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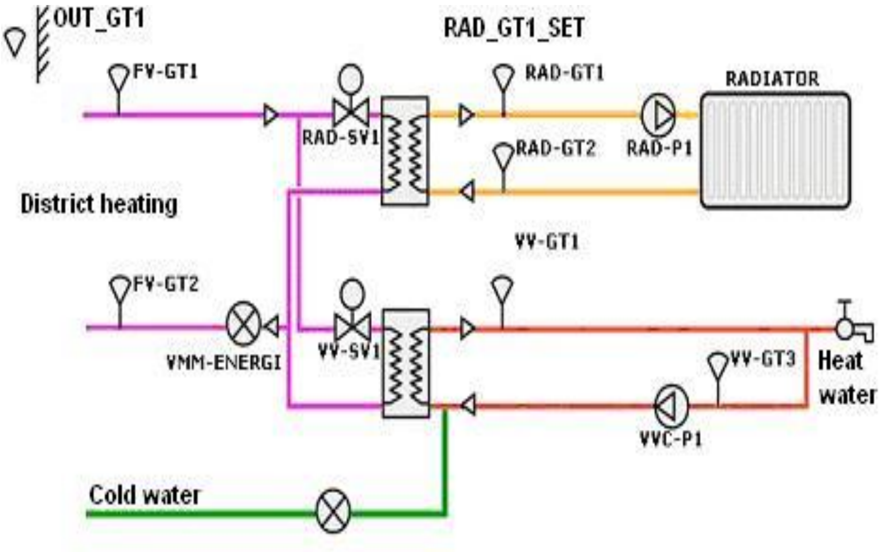

Analysis and development of control strategies for a district heating central

Energy and power optimization performed at Göteborg Energi AB

Master of Science Thesis in Systems, Control and Mechatronics

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Department of Signals and Systems
Division of Automation
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2009
Master's Thesis EX078/2009

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Abstract

District heating is a technology used to supply city districts with heat from a central heating system through a network of pipes. The systems are supplied with heat from one or more production plants, which converts energy-rich material into heat. The heat is then transferred from the district heating system via heat-exchangers to building's radiator and heat water systems. The heat transfer is mostly controlled by an outdoor temperature sensor. This means that the control is not optimized since it does not take into account the indoor climate or any heating impacts from the weather; like the sun and wind. This thesis therefore focuses on trying to obtain a smarter control strategy to achieve better comfort and lower energy consumption in buildings where the heating is controlled by the outdoor temperature, by analyzing existing controlling methods and by trying to develop our own. The objective is to determine which control methods that are the most optimal ones to use in terms of cost and energy saving, from the customer's point of view.

Two existing control functions and two own developed functions have been studied. The two existing functions are forecast control and indoor temperature control. The two own developed functions are power limitation and damped outdoor temperature. Also a combination of these two functions has been studied. A comparison between the four control methods has been done to evaluate how much energy and cost the different methods save per year. The savings of energy in percent for the different methods are; forecast control 13.9, indoor temperature control 14.1, power limitation 6.5, damped 24h outdoor temperature 6.9 and for the combined power limitation and damped 24h outdoor temperature 13.3. The cost savings in percent for the different functions are; 9.3, 9.3, 7.5, 4.3 and 11.2. It is a cost saving for the customers but a lower income for Göteborg Energi's point of view. Lower energy consumption also gives lower carbon dioxide emissions. All of the four controlling function provides a carbon dioxide reduction that is greater than 1000 tonnes per year.

District heating, Control, Temperature control, Forecast control, Power limitation, Damped outdoor temperature, Energy, Power, Energy signature, eGain, EnReduce.

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Content

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Gothenburg September 2009
Oskar Hilding
Simon Nilsson

1 Introduction

District heating is a technology used to supply city districts with heat from a central heating system through a network of pipes, where the heat carrier usually is water. The central heating system is supplied with heat from one or more production plants, which converts energy-rich raw material into heat. The raw material can be wood chips, pellets, garbage, natural gas or oil. Waste heat from various industries is often used to heat the district heating system, which reduces the use of fossil fuels thus gaining the environment. The district heating is then passed through distribution centers to the customers' substations. The heat is then transferred from the district heating system via heat-exchangers to building's radiator and heat water systems. The heat transfer from the district heating to the radiator system is often controlled by an outdoor temperature sensor. This means that the control is not optimized since it does not take into account the indoor climate or any impacts from the weather; like the sun and wind. This thesis therefore focuses on trying to get a smarter controller approach than to simply use the outdoor temperature sensor, by analyzing existing controlling methods and trying to develop our own.

1.1 Purpose

The purpose of this thesis is to evaluate and develop smarter control strategies to achieve better comfort and lower energy consumption in buildings heated by district heating. The strategies should also take into account to try to obtain optimal operation in Göteborg Energi's production facilities without compromise the reliability of the heat distribution to the customers.

1.2 Goal

The objective of this master's thesis is to determine which or what control methods that are the most optimal ones to use in terms of cost and energy saving, from the customer's point of view. Furthermore, it should be investigated how the objective affects Göteborg Energi, both in terms of economics, environmental impacts and competitiveness. Also if it has any affects on their production.

1.3 Delimitations

In this thesis, the thesis is limited to only analyze multi dwelling buildings that have no heat pumps, ventilating or cooling units installed. The reason for this is that the problem in these cases becomes very complex, especially concerning the hysteresis that occurs when two of the units cooling, heating and ventilation are running simultaneously. This restriction also simplifies the analysis and studies of the evaluated control methods carried out in this thesis. Another limitation is that the control strategies must be adapted to Göteborg Energi's tariff so that it promotes the customers heating cost in the event of an installation.

2 Theory

Every building has the ability to store energy within the material of the construction and every building has its own dynamical inertia depending on its construction. The building's dynamical inertia is greater for heavy than for lighter buildings. The benefit of using the buildings dynamical inertia is to reduce the need of energy from the heating system and to gain a smoother indoor climate. Every time when the outdoor temperature increases or decreases there need to be a new energy balance between the heats that is added and removed. The heating system, the solar radiation, the household electricity and people adds heat to the building. The heat transmissions through walls, the ventilation losses and the wind; removes internal heat from the building. See Figure 1 for illustration of the external and internal heating sources.

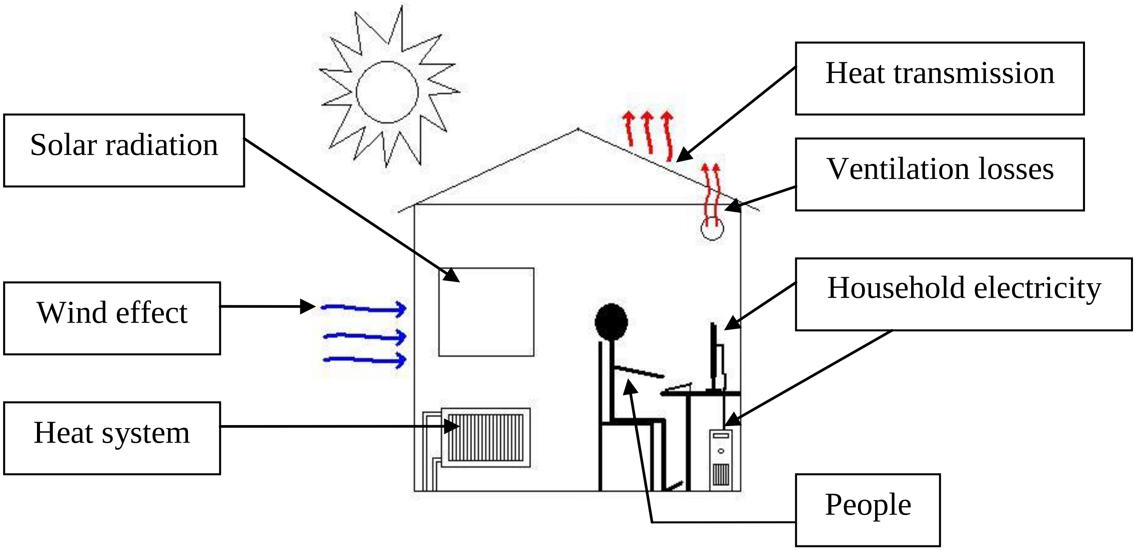

Figure 1: The figure shows different sources of energy inputs and outputs that affects the heating energy of the building.

2.1 Normal year correction

Normal year correction is necessary to perform when comparing data from one year to another. This is done to make the data from the different years comparable, independent of the climate. The only part that is normal-year-corrected is the data that is climate dependent. One method to use for normal-year-correction is the degree-days method [1]. The number of degree-days for heating is calculated as the difference between the balance temperature and the outdoor temperature expressed as the day average temperature. Those degree-days are then summarized by month or year, see Equation 1.

$$QD = \sum_i \left(t_{balance,i} - t_{out,i}\right) \quad i = 1,2,....., N \ days \qquad \textbf{(Equation 1)}$$

where QD = Number of degree-days
$t_{balance}$ = Balance temperature
t_{out} = Outdoor temperature

The balance temperature is equal to the outdoor temperature when no extra heat is needed to obtain the desired indoor temperature. This balance temperature differs during the year because of the changing sun radiation. The degree days are collected from SMHI (Sweden's meteorological and hydrological institute), see Table 1.

Table 1: This table shows the balance temperatures over the year, which are used when doing the normal year correction, see [2].

Month	**Balance-temperature [°C]**
May, June, July	10
August	11
April, September	12
October	13
Remaining time	17

$$Q_{corrected} = Q_{co} + (Q_{total} - Q_{co}) * \frac{GD_{normal\_year}}{GD_{current\_year}}$$ **(Equation 2)**

where
$Q_{corrected}$ = Energy usage corrected by a normal year [kWh]
Q_{co} = Part of the energy usage that is climate independent [kWh]
Q_{total} = Total energy usage [kWh]
QD_{normal_year} = Total number of degrees days during a normal year [°C days][a]
$QD_{current\_year}$ = Total number of degrees days during the current year [°C days]

25 percent of the total energy usage assumes to be climate independent, see Equation 3. The climate independent energy is used for heating the tap water.

$$Q_{co} = 0,25 * Q_{total}$$ **(Equation 3)**

2.2 The buildings dynamical inertia and time constants

One key value for the buildings energy storage is the time constant τ. The time constant describes how fast the building will react to changes in the weather and added heat. This time constant differs between buildings. A heavy building has a time constant around 160 hours, a medium building has around 66 hours and a light building has around 25 hours, cf. [3].

$$T_i = T_u + (T_{i,0} - T_u)e^{-t/\tau}$$ **(Equation 4)**

where
T_i = Indoor temperature
$T_{i,0}$ = Indoor temperature at the start
T_u = Outdoor temperature
τ = Time constant
t = Elapsed time from start

[a] The new SMHI standard from 1971-2000

$$\tau = \frac{\sum Mc}{\sum kA + nV\rho c_p}$$ **(Equation 5)**

where $\sum Mc$ = Buildings heat capacity [J/K]

$\sum kA$ = Sum of the transmission losses [W/K]

$nV\rho c_p$ = Heat power losses due to ventilation [W/K]

When the heat transfer is aborted the temperature starts to drop. In the first hour the temperature starts to decrease quite rapidly and that depends on the air-mass heat-capacity, see Figure 2. But after a while the temperature drop starts to decrease and that is because the building's heat capacity now starts to make effect, see [4] and [5]. The buildings cooling processes could now be described by two time-constants. One small time-constant is for the air-mass heat capacity and the other bigger time-constant is for the building's heat capacity. The heavier construction, the bigger differences between those constants.

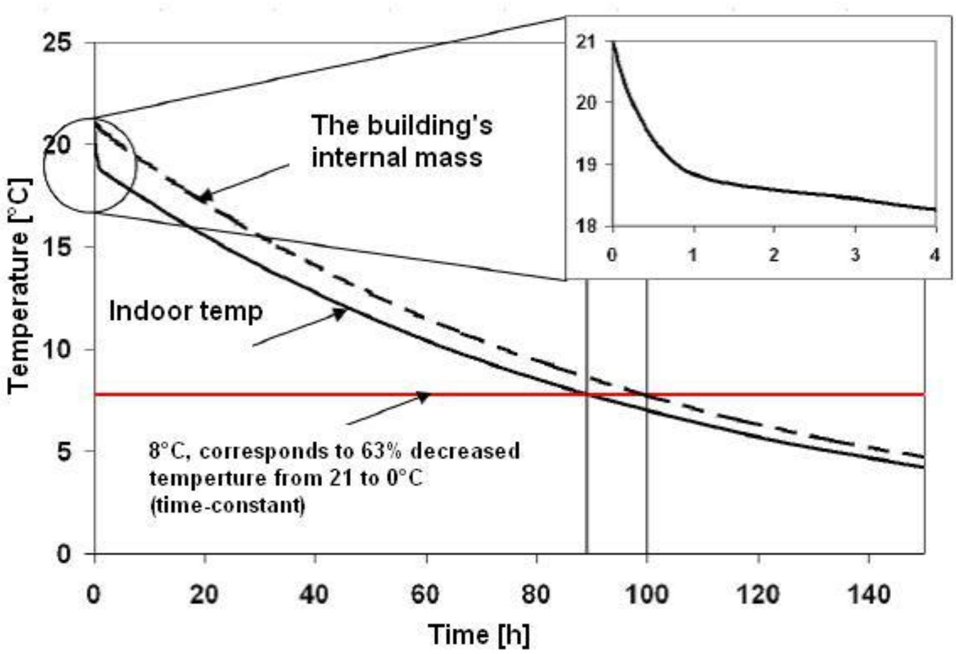

Figure 2: Temperature changes for the buildings internal mass and indoor temperature when the heat transfer is aborted. The red line indicates a temperature droop of 63 %.

2.3 An explanation of a buildings energy signature

The energy signature describes the total amount of energy the building need at a certain outdoor temperature, see Figure 3. The total share of energy is spent to heat the building and to heat the heat water draught. There are a lot of fluctuations in the energy signature and that depends on the heat water draught. The energy that is spent to heat the building is weather dependent. Every building has its unique energy signature. The energy signature looks the same from one year to another, if no changes have been done to the building. If one year has been colder than another year the only thing that differs is that the colder year have more values at colder temperatures. This is really good because this makes it possible to control the energy input at a certain outdoor temperature.

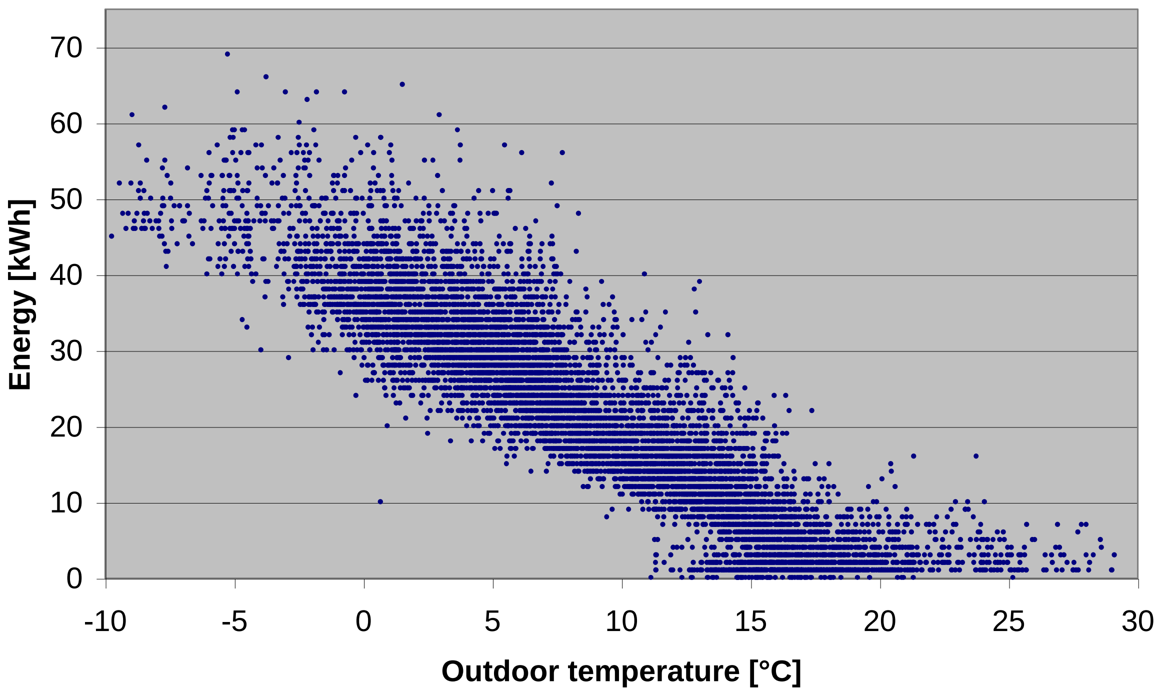

Figure 3: The figure shows the building's energy need at a certain outdoor temperature, where the blue dots represent the energy consumption for one hour over a whole year.

2.4 Pipe expansion due to temperature changes

The length of the heat water pipe will be changed when the heat water temperature increases or decreases, see Figure 4. When the heat water pipe goes near another material a knocking sound could appear. This phenomenon is caused by a very fast length change of the heat water pipe, cf. [6]. The pipe bounds on to the underlying material instead of smoothly move on to it. This problem could be avoided by not allowing a too big and fast temperature change in the radiator system. The thermal expansion is calculated according to Equation 6.

$$\Delta L = \alpha * L * \Delta T \qquad \textbf{(Equation 6)}$$

where ΔL = Changes of length [m]
L = Initial length [m]
α = Expansion coefficient [(°C)$^{-1}$]

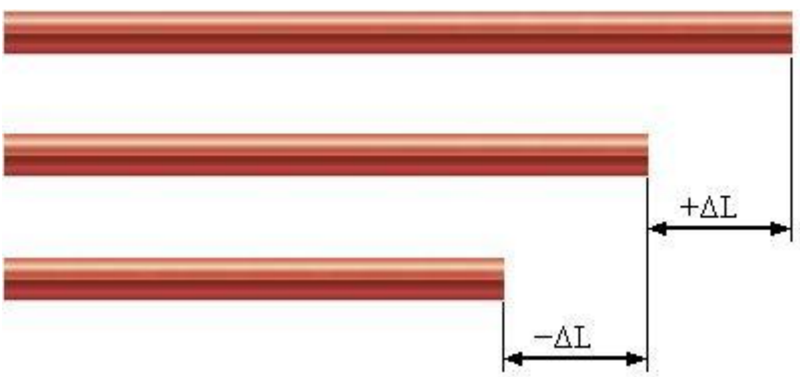

Figure 4: The figure shows the thermal expansions caused by increased or decreased temperature.

2.5 The least square method

The least square method is a special method which has the purpose to generate estimations of unknown quantities by using real observation values. This method is especially used in both regression and variance analysis. The method is implemented by adjusting a trend line so that the sum of square of deviation between the trend line and the points becomes as small as possible. The trend line is described by the direction coefficient b and the constant c, see Equation 7, and it is calculated by using the least square method, see Equation 8.

$$Q = k \times T + m \qquad \textbf{(Equation 7)}$$

$$\overline{A}^T \overline{A}\overline{x} = \overline{A}^T \overline{b} \qquad \textbf{(Equation 8)}$$

$$\begin{cases} T_1 \times b + 1 = Q_1 \\ T_2 \times b + 1 = Q_2 \\ \quad \vdots \\ T_n \times b + 1 = Q_n \end{cases}, \text{ where } \overline{A}x = \overline{b}, \ \overline{A} = \begin{pmatrix} T_1 & 1 \\ T_2 & 1 \\ \vdots & \vdots \\ T_n & 1 \end{pmatrix}, \ \overline{x} = \begin{pmatrix} k \\ m \end{pmatrix} \text{ and } \overline{b} = \begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_n \end{pmatrix}$$

where Q = Energy [kWh]
T = Temperature [°C]
k = Direction coefficient
m = Constant
n = Number of samples

2.6 The effect of internal heating sources

The internal heating sources, except from the heating system, are the household electricity and the people who live there. Household electricity is the electricity required for running all the electrical devices except from those devices that have to do with the building's heating system, for example a towel dryer. 70 to 80 percent of the household electricity is converted into heat which then contributes to the total amount of heat energy in the building. A person in a building emits 50 to100W depending on age and activity level. The amount of household electricity is 2000 to 7000 per year depending on the size of the building, see [7]. Assume a family that consists of 2 adults and 2 children; then the part from the household electricity that contributes to the heating of the apartment is between 16 to 40 kWh/year m^2. But if the person who lives in the apartment is two senior citizens this heating energy could become between 16 to 47 kWh/year m^2, since they spend more time in the apartment than middle-aged people do because of their work, see [8].

The household power usage varies depending on which month it is. The power usage is highest during the winter months: January, February, November and December, see Figure 5. The calculated heat needed for the building will be reduced between 5 to13 percent if the household electricity is included and taken into account in the calculations, see [9].

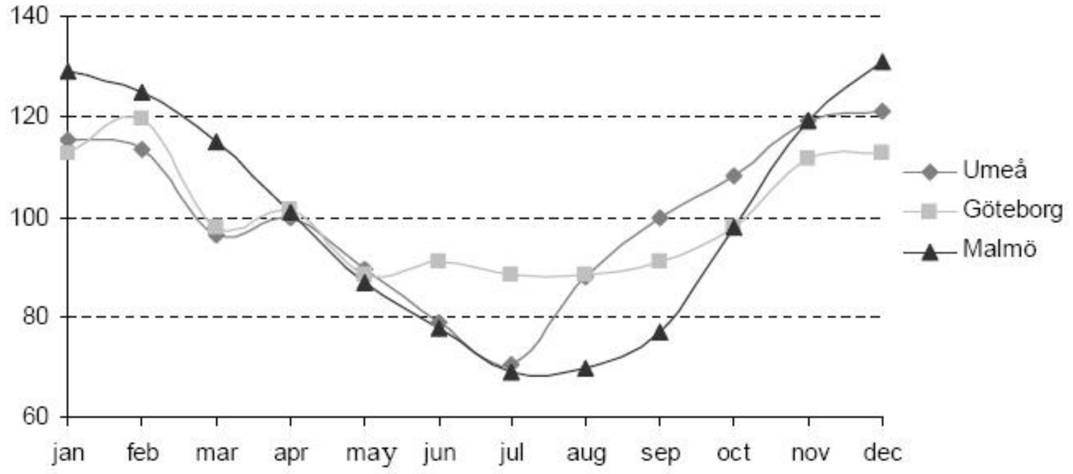

Figure 5: Households average power usage per month is shown, as a percentage of the year average power for Umeå, Göteborg and Malmö. This shows that the household electricity contributes even more to the building's total amount of heating energy during the winter months.

2.7 Solar radiation effect on the energy consumption for heating

Solar radiation is the power absorbed by a one square meter large horizontal surface, and it varies greatly depending on the seasons, from around 100 W/m² for the winter to approximately 1000 W/m² in the summer, see Figure 6 cf. [10]. Solar radiation, thus affecting the building's energy needs by the warming of facades and solar radiation through windows. The size of the effects varies depending on: the direction in which a building is located, how much that is exposed to sunlight and what design it has, see [11].

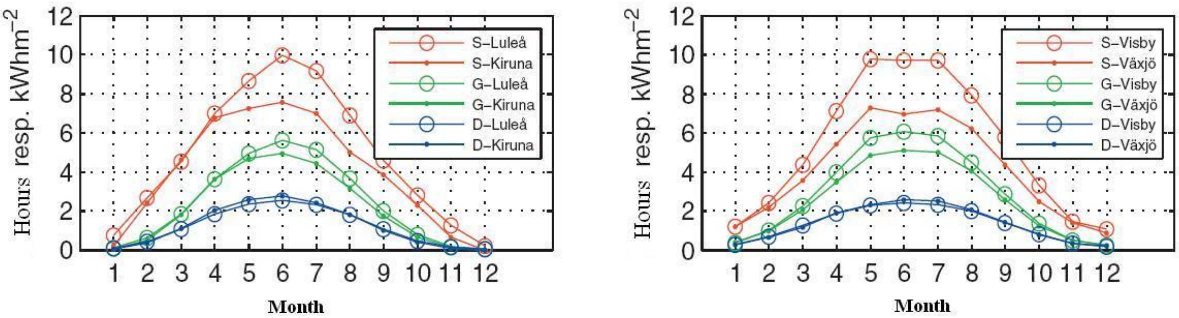

Figure 6: Monthly averages of sunshine duration (red), global (green) and diffuse solar radiation (blue) for Kiruna, Luleå, Växjö and Visby, during the years 1983-2005. Unit: hours per day respectively kWh/m2 per day.

The annual variation of solar radiation and sunshine duration is limited by how the altitude of the sun and day length varies over the year, since the earth axis is tilted to the plane in which the earth moves in its orbit around the sun, see Figure 7. It is winter in Sweden when the North Pole is facing away from the sun, which then is low on the sky with the energy distributed over a larger surface area. The sun's path across the sky varies with the seasons and for different latitudes. The sun is at its highest point at the summer solstice and its lowest point at the winter solstice.

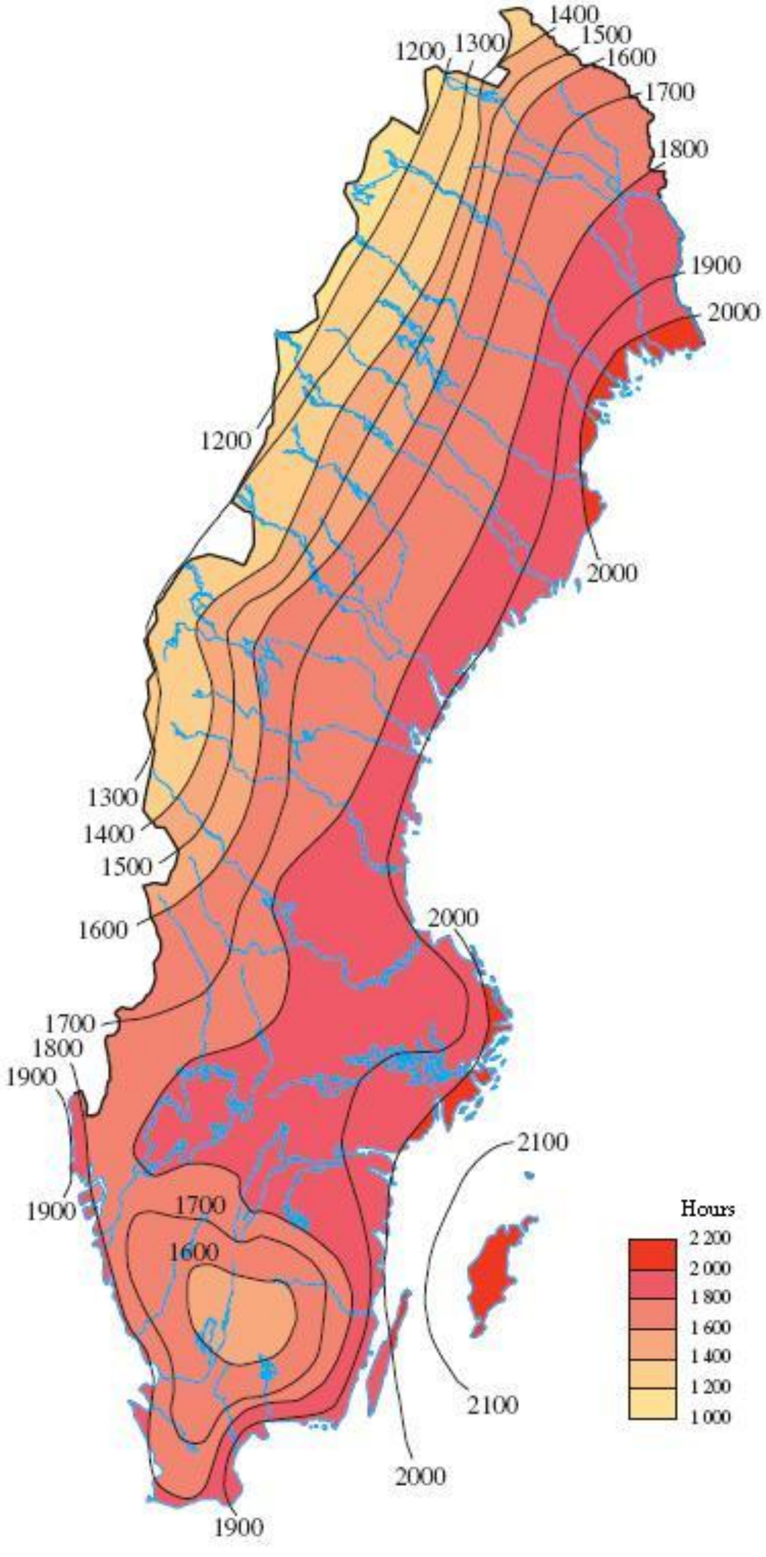

Figure 7: The figure shows the sunshine duration in Sweden in hours for the year 2006, based on measurements.

2.8 Wind effect on the energy consumption for heating

The wind affects the energy consumption and the comfort dissimilarly, depending on how the building is oriented towards the wind. The wind impact on comfort in form of draft occurs since buildings have different isolation thicknesses. The energy consumption is affected by the wind as outer walls are cooled, and cold air is pressed into the building via gaps and leaks. When constructing new buildings it is good to put as small areas as possible to the dominant wind direction to reduce the energy loss impact from the wind, see [12].

When the wind blows, a cooling affect will appear that is calculated by combining the temperature with the wind speed, which shows the wind-chilling effect on bare skin. This formula was developed by the American researcher Randall Oscevski and Maurice Blue Stein from Canada. The calculated cooling affects are shown in Table 2 for different temperatures and wind velocities, cf. [13].

Table 2: The table shows the temperature for the cooling effect that is calculated, as a function of the temperature and wind velocity.

Wind velocity [m/s]	Temperature [°C]								
	+10	+6	0	-6	-10	-16	-26	-30	-36
2 m/s	9	5	-2	-9	-14	-21	-33	-37	-44
6 m/s	7	2	-5	-13	-18	-26	-38	-44	-51
10 m/s	6	1	-7	-15	-20	-28	-41	-47	-55
14 m/s	6	0	-8	-16	-22	-30	-44	-49	-57
18 m/s	5	-1	-9	-17	-23	-31	-45	-51	-59

2.9 Air humidity effect on the energy consumption for heating

The air humidity in conjunction with the sun and wind has a large role on how we perceive the weather. Moisture evaporates more in dry than in moist air. The air humidity contributes by even out the temperature differences over the day. The heat radiation is greatest at the ground and the humidity is condensed into dew or fog when the temperature decreases. But when this happens energy from water molecules is released, which reduces the decreasing temperature.

The indoor climate is not affected so much by the prevailing outdoor air humidity as long as the building is heated enough and has well operating ventilation. But if the building gets cooled so that the air humidity can penetrate the walls, an impression of rawness can be perceived by the residents. This increases the energy consumption even more since it requires more energy to dry out the building and warm it up again, due to the air humidity, see [14]. This phenomenon is especially revealed in the autumn, since this is often a very rainy season in Sweden. Weather affects the buildings need for heating in a very complex and dynamic manner considering the temperature, sun and wind, which is revealed by increased energy consumption.

3 Analysis

This analysis chapter contains descriptions, studies and evaluations of existing and newly developed methods designed by the thesis authors. It also surrounds how an existing district heating central is controlled, the improvement potentials in the Gothenburg region and an explanation on how the district heating tariff is constructed.

3.1 Description of an existing district heating central

This section describes an ordinary district heating central and how it commonly locks like and what parts it contains. It also follows a description on how the control system usually is constructed.

3.1.1 The parts of a district heating central

The district heating central can be divided into two sides the primary and the secondary side. The primary side is the side before the heat exchanger and the secondary side is the side after the heat exchanger, see Figure 8. On the primary side there are three sensors and two actuators. One of the sensors measures the flow and the other ones measure the temperatures. $T_{FV\text{-}GT1}$ measures the temperature on the supply water from the heat producer and the $T_{FV\text{-}GT2}$ measures the return water temperature to the heat producer. $F_{VMM\text{-}ENERGY}$ measures the return flow to the heat water producer. The integration unit calculates the energy that has been consumed by knowing the values from the three sensors $T_{FV\text{-}GT1}$, $T_{FV\text{-}GT2}$ and $F_{VMM\text{-}ENERGY}$. By communicating through a GSM-modem the energy company can collect all the data from the integration unit. There are also two actuators on the primary side, $A_{RAD\text{-}SV1}$ who controls the flow in to the heat exchanger on the radiator system and $A_{VV\text{-}SV1}$who works in the same way but on the heat-water system.

The radiator system consists of two sensors and one circulation pump. T_{Rad_GT1} measure the temperature of the supply water and T_{Rad_GT2} measure the temperature of the return water. $T_{VV\text{-}GT1}$ and $T_{VV\text{-}GT3}$ are two temperature sensors that are placed on the heat water system. $T_{VV\text{-}GT1}$ measures the temperature of the supply water and $T_{VV\text{-}GT3}$ measures temperature of the return water before it is mixed with the cold water. The circulation pump F_{VVC_P1} circulates the heat water in the pipes so that the heat water temperature approximately is the same in the whole building, see Figure 8.

3.1.2 The control system

The most common way to control the district heating central is to measure the outdoor temperature $T_{Out\text{-}GT1}$. The outdoor temperature is then compared to a preset control curve to obtain a given supply water temperature $T_{Rad\text{-}GT1\_SET}$ on the radiator system, see Figure 8. A PI- controller is then used to control the supply water temperature. If the measured temperature T_{Rad_GT1} differs from the given temperature $T_{Rad\text{-}GT1\_SET}$ the PI-controller correct the error by open or close the actuator $A_{RAD\text{-}SV1,}$ see Figure 8. The heat water system is controlled in the same way except that the given supply water temperature $T_{VV\text{-}GT1\_SET}$ is always the same, around 55°C. The heating control may be by a stand alone regulator central or through a computer-under-central, which can be linked up to an overall system.

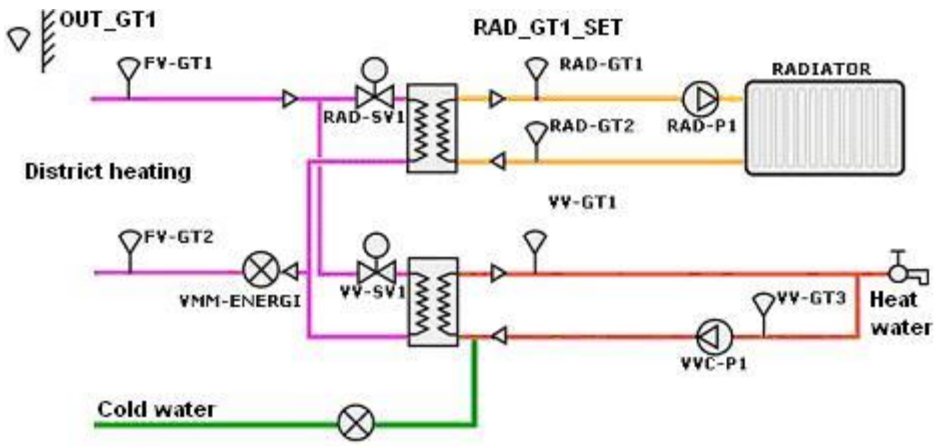

Figure 8: The figure shows a flow schedule of a common district heating central

3.1.3 Limitation on the present system

A common district heating central has some limitations. One problem is the placement of the outdoor sensor. The north side of the building is the optimal place for the outdoor sensor. This is because the outdoor sensor is then for the most of the day placed in the shadow. But if the sensor is placed in some other direction there could be problem with the sun radiation. For example when the sun is shining on the sensor it could make the outdoor sensor think that it is 20°C outside instead of the actual temperature 10°C. But why not always put the outdoor sensor at the north side? This has to do with the building orientation in the cardinal directions and the location of the district heating central. It could be located in any part of the building's basement.

The present system takes no consideration to the effect of sun radiation, internal heat sources, wind effect, or the precipitation. There could be a big energy saving potential by taking care of those effects. This is therefore a quit big limitation for a common district heating central. There are some power peaks during the day, see Figure 9. One of these peaks appears in the morning and another one in the evening. The power peaks appear when somebody starts to draught heat water, for example when somebody starts to draught heat water from a crane or taking a shower. If no draught is done during the day, it will be an even power outlet with no peaks, see Figure 9. A common district heating central has no chance to even out those power peaks.

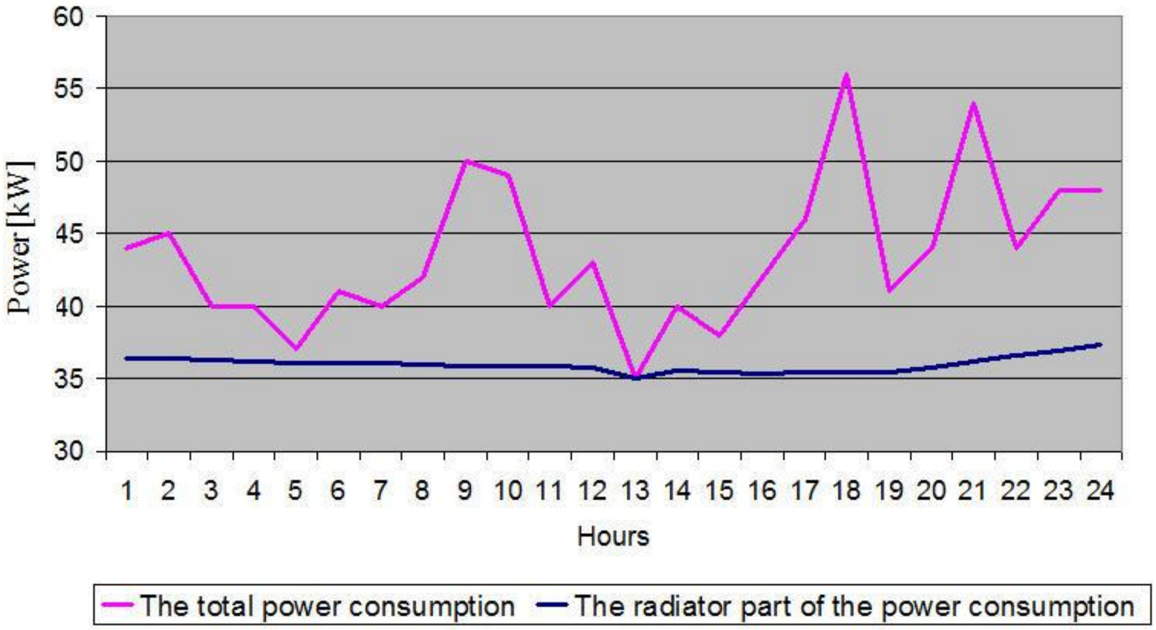

Figure 9: The figure shows the total consumption and the radiator consumption of power during the day.

3.1.4 Oversized flowmeter

The flow meter has a maximum flow q_{max}, a nominally flow q_n, a border flow q_t and a minimum flow q_{min}. The measurement error between q_n and q_t is ± 2 % and ± 5 % between q_t and q_{min}. This error is even worse if the flow is under the lower limit q_{min} or over the higher limit q_{max}. But a common way when constructing a district heating central is to oversize the pipes and the equipments. The flow meter is then chosen to fit those pipes. The result of this is that the flow meter operates between the border flow q_t and the minimum flow q_{min} and maybe even below q_{min}. This is not good at all, since it gives large measurement errors. Another problem with this is that the flow meter seldom updates its true value, because it is driven by the volume that passed through it. To solve this problem and to obtain as good measurement data as possible, the flow meter that is used should for the most of the time operate near its nominal flow q_n, cf. [15].

where q_{min} = The flowmeter's lowest test flow [m^3/h]
q_t = The flowmeter's border flow [m^3/h]
q_n = The flowmeter's nominal test flow [m^3/h]
q_{max} = The flowmeter's highest test flow [m^3/h]

3.2 Different tariffs and price models

Every energy company has their own tariff models. For example the tariff model could be based on the flow of the heat water or the power usage every hour. But in this master thesis the focus is on the price model of Göteborg Energi. Göteborg Energi's district heating price is calculated according to Equation 9.

$$District\ Heating\ price = Amount\ of\ energy * Energy\ price + Mean\ power * Power\ price$$

(Equation 9)

The district heating price consists of two parts, the energy part (Amount of energy * Energy price) and the power part (Mean power *Power price). Since power is the derivative of the energy this mean that you pay less per kWh if you have a constant consumption than if you have a fluctuating consumption. Approximately one third of the district heating price comes from the power part in the tariff. The energy part is divided into three seasons; winter, spring/autumn and summer, see Table 3.

Table 3: Contains the Göteborg Energi's energy prices for the seasons of the year 2009, cf. [16].

Season	Energy price	Month
Winter	0.469 SEK/kWh	January, February, Mars, December
Spring, Autumn	0.321 SEK/kWh	April, October, November
Summer	0.098 SEK/kWh	May, June, July, August, September

The power part of the tariff is calculated according to Equation 10. The mean of the three highest daily average powers from the last rolling twelve month period is the price founding mean power.

$$Power\ price = \left(C1 + P_{3days} \cdot C2\right) / 365 \cdot number\ of\ days \qquad \textbf{(Equation 10)}$$

where P_{3days} = Price founding mean power [kW]
C1 = Fixed price [SEK]
C2 = Floating price [SEK]

Table 4: Contains the fixed and floating power prices for different mean powers of the year 2009, cf. [16].

P_{3days} [kW]	C1: Fixed price [SEK]	C2: Floating price [SEK/kW]
0-50	0	800
50-100	8000	640
100-250	11000	610
250-500	18500	580
500-1000	78500	460
1000-2500	108500	430
>2500	183500	400

3.3 The energy amount of the heat and radiator water from the total consumption

The purpose of this analysis is to engender the best method for finding the heat water proportion of the total energy consumption for a building, in regarding to costs, accuracy of measurements and the need of installations. The resulting method from this analysis will be used to calculate the proportion of heat water, in order to calculate the energy consumption reduction for the different control functions.

3.3.1 Heat water measurement

This method can be implemented in two different ways, see Figure 8 for the location of the temperature sensors for the two following alternatives. The first alternative is to measure the temperature difference between the sensors RAD-GT1 and RAD-GT2, see Figure 8 and measure the flow with a flow meter for the radiator circuit, to calculate the energy consumption for the radiator part according to Equation 11. Then the draught heat water is calculated by taking the total consumption minus the measured radiators consumption. The result will contain some errors, because all heat losses in the system will be counted into the energy consumption for the heat water draught. The advantage is that the radiator system behaves very calmly, which makes it easier to dimension the flow meter correctly.

A second alternative is to measure the temperature difference between the sensors VV-GT1 and VV-GT3, see Figure 8, and measure the flow with a flow meter for hot water circuit to calculate the energy consumption for the heat water part according to Equation 11, see [17]. The locations of the measuring instruments are better with this method, since the heat water consumption is measured more accurate. However, there might be some mismeasurements of the flow, since it fluctuates significantly over short periods, which gives an increased uncertainty of the measurements accuracy.

$$P = c \cdot \rho \cdot Q \cdot \left(T_{w,in} - T_{w,out}\right)$$ **(Equation 11)**

where
P = Delivered power [W]
c = Water flow specific heat capacity [J/kg°C]
ρ = Water flow density [kg/m^3]
Q = The water flow [m^3/s]
$T_{w,in}$ = Inlet temperature [°C]
$T_{w,out}$ = Outlet temperature [°C]

3.3.2 Heat water estimation by using cold water measurements

Another method is to measure the cold water consumption for a building and calculate the heat water proportion by using known estimates. The heat water proportion usually lies between 25 and 45 percent of the total water consumption for multi-dwelling houses according to earlier studies, cf. [18]. In this thesis an estimate of a 25 percent heat water proportion is assumed and used in the calculations. There are two alternatives of achieving the cold water measurements data, either by retrieving it from the water treatment plant or by installing a flow meter. Both alternatives unfortunately require a quite extensive work effort before it is possible to retrieve and evaluate the data, which also makes them quite costly.

3.3.3 Heat water estimation by using effect-signature diagram

This method uses the energy signature to calculate the heat water proportions by extracting three hour energy values, on weekdays at 2, 3 and 4 a.m. By studying the energy signature for a whole year with the hour energy values pointed out, it is shown that almost all of these points are placed in the lower region of the energy signature, see Figure 10. It is therefore shown that there is rarely any heat water draught on weekdays between 2 and 5 a.m. By creating a trend line on these points the energy consumption for the radiator can be attained. The trend line is described according to Equation 7 and is calculated by using the least square method, see Section 2.5 and see also Equation 8.

The energy consumption of the heat water is then calculated by subtracting the radiator energy from the total consumption. This method requires the knowledge of hourly measured data of the buildings energy consumption as well as the outdoor temperature and at what time these measurements was performed. This method is quite straight forward and does not require any additional installations, since all data is already logged.

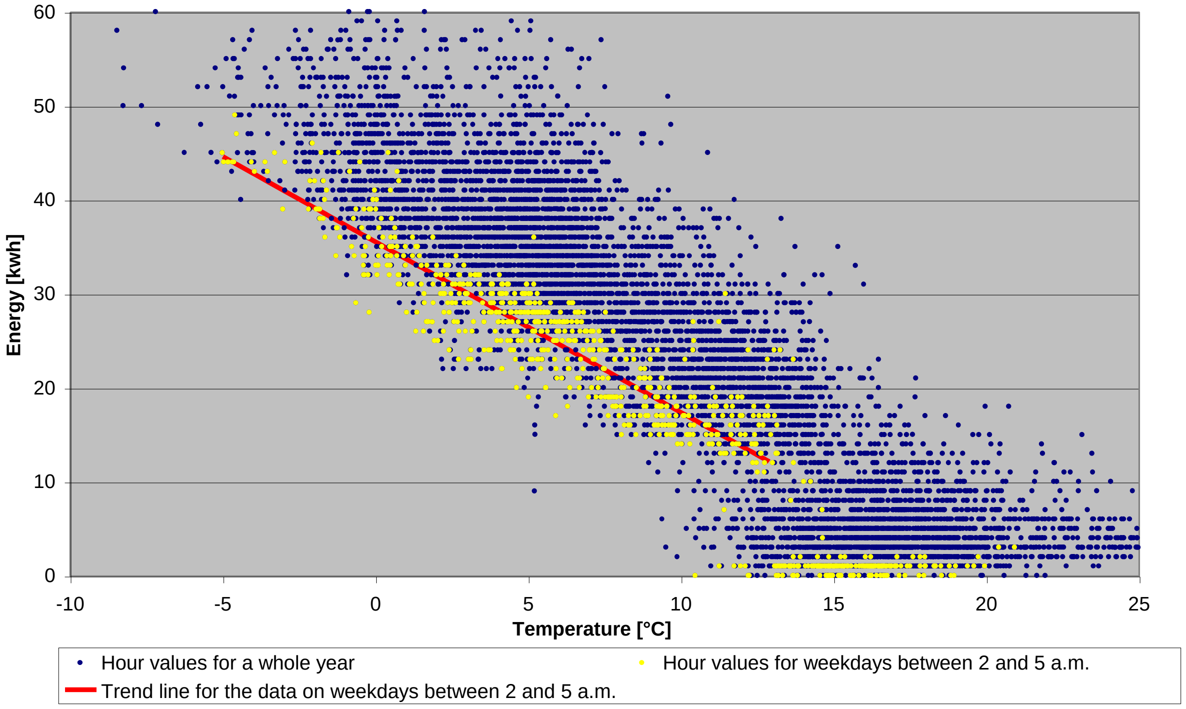

Figure 10: The graph shows a year of energy consumption for a multi-dwelling property with hour resolution for the values. For every energy value, the mean outdoor temperature is saved and used. Blue points correspond to all of the energy values for a full year and yellow points correspond to energy values for weekdays at 2, 3 and 4 a.m. The red line represents the trend line for the yellow points.

3.4 An analysis performed on the outdoor temperature and the coldest day for each of the years 2002-2008.

An important thing to analyze is how the distribution of the outdoor temperature looks like during a year. This is done to get an idea of how many days the outdoor temperature is within a certain temperature range. The analysis has been done by using temperature data from the years 2002 to 2008. See Figure 11 for the result. Note that these days do not need to be after each other but they can be scattered throughout the year. A normal year just have 11 days where the outdoor temperature is below -5°C. The power part of the tariff depends on these cold days with high power outputs. If the customers manage to lower their power outlet during these few cold periods, they can save a lot on the decreased heating cost.

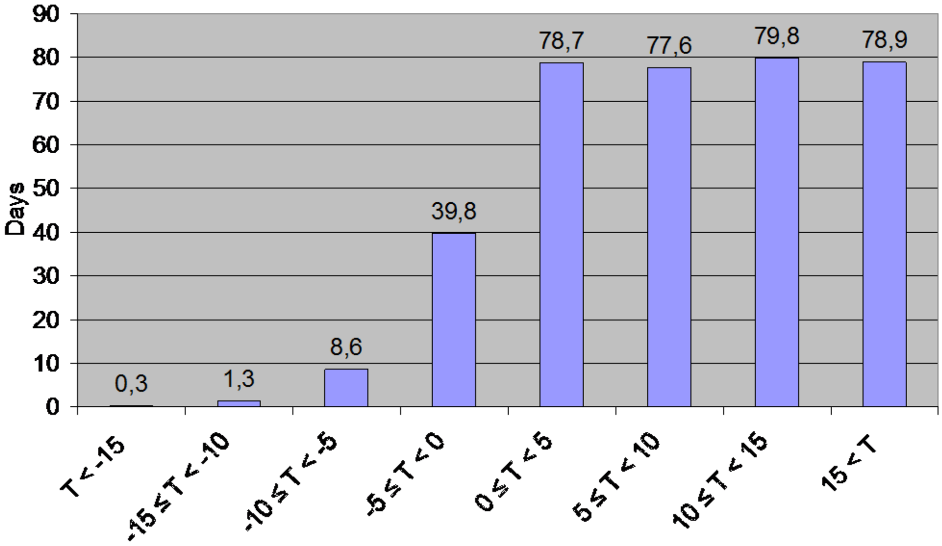

Figure 11: The figure shows the temperature distribution during a normal year divided into different temperature intervals, where T is the outdoor temperature in °C.

The temperature could change a lot from one day to another. To get some information how the temperature changes look like during a cold period, an analyses has been done. By taking the coldest day every year from 2002 to 2008 and the day before and after that day the following result was obtained. These periods with really cold outdoor temperature could last from 0.5 to 1.5 days with temperature drops between 7 to 12 °C. For an example, see the coldest day of 2002 in Figure 12. To view year 2003 to 2008, see Appendix A.

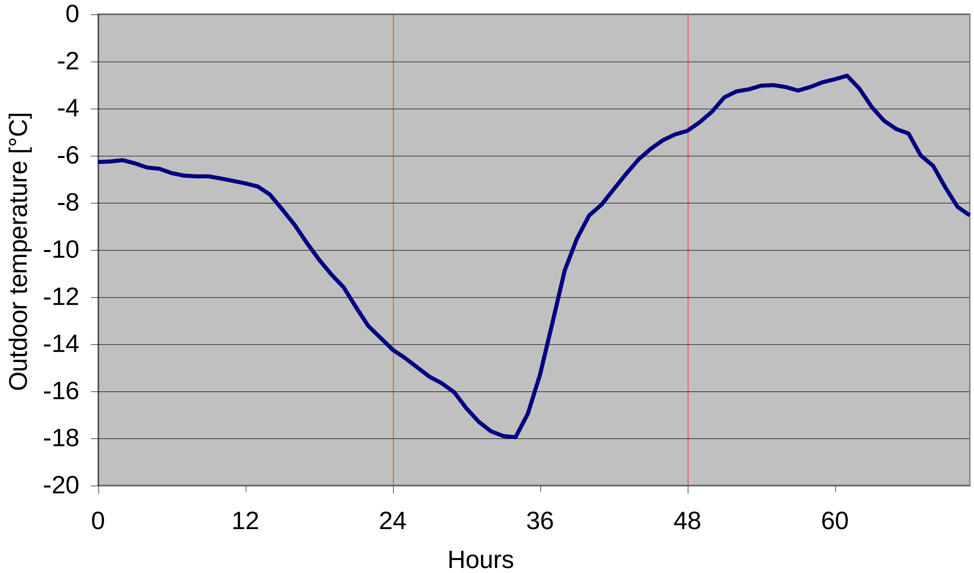

Figure 12: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2002. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.

3.5 Evaluation of existing regulation functions, advantages and disadvantages

This section describes different control functions that are implemented in products, which are available on the market today. There exists relatively many functions, but the ones mentioned in this section are the ones that are most interesting to evaluate for this thesis.

3.5.1 Indoor temperature control

This method calculates a new set value for the supply water temperature using a number of temperature sensors that are placed within some rooms in the building with the purpose of minimizing the buildings heat losses. This function has the benefit of measuring the exact indoor temperature which probably provides a better comfort to the apartment's environment by keeping the temperature within a certain level.

One disadvantage is that the temperature sensors must be connected to the computer-under-central either by wire or wireless communication. Both ways have their benefits and drawbacks, e.g. the wireless sensor has problems with the communications between thick concrete walls but does not need as much working effort as the wire sensor needs for the wall drilling and the cable installations. But a wireless sensor needs energy, either from batteries, solar cells or by a connection to the socket, where batteries and solar cells are most commonly used today. This type of sensor therefore needs to be much more efficient than the wire sensor, which is signified by a shorter range and lower sample of the send data to decrease the energy consumption as much as possible. The wire sensor acquires its energy from the installed cable and can therefore send data much more frequently than the wireless sensor, but at a higher installation cost.

Energy model with indoor temperature sensors

This method is further developed by the company EnReduce, where their system measures both the temperatures outdoor and indoor and then calculates a new fictive outdoor temperature by considering an energy model of the building, see [19]. This fictive outdoor temperature is then used to control the supply water temperature on the secondary side. This is a better way of controlling the supply water temperature according to Enreduce, since buildings are able to store a lot of energy in their framework. The heating energy is not just coming from the radiators; it also comes from people, electronic devices and from the sun. See Section 2.6, 2.7 and 0.

Indoor temperature sensors with interval limitations

There is a lot of internal heat and sun radiation that will affect the building's need of energy. If this heat should be used in an optimal way the indoor temperature should be allowed to change in a given range, see [3]. That is because if the temperature should be kept on a specific temperature then the heat and the cooling system has to work at the same time, which will increase the energy consumption. But if the indoor temperature has an allowed range it could vary inside, the produced heat from internal sources or by the sun radiation could be used instead of using the heating system. This is important to take into consideration if the residential has a cooling system. The heating and the cooling system could now also be interacted with each other so that the systems are not operating at the same time. The drawback of having varying indoor temperature is a fluctuating indoor climate.

3.5.2 Energy leakage

This function is used for finding energy leakage in the heating system of the building. Once a week the control valves for the radiator is programmed to close for a fixed amount of time, with the purpose of measuring the energy consumption and set an alarm if the energy leakage exceeds a predetermined value. This functionality is very useful for finding leakage in valves that have got stuck due to wear and attrition in the mechanical structure. One of the most important benefits with this functionality is that it could lead to less energy leakage, which itself indirectly will contribute to a lower energy consumption and therefore a lower environment impact. There is also a disadvantage to take into account. When the valves of the radiator and the heat water are closed, the heat water supply will be terminated and the water taps will only be provided with cold water. This is unfortunate from the comfort point of view and needs to be considered, even though the function can be performed a few minutes during the night, when the heat water usage rate normally is low, to obtain the benefits of decreasing the impact on the environment.

3.5.3 Night effect decreasing of the radiator system

The purpose of this function is to decrease the total energy output during the night or just for a couple of hours by simply setting the supply water curve at a lower level, which will cut back the radiator valve to an even lower level than expected from the outdoor temperature. The first noticeable change is the indoor temperature that will slowly decrease until it reaches a steady state between the energy losses and the energy input for the building or until the night decreasing function is completed.

The question is, if this function has a positive or negative impact on the total energy consumption? It is obvious to distinguish, that a lower instantaneous power on the radiators will give a lower total energy output, but at what costs? A rule of thumb is that a decreasing of the total energy need with 6 percent will lower the indoor temperature with one degree. But this problem is quite complicated since a lower temperature indoors will also increase the flow into the radiators due to the thermostats, which controls the flow depending on the indoor temperature. The night decreasing function could therefore in theory be compensated by the self regulation in the thermostats, if their functionality worked as it should. This is unfortunately not the case according to operating technician on Göteborg Energi, which comment that approximately 80 to 90 percent of the total amount of the thermostats are broken or jammed.

The second noticeable change is the difference between the total energy need during the night decreasing function and one hour after completion, which often differs more than 100 percent. This has the effect that the need for more power becomes much higher over these hours. This phenomena is really bad for the production facilities, that needs to increase their production capacity over a very short-time period. These quick changes in the power need are almost just possible to match with an oil boiler facility since other facilities, like those driven by wood chips and garbage, have much longer start-up time. The consequence of this sudden increase of power will result in a larger impact on the environment, since the energy comes from a fossil fuel facility instead of a more environment-friendly facility.

3.5.4 Forecast control by estimating an equivalent outdoor temperature

The idea with this function is to generate an equivalent outdoor temperature by calculating the parameters; sun, wind, precipitation and temperature. Those parameters as well as the equivalent temperature can be obtained from meteorology institutes like SMHI. The institute gives the parameters by a five-day weather forecast. The company eGain uses forecast control by calculating an own estimated equivalent outdoor temperature, see [20]. eGain, as well as any forecast control function, changes the existing outdoor temperature with an estimated temperature.

3.5.5 Forecast control by using a barometer

This function uses a barometer and the outdoor temperature to determine the energy impacts from the weather and is therefore a lighter version of forecast control than forecast control by using estimated equivalent outdoor temperature. It is generally cloud free during high pressure weather, which gives warm sunny days, cold nights and a low wind impact. In the converse case with low pressure weather, it most generally becomes cloudy, which gives a low sun radiation impact during the day and higher temperatures during the nights, cf. [21].

3.5.6 Energy limitation by controlling the district heating water flow

Another way of limiting the energy is done by placing a power limiter on the primary side on the district heating central. The power limiter will decrease the flow on the primary side if the power output is too high. This will affect both the radiator system and the heat water system because the total input of energy is limited. The power limiter will not decrease the power peak that happens in the morning and the evening because the power limitation is constant and independent of the outdoor temperature. But this is not the whole truth, since the energy peaks will be leveled out when the outdoor temperature is high enough. The energy limiter calculates the energy that is used by knowing the input- and the output temperature and the flow at the primary side of the district heating central, cf. [22].

3.5.7 Energy limitation by installing an accumulator tank

A way for the production planners to deal with the power peaks that occurs during the day is by constructing a huge accumulator tank that can contain approximately four times more volume then the district heating pipe system does, cf. [23]. The main benefit with this tank is to reduce the top of the energy load and by that unlock boiler power, see [24]. The tank also makes it possible to even out the production during the day and by that; minimize the need for fossil fuel. Given that you have access to other fuels than fossil fuel for the base load.

3.5.8 Individual measurements and increased awareness

Individual measurement means that every apartment is equipped with a readout system for the total consumption of electricity, radiator heat and water or just some of these. This gives the apartment owner a better overview on their energy consumption since it increases their awareness level, which will also increase their desire of make positive changes that contributes to a better environment. Many research results show that individual measurements are a very effective way to reduce the total energy consumption by up to 20 to 30 percent, cf. [25].

3.6 Development and evaluation of own designed functions

In this section, two own developed functions are explained and analyzed. The two functions are damped outdoor temperature and power limitation. A combination of these two functions has also been analyzed. The idea with these two functions is that they should solve the problems that have been revealed earlier in the thesis, saving energy and money for the customer and to reduce the maximum power outlet from the production facilities.

3.6.1 Damped outdoor temperature

Outdoor temperature can vary a lot during the day and can decrease by 12 °C within a few hours, but these temperature variations are often just lasting for 0.5 to 1.5 days, see Section 3.4. In a traditional District heating central the supply water temperature is depending on the outside temperature, see Section 3.1. It is not necessary to compensate for the temperature variation because of the building's dynamical inertia, see Section 2.2. A lot of energy can be saved if a delay to the outdoor temperature is used and also a lot of money can be saved in the power part of the tariff due to the lower power outlet during the coldest days. The outside temperature needs to be damped to solve this problem.

A damped outdoor temperature can be developed in the following way; by using the past hour's temperature values to form a mean outdoor temperature, for example over 24 h, where the temperature value from the last hour will replace the oldest temperature value of the mean. The damped outdoor temperature is calculated according to Equation 12.

$$T_{Mean}(T) = \frac{1}{n}\sum_{i}^{m} T_i \qquad \textbf{(Equation 12)}$$

$$m = n + i - 1 \qquad \textbf{(Equation 13)}$$

where $(T_i, T_{i+1}, \ldots\ldots\ldots\ldots T_m)$ and $i \geq 1$

$T_{Mean}(T)$ = Mean outdoor temperature [°C]

T_{index} = Outdoor temperature during the hour given by the index [°C]

n = The number of past hours that is forming the mean

i = Index of the oldest temperature value of the mean [h]

m = Index of the latest temperature value of the mean [h]

The size of the damping depends on how many past hours that is forming the mean, see Figure 13. Using a damped outdoor temperature that depends on a 24-hour average seems to be the best because of the variation length of the outdoor temperatures, see Figure 16. The maximum temperature of the current and the damped outside temperature should be used as the controlling outdoor temperature to avoid that the outdoor temperature is equally damped as it rises and falls, see Figure 14. If this is not done the result will be that no energy savings is obtained. A problem by using a damped outdoor temperature is that the energy supply of the building will decrease and this leads to a lower indoor temperature, see Figure 15. How much of the decrease in the energy supply from the radiator system, that will be compensated out from the internal heat sources and the solar radiation is difficult to say. The indoor climate could also be better by using a damped outdoor temperature since large temperature fluctuations outdoors also gives temperature fluctuation indoors, see [9].

Real energy values from existing residences have been used in this theoretical analysis of damped outdoor temperature. By using the trend that describes the radiator part in the energy signature and the damped outdoor temperature, the new energy consumption can be obtained for the radiator part. The damped energy consumption will be obtained by adding the energy of the heat water draught to the damped radiator consumption. The original and the damped energy consumption have then been compared by using Göterborg Energi's tariff, see Section 3.2.

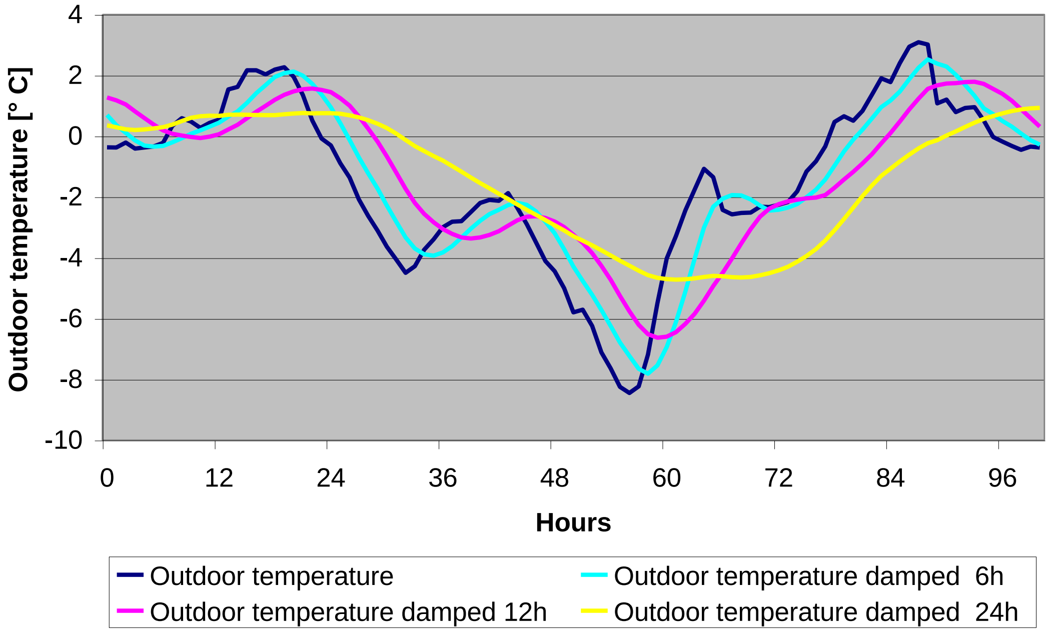

Figure 13: The figure shows the outdoor temperature damped with 6, 12 and 24 hours.

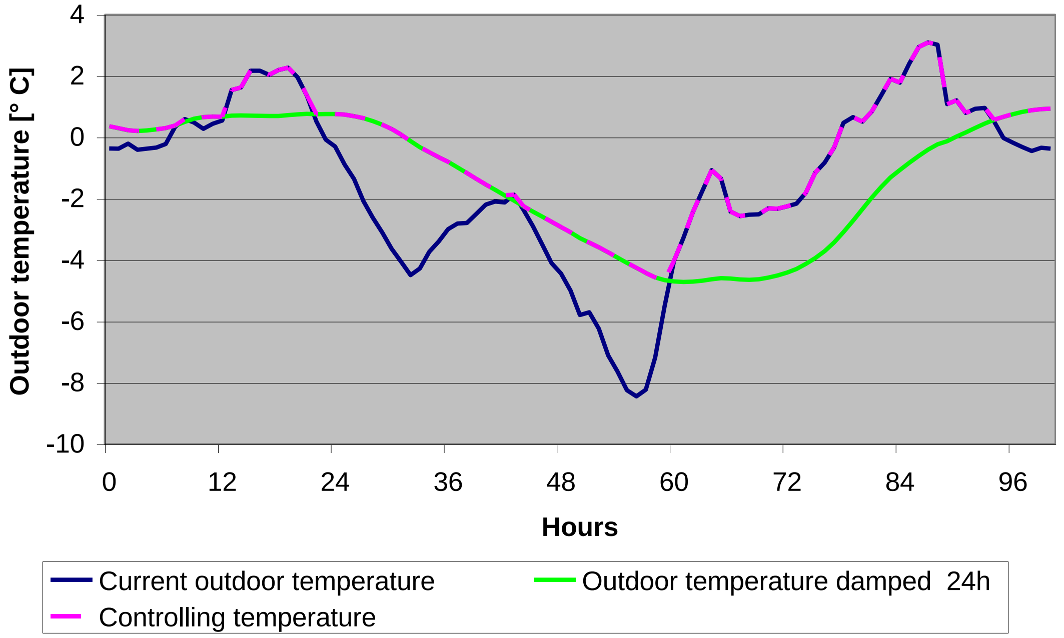

Figure 14: The figure shows the current outdoor temperature and the outdoor temperature with damped 24 hour and the highest of these that is used as the controlling temperature.

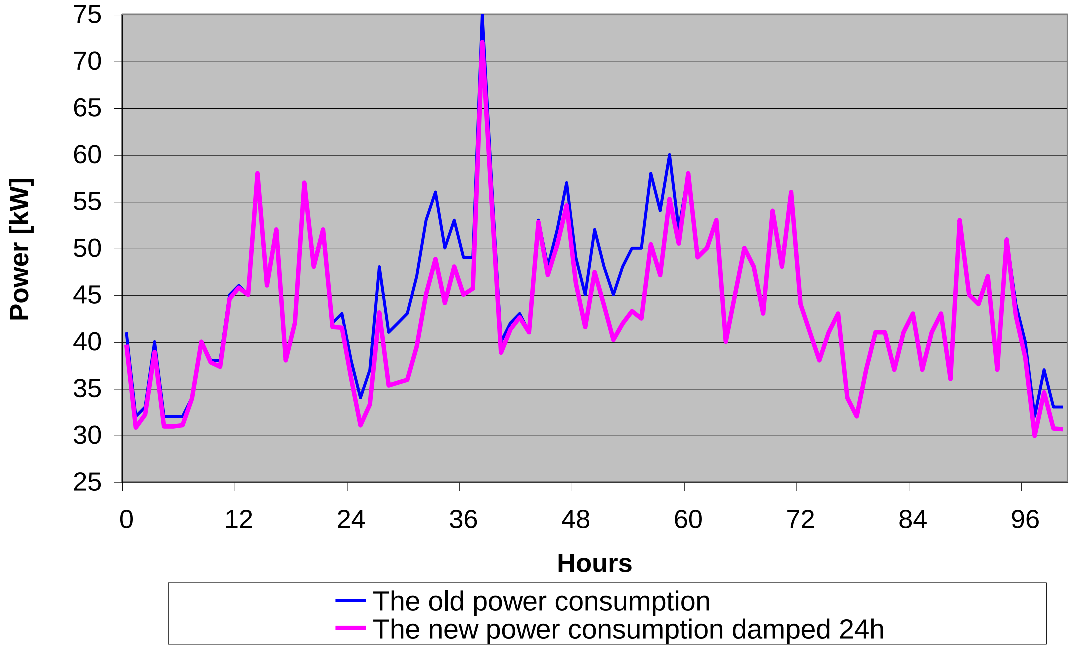

Figure 15: The figure shows the new power consumption when using the highest temperature that either is the damped 24 hour or the current temperature.

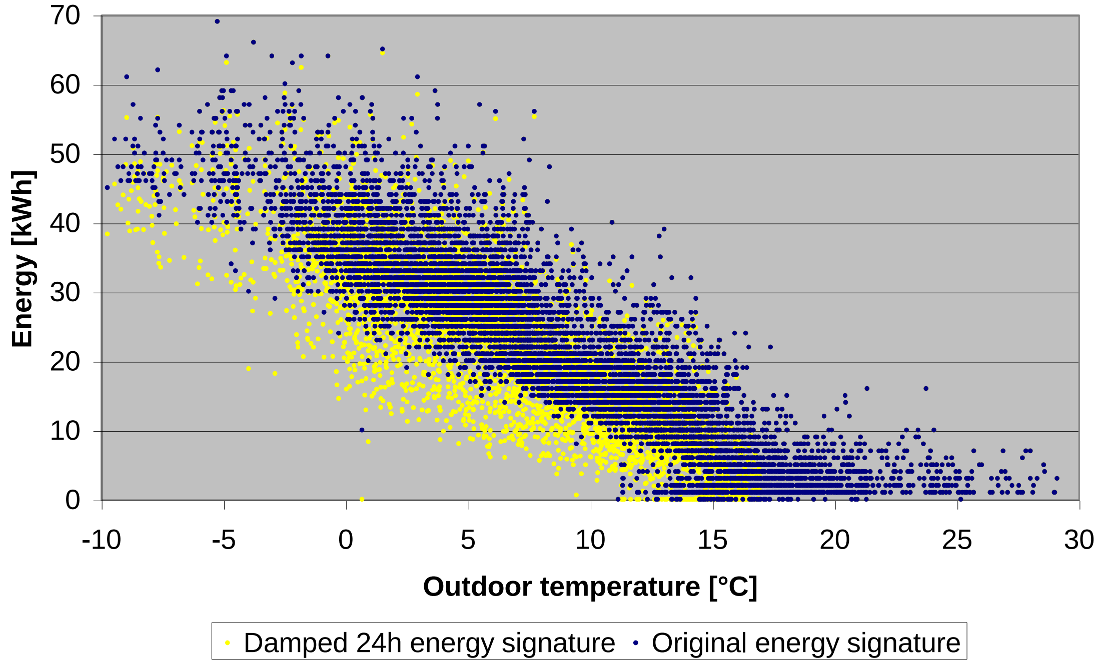

Figure 16: The figure shows the energy signature for a 24 hour damped outdoor temperature with hour resolution for the values. The blue points represent the original energy signature and the yellow points represent the energy signature of the damped 24 hour method.

3.6.2 Power limitation control

The power control function is used to minimize the power peaks during the day as the result of heat water draught, see Section 3.1.3. Another reason is to minimize the power output during the days with maximum load at the production facilities. These days usually occurs when the outdoor temperature is very low. One advantage with this is that maximum load facilities not have to be started, which decreases the environmental impact since they usually uses fossil fuels. Another advantage with decreasing the power peaks is that it releases capacity in the current district heating pipes. The customers could lower the district heating bill by lowering the power peaks since the power parts of the Göteborg Energi's tariff stands for one third of the cost, see Section 3.2. A day with and without power control can be viewed in Figure 17.

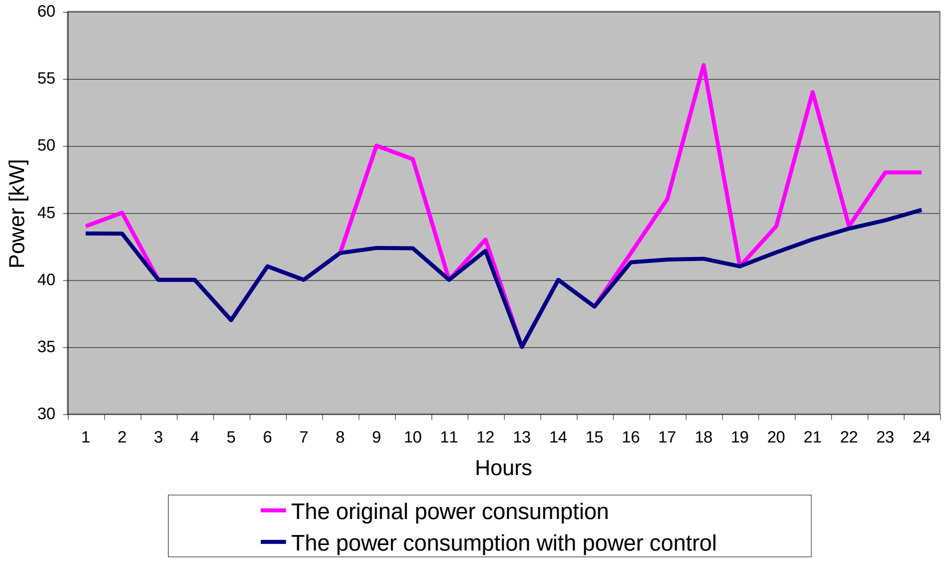

Figure 17: The figure shows the power consumption with and without power control over 24 hours.

All buildings have a unique energy signature, see Section 2.3. In this energy signature, a power limitation line is placed that varies depending on the outdoor temperature. The power limitation should be placed approximately 15 percent above the line that describes the radiator part of the energy signature, see Section 3.3.3. This is done to avoid that the power limitation occurs during all hours even at small heat water draught. The power limitation line is described by the Equation 14.

$$Q = b * T + d \qquad \textbf{(Equation 14)}$$

where Q = Energy [kWh]
T = Temperature [°C]
b = Direction coefficient $= k$, that is described in Section 2.5

d = Constant $= m * \left(1 + \frac{procent\ above\ the\ radiator\ part}{100}\right)$

m = Constant that is described in Section 2.5, see also the red line in Section 3.3.3 for an illustration.

The power part is in this case calculated by 15 percent of the radiator power at the outdoor temperature 0 °C. The function works in the following way; the power to the radiator system will be decreased if the total power output from the district heating central exceeds the power limitation, see Figure 19. The controller of the radiator system lowers the power by changing the supply water temperature. Power surplus can be reduced away momentarily. But this can lead to noises in the pipes because there are big power surplus that fast have to be reduced, see Section 2.4. Another problem is that the controller that controls the radiator system must have enough time to set the right supply water temperature. A better way to reduce the surplus of power is to measure the accumulated energy in a preselected time period and then remove the surplus in the next time period. This method makes it easier to get rid of the noises that could appear in the pipes, because the controller has now more time to set the right supply water temperature. This method is mainly used to remove the power peaks and is therefore called power limitation control instead of the more correct name energy limitation control.

An example is now presented to give a better understanding on how this function works. During a time period the energy consumption is Q2 [kWh], see Figure 18.

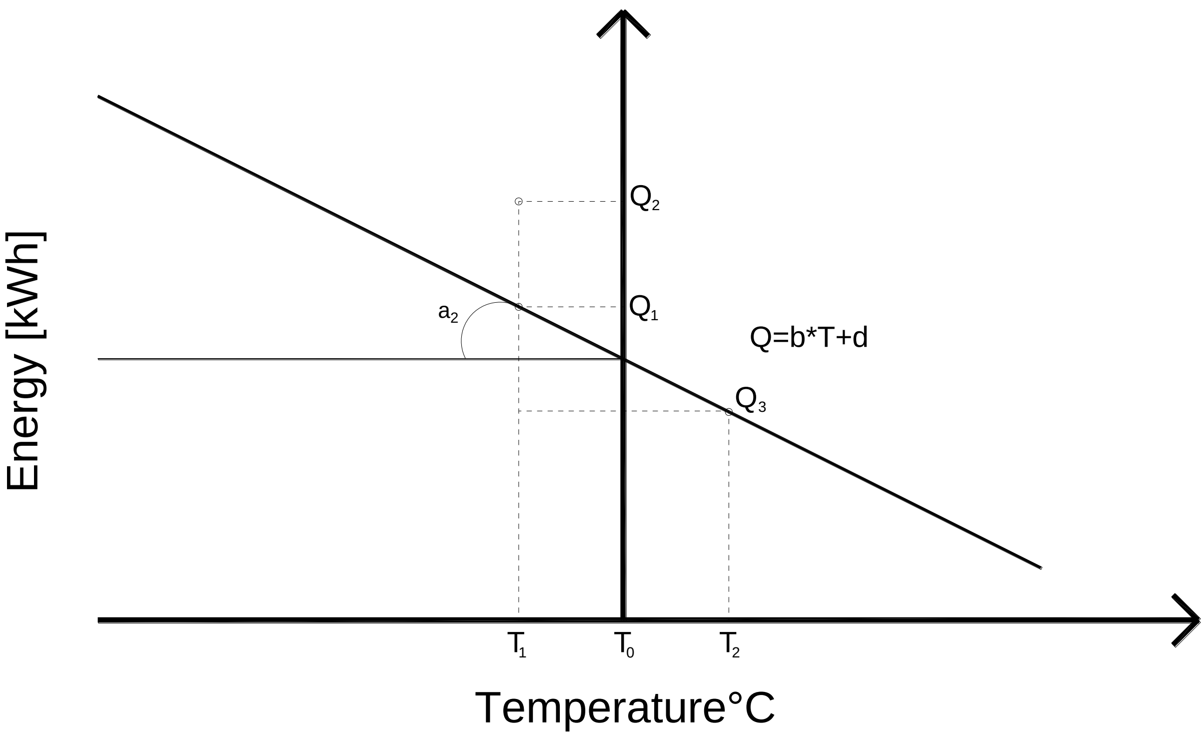

Figure 18: The figure shows the power limitation line and the consumption of power during a time period where the energy consumption is Q2.

In this case the energy consumption Q_2 is bigger than the allowed consumption Q_1.
The allowed power input next time period has to be decreased to reduce the energy surplus of this time period. It should be decreased as much as the surplus of this time period.
The allowed power input the next time period is calculated from Equation 14, see also Figure 18.

$$Q_3 = 2 * Q_1 - Q_2 \qquad \textbf{(Equation 15)}$$

To be able to reduce energy input to Q_3 [kWh] a new higher fictive outdoor temperatures has to be transmitted to the controller for the radiator system. This is calculated by following the power limitation line, see Equation 14. By rewriting Equation 14 the temperature T_2 could be calculated, see Equation 16, see also Figure 18.

$$T_2 = \frac{Q_3 - d}{b} \qquad \textbf{(Equation 16)}$$

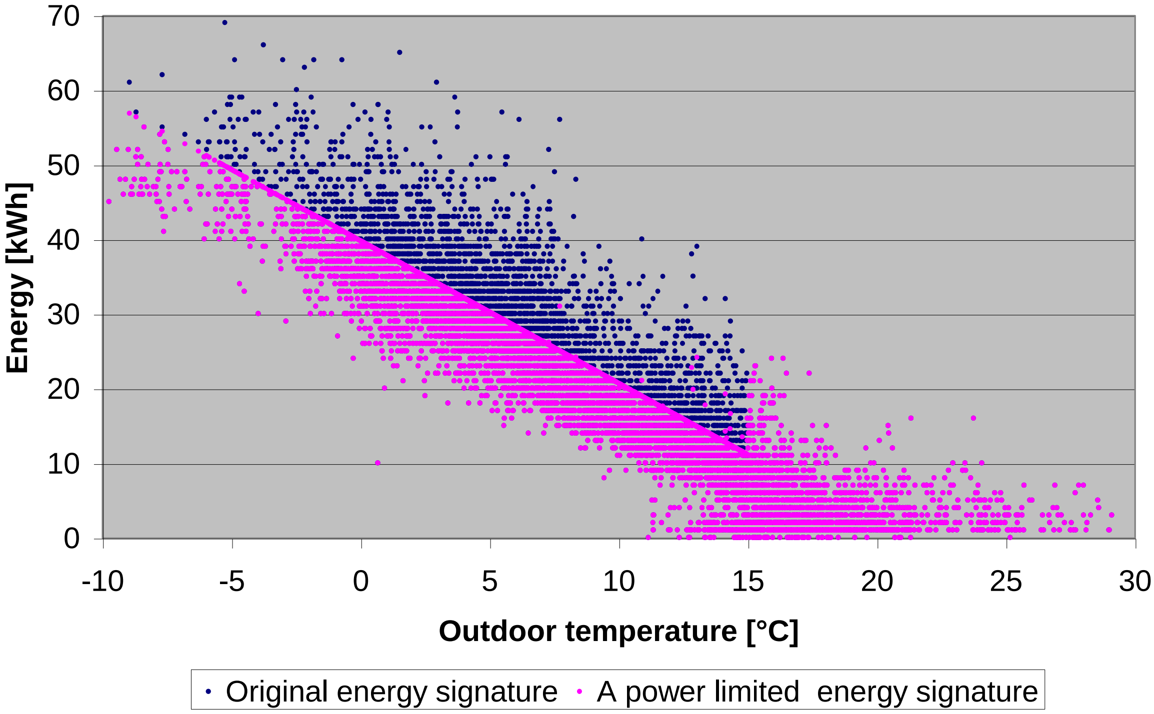

Figure 19: The figure shows two energy signatures; one that is blue with no power control and one that is pink with power control.

Power control can result in a colder indoor climate as energy decreases. But during these periods of heat water draught, there is much internal heat coming from household electricity and from people that are living in the building, see Section 2.6. This internal heat can compensate for the reduced energy from the radiators. The household electricity usage is even higher in January, February, November and December, see Section 3.4. The affect of this is that the household electricity compensation becomes even better these cold months.

Placing a maximum power limit when the outdoor temperature gets really low, can further improve the outcome of the power savings. A good place to put the maximum power limit is at the outdoor temperature -5 °C, since the average year only has 11 days that are colder than that, see Section 3.4. During these few days the indoor climate can become a little bit colder, but the customers would be compensated by the lower fee on the power part of the tariff, see Section 3.2. It is even better to place the maximum power limit at even warmer outdoor temperatures, since the coldness of the outdoor temperature could vary a lot for one year to another. Now the power limit control consist of two parts the power limitation line and the maximum power limit line.
A corresponding example is now introduced to illustrate how this functions works. During a time period the energy consumption is Q_2 [kWh], see Figure 20.

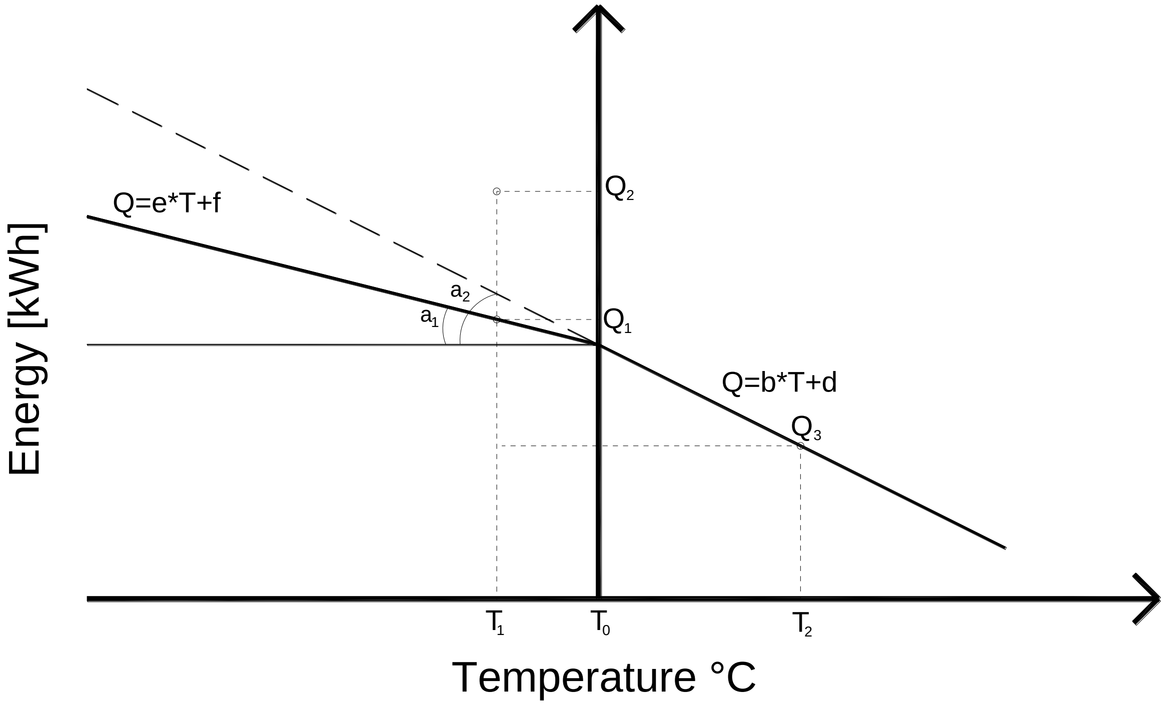

Figure 20: The figure shows the power limitation line described by Equation 14, together with the maximum power limit line described by Equation 17 and the consumption of power during a time period where the energy consumption is Q2.

The maximum power limit line is described by Equation 17, see also Figure 20.

$$Q = e * T + f \qquad \textbf{(Equation 17)}$$

If the starting point T_0 of the maximum power limit line is placed below -5 °C then variable "e" could be put to zero, see Equation 19. But if the maximum power limit line is placed at an warmer outdoor temperature than -5 °C, then it should have a limitation angle to ensure that the indoor temperature does not get too low. The limitation angle should be put in the interval $0 < a_1 \leq a_2$.

$$a_2 = \tan^{-1}(b) \qquad \textbf{(Equation 18)}$$

$$e = \tan \alpha_1 \qquad \textbf{(Equation 19)}$$

The constant f is calculated by setting Equations 14 equal to Equations 17 at the temperature T_0, see Equation 20 and Equation 21.

$$b * T_0 + d = e * T_0 + f \qquad \textbf{(Equation 20)}$$

$$f = T_0 (b - e) + d \qquad \textbf{(Equation 21)}$$

Also in this case the energy consumption Q_2 is bigger than the allowed consumption Q_1. The allowed power input next time period has to be decreased to reduce the energy surplus of this time period. It should be decreased by as much as the surplus was this time period. The allowed power input the next time period is calculated from Equation 22, see also Figure 20.

$$Q_3 = 2*Q_1 - Q_2 = 2*(e*T_0 + f) - Q_2$$ **(Equation 22)**

To be able to reduce the energy input to Q3 [kWh] a new higher fictive outdoor temperature has to be transmitted to the controller for the radiator system. The fictive outdoor temperature T_2 is calculated by Equation 16, see also Figure 20.

The analysis has been done in the following way; Real energy values from existing buildings have been used in this theoretical analysis of the power limitation control. In the first step the new energy consumption with power limitation control has been calculated by lowering the power peaks down to the power limitation control line. In this case the maximum power limit is placed at the outdoor temperature 0 °C with the limitation angle 45°, see Figure 21. The original and the power limited controlled energy consumption has then been compared by using Göteborg Energi's tariff, see Section 3.2 .

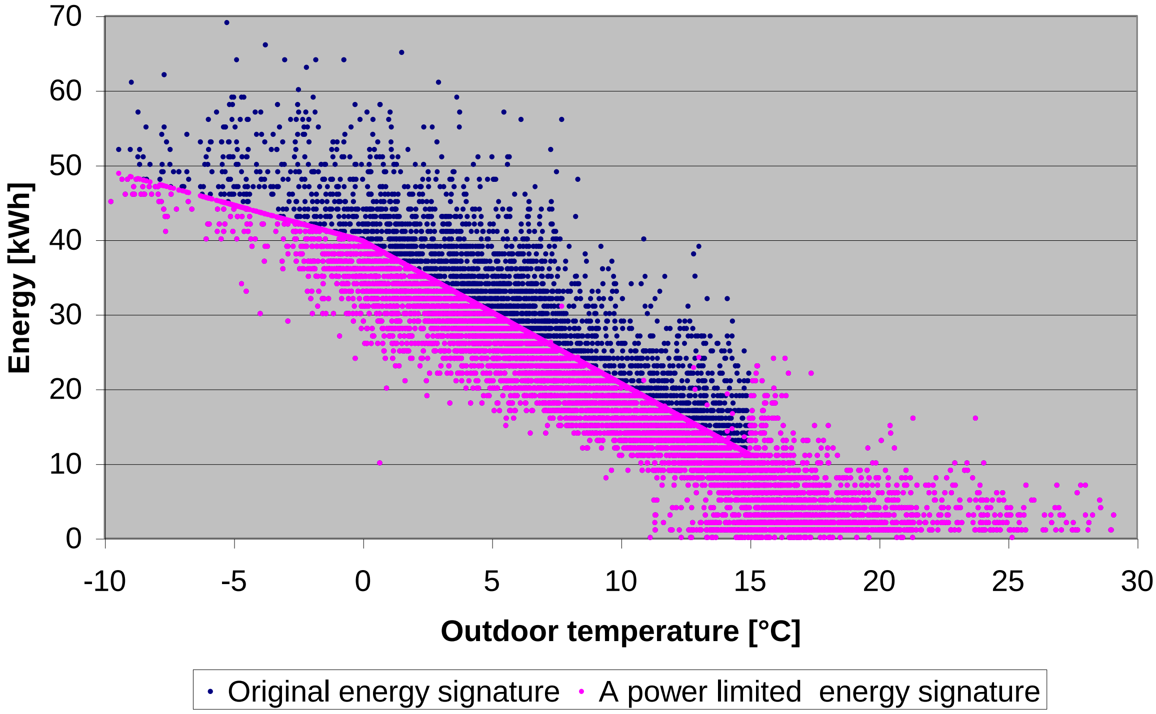

Figure 21: The figure shows two energy signatures one that is blue with no power control and one that is pink with power control. The power control has also a maximum power limit with an angle starting from the outdoor temperature 0 °C.

3.6.3 Combined power limitation and damped outdoor temperature

An interesting thing to evaluate is what happens if the two functions power limitation and damped outdoor temperature are combined. By first calculate the new energy based on damped outdoor temperature, see Section 3.6.1, and then calculate this energy based on the power limitation, see Section 3.6.2. The new hourly based energy consumption with damped outdoor temperature and power limitation could be viewed in the energy signature, see Figure 22. All the advantage from the power limitation and the damped outdoor temperature could in this way be combined. The original and the new combined energy consumption have then been compared by using Göteborg Energi's tariff, see Section 3.2.

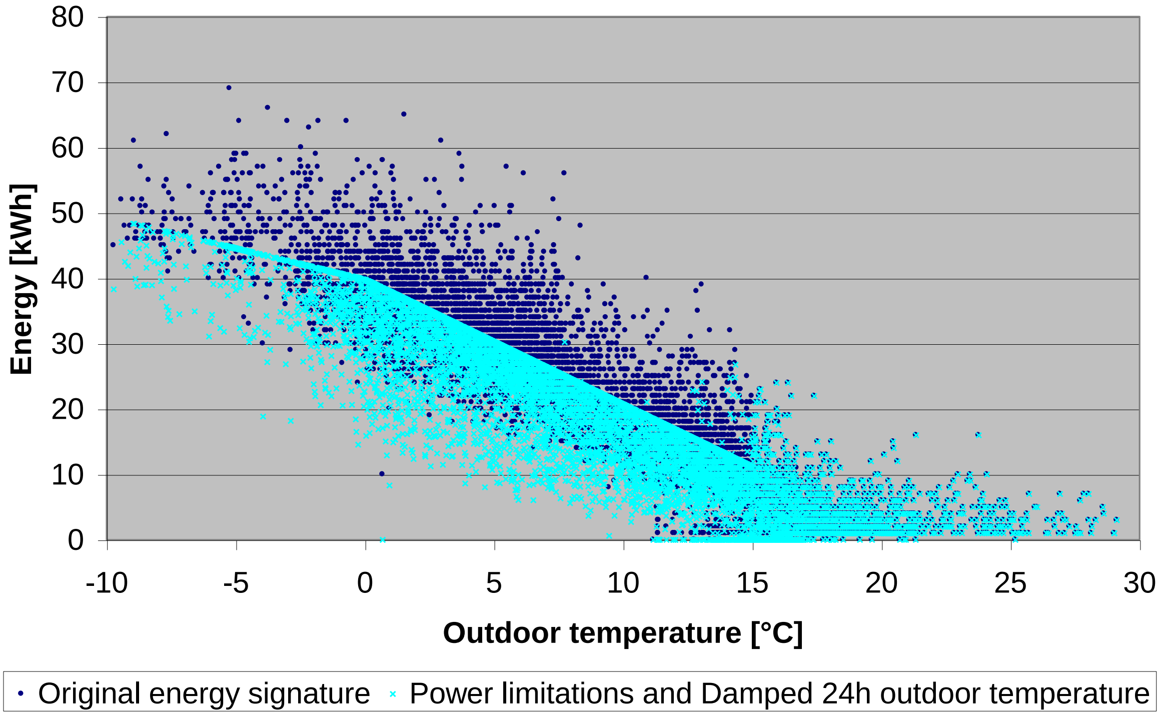

Figure 22: The figure shows the energy signature for a building with the combined control function of power limitation and 24 hour damped outdoor temperature.

4 Case studies of different installations

The case studies described in this chapter were carried out on different apartment blocks in the Gothenburg region. It had the main purpose to investigate if the two tested controlling functions, Forecast control and Indoor temperature control, could accomplish a decreased effect usage, compared to the ordinary outdoor temperature control method. These studies were carried out by using known measurement parameters from the apartment blocks, such as the outdoor temperature, the time of the measurement and the energy usage. The studies are based on measurements that were done continuous at the test facilities, one year before and one year after the installation of the test control functions. The values from the year before and after the installation are normal year corrected in order to make a fair comparison between the two years, as described in Section 2.1.

These installations were performed before this thesis had its start and the choice of the different control functions was therefore limited. Two different products were evaluated in this study to establish a good comparison between the different products as well as between the methods they use to decrease the energy utilization. Göteborg Energi has been sampling measurements from the test facilities in forms of, outdoor temperature, energy usage, date and time of the measurement since 2006-01-01, which now are used in this study of evaluating the eGain forecast control method and the EnReduce indoor temperature control.

Some necessary assumptions were made to make it possible to calculate the cost savings for eGain and EnReduce control methods, since it is not possible to compare the energy consumption month by month due to that the degree day corrected values can give misleading values when only using one month as range. To circumvent the problem a study of the buildings energy consumption was performed with the purpose to investigate how the energy consumption was distributed over the different seasons. The study was conducted on six different buildings which together created a distribution of the energy consumption by 50 percent for winter, 20 percent for the summer and 30 percent for spring and autumn.

The distribution of energy consumption over the seasons was then used to calculate the cost savings of eGain and EnReduce control methods by Equation 23. The results of these calculations are revealed in Section 5.2.

$$\begin{aligned} Costreduction &= \left(S_{energy} \cdot DP_{winter} \cdot EP_{winter}\right) + \left(S_{energy} \cdot DP_{summer} \cdot EP_{summer}\right) \\ &+ \left(S_{energy} \cdot DP_{Spring\&Autom} \cdot EP_{spring\&autom}\right) \end{aligned} \qquad \textbf{(Equation 23)}$$

where S = Total amount of energy saved due to a specific installation
DP = Energy consumption distribution percentage for the season
EP = Energy price for the season

4.1 Study of eGain forecast control method

The study on eGain was performed on two district heated test facilities, facility A1 (Carl Larssonsgatan 3) and facility A2 (Olivedalsgatan 25). Facility A1 provides five apartment blocks with district-heating. These apartment blocks are three-storey high and consist of approximately 4000 m² divided on 84 apartments with normal energy consumption of 831 MWh per year. This corresponds to a consumption of 208 kWh/m^2 per year.

Facility A2 differs a bit from facility A1 since it provides three apartment blocks with district-heating instead of five, and the buildings are seven-storey high instead of three. The total living space for facility 2 are 3600 m² divided on 40 apartments with normal energy consumption of 352 MWh per year. This corresponds to a consumption of 98 kWh/m^2 per year which is approximately 50 percent less than facility A1.

As mentioned in Section 3.5.4, the eGain method is to calculate the future energy need by using a five-day weather forecast to create a fictitious outdoor temperature. This method was used in both test facilities during a longer period to make it possible to evaluate the result of the method. The results are presented in Section 5.1.1.

4.2 Study of EnReduce indoor temperature control method

The study on EnReduce was performed on four district heated test facilities, facility B1 (Astronomgatan 15), facility B2 (Eklandagatan 41), facility B3 (Gibraltargatan 82-94) and facility B4 (Mejerigatan 18-22). Facility B1 provides three apartment blocks with district heating. These apartment blocks are four-storey high and consist of approximately 4200 m² divided into 66 apartments with a normal energy consumption of 1060 MWh per year. This corresponds to a consumption of 252 kWh/m^2 per year.

Facility B2 differs a bit from facility B1 since it provides one apartment block with district heating instead of three and that the buildings are five storeys high instead of four. The total living space for facility B2 are 2150 m² divided on 48 apartments, but also 120 m² of commercial shops that are located at the lowest floor of the building. The normal energy consumption for the building is 485 MWh per year. This corresponds to a consumption of 226 kWh/m^2 per year.

Facility B3 is a much larger building complex and provides three apartment blocks with district heating. Two apartment blocks are nine storeys high and the last one is four-storeys high. The total living space for facility B3 are 16500 m² divided into 648 apartments. The normal energy consumption for the buildings is 4359 MWh per year. This corresponds to a consumption of 264 kWh/m^2 per year.

Facility B4 provides one apartment block with district heating and the building is nine storeys high. The total living space for facility B4 are 6000 m² divided on 74 apartments. The normal energy consumption for the building is 902 MWh per year. This corresponds to a consumption of 150 kWh/m^2 per year.

As mentioned in Section 3.5.1, the EnReduce method is to control the buildings energy need by using indoor and outdoor temperature measurements together with an energy model of the building to estimate the most optimal indoor climate. This method was used in the four test facilities during a long period to make it possible to evaluate the result of the method. The results are presented in Section 5.1.2.

4.3 Potential for improvement in the Gothenburg region

It is very interesting to find out the positive environmental effects caused by different control functions. By using knowledge about how much of the total energy production the residences consumes. This knowledge is achieved by comparing how large part of the total amount of the heated square meters that belongs to the residences.

4.3.1 A study concerning the real estate's distribution on residences, industries and offices

All the buildings in Gothenburg are not heated with district heating. Therefore, the square meters for the different buildings have been recalculated to only show the square meters that have district heating, see Table 5, and see also [26]. Here is the assumption done that all of the real estate's consume the same amount energy per square meter. This gives in percent the real estate's use of district heating.

Table 5: The table shows the square meter distribution between the different types of real estates.

Type of real estate	Real estate, district heating[b] [m^2]	Heat distribution[c] [%]
Residences	12 323 700	59,0
Villas	1 651 600	7,9
Offices	4 957 200	23,7
Industries	1 954 500	9,4

4.3.2 The potential of reducing the environmental impact

Göteborg Energi's vision is to contribute to a sustainable society, through the gradual replacement of fossil fuels to bio fuels, see [27]. Another important aspect to achieve this goal is to optimize the usage of energy. Approximately 50 percent of Göteborg Energi's district heating is produced from waste heat. The remaining district heating comes from the burning of wood chips, garbage, natural gas or oil, cf. [28].

Göteborg Energi produced 3500 GWh district heating water in the year 2008. The residential consumed 59 % of that energy see Section 4.3.1. The average emissions of carbon dioxide produced from Göteborg Energi 2008 were 15 g/kWh, cf. [29].

[b] Real estate's with district heating divided into square meters in the Gothenburg region.
[c] The utilization percentage of the produced district heating that the different real estates use.

5 Results

This chapter reveals the outcome from the studies of the eGain and EnReduce installation explained in Section 4, and from the newly developed methods explained in Section 3.6. The chapter also contains an economical and efficiency comparison between the different control methods.

5.1 The results of the eGain and EnReduce studies

In this section the results of the installed control function study is evaluated and revealed.

5.1.1 Results of the eGain Forecast control study

The comparison of the energy consumption one year before the eGain installation and one year after makes it clear that the eGain method decreases the energy consumption. In facility A1, the energy consumption was decreased with 14.0% with a normal year correction. See Table 6 for the measurement data, Figure 23 for the energy signature diagram and Figure 25 for a time chronological energy usage over facility A1.

Facility A2 also got reduced energy consumption by 13.7% with a normal year correction. See Table 6 for the measurement data, Figure 24 for the energy signature diagram and Figure 26 for a time chronological energy usage over facility A2.

Table 6: The table represents data of the two test facilities, one year before and one year after the eGain installation. To obtain a more equitable result the energy usage has been corrected by the method normal year correction, see Section 2.1. The energy saving in percent is calculated according to Equation 24.

eGain test facilities	Before installation $Q_{Corrected,B}$ [MWh]	After installation $Q_{Corrected,A}$ [MWh]	$Q_{\%,C}$ [%]
Facility A1	856	736	14,0%
Facility A2	386	335	13,7%

$$Q_{\%,C} = \left(1 - \frac{Q_{corrected,A}}{Q_{corrected,B}}\right) * 100 \qquad \textbf{(Equation 24)}$$

where $Q_{Corrected,B}$ = Energy usage before installation during a year corrected by a normal year [kWh]

$Q_{Corrected,A}$ = The energy usage after installation during a year corrected by a normal year [kWh]

$Q_{\%,C}$ = The energy savings in percent

The limitations in this comparison are that there are just two building that has being compared before and after an eGain installation. But all data points in the same direction; that energy can be saved with the weather forecast method. It is comparatively easy to see the positive effects of the eGain installation by viewing Figure 23 and Figure 24. The first thing to notice is that the red dots, which represents the year after the installation, have a much lower energy mean over all temperatures than the blue dots, which represents the year before the installation. But this is especially shown at higher temperatures above 7˚C. One explanation for this could be that at higher outdoor temperatures the solar radiation increases and therefore, as a positive side-effect, heats up the buildings. This solar radiation is probably taken into account when controlling the district heating central, and therefore there is a much lower need for adding extra energy to the buildings radiator systems when using the weather forecasts at temperatures above 7˚C. Another benefit is that the circulating pumps are being better controlled, which saves energy since they do not need to start as often at high temperatures as before the installation.

There is also an aspect of energy storage to take into account. The eGain weather forecast can predict an increased or decreased outdoor temperature which can be used for optimizing the energy need for the building. For example, if it is cold outside and the forecast predicts an increasing outdoor temperature; then the system can decrease the energy need for the building by using the energy that is stored into the building instead of adding too much extra energy from the radiator systems, as the usual outdoor temperature sensor system would do. But in the opposite case, the control system could also prepare the buildings energy consumption if the outdoor temperature would decrease. This could cause a problem, since it could increase the power input on a cold day, when the building already has a big power input. This could increase the cost for the power part on the tariff, see Section 3.2. The function of stocking energy into the building is a good way for obtaining smooth indoor climate but at the same time increase the energy consumption, since this function adds extra energy into the building.

To sum up there are, as what can be viewed in Figure 23 and Figure 24, positive things to gain from the eGain installations. But there are always things to consider when evaluating a new installation or improvement. For example, were there any other optimization arrangements made during this installation that could have affected the result of the eGain analysis? Such as thermostat adjustments, replacements of the valves by optimizing their dimensions or perhaps by changing the radiator curve? In these test facilities there was no evidence that any such improvement was conducted during the test period. Altogether it is however reasonable to believe that the forecasting method is a better method for controlling the district heating central than the ordinary method of using an outdoor temperature sensor.

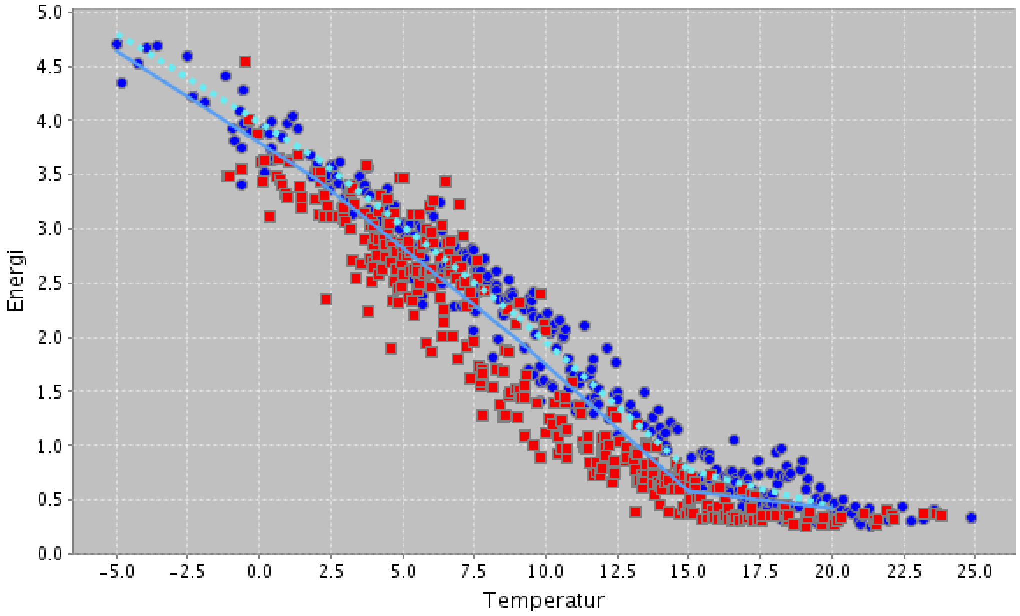

Figure 23: Energy signature diagram for facility A1, where the dots are representing the energy consumption at a mean temperature value per day of the year. The blue spots represent the values one year before the installation of the eGain method and the red dots represents the values one year after the installation. Finally the light blue doted line represents the mean of the blue doted values at each temperature, and the blue continuous line represents the mean of all of the values at each temperature.

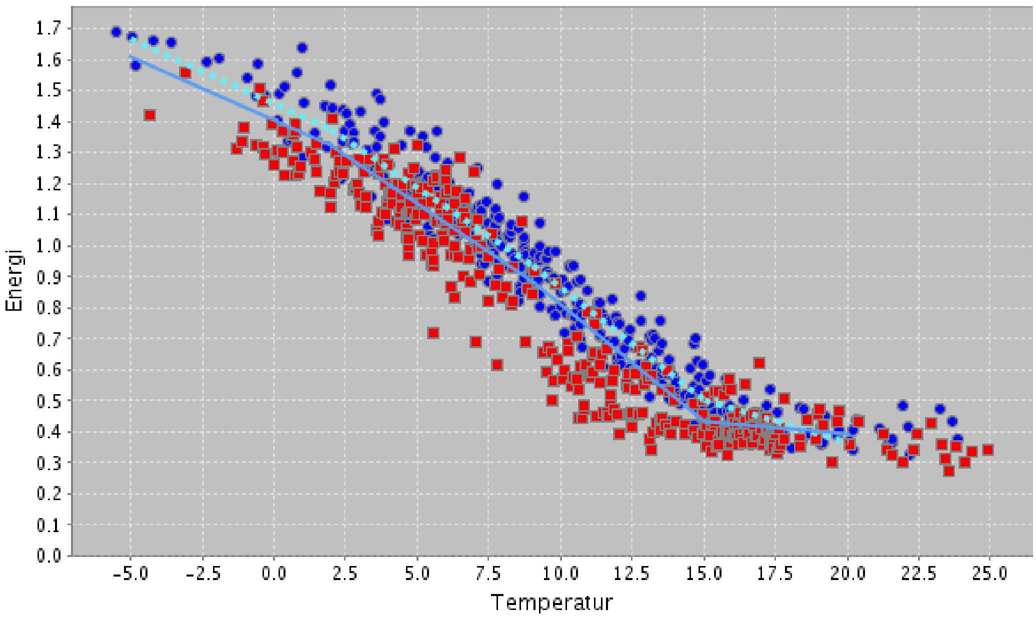

Figure 24: Energy signature diagram for facility A2, where the dots are representing the energy consumption at a mean temperature value per day of the year, see Figure 23.

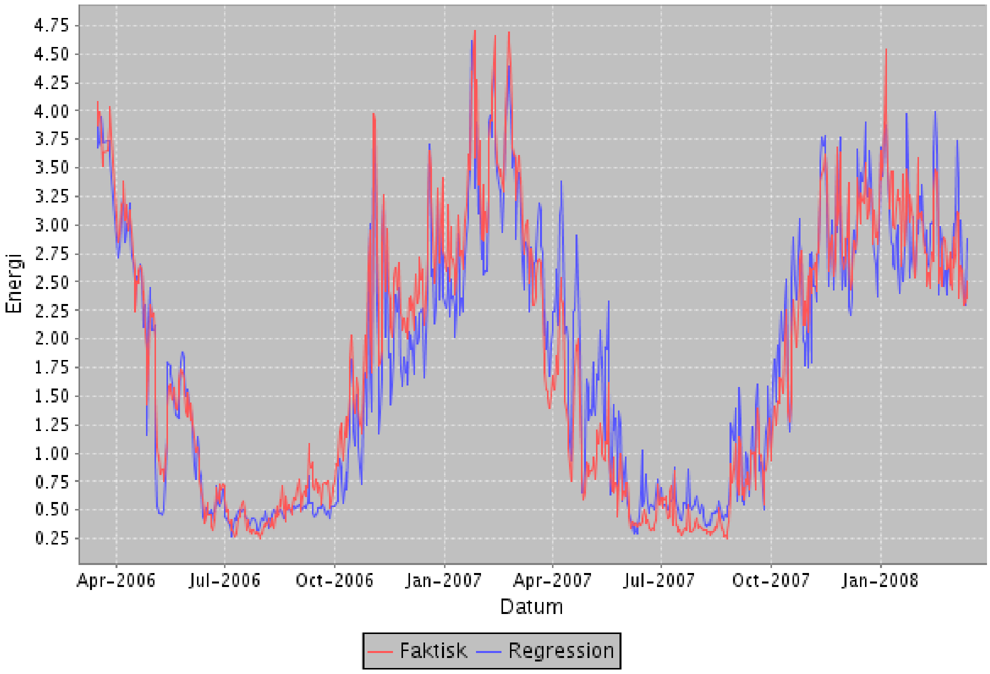

Figure 25: A time chronological energy diagram for facility A1, where the energy consumption is shown over a time period of two years, from 2006-03-15 to 2008-03-14. The installation of the eGain application occurred 2007-03-15. The red line represents the actual energy consumption over the period and the blue line represents a regression from the energy values of 2006-03-15 to 2007-03-14, estimated on the temperatures on the whole period. The blue line is to be viewed as estimated values which characterize the system if it would have been unchanged over the whole time period. It is easy to see the effects on this installation by simply comparing the red and blue line before and after the installation.

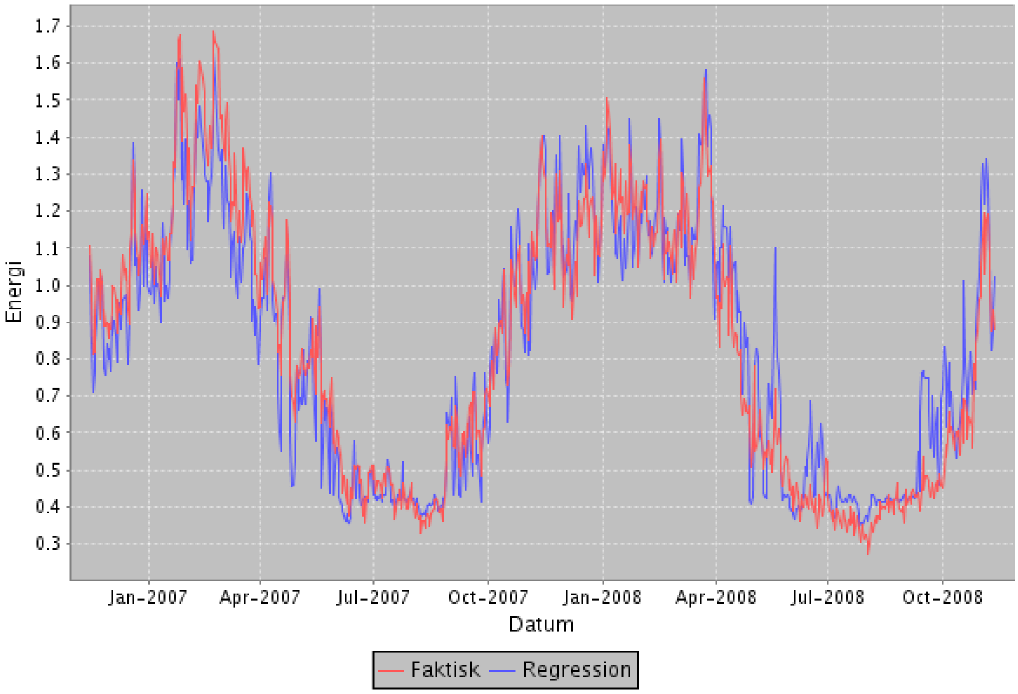

Figure 26: A time chronological energy diagram for facility A2, where the energy consumption is shown over a time period of two years, from 2006-11-13 to 2008-11-12. The installation of the eGain application occurred 2007-11-13. The red line represents the actual energy consumption over the period and the blue line represents a regression from the energy values of 2006-11-13 to 2007-11-12, estimated on the temperatures on the whole period, see Figure 25.

5.1.2 Results of the EnReduce indoor temperature control study

By comparing the energy consumption one year before the EnReduce installation and one year after, reveals that the EnReduce method decreases the energy consumption. In facility B1, the energy consumption was decreased with 10.2% with a normal year correction. See Table 7 for the measurements data, Figure 27 for the energy signature diagram and Figure 29 for a time chronological energy usage over facility B1.

Facility B2 also got reduced energy consumption by 13.4% with a normal year correction standard. See Table 7 for measurements data, Figure 28 for the energy signature diagram and Figure 30 for a time chronological energy usage over facility B2. Also the facility B3 and B4 shows the same tendency of reducing the energy consumption as B1 can B2. The energy reduction with a normal year correction was 15.9% for facility B3 and 16.6% for facility B4. See Table 7 for the measurements data.

Table 7: The table represents data of the four test facilities, one year before and after the EnReduce installation. To obtain a more equitable result the energy usage has been normal year corrected by the method degree days, see Section 2.1. The energy saving in percent is calculated according to Equation 24.

EnReduce test facilities	Before installation $Q_{Corrected,B}$ [MWh]	After installation $Q_{Corrected,A}$ [MWh]	$Q_{\%,C}$ [%]
Facility B1	1080	970	10,2
Facility B2	497	430	13,4
Facility B3	591	497	15,9
Facility B4	620	518	16,6

The limitations in this comparison are the few building that is being compared before and after the EnReduce installation. But all the data points in the same direction; that energy can be saved with the indoor temperature sensor method. The EnReduce control strategy with indoor temperature sensors influences the system in a positive way by reducing the total amount of energy that is needed to heat the building. This control method has its greatest impact on the energy usage at temperatures above 7˚C just as the eGain method has. This energy reduction can easily be viewed in Figure 27 and Figure 28. The most probably cause for this result is that the solar radiation often are higher at greater temperatures which consequently heats up the building and the indoor temperature, which therefore decreases the need for additional heating just as for eGain.

By viewing the Figure 27 and Figure 28, it is revealed that the result of the EnReduce control method unfortunately differs a bit between the test facilities B1 and B2. The figures show a tendency of a decreased total energy sage for all outdoor temperatures after the installations. But at temperatures below 7˚C the B1 facility also has energy consumptions that are slightly higher than before the installation.

This could be a consequence from the reduced amount of energy that are injected into the building, since a lower energy input also means a lower energy storage in the buildings. The direct effect will therefore be higher energy consumptions during colder periods, since the building cannot resist fast decreasing outdoor temperatures. Even though the energy usage after the installation sometimes overcomes the energy usage before the installation, it still decreases when comparing the total amount of energy usage. This could probably also be explained by the effect of the solar radiation and other internal heating sources that influences the indoor temperature, see Section 2.6 and 2.7.

To summarize; the EnReduce indoor temperature control method seems to work quite well according to the collected data. But the evaluation has the disadvantage of a low amount of test facilities, which makes the results only base on the four objects, B1, B2, B3 and B4. Still, the results show a clear tendency of decreasing the energy consumption by indirect take into account the solar radiation, internal heating sources and the buildings heating capacity by measuring the indoor temperature to establish the optimal energy consumption for the building.

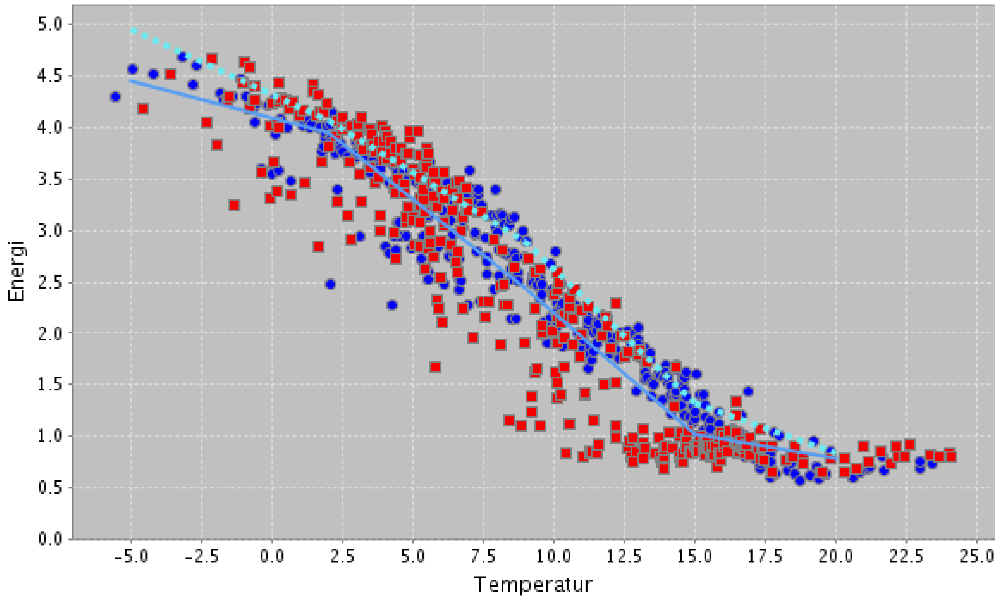

Figure 27: Energy signature diagram for facility B1, where the dots are representing the energy consumption at a mean temperature value per day of the year. The blue spots represent the values of one year before the installation of the EnReduce method and the red dots represents the values of one year after the installation. Finally the light blue doted line represents the mean of the blue doted values at each temperature, and the blue continuous line represents the mean of all of the values at each temperature.

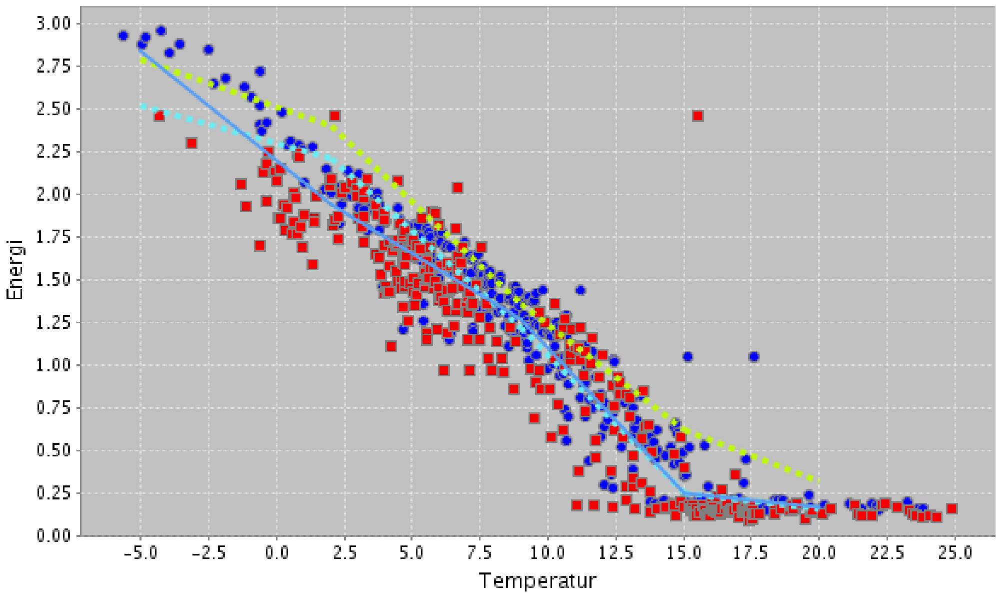

Figure 28: Energy signature diagram for facility B2, where the dots are representing the energy consumption at a mean temperature value per day of the year. The blue spots represent the values of one year before the installation of the EnReduce method and the red dots represents the values of one year after the installation. The yellow and light blue doted lines represent the mean of the blue doted values at each temperature the year before the installation. There exist two lines since there were two different energy signatures during this period, probably due to different control curves for the weekdays and for the weekends. Finally the blue continuous line represents the mean of all of the values at each temperature over the whole period.

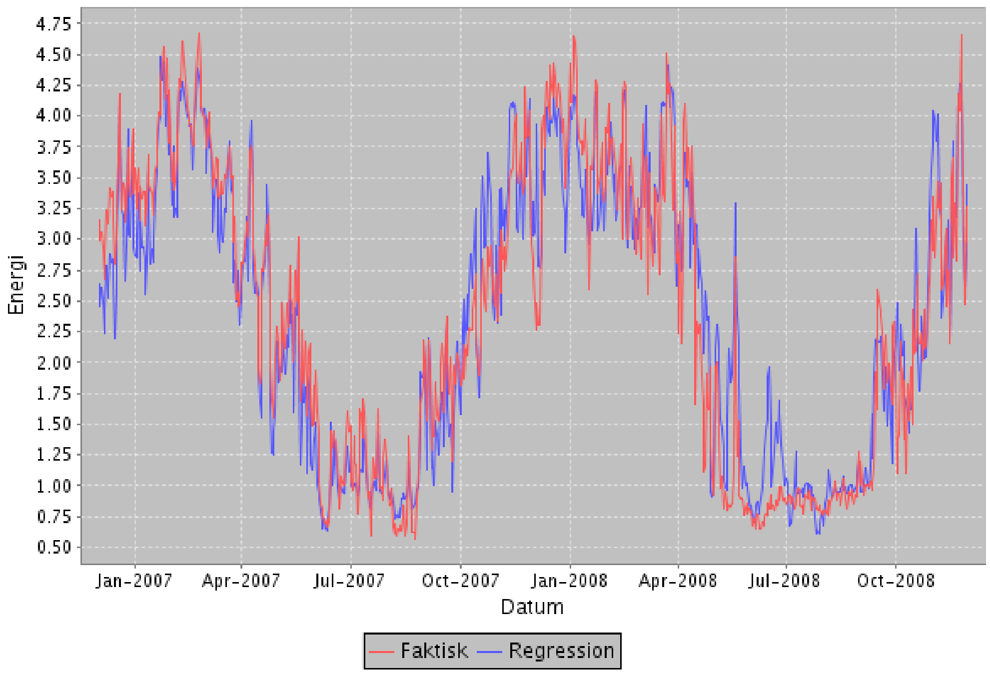

Figure 29: A time chronological energy diagram for facility B1, where the energy consumption is shown over a time period of two years, from 2006-12-01 to 2008-11-30. The installation of the EnReduce application occurred 2007-12-01. The red line represents the actual energy consumption over the period and the blue line represents a regression from the energy values of 2006-12-01 to 2007-11-30, estimated on the temperatures on the whole period. The blue line is to be viewed as estimated values which characterize the system if it would have been unchanged over the whole time period. It is easy to see the effects on this installation by simply comparing the red and blue line before and after the installation.

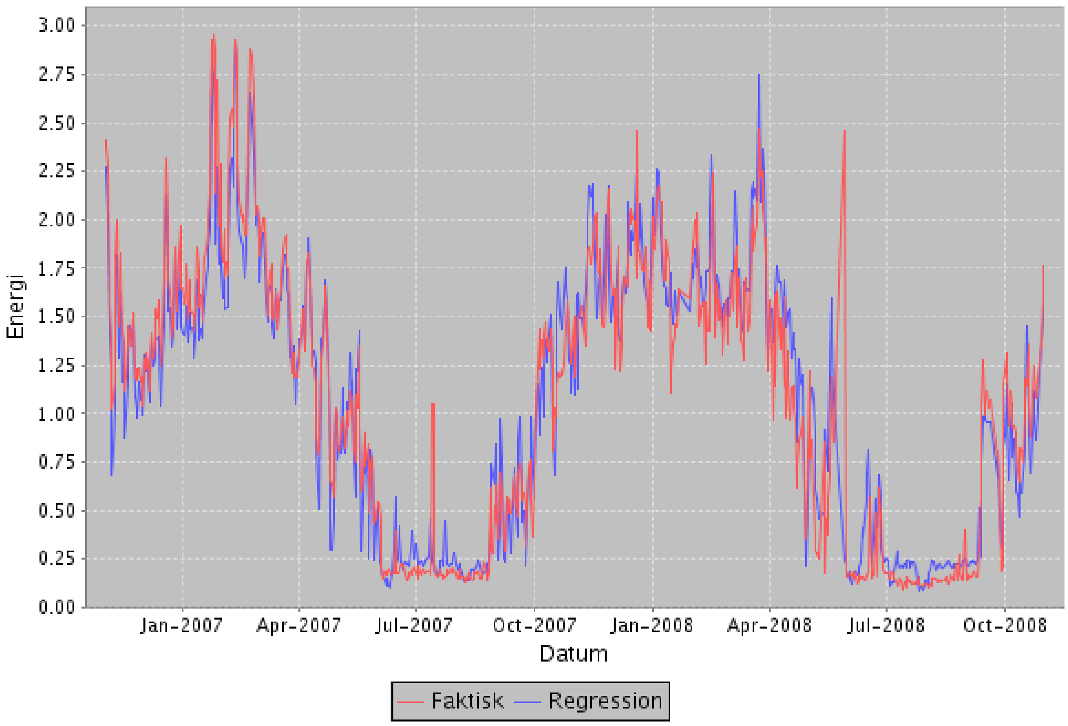

Figure 30: A time chronological energy diagram for facility B2, where the energy consumption is shown over a time period of two years, from 2006-11-01 to 2008-10-31. The installation of the EnReduce application occurred 2007-11-01. The red line represents the actual energy consumption over the period and the blue line represents a regression from the energy values of 2006-11-01 to 2007-10-31, estimated on the temperatures on the whole period. The blue line is to be viewed as estimated values which characterize the system if it would have been unchanged over the whole time period. It is easy to see the effects on this installation by simply comparing the red and blue line before and after the installation.

5.2 A comparison between the control methods

A comparison between the four controlling methods has been done to get a more clear overview of how much energy and cost the different methods save per year. Lower energy consumption also gives lower carbon dioxide emissions. All the controlling function provides a carbon dioxide reduction of more than 1000 tonnes per year. To better understand the magnitude of the environmental savings, an example is calculated on how many laps a car can travel around the Earth to emit the same amount of carbon dioxide. Forecast control, indoor temperature control and the combination power limitation and damped 24h outdoor temperature gives about the same savings. Only by using a fairly simple function that damped 24h outdoor temperature gives the customer a 4.3 percent cost savings see Table 8.

Table 8: The table shows a comparison of the results for the different control functions for a whole year.

Savings over a year	Forecast control[d]	Indoor temperature control[e]	Power limitations[f]	Damped 24 h outdoor temperature [f]	Power limitations and Damped outdoor temperature [f]
Energy [% kWh]	13,9	14,1	6,5	6,9	12,3
Power peak reduction [%]	0	0	8,5	2,8	11,3
Cost savings Energy [%] [g]	13,9	14,0	7,1	5,3	11,3
Cost savings Power [%] [h]	0	0	8,0	2,6	10,7
Cost savings (Energy + Power) [%] [i]	9,3	9,3	7,5	4,3	11,2
The total savings of CO2 [ton] [j]	4275	4367	2168	1735	3810
Laps around the earth.[k]	89	91	45	36	79

[d] The results are mean values from the two analyzed buildings that are run by eGain's forecast control.
[e] The results are mean values from four analyzed buildings that are run by EnReduce's forecast indoor temperature control.
[f] The results are mean values from two buildings that are simulated by our own devolved function. It is a theoretical result, but real energy values from the two buildings have been used.
[g] Percentage cost savings for the energy component of the tariff.
[h] Percentage cost savings for the power component of the tariff.
[i] Total percentage cost savings for the power and the energy part of the tariff.
[j] Reduced emissions of carbon dioxide due to energy savings. For more information see Section 0.
[k] The number of laps around the earth a car can drive to produce the same amount of carbon dioxide. In the calculations has an eco car been used that produces 120 g CO_2 /km and that the Earth's circumference is 40000 km.

5.3 Economics

Production savings for the month January and February have been obtained, by giving load curves before and after installation to Göteborg Energi's financial production division. Production savings for the winter months December, January, February and March have been obtained by calculating the mean value of the saved production energy of the months January and February, and then multiplying it with the number of winter months. Production savings for the spring months; April, October and November have been obtained by taking the same mean value as before and then multiplied it by 50 percent and the number of spring month, see the energy tariff. Göteborg Energi's lower incomes have been calculated by multiplying the turnover net sales of district heating in 2008 that is 2349.4 million by the percentage of cost reduction for the four different functions, cf. [30].

For the functions forecast control and indoor temperature control, there are no calculated production savings. This is because there were no comparable load curves before and after the installation. Of course there are some production savings for these functions. Since there is lower energy consumption, which leads to a reduced amount of district heating that is needed to be produced. It will be a significant part of Göteborg Energi's incomes that will be lost, if any of these energy efficiency functions are placed in the entire residence stock. But fewer started maximum load facilities and less purchased fuel due to energy savings could to some extent lower the income losses, see Figure 31.

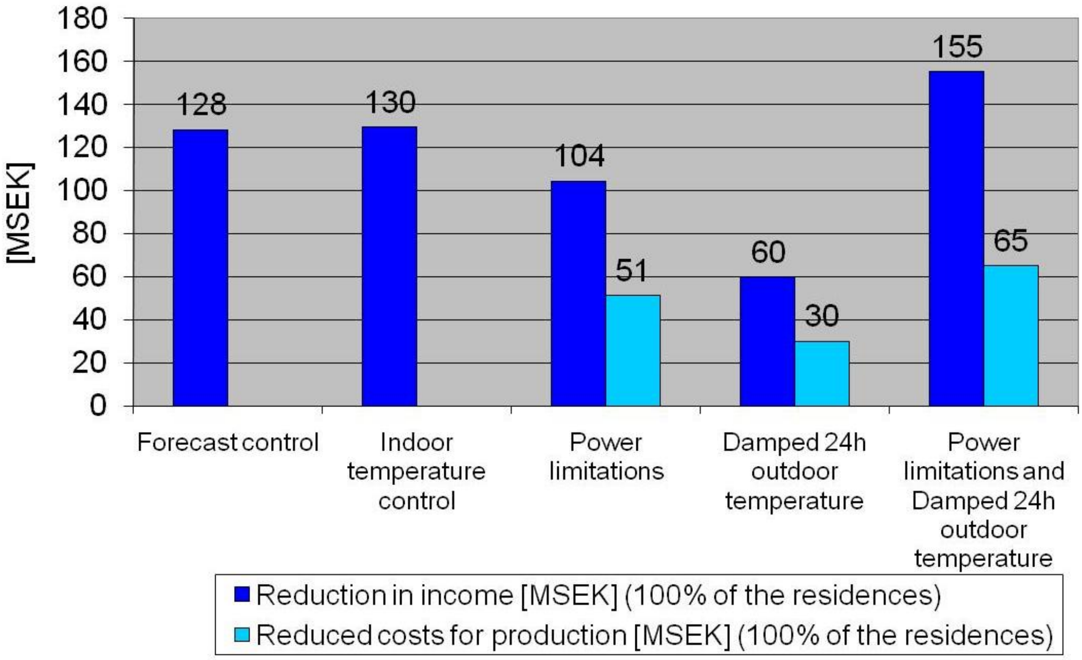

Figure 31: Reduced income and reduced production cost in millions SEK for Göteborg Energi due to energy efficiency.

6 Discussion

The results in Table 8 show that, with respect to the environment, the indoor temperature control, the forecast control and the combined method of power limitation and damped outdoor temperature approximately give the same positive outcome.

But neither forecast control nor indoor temperature control reduces the power peaks, which contributes to increased fossil fuel consumption, in contrast to the power limitation and the damped outdoor temperature. High power peaks often lead to startups of maximum load production facilities to meet the increased power demand, which uses fossil fuels. The amount of CO_2 emissions per produced kWh for Göteborg Energi is 15g, but this is a mean value for the entire production. This means that if the power peaks can be decreased, than a reduction of the fossil fuels usage can contribute to an even lower amount of CO_2 emissions. The cost savings are also largest for the combined method of damped 24h outdoor temperature and power limitations. Therefore it can be assumed that the combined method of damped 24h outdoor temperature and power limitation is the most optimal one, with respect to the environment, since it decreases the power peaks by 11.3 percent and therefore decreases the need for maximum load production facilities, see Table 8.

Another uncertainty factor is how the methods; forecast control, damped outdoor temperature and power limitation affects the indoor climate. The indoor temperature should theoretical be decreased if the supply water temperature is reduced. But at the same time the building will get an increased energy boost from enhanced activities from people, heat water and household machinery, see Section 2.6. This uncertainty factor can only be eliminated by performing measurements and studies of buildings with the methods installed.

7 Further work

Until now, the studies and evaluations on the damped outdoor temperature and the power limitation method have been theoretical estimations and calculations based on real measurements. Hence, a real test should be carried out to verify the theoretical assumptions, conclusions and results of the damped outdoor temperature and power limitation method. A possible test should be implemented in a variety of multi dwellings to ensure the results accuracy.

To gain the most optimal solution a strategy should be developed of how a multi control method should work, containing the methods; damped outdoor temperature, the power limitation, forecast control and indoor temperature control. Further, it will then be necessary to analyze how the prioritization between the methods should work. This multi control method also needs to be thoroughly studied to ensure reliable and accurate results.

8 Conclusions

There is a large energy reduction potential in the current traditional way to control the district heating supply. Only in one year, several tonnes of produced carbon dioxide could be saved. There are also big cost savings potential for the customers by changing their control methods. These lower costs for customers are also income decreases for Göteborg Energi. But fewer started maximum load facilities and less purchases of fuel because of energy savings could to some extent decrease the offset between the cost and the income. Increased energy efficiency supports Göteborg Energi's vision to achieve a sustainable society.

By combining all the four control methods, forecast control, indoor temperature control, power limitation control and damped outdoor temperature, a very good indoor climate and an optimal power input can be obtained. This is because the forecast control makes sure that no unnecessary energy is added when the sun shines outside. Indoor temperature control makes sure that there will be no over temperatures inside, because of too high power inputs. Power limitation control reduces the power peaks which gives lower heating costs for the customer, increase the capacity of the district heating net and reduces the use of expensive maximum load facilities. Damped outdoor temperature brakes the power output at short temperature drops. All of these four controlling functions save energy which reduces the environmental impact.

Using a combination of these four functions is rather complex but it is something building owners should work for, to get an as optimal energy solution and usage as possible. If the combined solution becomes too complex a good compromise is to use one or more of these functions, since they are better to use than the traditional control equipment with an outdoor temperature sensor.

8. References

[1]. **Schulz, Linda.** Normalårskorrigering av energianvändningen i byggnader - en jämförelse av två metoder. *Effektiv.* [Online] February 18, 2009. http://www.effektiv.org/pdf_filer/Rapport%202003-01.pdf. ISBN: 91-7848-932-6.
[2]. SMHI. *Swenden's Metrological and Hydrological Institute.* [Online] February 16, 2009. http://www.smhi.se.
[3]. **Brömms, Gunnar and Isfält, Engelbrekt.** *Effekt- och energibesparing genom förenklad styrning och drift av installationssystem i byggnader.* Stockholm : Institutionen för installationsteknik, KTH, 1992. ISSN: 0284-141X.
[4]. **Ljunggren, Patrik and Wollerstrand, Janusz.** *Optimal radiatorreglering för att nå låg fjärrvärme returtemp.* Instutionen för Energivetenskaper, LTH. s.l. : Svensk Fjärrvärme AB, 2005. ISSN: 1401-9264.
[5]. **Ljunggren, Patrik.** *Optimal och robust drift av fjärrvärmecentraler - Avkylning och egenskaper vid elavbrott.* LTH. Lund : Media-Tryck, 2006. ISSN: 0282-1990.
[6]. Glynwed. [Online] Mars 5, 2006. http://www.glynwed.se/pdf/SANITARY/GIRAIR/GIRAIR%20monteringsanvisning%2010%202006.pdf.
[7]. **Ruud, Svein H.** *Reglerstrategier och beteendets inverkan på energianvändningen i bostäder.* Centrum för Effektiv Energianvändning(CEE). Borås : Illustration & information, 2003. ISBN: 91-7848-968-7.
[8]. **Eriksson, Jörgen and Wahlström, Åsa.** *Reglerstrategier och beteendets inverkan på energianvändningen i flerbostadshus.* Centrum för Effektiv Energi användning (CEE). 2001. ISBN: 91-7848-858-3.
[9]. **Bagge, Hans, Hiller, Carolina and Sjögren, Jan-Ulric.** Lunds tekniska högskola. *Byggnadsfysik.* [Online] April 5, 2006. http://www.byfy.lth.se/Publikationer/semuppg2006/_Q_Bagge=2Cm=2Efl=2EUppsats=2CslutversionHush=E5llsel_i_direkti_=v%20ber%E4kningar%20och%20verklighet.060616.pdf.
[10]. **Harvey, Danny L.D.** *A Handbock on Low Energy Buildings and District-Energy Systems.* Bath : Bath Press, 2006. p. 432. ISBN: 978-184407-243-9.
[11]. **Södergren, David.** *Värmekapacitet i byggnadsstommar - Stommens tillgänglighet för energilagring.* Statens råd för byggnadsforskning. Stockholm : Liber Tryck AB, 1985. p. 4. ISBN 91-540-4402-2.
[12]. **Kavarén, Erik and Svensson, Johan.** Passivhusguiden. [Online] June 10, 2009. http://www.passivhusguiden.se/docs/guidedokument.pdf.
[13]. SMHI. [Online] June 10, 2009. http://www.smhi.se/cmp/jsp/polopoly.jsp?d=10059&a=31802&1=sv.
[14]. SMHI. [Online] June 12, 2009. http://www.smhi.se/cmp/jsp/polopoly.jsp?d=10487&a=34094&1=sv.
[15]. **Aronsson, Stefan.** *Fjärrvärmekunders värme- och effektbehov.* Institutionen för installationsteknik, Chalmers tekniska högskola. 1996.
[16]. Goteborg Energi AB. [Online] April 1, 2009. http://www.goteborgenergi.se/Foretag_Fjarrvarme_Erbjudande_och_priser_DXNI-5173529_.aspx.
[17]. **Trüschel, Anders.** *Värmesystem med luftvärmare och radiatorer - Utformingens inverkan på systemets känslighet.* Institutionen för Installationsteknik, Chalmers Tekniska Högskola. Göteborg : s.n., 2002. ISBN 91-7291-175-1.
[18]. **Andreasson, Mats, Borgström, Margaretha and Werner, Sven.** Svensk Fjärrvärme AB. [Online] 2009. http://www.svenskfjarrvarme.se/download_biblo/1436/2009;4%20V%C3%A4rmeanv%C3%A4ndning.pdf. ISBN 978-91-7381-019-7.

[19]. Enreduce Energy Control AB. [Online] February 17, 2009. http://www.enreduce.schotte.se/data/Infoblad.pdf.
[20]. eGain Sweden AB. [Online] February 17, 2009. http://www.egain.se.
[21]. **Hillberg, Anders.** SMHI. [Online] May 4, 2009. http://www.smhi.se/content/1/c6/02/96/74/SMHI_WeatherSync_fastighet_fordjupning.pdf.
[22]. Elvaco AB. [Online] V.02, May 5, 2009. http://www.elvaco.se/pdf/effektreglering_datasheet_sv.pdf.
[23]. **Jonsson, Bertil.** *Borås Energi & Miljö.* [interv.] Simon Nilsson and Oskar Hilding. Borås, April 15, 2009.
[24]. **Margen, Peter.** *Värmelagring.* Svenska Mekanisters riksförbund. Stockholm : s.n., 1977. ISBN 91-7082-134-8.
[25]. Göteborg Energi AB. [Online] June 24, 2009. http://www.goteborgenergi.se/Foretag_Energitjanster_Erbjudande_och_priser_Individuell_matning_DXNI-7140090_.aspx.
[26]. **Mårtensson, Mats.** *Product manager of energy services at Göteborg Energi.* Gothenburg, April 6, 2009.
[27]. Göteborg Energi AB. [Online] June 30, 2009. http://www.goteborgenergi.se/Om_oss_Var_versamhet_Affarsid_och_Vision_DXNI-491159_.aspx.
[28]. Göteborg Energi AB. [Online] June 30, 2009. http://www.goteborgenergi.se/Om_oss_Var_versamhet_Energileveranser_Mer_om_fjarrvarme_DXNI-659003_.aspx.
[29]. Göteborg Energi AB. [Online] June 1, 2009. http://www.goteborgenergi.se/Om_oss_Informationsmaterial_Arsredovisningar_DXNI-6489_.aspx.
[30]. Göteborg Energi AB. [Online] June 16, 2009. http://www.goteborgenergi.se/Om_oss_Informationsmaterial_Arsredovisningar_DXNI-6489_.aspx.

Appendix A Figures and diagrams

A.1 An analysis performed on the outdoor temperature and the coldest day for each of the years 2002-2008.

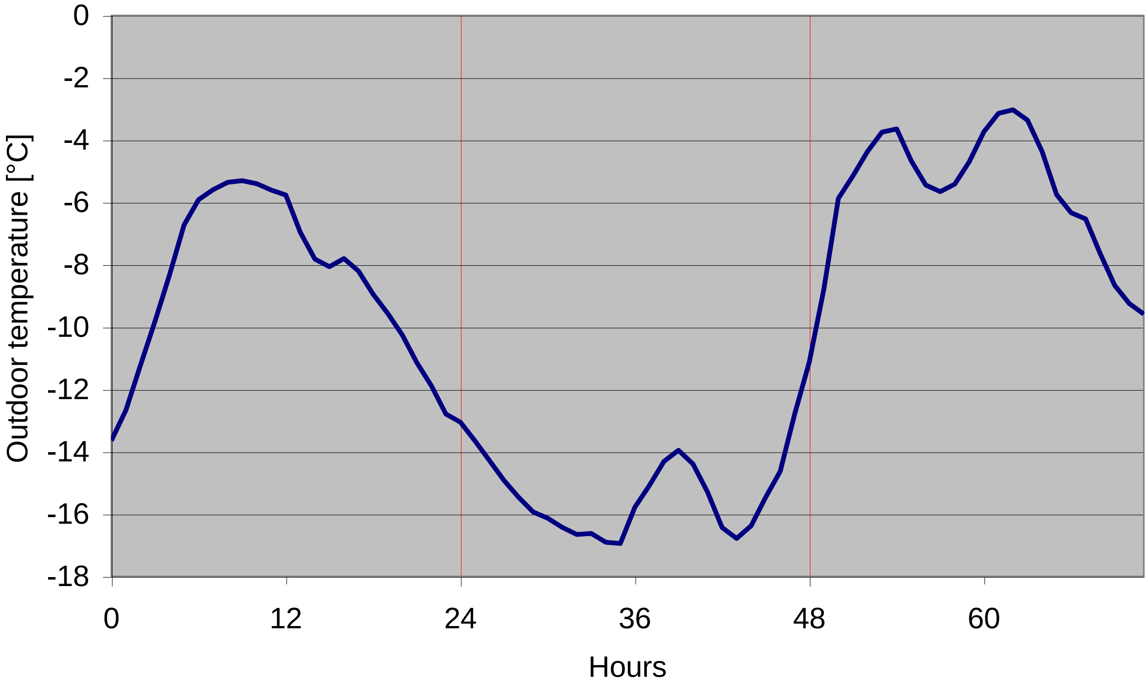

Figure 32: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2003. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.

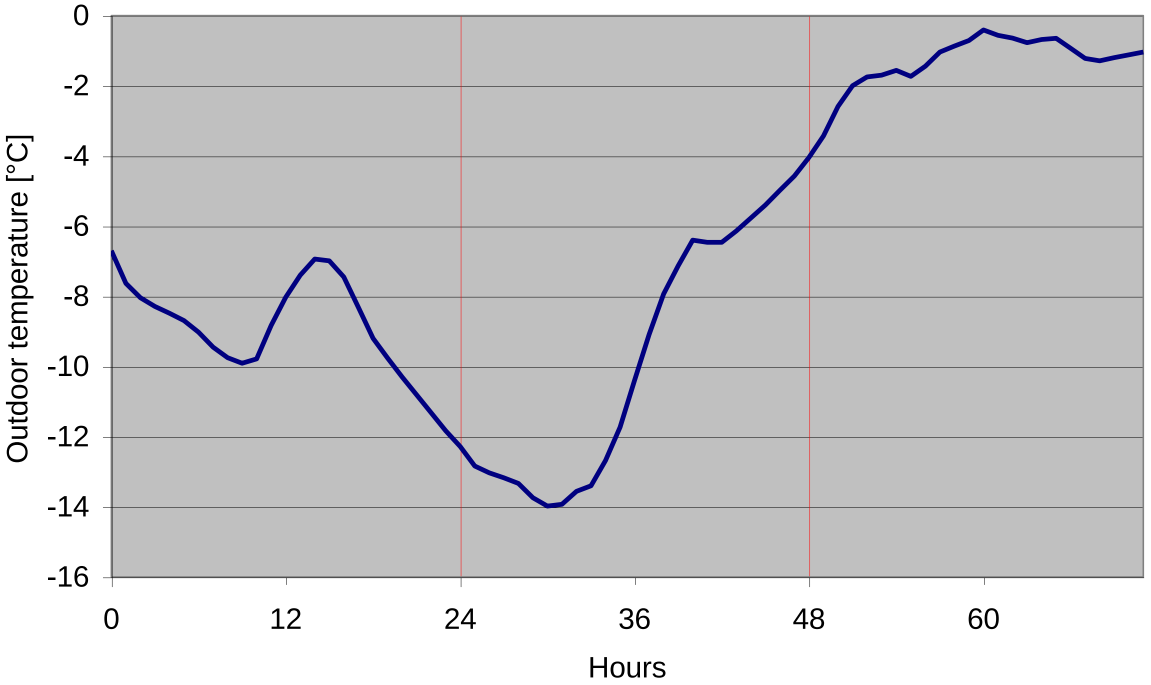

Figure 33: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2004. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.

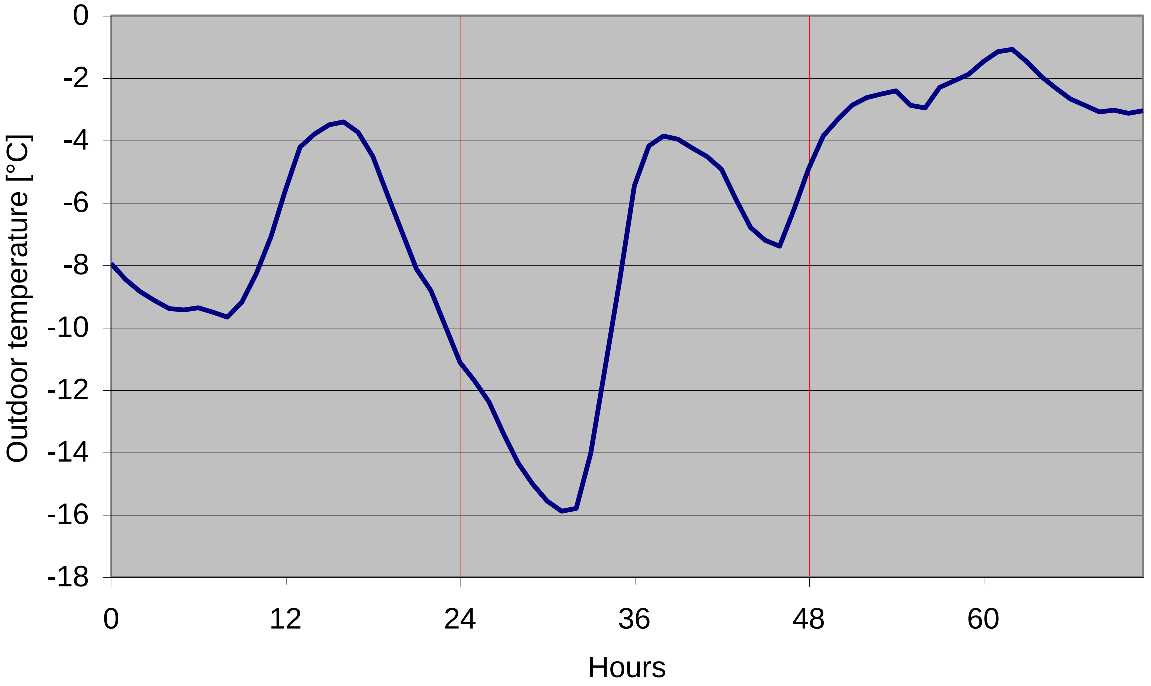

Figure 34: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2005. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.

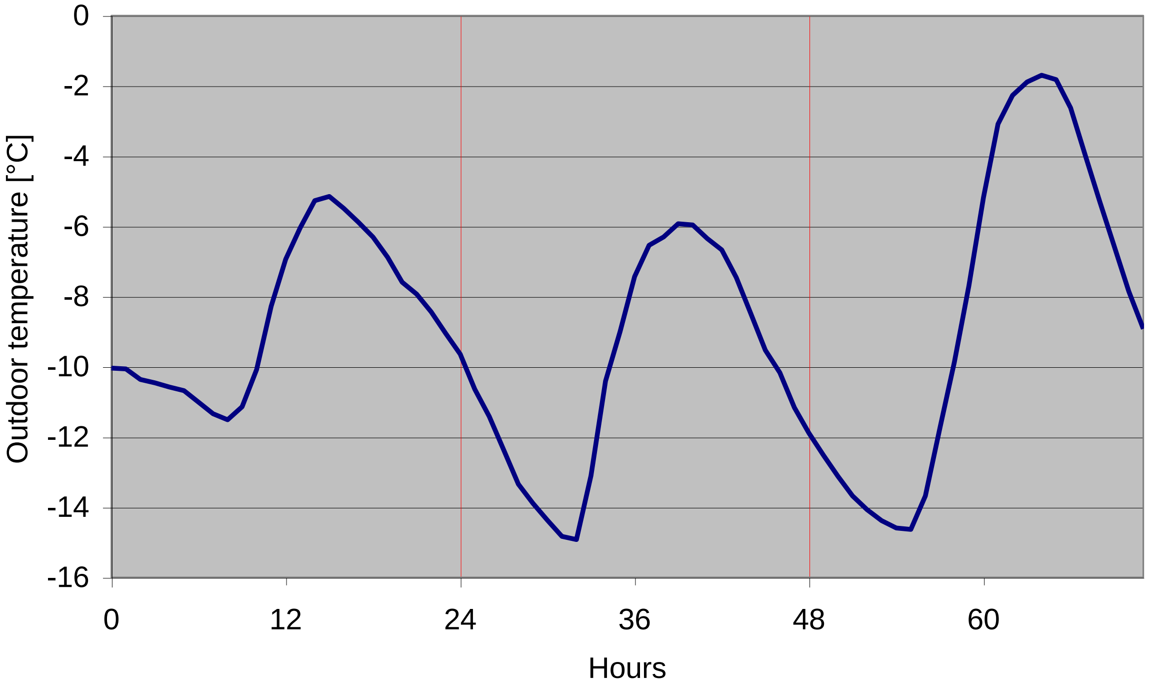

Figure 35: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2006. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.

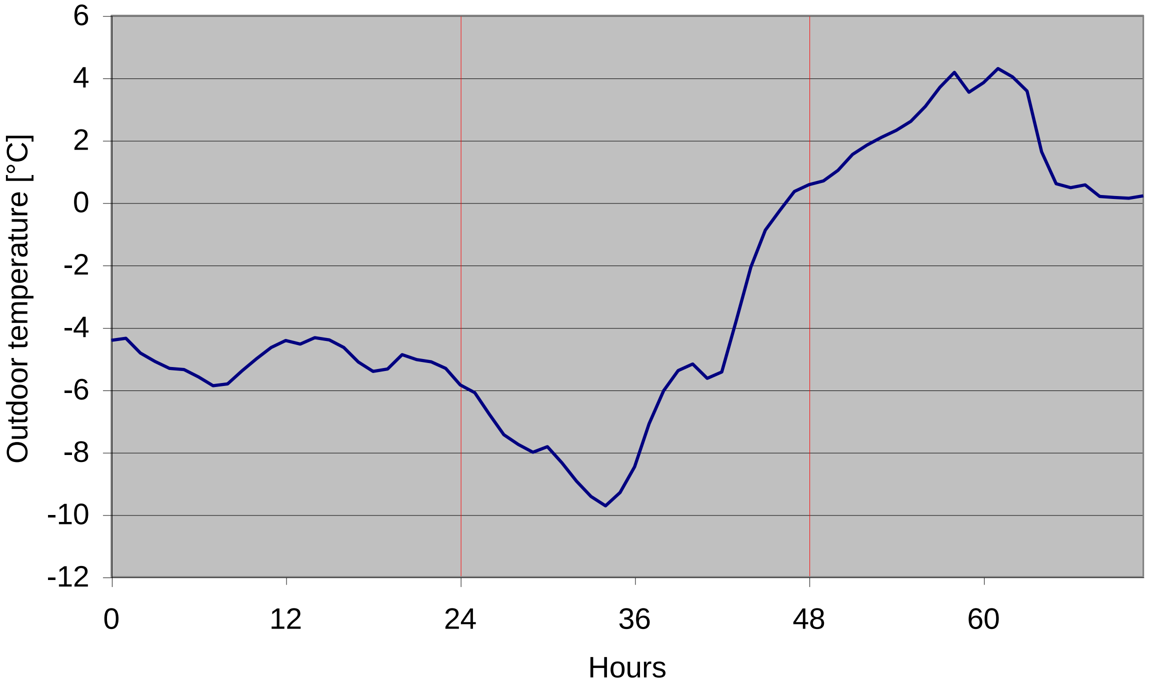

Figure 36: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2007. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.

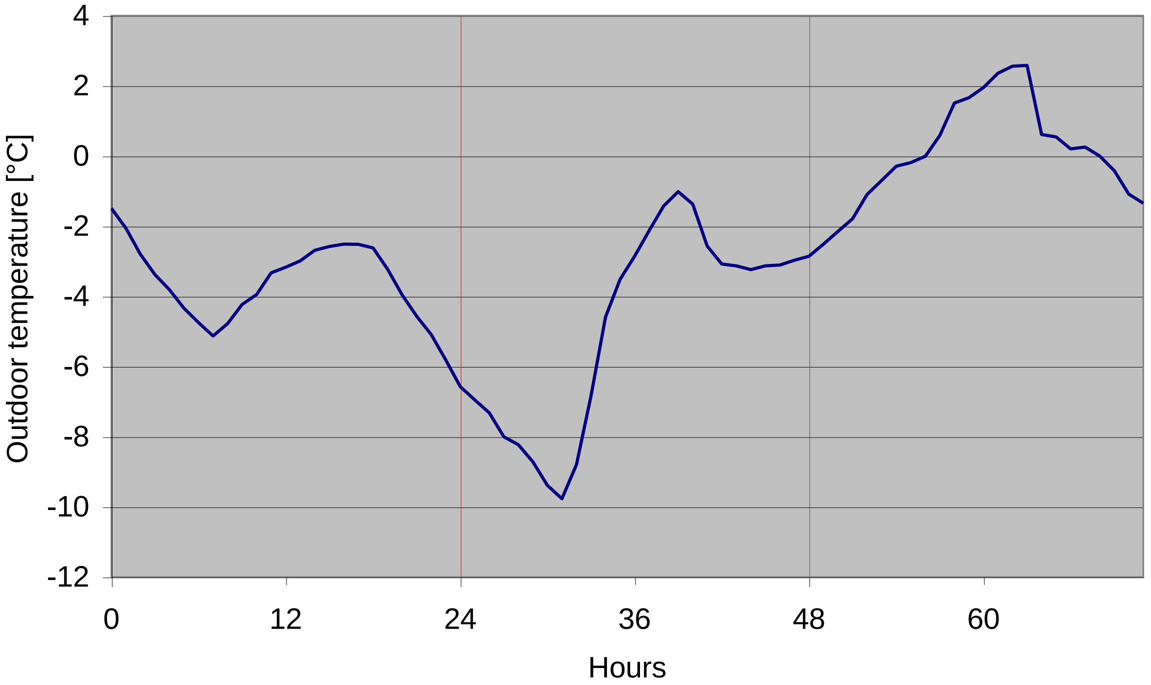

Figure 37: The figure shows the outdoor temperature variation, one day before and one day after the coldest day in the year 2008. The coldest day is between the two red lines and starts at hour 24 and ends at hour 48.