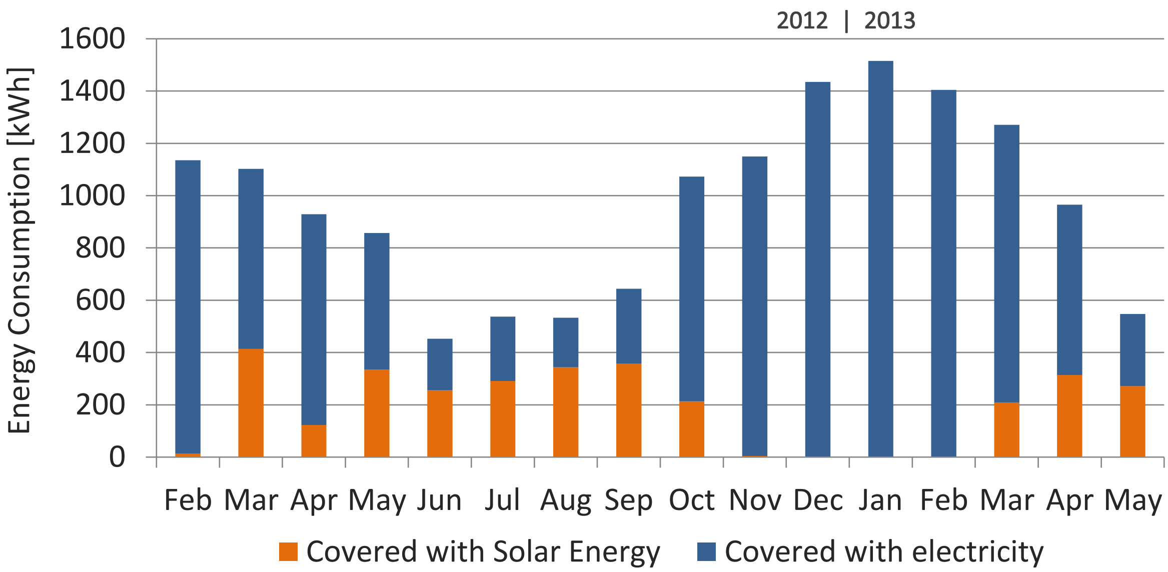


Figure 6.13: *Monthly energy consumption for space heating and DHW. Lower part delivered by solar collector. Collector data obtained with calorimetric method, other data from measurements.*

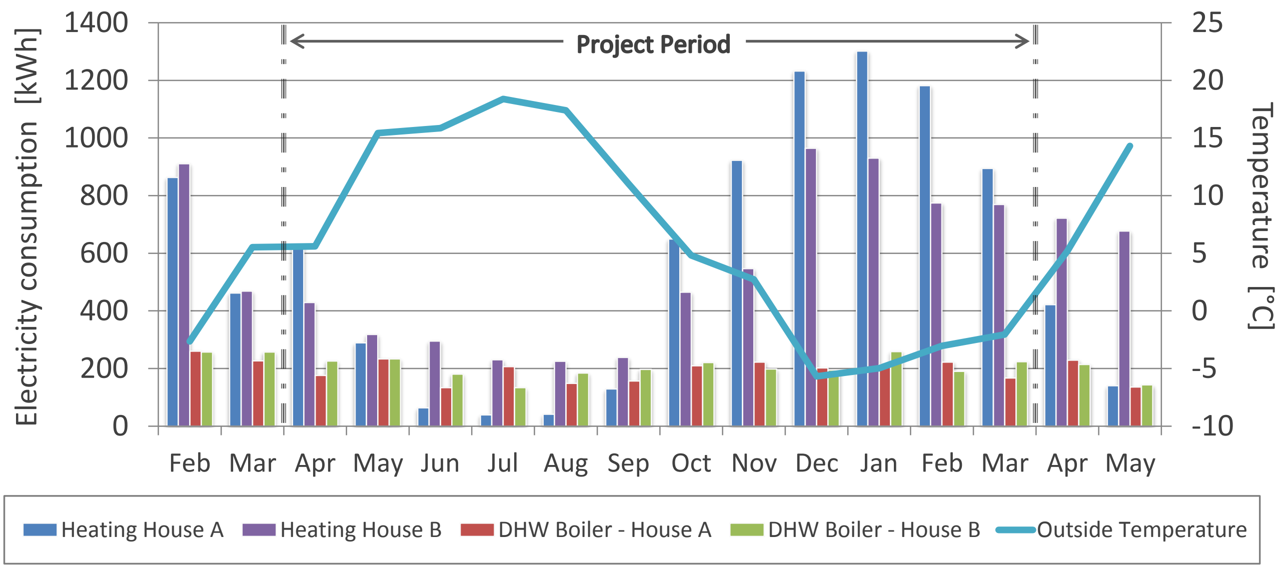


Figure 6.14: *Energy delivered to the technical room and fan coil **(Heating House A)**, to the heat pump, heat store and fan coil **(Heating House B)** and DHW boiler in both houses, with the monthly mean outside temperature.*

Table 6.3: Exterior Variables

Monthly mean outside temperatures from measurements. Daily mean insolation on pyranometer. Monthly mean cold water temperatures from weekly measurements at Bjørndalen Pump Station, obtained from the Water and Sewerage Department. (Oslo Water and Sewerage Department, 2013)

Month	**Outdoor Temperature, °C**	**Cold Water Temperature, °C**	**Insolation, kWh/m^2 day**
February 2012	-2.6	4.7	1.13
March 2012	5.53	4.6	2.87
April 2012	5.6	5.1	2.17
May 2012	15.4	6.6	3.15
June 2012	15.9	7.6	2.27
July 2012	18.4	8.6	2.28
August 2012	17.4	9.6	2.66
September 2012	11.0	10.6	2.70
October 2012	4.82	8.9	1.36
November 2012	2.73	7.0	0.19
December 2012	-5.69	5.1	0.11
January 2013	-4.98	4.8	0.21
February 2013	-3.04	4.4	1.06
March 2013	-2.05	4.4	3.37
April 2013	5.17	-	2.97
May 2013	14.3	-	2.19

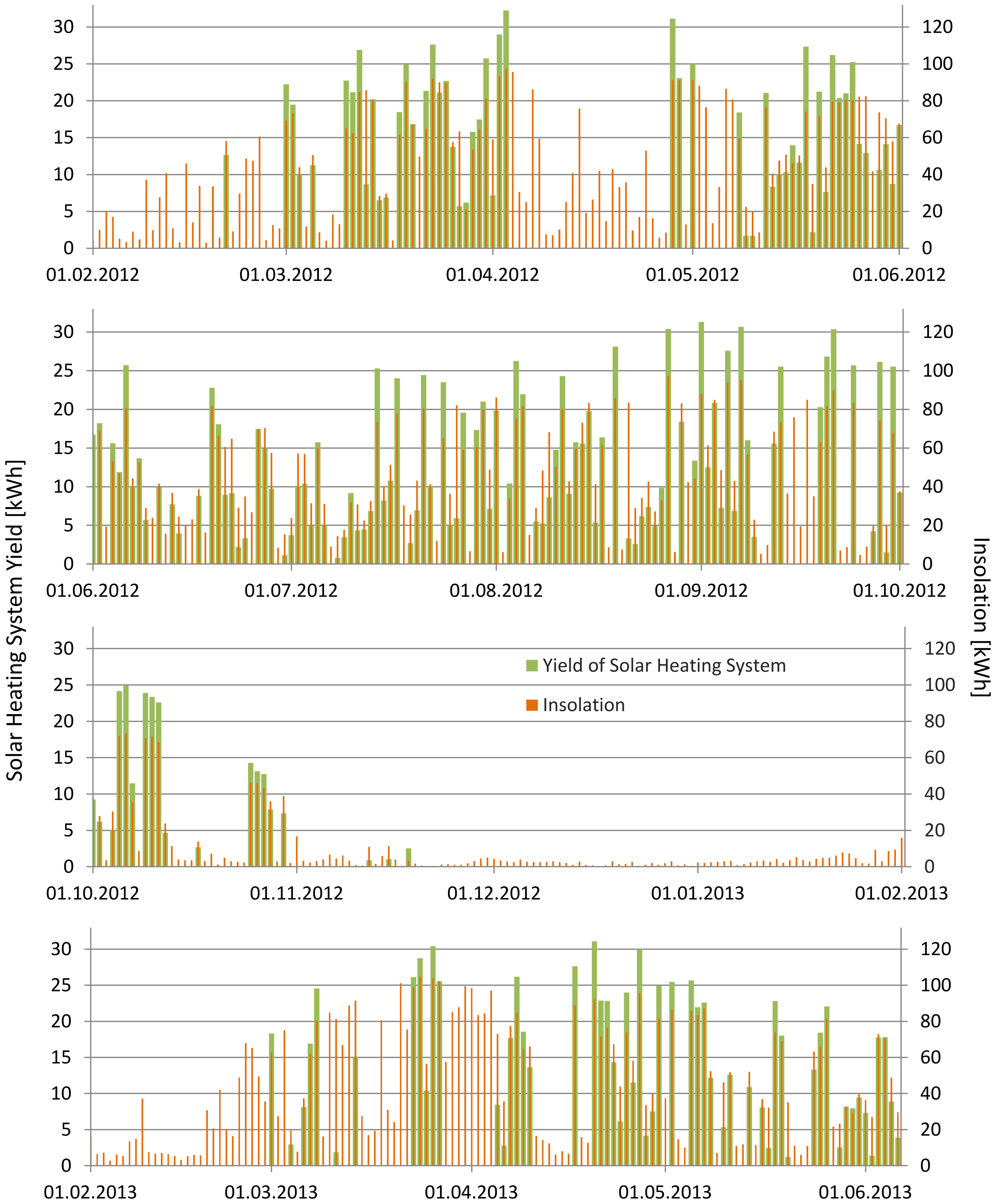


Figure 6.15: *Yield of solar heating system found with calorimetric method, and insolation on collector, both in kWh/day. Solar heating yield is green and refer to left axis, while insolation is orange and refer to the right axis.*

Chapter 7

Analysis

7.1 Projected Energy Consumption

As mentioned in Section 2.1.5, houses only need heating when the difference between indoor temperature and outdoor temperature is above a certain value, due to internal gains. This temperature difference is defined as

$$\Delta T_D = \frac{\text{Internal Gain}}{\text{House's U-value}}$$

Prior to the construction of the passive houses at Rudshagen, the contractor Mesterhus made calculations of the expected energy consumption and heat losses of the houses, see Appendix A. They found a total U-value for the houses of 64.4 W/K and a specific U-value of 0.56 W/(m^{2}K). Assuming an internal gain level of 4 W/m^2 as suggested by Dokka and Andresen (2006), there will only be a need of heating when the daily mean outside temperature drops 7.2 K below the desired indoor temperature. An internal gain of 2.1 W/m^2, as suggested by the Passivhaus Institut gives us instead a ΔT_D of 3.8 K. Readings of the houses' electricity meter[1] revealed an average use of electricity not used for space heating or domestic hot water, of 528 W for House A, and 540 W for House B. Including the heat loss from the DHW boilers of 79 W and 64 W for House A and B respectively, result in the very similar figures of 607 W for House A and 604 W for House B, corresponding to an internal gain of 5.2 W/m^2 for both houses. There are some uncertainties to whether all this energy is used indoor and in this section a value for the internal gain of 5 W/m^2, which gives a ΔT_D of 9.0 K, will be used. It should here be noted that for several of the last months, the residents in House A have been in possession of an electric car, which have consumed electricity not contributing to internal gain.

As can be seen in Table 7.1, House A had a mean indoor temperature of 22.5 °C and House B 23.8 °C. This affects their need for heating. Assuming there was no passive solar gain, the houses' need for space heating during the period was calculated using the heat degree days[2] method, described in Section 2.1.5. In this calculation, corrected outdoor temperatures were used, see Section 5.2.4, and the corrected values from the two outdoor sensors averaged. The indoor temperatures were an average of the 1st and 2nd floor measurements. The calculation was done with values for every 15 minutes. The assumption of no passive solar gain will lead to an overestimation of the demand for space heating, but the calculation can still be informative for comparison.

[1] Averaged over the period March 23 2012 to June 27 2013

[2] Sum of ΔT_D for all days in a year.

Heating degree days, the number of days the houses should have a need for heating (Outdoor temperature 9 K below indoor temperature), calculated space heating demand and energy delivered for space heating can be seen for both houses and for a reference house in Table 7.1. The calculated demand of delivered energy for space heating for House A and B, is based on a house with a heat pump with a constant COP of 2.5. Again, delivered energy for space heating is the measured use of electricity in the technical room and by fan coil for House A, and by the heat pump, the heat store and the fan coil for House B, but with energy used to preheat domestic hot water subtracted according to the method described in Section 5.2.2. Table 7.1 also shows the mean daily delivered energy for space heating on the ten coldest and ten warmest days. The displayed temperature is the average temperature on these ten days. The reference house is an envisioned house which is similar to House A and B, but has a constant indoor temperature of 20 °C and is heated with a heat pump with a constant COP of 2.5. Its space heating consumption on the coldest and warmest days, not listed in the table, would have been 319 Wh/m^{2}day and 0 Wh/m^{2}day respectively, calculated using the contractor's estimated U-value of 64.4 W/K and the measured daily average outdoor temperatures on the relevant days, and an internal gain of 5 W/m^2.

Table 7.1: *Calculated space heating demand and measured delivered energy for space heating for House A and B and an envisioned reference house with a constant indoor temperature of* 20 °C

April 1 2012 to March 31 2013	House A	House B	Reference House
Average Indoor Temperature	22.5 °C	23.8 °C	20.0 °C
Heating Degree Days	3132	3437	2553
Heating Days	258	287	237
Calculated Demand for Space Heating	41.7 kWh/m^2	45.8 kWh/m^2	34.0 kWh/m^2
Calculated Demand of Delivered Energy for Space Heating	16.7 kWh/m^2	18.3 kWh/m^2	34.0 kWh/m^2
Total Delivered Energy for Space Heating	6215 kWh	5474 kWh	—
Delivered Energy for Space Heating per m^2	53.6 kWh/m^2	47.2 kWh/m^2	—
Mean Delivered Energy for Space Heating on the Ten Coldest Days (−13 °C)	416 Wh/m^{2}day	311 Wh/m^{2}day	—
Mean Delivered Energy for Space Heating on the Ten Warmest Days (22 °C)	1.5 Wh/m^{2}day	44 Wh/m^{2}day	—

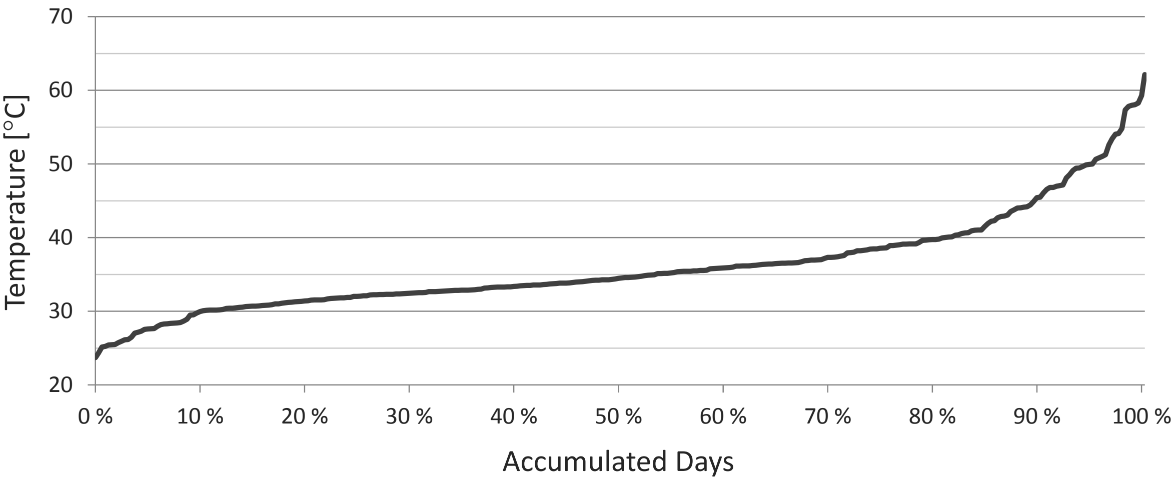


Figure 7.1: *Daily average temperatures of preheated DHW for the project period, in ascending order. Includes the 322 days when DHW was consumed. X-axis show the percentage of days.*

7.2 Analysis of House A

7.2.1 Domestic Hot Water - Temperature and Heat Loss

The heat store preheats the domestic hot water before it enters the designated 76 liter DHW boiler. A pressurized steel tank immersed inside the heat store receives cold water which is heated by the ambient water in the heat store, see Section 4.2.1. On average the preheated water holds a temperature of 35.6 °C when leaving the heat store, but as the temperature in the heat store varies with solar irradiation so does the temperature of the preheated water. The standard deviation on the daily averages is 6.7 K. Figure 7.1 shows the distribution of the preheated water temperatures. Values shown are daily averages, from the temperatures measured by the *T Forward DHW* sensor, weighted with values from the *Flow DHW* sensor. The temperature of the preheated water is higher than 50 °C on 16 days, and as mentioned in section 4.2.1 the thermostatic mixing valve should then hinder mixing with water from the DHW boiler. However, this does not work properly and, accounting for heat loss from the boiler, the water on these days is heated on average 16 K, giving a mean temperature for the domestic hot water of about 70 °C on these days.

Figure 7.2 shows a plot of the DHW boiler's daily energy consumption as a function of domestic hot water consumption. A linear trend is quite clear, with a constant representing the heat loss from the boiler. The lower outliers come from days when the heat store preheats the water to higher temperatures and from days when domestic hot water is consumed faster than the DHW boiler can heat it. The plot has a resolution of days and to some extent chance decides whether boiler activity is recorded on one day or another.

The linear fit equation in Figure 7.2 shows that the heat loss is 1.97 kWh/day. An analysis of the days with no domestic hot water consumption indicates an average heat loss which is slightly less, about 1.9 kWh/day, and this value will be used in other calculations. It is worth noting that the heat loss from the DHW boiler will contribute to the internal gain. The slope of the linear fit gives the energy used by the DHW boiler to heat every liter of domestic hot water. This value of 36.8 Wh/liter corresponds to a mean heating of 31.7 K. As the average temperature of the

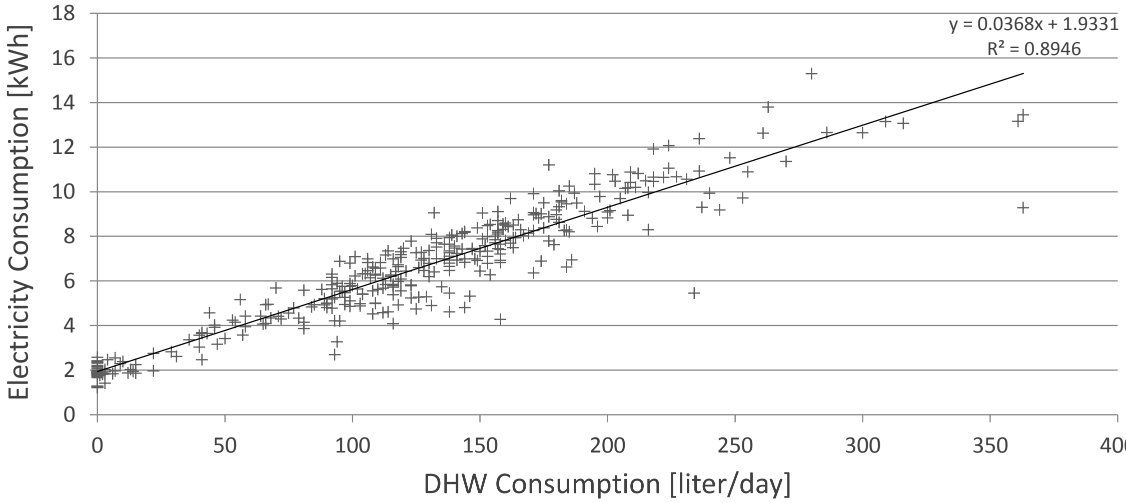


Figure 7.2: *Energy consumption by DHW boiler in House A versus domestic hot water consumption.*

preheated water is 35.6 °C, assuming no heat loss in the pipes, the domestic hot water should keep 67.3 °C. In fact, utilizing the method described in Section 5.2.2, the domestic hot water of House A is found to keep an average temperature of 67.6 °C when leaving the thermostatic mixing valve for the taps. A one time measurement of the domestic hot water temperature yielded a result of 70 °C, indicating that this could be correct.

7.2.2 Heat Loss from Heat Store

The heat store is thermally insulated with a 100 mm layer of polyurethane foam with a thermal conductivity, λ, of 0.022 W/(m K) except underneath where there is a 50 mm thick layer of expanded polystyrene with a λ-value of 0.035 W/(m K). The tank is 80 cm wide, 80 cm deep and 125 cm high. The bottom area is $0.8\,\text{m} \times 0.8\,\text{m} = 0.64\,\text{m}^2$. Top and side area is $0.8\,\text{m} \times 0.8\,\text{m} + 4 \times 0.8\,\text{m} \times 1.25\,\text{m} = 4.64\,\text{m}^2$. For the top and sides, this yields an U-value of

$$U_1 = \frac{0.022\,\text{W/(m K)}}{0.1\,\text{m}} \times 4.64\,\text{m}^2 = 1.02\,\text{W/K}$$

While for the bottom the U-value becomes

$$U_2 = \frac{0.035\,\text{W/(m K)}}{0.05\,\text{m}} \times 0.64\,\text{m}^2 = 0.45\,\text{W/K}$$

From measurements it is seen that the temperature at the bottom of the tank is on average 10 K lower than in the middle. The upper thermocouple measures on average a temperature 2 K higher than the middle. When the solar collector is active, the temperatures equalize. For the bottom of the tank it is assumed a temperature 10 K lower than the middle, while for the rest of the tank it is assumed that the middle temperature is correct. This is a fair assumption as there will be a gradient from cold to warm from the bottom towards the top. With the added assumption that the temperature in the technical room is isotropic, and also that the concrete floor beneath the tank, with its rather high λ of 1, shares the temperature of the technical room, the following heat loss for the heat store is arrived at:

$$\begin{aligned}
\text{Heat Loss} &= U_1 \Delta T + U_2(\Delta T - 10) \\
&= 1.02\,\text{W/K}\ \Delta T + 0.45\,\text{W/K}\ (T - 10) \\
&= 1.02\,\text{W/K}\ \Delta T + 0.45\,\text{W/K}\ \Delta T - 4.5\,\text{W} \\
&= 1.47\,\text{W/K}\ \Delta T - 4.5\,\text{W}
\end{aligned} \tag{7.1}$$

In this equation, ΔT is the difference between the temperature in the technical room and the middle of the tank. In the project period, 01.04.2012 till 31.03.2013, the average temperature in the technical room was 21.4 °C and in the middle of the tank, 36.5 °C, a difference of 15.1 K. Inserting this into Equation 7.1 yields an average heat loss from the heat store of 17.7 W. Over the period this sums up to 155 kWh. A calculation using daily averages gives the somewhat higher figure of 167 kWh. Both can be said to be acceptable if compared to the heat loss from the DHW boiler of about 700 kWh a year. Heat losses from the heat store do not contribute to internal gain, but are lost to the ambient as the heat store is situated in the technical room outside the main envelope of the house.

The relatively high temperature in the technical room indicates that the estimations above are not correct. Therefore, an analysis of the heat loss from the technical room was done. The technical room is 2.09 m long, 1.37 m wide and 2.65 m high. One of its walls is shared with the building envelope and is not counted in here. The northern wall is for the most part covered by a door, and the rest of the area is disregarded. According to drawings from the contractor, the technical room is thermally insulated with 100 mm mineral wool in the walls and 200 mm in the roof. Beneath the concrete slab lies 50 mm of expanded polystyrene. All thermal insulation will be assumed to have a thermal conductivity of 0.035 W/m K. The door is assumed to have an U-value of 2 W/(m^{2}K). This gives the following:

$$\begin{aligned}
\text{Wall} &= 2.65\,\text{m} \times (2.09\,\text{m} + 1.37\,\text{m}) \times 0.33\,\text{W/(m}^2\text{K)} && = 3.03\,\text{W/K} \\
\text{Door} &= 2.1\,\text{m} \times 1.0\,\text{m} \times 2\,\text{W/(m}^2\text{K)} && = 4.20\,\text{W/K} \\
\text{Roof} &= 2.09\,\text{m} \times 1.37\,\text{m} \times 0.167\,\text{W/(m}^2\text{K)} && = 0.48\,\text{W/K} \\
\text{Floor} &= 2.09\,\text{m} \times 1.37\,\text{m} \times 0.7\,\text{W/(m}^2\text{K)} && = 2.00\,\text{W/K} \\
\hline
&\textbf{U-value, technical room} && = 9.71\,\text{W/K} \\
\hline
\end{aligned} \tag{7.2}$$

The amount of heating degree days for the technical room during the project period, taking the daily average temperature measured by *T Technical Room* as T_{Base}, is 5439. Multiplying this with the estimated heat loss per day per Kelvin, 233 Wh/K, gives a heat loss from the technical room during the project period of 1268 kWh, which is considerably higher than what was found from the heat store. This might be due to heat loss from all the pipes going in and out of the heat store which are less insulated than the heat store itself, and it is also possible that the thermal insulation around the heat store is not air tight, leading to extra losses.

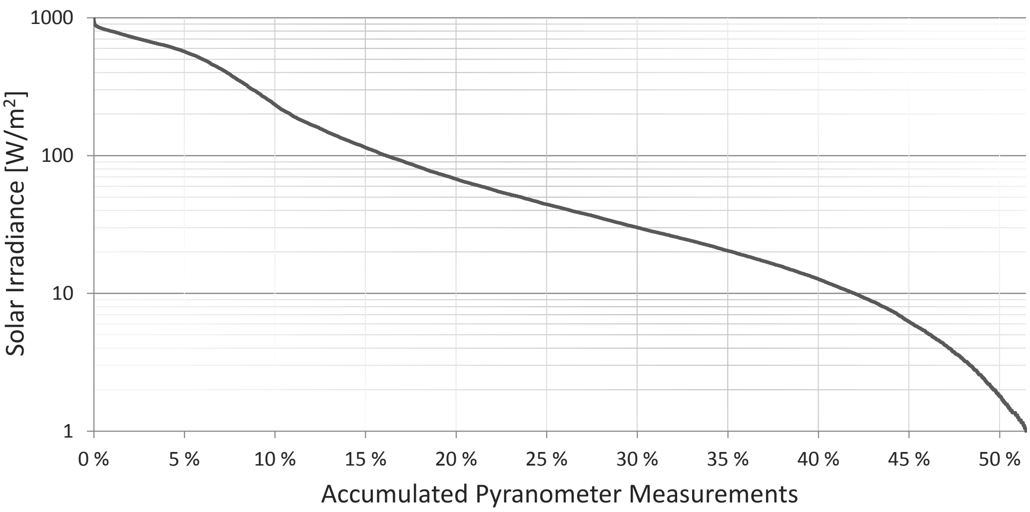


Figure 7.3: *The* 18 030 *Pyranometer measurements, of a total of* 35 044*, with values higher than* 1 W/m^2 *in descending order. On x-axis,* 10 % *corresponds to* 876 *hours of measurements.*

7.2.3 Yield of the Solar Heating System

The activation of the solar heating system was dependent on the temperature difference between the heat store and the temperature of the solar collector, but the collector temperature was again dependent on the outside temperature, as seen in Equation (2.6). When the heat store temperature was about 10 K higher than the outside temperature, the solar system could start with solar irradiances as low as 150 W/m^2, but out of 160 starts of the solar heating system, almost half needed an solar irrandiance of 500 W/m^2 for the system to activate.

A total insolation of 657 kWh/m^2 was measured by the *Pyranometer* during the project period, on the south façade with the solar collector. Of this, 500 kWh/m^2 had an solar irradiance of more than 200 W/m^2, which was chosen as a rough limit for when the solar collector could be operational. This will of course vary widely with different ambient and heat store temperatures, but gives an estimate. Given the collector's active area of 18.9 m^2 the solar potential, that is the solar collector yield given an efficiency of 100 percent, over the year was in the order of 9500 kWh. Figure 7.3 shows the distrubution of the *Pyranometer* measurements. Here it can be seen that the solar irradiance is stronger than 200 W/m^2 about 11 percent of the time.

The solar thermal system was active on 157 days in the project period, which is 43 percent of the year. If the period November 16 to February 15 is omitted, being a period when the collector cannot be used because of nearby shadowing buildings, the solar thermal system was active for more than 57 percent of the remaining days. In this period 28 days were registered when solar conditions indicated that the solar collector should have been active but was not due to issues discussed in Section 8.1. Had the collector been active during these days as well, it would have been active during 68 percent of the possible days of the project period.

The heat flow method, as described in Section 5.2.3, was applied to the whole project period using Excel. This resulted in an energy yield from the solar collector of 1349 kWh. But the method had several weaknesses, one of which was the solar collector flow meter, *Flow Collector*, that in periods gave wrong or no values.

Table 7.2: Analysis of solar collector output using calorimetric method. Efficiency is related to the calorimetric method. Data from heat flow method presented for comparison. Total insolation as measured by the pyranometer, mean daily yield and number of active days can also be seen.

Month	Days Active	Calorimetric Method [kWh]	Efficiency [%]	Mean Daily Energy [kWh]	Heat Flow Method [kWh]	Insolation [kWh]
March 2012	24	413.8	35.2	17.2	217.1	1679
April 2012	5	122.6	36.4	24.5	105.4	1233
May 2012	26	334.0	33.6	14.5	384.1	1845
June 2012	22	255.8	33.1	11.6	137.3	1289
July 2012	26	291.1	32.4	11.2	60.7	1334
August 2012	25	343.3	36.2	13.7	412.0	1560
September 2012	23	358.2	36.2	18.9	159.2	1533
October 2012	16	213.6	35.1	13.4	268.4	799
March 2013	12	209.1	39.4	17.4	194.8	1974
April 2013	18	314.4	38.7	17.5	296.5	1682
May 2013	20	271.3	37.8	13.6	257.9	1281
February 1 2012 to June 6 2013	226	3201	35.6	14.2	2532	17 966

Calorimetric Analysis and Example Days

The quantitative heat flow method used to evaluate the solar heating system, as described in Section 5.2.3, had certain limitations. To better understand the solar system, a qualitative approach was needed. In this section, days with different climatic conditions will be analyzed in more detail. In addition, 220 days were analyzed using the calorimetric method, described in Section 5.2.3. The results are shown in Table 7.2. The solar collector flow meter failed in periods of March, June, July and September 2012, resulting in large discrepancies between heat flow and calorimetric method. As mentioned in Section 5.1.2, Datalogger2 did not record data on 13 days. From temperature measurements of the preheated hot water it was deduced that the solar collector was active on at least seven of these days. These are not included in Table 7.2 as not enough data was available to conduct an analysis.

April 28 2012

Figure 7.4 A shows measurements from April 28 2012. It was a sunny day, as can be seen by the *Pyranometer* measurements. It was a Saturday and we can see that there was people at home the whole day as domestic hot water was being used throughout the day. When the solar heating system starts, as can be seen by the collector flow, the 3 kW heating element is turned off and the pump for the solar collector is the main source of electricity usage. The outside temperature, not shown in the figure, is 5 °C at 08:00 rising to 13 °C after noon. The temperatures in the heat store were stratified before startup of the solar system with 20 °C in the bottom and around

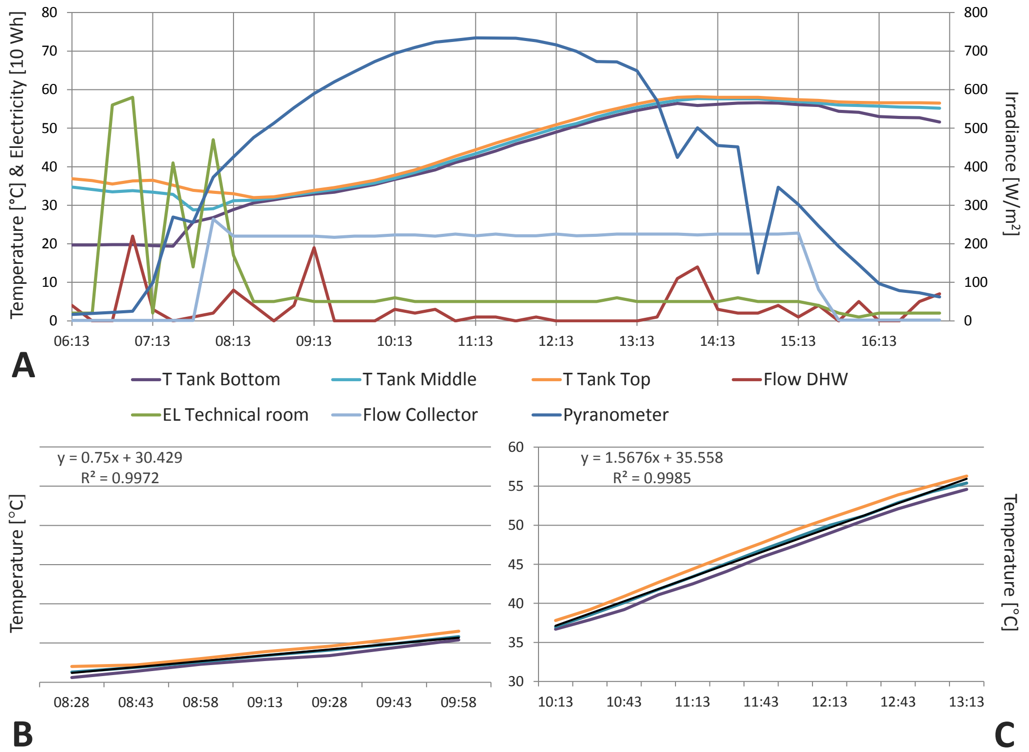


Figure 7.4: *Measurements from April 28 2012. Liter of DHW consumption is seen on left axis. Flow Collector refer to left axis and is measured in liter per minute.*

35 °C in the middle and top. The average system temperature before startup was 29.2 °C. When the system starts the stratification disappears, and in our figure this actually happens before the startup. This is probably because the solar pump started and stopped again at an earlier time, without being registered by the datalogger. The solar collector is active throughout most of the day, starting around 08:00 and stopping at 15:15, when the solar irradiance falls below 300 W/m^2. The temporary fall in solar irradiance around 14:45, is due to shadowing from the nearby hill and trees.

The Figures 7.4 B & C show two nearly linear parts of the heat store temperature plot. For each a linear regression was made with equation and R^2-value displayed in the upper left corner. As can be seen the temperature rises with 0.75 °C per 15 minutes in the morning and 1.57 °C mid day. This corresponds to a heating of 2.6 kW and 5.5 kW respectively for morning and mid day, while the solar irradiance on the solar collector during these times are approximately 11 kW and 13 kW

October 26 2012

October 26 2012 was a Friday. What is most prominent when comparing Figure 7.5 A with Figure 7.4 A, is the absence of solar irradiance in the morning and in the afternoon. Also the maximal solar irradiance is higher than on April 28. Both are due to the sun's low position in the sky late in October. Not until 09:30 does the sun come over the nearby buildings and at around 12 o'clock the solar radiation is probably being blocked by the nearest building to the

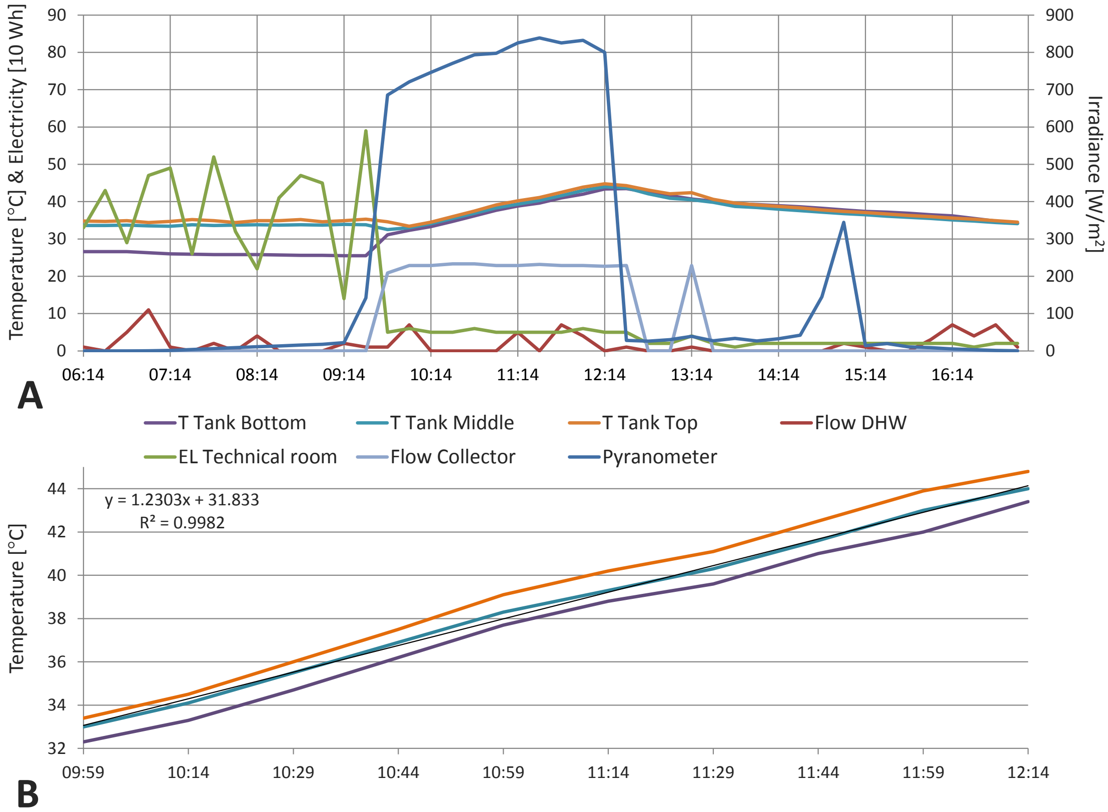


Figure 7.5: *Measurements from October 26 2012. Flow DHW use left axis and is measured in liters. Flow Collector use left axis and is measured in liters per minute.*

south. Just before 15 o'clock the sun comes out briefly after passing the neighboring house or clouds, then sets below the horizon. The sun's low position makes the angle of the incoming radiation almost normal to the solar collector, hence giving a high solar irradiance.

Despite the short timespan and low outside temperature of around 4 °C, the solar collector is relatively efficient this late in the year. Figure 7.5 B shows how the heat store is heated with an average effect of 4.3 kW[3]. And this is while heat is being removed from the heat store through space heating and domestic hot water. A total of 13 kWh is collected in less than three hours, with a mean efficiency of 32 percent.

7.3 Analysis of House B

7.3.1 Domestic Hot Water Temperature and Heat Loss

In House B the preheated water comes from the heat store before entering the DHW boiler. A schematic overview can be seen in Figure 4.7. In the figure we can see that the preheated water comes from the heat store which is heated by the heat pump and a 3 kW electric heating element. In the project period the heat store temperature seemed to be quite stable around

[3] $1.23\,\mathrm{K}/0.25\,\mathrm{hour} \times 4 \times 750\,\mathrm{liter} \times 1.16\,\mathrm{Wh/K\,liter}$

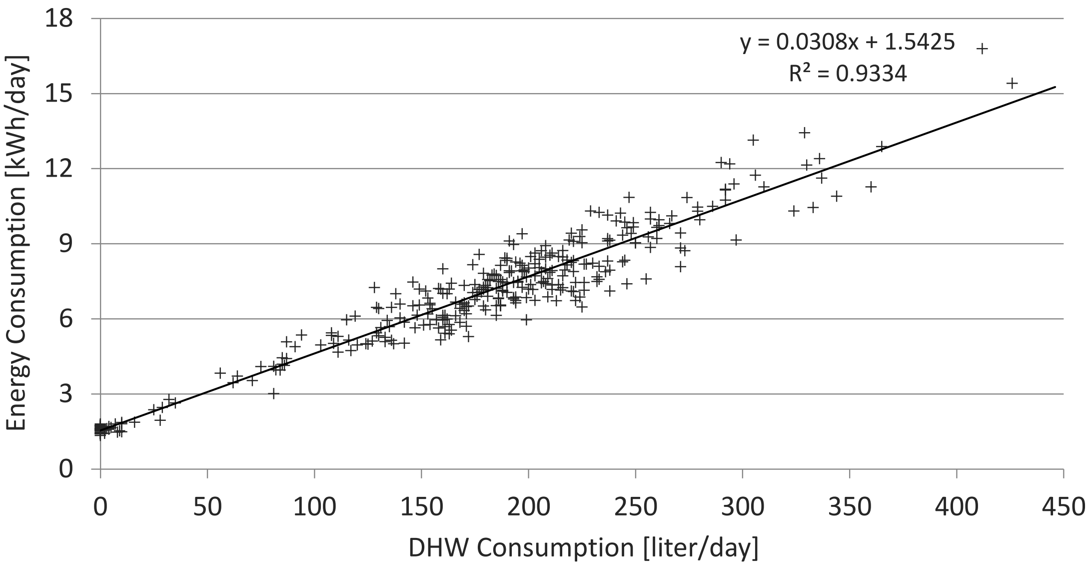


Figure 7.6: *Daily energy consumption by DHW boiler in House B as a function of tap water consume.*

40 °C and as a result the temperature of the preheated water varies less than in House A. The mean temperature of preheated water is about same as for House A, 36.0 °C, but the standard deviation of the daily mean temperature for the preheated water is only 1.3 K, compared to 6.7 K in House A.

Daily energy consumption by the DHW boiler is plotted as a function of daily domestic hot water consumption in Figure 7.6. Comparing this figure with Figure 7.2 it is clear that the data points are more aggregated around the linear fit. This is reflected in the R^2-value, which is closer to 1 for House B. The heat loss from the boiler can be seen in the figure as the constant in the linear fit equation, 1.54 kWh/day. This is less than in House A due to the fact that the ambient temperature of the boiler, which is situated below the stairs, is around 35 °C and considerably higher than in the bathroom of House A. An analysis of the days with no consumption of domestic hot water gave a slightly lower value of 1.53 kWh/day. This corresponds quite well with the lower average temperature of the domestic hot water in House B, compared to House A. The slope of the linear fit representing the average energy used to heat every liter of domestic hot water by the DHW boiler is 30.8 Wh, 17 percent less than in House A.

7.3.2 Heat Pump Efficiency's Dependence on Outdoor Temperature

As can be seen in Figure 5.2, the heat pump has a continuous use of electricity, mostly between 100 W and 200 W. When the heat pump is active it consumes between 1500 W and 2500 W for short periods, hereafter referred to as pulses. As mentioned in Chapter 2, the efficiency of a heat pump depends heavily on the temperature difference it is to create. As the inside temperature is almost constant, in practice it is the outside temperature that is the important parameter. The heat pump efficiency's dependence on the outside temperature will here be analyzed.

Detailed information about the functioning of the heat pump was not available, but for this analysis the following assumptions will be made:

- The heat pump starts when the temperature of the heat store reaches a lower limit and stops again when an upper limit is reached. These limits are constant.

- The heat needed to raise the temperature in the heat store from the lower to the upper level is constant.
- No energy leaves the heat store during heat pump operation.

Assumptions 2 and 3 are not strictly valid, but will be tried to be made plausible.

In order to analyze the heat pump a MATLAB script was made, which integrated the area under the pulses seen in Figure 5.2 and removed the base level of consumption by the heat pump. It also registered domestic hot water consumption during and between the pulses, mean solar irradiance during pulses, mean temperatures inside and outside, consumption of the heat store heating element during and between pulses, day of the year, the fan coil's consumption and time since the last pulse.

This information was printed on a spreadsheet and analyzed in two ways, with Microsoft Excel and with STATA[4].

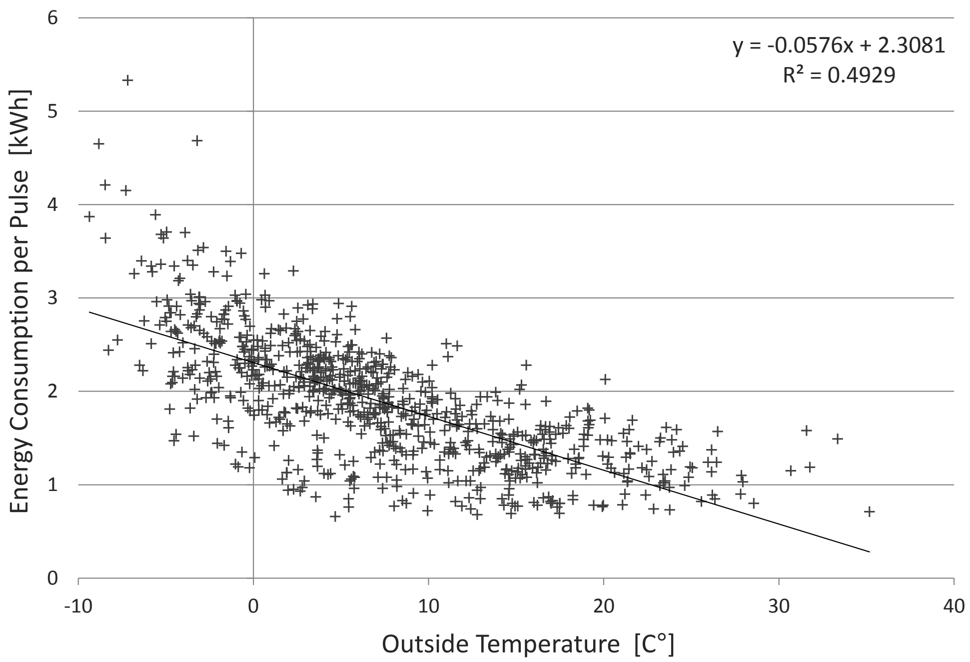


Figure 7.7: *Heat pump's energy consumption versus outside temperature. 844 data points, each a pulse or period in which the heat pump has been active. A linear regression, with formula and R^2-value in upper corner.*

Excel Analysis

One thing worth analyzing was how the outside temperature affected the heat pump's efficiency. By the above assumptions, all pulses should be equally large given a similar outside temperature. To make reality closer to these assumptions Excel was used to sort out all the pulses where more than 5 liter of domestic hot water were consumed during heat pump activity or more than 0.3 kWh were used by the heat store's heating element. Consumption of domestic hot water replaced water

[4]Software for Statistical analysis.

of about 35 °C with water of 4 °C to 10 °C in the heat store, thereby breaking assumption 3. An activated heat element breaks assumption 2, as it lowers the amount of heat needed from the heat pump. The limits of 5 liter and 0.3 kWh where chosen to remove most invalid pulses while still keeping a statistical valid amount of data. What is unknown is how much energy is taken from the heat store for space heating purposes during pulses, but it is assumed to be zero.

The MATLAB script produced 2025 pulses from January 29th 2012 to April 9th 2013, of which 844 met the criteria set above. These had a mean outside temperature of 4 °C and an average energy consumption of 1.89 kWh. The idea is that each pulse should need the same amount of energy and that the energy used by the heat pump will depend on its coefficient of performance, which again will depend on the outside temperature. Figure 7.7 shows the energy consumed during each pulse versus the outside temperature and a linear regression performed on the data. The dependence of the energy consumption on the outdoor temperature is perhaps not best described by a linear fit. However, in a certain range it gives a fair result. As can be seen in the figure, this gave the following:

$$\text{Energy Consumption per Pulse} = -57.6\,\text{Wh}/^\circ\text{C} \times T + 2310\,\text{Wh} \tag{7.3}$$

Where T is the outside temperature. As can be see from Equation 7.3, a temperature increase of 1 K from the average of 4 °C, reduces the energy needed by 3 percent. These numbers must be seen as fairly approximate as the curve fit is rough and the assumptions are somewhat faulty. Still it is clear that there exists a dependence between the heat pump's efficiency and the outside temperature, as expected.

Figure 7.8 shows heat pump consumption for the whole period as a function of time. We can see that the heat pump is active at all hours, with extra activity in the morning and in the afternoon most likely caused by showering and dinner preparation respectively. Also in the figure the mean outside temperature during the day is plotted. We can see that the temperature difference from night to day is almost 8 K at the most. From 10 till 18 the mean temperature is 7 °C or more, while from 22 till 07 it is 3 °C or less. Assuming that Equation 7.3 is correct, this means a reduced efficiency of between 12 and 22 percent in the mentioned night period compared to the day period.

STATA Analysis

Of the 2025 pulses produced by the MATLAB script mentioned above, 52 did not have a corresponding outside temperature as Datalogger2 was inactive in two periods of six and seven days. The remaining 1973 observed pulses where inserted into a statistical program called STATA, version 12. A linear regression was attempted using an increasing number of parameters. The best match was found with the following parameters: DHW flow during heat pump activity, Flow_{DHW}, heating element electricity consumption during activity, E_{HS}, fan coil consumption during activity, E_{F}, and outside temperature during activity, T.

$$\text{Heat Pump Pulse} = 15.7\,\text{Flow}_{\text{DHW}} - 0.55\,\text{E}_{\text{HS}} + 1.9\,\text{E}_{\text{F}} - 74\,\text{T} + 2.13 \times 10^3 \tag{7.4}$$

According to Equation 7.4, every liter of domestic hot water increases the heat pump pulse by 15.7 Wh, for every Wh spent by the heating element in the heat store or by the fan coil, the heat pump will spend respectively 0.55 Wh less or 1.9 Wh more. For every degree colder the heat pump will consume 74 Wh more. This linear regression has a R^2 value of 0.558, which is quite good for such a wide spread dataset and number of variables. All coefficients have a standard error of 2 till 4 in the last digit. In the Excel analysis it was found that every additional degree

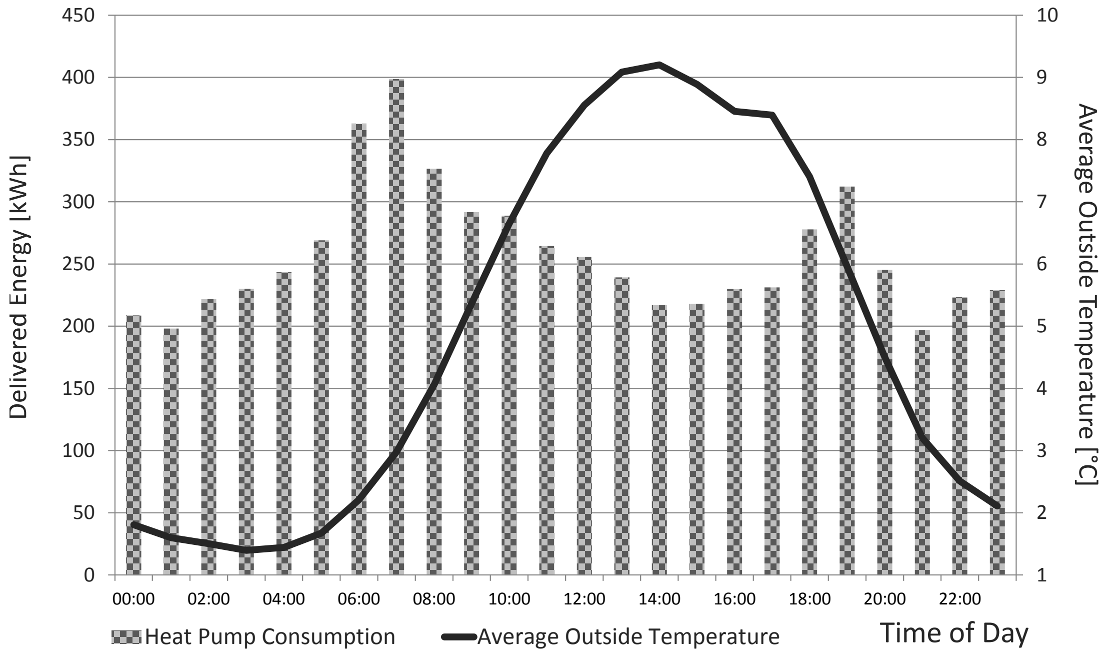


Figure 7.8: *The heat pump's energy consumption as a function of time of day, together with mean outside temperature over the year.*

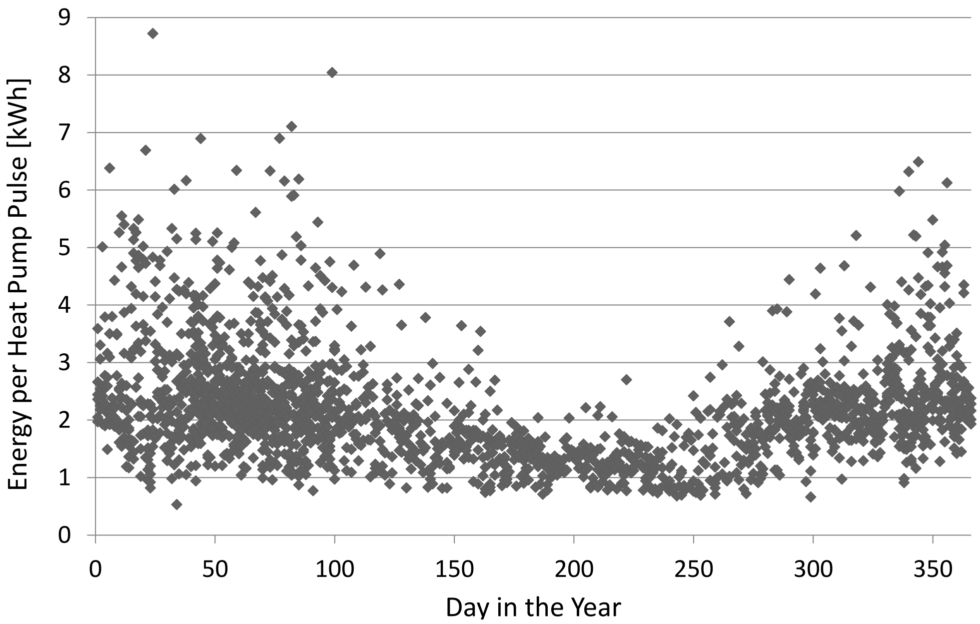


Figure 7.9: *Energy per heat pump pulse as a function of day in the year, January 1 being day 1.*

would reduce the heat pump pulse with 58 Wh and at 0 °C, 2.3×10^3 Wh would be consumed. This is consistent with the finds in STATA.

As mentioned, each liter of domestic hot water increases the heat pump's electricity consumption by 15.7 Wh. Interestingly, every liter of domestic hot water passing through the heat store picks up an average of 35 Wh, giving the heat pump a mean COP of 2.2. Use of the fan coil increases the size of the heat pump pulses. This is probably because increased use of the fan coil indicates an increased need for heating, hence more heat is being drawn from the heat store by the hydronic system during heat pump activity. But as the use of the fan coil is relatively constant over the year, this effect is small. The heating element of 3 kW in the heat store is used on cold days when the heat pump cannot deliver enough heat. For every Wh the heating element uses, the heat pump uses 0.55 Wh less. This suggests that the heat pump has a mean COP of 1 Wh/0.55 Wh = 1.8 in these temperatures which range from 0 °C to −15 °C.

The dependency on outdoor temperature found with STATA is greater than that found with Excel. Here an increase of 1 K from the mean temperature lowers the energy needed by more than 4 percent. The example from page 56 of a day time temperature of 7 °C or more and a night time temperature of 3 °C or less gives a raised energy consumption during night of at least 18 percent.

7.4 Weather Analysis

Given the nature of this study, the weather conditions of the period in question will obviously effect the results, and it could therefore be interesting to compare the weather in the period with weather from previous years. Especially temperature and insolation is of interest. It proved difficult to obtain an unbroken record of such data from the close vicinity of Rudshagen, but data from the University of Life Sciences at Ås turned out to be helpful (Thue-Hansen & Grimenes, 2013). Ås is situated 21 km to the south of Rudshagen, and comparisons of mean daily temperatures show that the weather is very similar in the two places. It is common to use the period 1961 - 1990 as a normal, but as newer data were available, it was decided to employ data from the period 2000 till April 2013. Daily data from 2000 till 2011 were averaged day by day, and used to compare against the period February 2012 till April 2013.

Mean temperature, precipitation and global radiation were chosen as the basis for comparison, and can be seen in Figure 7.10. Global radiation includes direct solar radiation as well as radiation from other surrounding sources, typically being secondary solar radiation. The monthly mean temperature difference is the difference in °C between the month in question and the average from 2000 - 2011, from now on just referred to as the historical average. In the project period, April 1 2012 till March 31 2013, the mean temperature was 4.9 °C, 1.4 °C lower than the historical average. As can be seen, only May and November were warmer than the historical average.

Precipitation in the period turned out to be very close to the historical average, but not evenly distributed over the year. In particular there was a wet autumn and a dry winter, as can be seen in the figure. Precipitation is shown as the difference in mm/month to the historical average.

Global radiation is measured on a surface parallel to the surface of the earth. Direct solar radiation makes up the majority of the global radiation, but diffuse solar radiation and radiation from ambient surfaces are also included. Global radiation in the project period was 909 kWh/m^2 which was slightly less than the historical average of 913 kWh/m^2. But again the distribution was different from the historical average. Figure 7.10 shows global radiation as the difference in percent for each month compared to the historical average. March 2013 yielded a 25 percent increased radiation, while the summer of 2012 had less sun than the historical average.

To summarize, the weather as a whole during the project period was not far from an average

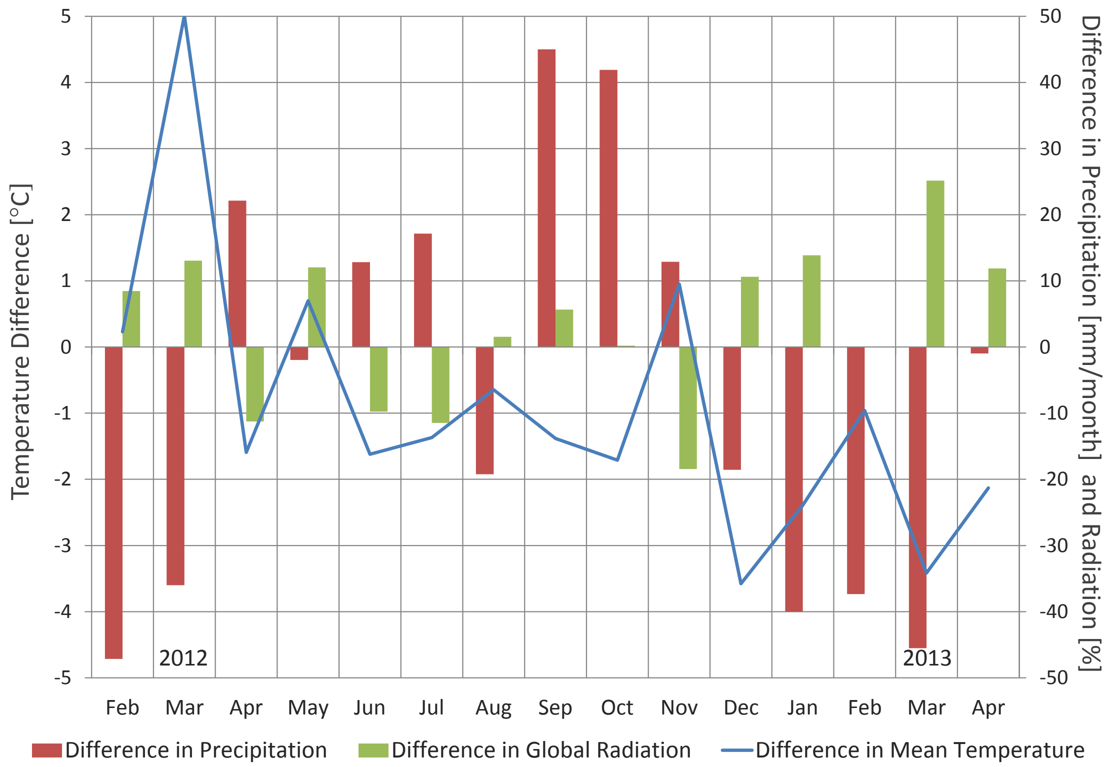


Figure 7.10: *Comparison of the weather in the period February 2012 - April 2013 and the average of the 12 preceding years. Note that it is the difference from the average that is displayed, with different units for the three parameters.*

year, but shorter periods show large variation. What is most important for this study, is the rather low temperature throughout the year, increasing the need for space heating. Also, periods of less or more solar radiation will naturally affect the yield of the solar collector. But in this aspect, the project period seems to be close to a normal year with some good months and some bad months.

According to Standard Norge (2007), a standard reference year in Oslo yields an annual insolation on a horizontal surface of about 960 kWh/m^2. The same source states 840 kWh/m^2 as the standard reference year insolation on a vertical, south facing surface. This is 28 percent more than what was measured by the *Pyranometer*, indicating the solar potential lost due to shadowing from nearby buildings.

Chapter 8

Discussion

8.1 Heating Systems - Operation and Adjustment

The Project Period

The project period was initially chosen as the first year after measurements begun, which would have been February 2012 to January 2013. But as the electricity meter for the DHW boiler in House B did not function until March 2012, and temperature sensors for the preheated water were not in place in any of the houses until the same month, this period was shifted to April 1 2012 to March 31 2013. The idea was to get data from a whole year, as important parameters such as solar irradiance, temperature and also user behavior change in the course of a year. As some of the discussion below will show, this rather arbitrary selection of a project period gave some unintended consequences. Both houses experienced problems with their heating systems in the startup phase, but due to the period selected the outcome of these problems is not distributed fairly among the houses. Because of this, some figures and results includes data collected outside of the chosen project period, as measurements continued after March 2013.

In hindsight, the project period could have been based on the entire measurement period, with an average of the overlapping months of the year. It would also have been wise to delay the start of the measurements until after dealing with startup issues.

Solar Heating System

The solar collector was out of operation in several periods for different reasons. The heat store and the control system had new designs, and minor issues were corrected as they were discovered.

After installation, the pipe leading from the heat store to the solar collector was found to be too thin, causing the pump for the solar collector to be filled with air. Also the flow meter measuring flow through the collector was placed the wrong way, giving wrong measurements. The flow meter was replaced in March 2012, but the problem with air in the pump was not eliminated until late April, resulting in several sunny days with a non-working solar thermal system.

Due to product improvements, Aventa, the manufacturer of the solar heating system, wanted to exchange the installed collectors on House A with improved collectors. The installation of the new design was finished early in April 2013. One improvement of the new collectors was that the flow rate through the collector increased from about 22 liter/minute to 25 liter/minute. But the installation of new collectors obstructed the use of the solar collectors on several days in February and March 2013.

There was counted a total of 36 days when, given the measured solar irradiance, the thermal solar system should have been in operation, but was not, due to the issues mentioned above. Of these, 28 days where in the project period.

Heat Pump Heating System

The heat pump seemed to generally function well during the project period, but had some difficulties in the first couple of months after installment, when it did not function properly. Whether this had to do with some fault in the heat pump itself or with some other part of the heating system in House B, is unknown to us. According to a consultant (Consultant, 2013), many of the houses in the housing cooperative had unexpectedly high energy consumption. As might be remembered from Chapter 4, there were 16 houses that all had air-to-water heat pumps. A design error was found in the heat stores belonging to the heat pump systems. This error does not seem to have affected House B. The consultant informed us that the heat stores should keep about 60 °C, but temperature measurements of the preheated domestic hot water suggests that the heat store in House B had a temperature closer to 40 °C. Since the design flaw was related to temperature sensors in the heat store preventing the heat pump to operate, but instead triggering the heating element in the heat store, a lower heat store temperature would probably avoid this flaw. However, on April 16 2013 a change in the heat pumps' normal operation was detected in House B. Again, looking at the temperatures of the preheated domestic hot water, it seems that the heat store temperature had risen to about 60 °C. And the heating element of the heat store, rarely used in the spring and summer of 2012, was in frequent use in April, May and June of 2013. This can clearly be seen in Figure 6.14, where delivered energy to the heat pump and heating element in House B is almost the same in April and May of 2013 as the much colder months of February and March 2013. A slight reduction in delivered energy to the DHW boiler can also be spotted in May 2013, stemming from the elevated temperatures of the preheated water. As can be seen in Figure 6.6, these issues even out the amount of energy delivered to the two houses for heating purposes, when the entire measurements period is considered.

8.2 Passive Houses - Fulfillments of Energy Goals

The houses at Rudshagen were designed to be passive houses. Based on the estimations by Mesterhus, see Appendix A, the houses were supposed to have an annual demand for delivered energy for space heating of 12 kWh/(m^2) given a space heating consumption of 23 kWh/m^2a. According to Dokka and Andresen (2006), a passive house in Oslo with an internal gain of 4 W/m^2 would need the properties listed under Zürich in Table 3.1. The houses at Rudshagen match these properties and are even close to some of the properties listed under Oslo. The specific heat loss estimated by Mesterhus is only slightly higher than that of the *detached house in Zürich*, indicating that the houses at Rudshagen should meet the standards for passive houses. The measurements from the project period show that House A had a delivered energy of 52.9 kWh/(m^2a) for space heating and House B had a delivered energy of 46.7 kWh/(m^2a). This is significantly higher than the projected value of 12 kWh/(m^2a).

There could be several reasons for this excess use of energy. As can be seen in Table 7.1, the Houses did not keep the intended indoor temperature of 20 °C. The table shows the calculated space heating demand for a house in which the temperature was held at 20 °C, based on daily averages of the measured outdoor temperatures from the period. A value of 3817 kWh/a is arrived at, which corresponds to 32.9 kWh/m^2a. Given a heat pump with a constant COP of 2.5 as required in the energy calculations by the contractor, this corresponds to 13.6 kWh/(m^2a), which is slightly higher than the expected 12 kWh/(m^2a). This discrepancy is probably due to the cold weather in the period, see Section 7.4. However, the high indoor temperatures and the low outdoor temperatures can only explain a small part of the large discrepancy between projected and actual delivered energy for space heating.

In this thesis, only two housing units were considered, and it is difficult generalize based on their consumptions. As seen in Section 3.1, individual units within one project display large variations in energy consumption for space heating. However, it turned out that several of the other houses at Rudshagen had higher energy consumptions than expected (Consultant, 2013).

As mentioned, the projections done by Mesterhus were based on a house with a heat pump, and were thus unlikely to apply to House A which had solar thermal heating. Given the average indoor temperature in House A, the daily average outside temperature and the total U-value as provided by Mesterhus in Appendix A, had House A had a heat pump with an constant COP of 2.5, it should have had a demand of delivered energy for space heating of 16.7 kWh/m^2, see Table 7.1. This was calculated using the heating degree days method. But measurements show that in the project period, 53.6 kWh/m^2 was delivered to House A as space heating. This figure would have been somewhat smaller had the solar heating system been active on more days, see Section 8.1.

For House B, it can be seen in Table 7.1 that its measured delivered energy for space heating during the project period was 47.2 kWh/m^2, slightly more than the stipulated consumption of 45.8 kWh/m^2. But as this house has a heat pump with an expected average COP of at least 2.5, this value should have been closer to 18 kWh/m^2. This anomaly is difficult to explain. The period in question was one where the heat pump seemed to work properly, unlike other periods mentioned in Section 8.1. There are no indications that the heat pump should have had a lower efficiency than expected.

The above indicates that at least 60 kWh/m^2 of heat have been supplied to both houses as space heating during the project period, which should have resulted in significantly higher indoor temperatures, if we assume that the total U-value for the houses is correct. This indicates that either the real U-value is considerably higher, or there is some unknown user behavior, like venting through windows, affecting the heating consumption substantially.

As shown in Table 6.1 and 6.2, the total amount of delivered energy for both houses is close to the demand set by TEK10 of 134 kWh/m^2, as seen in Section 2.1.6, and around 50 percent higher than the requirement for passive houses. The reason for this excess consumption is energy used on space heating and domestic hot water. Technically, the houses fulfill the passive house standard, and delivered energy for space heating on the coldest days of the year, see Table 7.1, also point in this direction.

8.3 Solar Heating - A Viable Option for Passive Houses?

The main goal of this thesis was to investigate solar collectors as a heating alternative for passive houses in Norway.

The energy delivered to the heat pump was expected to be fairly stable, as its efficiency mainly depended upon outdoor temperature. The thermal solar heating system was expected to outperform the heat pump on sunny days, but also display an irregular need for delivered energy as it was weather dependent. Poorer performance was expected from both heating systems during the colder part of the year. As can be seen in Figure 6.6, these expectations were in large part met. As the figure shows, both houses display an S-shaped consumption, inverted from the S-shape of the temperature curve. But the S-shape is more profound on House A as it has a large need for delivered energy in winter and very little need for delivered energy during summer, whilst House B can be said to have a medium low need in summer and a medium high need during winter.

As mentioned in Section 8.1, both systems had periods of poor performance. Looking again at Figure 6.6, the heat pump's bad periods are more or less before and after the project period, whilst the solar heating system has down-periods both in the beginning and the end of the project period. This figure also shows that if the entire measurement period is considered, the amount of energy delivered for heating purposes is almost equal for the two houses.

Despite the mentioned problems and the relatively low solar fraction, that is the fraction of space heating consumption and/or domestic hot water energy consumption that is covered by solar energy, the solar heating system had periods where it functioned well. The calorimetric analysis shows how in these periods a large portion of the heating is covered by the solar collector, see Figure 6.15. If the need for space heating had been closer to the projected values, the solar fraction would have been considerably higher. As mentioned in the beginning of Chapter 4, it was decided fairly late that House A should have a solar heating system. For such a system to function optimally, it should be a part of the project from the start. For instance, the technical room outside of the building envelope caused the heat loss from the heat store in House A to be lost to the ambient and not contribute to the internal gain, see Section 7.2.2. But for a solar heating system to be a viable option for passive houses, it must be able to operate during larger parts of the year including winter when heating is most needed. As seen in Figures 7.4 and 7.5, albeit a shorter period with solar radiation, solar irradiance is higher in late October than late April. But in order to exploit solar energy during winter months, the solar collector must have a clear view to the south, unlike House A.

Domestic Hot Water

Both houses used considerably more energy on domestic hot water than the 16 kWh/(m^{2}a) estimated by the contractor, 29.8 kWh/(m^{2}a) and 27.2 kWh/(m^{2}a) respectively for House A and B. Consumption of domestic hot water is different in the two houses with House A having a consumption of 43 113 liter in the project period and House B consuming 60 904 liter. But although the quantity is different, the consumption habits are quite similar, as can be seen in Figure 6.10, with a majority of the consumption taking place in the morning and in the evening. And as mentioned in Sections 7.2.1 and 7.3.1 the average temperature of the domestic hot water is different in the two houses, 67.6 °C and 62.8 °C for House A and House B respectively. Thus House B's 41 percent higher consumption is reduced to a 30 percent higher consumption when the temperature of the domestic hot water is taken into account. Most of this temperature difference is probably a result of the habits in House B, where domestic hot water was often tapped in volumes two and three times as high as in House A. Perhaps related to bathing. (Both houses have bathtubs.) The more hot water one taps at once, the colder the average temperature of that water becomes, as the DHW boiler has a relatively small volume of 76 liter. This could explain some of the difference in the temperature of domestic hot water between the houses, but part of the discrepancy could also be attributed to the fact that the temperature of the preheated water in House A at times was in the range of 40 °C to 65 °C, resulting in high temperatures of the domestic hot water.

The Heat Store and the Heat Pump

Looking back at section 7.3.2 and Figure 7.8, it seems clear that it would be advantageous if the heat pump could be active only during day time when the outside temperature usually is several degrees higher than during the night. Unfortunately this is not completely possible as the energy needs to be consumed within a few hours of being collected. And if one would want to store energy from the period of the day when it is warm, one would have to heat the store some degrees above standard temperature which would take away most of the gain associated with a higher outside temperature.

For both houses, the size of the heat store is an important parameter. A larger heat store in House A could enable usage of energy collected up to two days earlier for a larger part of the year. For House B a larger heat store could mean less nighttime activity, thus improving the efficiency of the heat pump.

But for both houses a larger heat store would of course come with a cost. It it a slightly larger investment, the heat losses would be larger and, maybe even more important, a larger heat store would occupy more space.

Chapter 9

Conclusions and Outlook

The goal of this thesis was to examine solar energy as an alternative source for heating in passive houses in Norway. Heat pumps are a more common source for heating, and in this thesis two similar houses, one with a heat pump heating system and one with a solar heating system were compared and contrasted to elucidate the potential of the solar heating system in Norwegian passive houses.

As in all *in situ* research projects, unforeseen events occurred. For example both heating systems had periods were they did not function properly, making it more difficult to directly compare the two systems. As with all new buildings, estimations of energy consumption were made in advance. Energy delivered for space heating during cold periods, indicate that the estimated U-value was in the right range, but the annual amount of delivered energy for space heating far exceeded the estimated value. The contractors estimation was based on Norwegian Standard NS 3031:2007 and may have been too optimistic. In general, it seems like the effects of user behavior was not emphasized enough. The larger than expected consumption makes it difficult to conclude as to the viability of solar heating.

However, the results and analysis indicate that solar collectors can give a large contribution to a building's energy consumption for space heating and domestic hot water. To find out if these indications are correct, measurements should be done on a building in which the consumption is closer to the expected and where the conditions are conducive. For instance, due to local solar conditions the solar heating system could not operate during several winter months when the need for heating was largest, and for different reasons mentioned in the previous chapter, the solar heating system was not in operation on several occasions. In this project, energy delivered to space heating and energy delivered to domestic hot water was not clearly separated, and in possible future projects it would be advantageous to have more knowledge of the energy consumed for space heating.

All in all, solar heating seems to be a viable option for passive houses in Norway, but for the choice of heating system to be optimal, several aspects must be considered. For a solar heating system, the solar conditions are of course paramount. But also user needs and architectural restraints must be taken into account. For buildings with larger energy demands, solutions including multiple heating systems could be an option.

Given the right circumstances, solar heating systems can definitely contribute to a Norwegian passive house future.

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Appendices

Appendix A

Estimations by Mesterhus

Energitiltak og samlet netto energibehov

Kontroll og dokumentasjon av bygningers energieffektivitet

Resultater

Prosjektbeskrivelse:	
	Obos Felt BK Versjon 4, tilsv tegn 26.11.09 Inkl. levert energi med varmepumpe

Type bygning:		
Småhus	Oppvarmet bruksareal (m^2):	116,00
	Oppvarmet volum (m³)	250,56

Energitiltak

Varmetapstall og varmetapsramme

	Denne bygning			Krav i TEK
	Areal m²	U-verdi W/(m²K)	Varmetap W/(m²K)	Varmetapsramme W/(m²K)
Yttervegger, netto areal	137,1	0,10	13,7	24,7
Vinduer og dører	23,2	0,78	18,1	27,8
Tak	116,0	0,07	8,1	15,1
Golv på grunn	116,0	0,08	9,7	17,4
Normalisert kuldebroverdi	116,0	0,03	2,9	3,5
	Luftmengde m³/h	Virkningsgrad %		
Infiltrasjon	11	-	3,5	14,5
Ventilasjon	139	82	8,3	13,8
Varmetransportkoeffisient			64,4	116,7
Varmetapstall (W/(m²K))	**-**	**-**	**0,55**	**1,01**

Spesifikk vifteeffekt (SFP)	1,5 kW/(m³s)

Samlet netto energibehov

Netto energibudsjett og energiramme

	Denne bygning			Krav i TEK
Energipost	Energibehov kWh/år	Spesifikt energibehov kWh/(m²år)	Levert energi med vp kWh/(m²år)	Energiramme kWh/(m²år)
Romoppvarming	2613	23	12	
Varmtvann	3480	30	16	
Vifter	508	4	4	
Belysning	1473	13	13	
Teknisk utstyr	1951	17	17	
Totalt	**10026**	**86**	61	139

Energimerke **A** I hht. energimerkemetoden 1.1. 2010

Sted	Dato	Navn og firma
Oslo	06.01.2010	Trine Dyrstad Pettersen, Mesterhus Norge

Energitiltak og samlet netto energibehov

Kontroll og dokumentasjon av bygningers energieffektivitet i henhold til TEK

Type bygning:	Småhus
Oppvarmet bruksareal (m^2):	116
Oppvarmet volum (m^3):	251
Eksponert omkrets (m)	36

Prosjektbeskrivelse

Obos Felt BK
Versjon 4, tilsv tegn 26.11.09
Inkl. levert energi med varmepumpe

Energitiltak

Krav i TEK

Bygningsdeler	Netto areal m^2	U-verdi $W/(m^2K)$	Varmetap W/K	U-verdi $W/(m^2K)$	Varmetap (W/K)	Kommentar
Yttervegger		0,1000	**13,71**	0,18	**24,68**	
Yttervegg mot terreng						
Yttervegg	137,1	0,1				400 mm isolasjon
Yttervegg						
Yttervegg						
Yttervegg						
Yttervegg						
Vinduer og dører	20 %	0,78	**18,14**	1,20	**27,84**	
Vindu/dør	16,92	0,74				Passivhusvinduer, Nordan Ntech
Vindu/dør	2,31	0,8				Passivhus ytterdør
Vindu/dør	1,89	0,93				Passivhus balkongdør
Vindu/dør	2,1	0,93				Passivhus balkongdør
Vindu/dør						
Vindu/dør						
Vindu/dør						
Vindu i skråtak						
Tak		0,07	**8,12**	0,13	**15,08**	
Isolert takflate/loftsbjelkelag	116	0,07				500 - 600 mm isol, flatt tak.
Isolert takflate/loftsbjelkelag						Extrem 33 og EPS
Isolert takflate/loftsbjelkelag						
Golv		0,08	**9,75**	0,15	**17,40**	
Golv mot grunnen	116	0,10				400 mm isol
Kuldebroer	$W/(m^2K)$					
Normalisert kuldebroverdi	0,025		**2,90**	0,03	**3,48**	
Lufttetthet	Luftveksling per time (1/h)			1/h		
Lekkasjetall n_{50}	0,6		**3,47**	2,50	**14,47**	Ekstrem god vindtetting og utførelse
Ventilasjon				%		
Varmegjenvinning	82	%	**8,27**	70,00	**13,78**	Roterende veksler, eks. VR 700
Luftmengde	1,2	$(m^3/(m^2h)$				
Totalt varmetap						
Bygningens varmetransportkoeffisient (W/K)			64		117	
Bygningens varmetapstall (W/(m²K))			**0,55**		**1,01**	**Foreslått kravsnivå 0,55**

Beregnet varmetapstall er høyere enn foreslått nivå i kommende passivhusstandard

Samlet netto energibehov

Ventilasjon og varmekapasitet				
Bygningens varmekapasitet	34	$Wh/(m^2K)$		
Spesifikk vifteeffekt (SFP)	1,5	$kW/(m^3/s)$		
Soltilskudd	Himmel-retning	Lysåpning m^2	Solfaktor glass	Type sol-avskjerming
Nordvendt fasade	N		0,50	Ingen avskjerming
Østvendt fasade	Ø	6,2	0,50	Ingen avskjerming
Sydvendt fasade	S	2,9	0,50	Ingen avskjerming
Vestvendt fasade	V	9,5	0,50	Ingen avskjerming
Takvindu	S		0,56	Ingen avskjerming

Bygningens samlede netto energibehov	**86**	$kWh/(m^2år)$	
Forskriftens energiramme	**139**	$kWh/(m^2år$	Energirammen er tilfredsstilt

Totalt levert energi	61	kWh/m2	Basert på luft til vann varmepumpe, COP 2,5
Energimerke	**A**		I hht. energimerkemetoden 1.1. 2010
Oppvarming, krav	**22,7**	kWh/m2	**Foreslått passivhuskrav for det aktuelle huset (NB HELT NYTT)**
Oppvarming, beregnet	**22,5**	kWh/m2	Beregnet i hht til NS 3031, og angivelser i kommende passivhus-standard

OK

Sted	Dato	Navn og firma
Oslo	06.01.2010	Trine Dyrstad Pettersen, Mesterhus Norge

Appendix B

Heat Pump - Technical Specifications

Innedel modellbetegnelse:	**HWS-603XWH-E** oppvarming og tappevann, **HWS-603XW-E** tappevann, **HWS-603XH-E** oppvarming		
Utedel modellbetegnelse:	**HWS-603H-E**		
Trinnløs varmekapasitet	kW	2,0 - 6,0	
Effektfaktor - oppvarming / tappevann	COP	4,00 / 3,30	
Avgitt varme/effektfaktor ved utetemperatur:		Oppvarming 35°C [1)]	Tappevann 65°C [2)]
25^{0}C	kW / COP	6,92 / 6,18	6,32 / 4,14
16^{0}C		6,28 / 4,81	6,13 / 3,68
7^{0}C		6,00 / 4,00	6,00 / 3,30
2^{0}C		6,00 / 3,10	6,00 / 2,70
- 7^{0}C		4,10 / 2,30	4,90 / 2,30
- 15^{0}C		3,40 / 1,90	3,50 / 1,80
Driftsområde utetemperatur	^{0}C	-20 til 43	
Lydtrykk innedel [3)] / utedel [3)]	dB(A)	33 / 50	
Kompressortype	-	Dobbel rullestempel	
Maks rørlengde (innedel - utedel)	meter	15	
Maks høydeforskjell (innedel - utedel)	meter	10	
Maks rørlengde (innedel - varmtvannsbereder)	meter	5	
Spenningstilførsel for varmepumpe (innedel)	V / ~ / Hz	230 / 1 / 50	
Sikring	A	16	
Innedel - høyde / bredde / dybde - vekt	mm - kg	770 / 500 / 280 - fra 30 - 43	
Utedel - høyde/bredde/dybde - vekt	mm - kg	550 / 780 / 290 - 38	

kWsmart varmtvannsbereder		**200 liter**	**300 liter** [4)]
Materiale tank / isolasjon		rustfri / PUR-skum	rustfri / PUR-skum
Maks. trykk	bar	9	9
Spenningstilførsel - sikring	V / ~ / Hz - A	230 / 1 / 50 - 10	230 / 1 / 50 - 16
Effekt el.kolbe	kW	2	3
Mål - høyde / bredde / dybde	mm - kg	1470 / 596 / 620 - 62	1900 / 596 / 620 - 82

kWsmart Modul 1 el.kassett		**6,0 kW**	**9,0 kW**
Vannvolum	liter	9	9
Spenningstilførsel	V / ~ / Hz	230 / 3 / 50 eller 400 / 3+N / 50	som 6,0 kW
Sikring 230 / 400 V	A	16 / 10	25 / 16
Maks. trykk	bar	9	9
Mål - høyde / bredde / dybde - vekt	mm - kg	600 / 500 / 280 - 22	600 / 500 / 280 - 22

kWsmart Modul 2 komplett varmesentral el.kassett		**6,0 kW**
Vannvolum	liter	11
Spenningstilførsel	V / ~ / Hz	230 / 3 / 50 eller 400 / 3+N / 50
Sikring 230 / 400 V	A	16 / 10
Maks. trykk	bar	2,5
Mål - høyde / bredde / dybde - vekt	mm - kg	1110 / 500 / 280 - 51

Reléboks for styring av tilleggsvarme
Opptil 9 kW i tre steg for oppvarming, og opptil 3 kW for varmtvannsbeholder
Bryter for manuell styring av el.kolbe i varmtvannsbereder. Signal fra Toshiba kWsmart innedel styrer 16 A reléer.

Appendix C

Data Sheet - Collector and Store

Aventa Varmesentral - modell 800 l

Komplett Varmesentral 800 l *(bilde, side 2)*	Ytermål med isolasjon (bredde x dybde x høyde)	102 cm x 120 cm x 144 cm
	Vekt med utstyr (uten vann)	ca. 100 kg
	Levering	Teknisk/elektrisk utstyr og rørtilførsel er ferdig montert; isolasjon er ikke montert;
	Farge	grå
Hovedtank	Funksjon	Buffertank; inneholder systemvann, som oppvarmes av solvarme og elektrisk varmekolbe
	Material	Rustfritt stål
	Drift	ikke trykksatt
	Brutto volum	800 l
	Netto volum	672 l
	Bredde / dybde (uten isolasjon)	80 cm / 80 cm
	Høyde (uten isolasjon)	125 cm
	Bredde / dybde (med isolasjon)	102 cm / 120 cm
	Høyde (med isolasjon)	144 cm
	Tekn. installasjoner	Alle tekniske installasjoner er bak isolasjonens frontdeksel.
	Topp, rørtilførsel	Alle rørtilførsler føres gjennom isolasjonens toppdeksel.
	Innhold (i drift)	Systemvann (uten tilsetninger)
Innertank Serie 8RT 100 *(bilde, side 2)*	Funksjon	Forvarming av tappevann
	Plassering	Nedsenket i varmesentralens hovedtank, 14 cm over hovedtankens bunn-nivå
	Material	Rustfritt stål
	Driftstilstand	trykksatt
	Volum	96 l
	Diameter	35 cm
	Høyde	111 cm
	Innhold (i drift)	Drikkevann
Termisk isolasjon	Material, bunn / λ-verdi	Isopor, 50 mm / 0.035 W/(m K)
	Material, sider og topp / λ-verdi	INOTAN 65M plate i stivt polyuretanskum, 100 mm / 0.022 W/(m K) (tilsatt flammehemmende middel)
	Konstruksjon/levering	Leveres som platemoduler separat for hver side og settes på i teknisk rom;
	Frontside	med handtak og lufteåpninger for regulator uc:symphony
Utstyr, front *(bilde, side 2)*	Elektrisk varmekolbe, effekt	3 kW - TERMOSKT Hus K11A
	Solpumpe	GRUNDFOS UPS 25-80N
	Gulvvarmepumpe	GRUNDFOS UPS 25-60N
	Shuntventil for gulvvarmeanlegget	T6102AUB 15 m/ sjult termostat
	Regulator	uc:symphony (se eget datablad)
	Koblingsboks	til temperaturfølere, aktuatorer, nivåvakt, jordledning solfangerfelt
Tilkoblinger, topp	gulvvarme tur/retur	Ø 18 mm
	tappevann tur/retur (Innertank)	Ø 18 mm
	solfangerkrets tur/retur	Ø 22 mm
	Nivåvakt	koblet opp til regulator uc:symphony

TECHNICAL DATASHEET - v. 2 - 10012012

AventaSolar collector
for building integration

Absorber	Material	PPS, polyphenylene sulfide (Xtel®XE4500BL/XE5032BL)[1]
	Producer	Chevron Philipps Chemicals Int.
	Heat conductivity	2.6 BTU·(in/hr·ft^2 °F) [in metric units: 0.375 W/(m K)]
	Coefficient of linear thermal expansion, ISO11359-2	$9.0 \cdot 10^{-5}$ K^{-1} (-50 to 50 °C)
		$17.0 \cdot 10^{-5}$ K^{-1} (100 to 200 °C)
	Flammability	UL94 HB Burn Rate: 0 in/min at 0.8 mm
		UL94 V-1 at 1.6 mm and 3.2 mm
	Intrinsic design / envelope wall thickness	twin-wall sheet / 0.5 mm
	Standard width	560 mm
	Absorber height	6 mm
	Standard absorber lenghts	= standard collector length L - 7 cm
	Connections inlet	Ø 20 mm
	Connections outlet	Ø 20 mm
	Parallel tube segments	56
	Reccomenced volume flow	ca. 2.0 - 2.5 l/(min module) = ca. 120 - 150 l/(h module)
	Max. gauge pressure	approx. 0.8 bar
	Heat carrier	pure water without additives
	Heat carrier volume	ca. 3 l/m^2
	Coating, Solarlack[2]: Absorptance / emittance	0.95 / 0.86
Cover sheet	Material	PC, polycarbonate
	Producer	DS Smith Kaysersberg Plastics
	Type	Akyver® Sun Type, clear type, with anti-UV treatment
	Intrinsic design	Twin-wall sheet, rectangular structure 10 x 10 mm
	Weight	1.7 kg/m^2
	Transmittance (light) [3] /(solar)[4]	0.85 / 0,77
	Fire retardency [5]	B, s1, d0
	U-value	3.1 W/(m^2 K)
	Thermal conductivity	0.20 W/(mK)
	Coefficient of linear thermal expansion, DIN 53752	$7.0 \cdot 10^{-5}$ K^{-1} (23 - 80 °C)
	Standard width	585 mm
	Sheet height	10 mm
Thermal insulation	Material	Mineral wool
	Producer /type	GLAVA roll A37
	Thickness	25 mm
	Width	570 mm
	U-value	0.037 W/(mK)
	Specific weight	16 kg/m^3
	Flammability	non-flammable, class A1
Framing	Material, framing	Aluminium, anodized
	Height, side / top / bottom[6]	55 mm / 60 mm / 57 mm
	Width, side / top / bottom[8]	30 mm / 75 mm / 20 mm
Collector	Mounting	roof or facade integrated
	Standard width	60 cm
	Standard length L	205 250 300 350 400 500 580 cm
	Aperture area	1.11 1.36 1.62 1.89 2.16 2.70 3.13 m^2
	Gross area	1.23 1.50 1.80 2.10 2.40 3.00 3.48 m^2
	Weight (without heat carrier) [7]	approx. 7.7 kg/m^2
	η_0	0.77
	K_1 / K_2	3.0 W/(m^2 K) / 0.035 W/(m K)^2

[1] Sheet/endcap
[2] TRANSFER ELECTRIC - Solarlack M40 Li /E
[3] Measured with a lux-meter as per NF P38-511.
[4] g-factor total solar radiant heat energy transmitted (solar factor) according to EN410;
[5] European SBI-classification EN 13501 test report
[6] Compare: Longitudinal section drawings in "AventaSolar collector Mounting Manual";
[7] Collector module weight depends on collector module length (approx. 8.1 kg/m^2 for 205-cm-modules and approx. 7.3 kg/m^2 for 580-cm-modules).

Appendix D

Heat Capacity of Water

Table D.1: *Specific Heat Capacities per liter of water for different water temperatures, both in joule and watt hours. (Lide, 2005)*

Temperature [°C]	Density [g/l]	Specific Heat Capacity [J/gK]	Specific Heat Capacity [J/lK]	Specific Heat Capacity [Wh/lK]
0	999.84	4.2176	4.217	1.1714
4	999.97	4.2049	4.205	1.1680
10	999.70	4.1921	4.191	1.1641
15	999.10	4.1870	4.183	1.1620
20	998.21	4.1818	4.174	1.1595
22	997.77	4.1816	4.172	1.1590
25	997.05	4.1814	4.169	1.1581
30	995.65	4.1784	4.160	1.1556
40	992.20	4.1785	4.146	1.1516
60	983.20	4.1843	4.114	1.1428
80	971.80	4.1963	4.078	1.1328

Appendix E

Sensor Data

Table E.1: *List of sensor types, manufacturer, resolution and accuracy.*

Sensor Type	Manufacturer	Resolution	Accuracy	Sensor Name
FSTF-1-Pt1000	S+S Regeltechnik	0.01 °C	± 0.1 K	*T Inside 1st* *T Inside 2nd* House A & B
residia^{JET}	Sensus	1 liter	± 2 %	*Flow DHW* House A & B
EM30-C	CIRCUTOR	0.1 kWh	± 2 %	*EL Technical Room* *EL DHW* *EL Fancoil (A)* *EL Heat Pump* *EL Heat Store* *EL DHW small* *EL Fancoil (B)*
80spc	SolData	0.01 mV	± 3 %	Pyranometer
FVA645GV100QT	Ahlborn	0.1 liter/min 0.1 °C	± 1.5 % ± 1 K	*Flow Collector* *T Collector Forward*
Thermocouple Type K	Ahlborn	0.1 °C	± 0.05 K	*T Tank Bottom*
Thermocouple Type T	Ahlborn	0.1 °C	± 0.05 K	*T Solar Pump* *T East* *T North* *T Technical Room* *T Tank Middle* *T Tank Top* *T Elbox* *T Collector Return* *T Below Stairs* *T Forward DHW (A)* *T Forward DHW (B)*
ALMEMO 2890-9	Ahlborn	-	± 0.02 %	Dataloggers