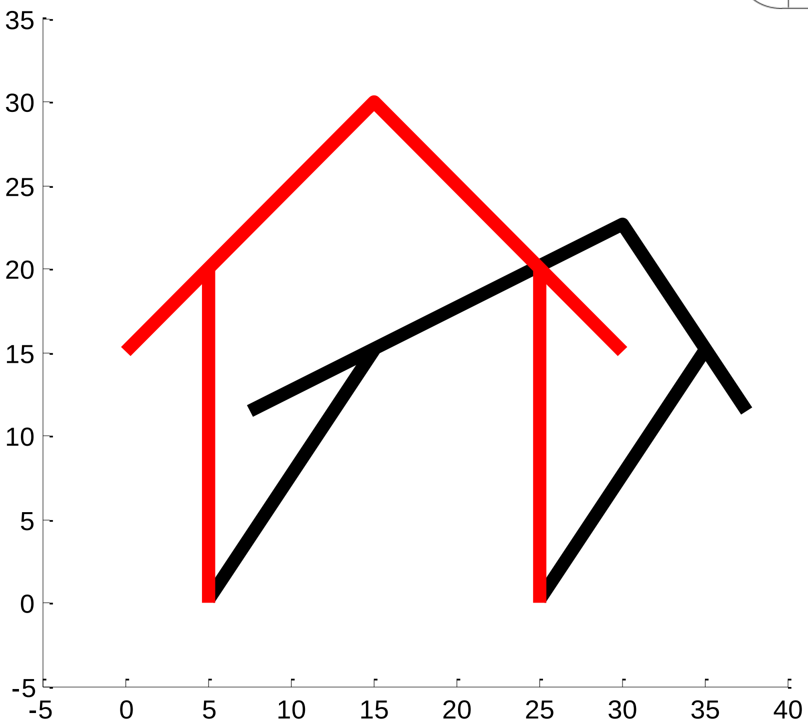

Evaluation of buildings' suitability as thermal energy storage in a district heating system

Master of Science Thesis in the Master's Programme Sustainable Energy Systems

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DAVID PETERSSON

Department of Energy and Environment
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis E2013:02

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ABSTRACT

When there are peaks in the power demand for district heating, back-up boiler plants using fossil fuels are often used in order to satisfy the demand. These plants are less efficient and less environmental friendly than base load plants. In an effort to reduce the need for back-up boilers, a share of the buildings in the network could be used as thermal energy storage. By moving the time of their heat deliveries peaks could be avoided, resulting in a more even load supplied by base load plants. The question is to what extent buildings are suitable of withstanding adjustments in heat delivery.

This thesis examines the possibilities of using buildings as thermal energy storage, by analysing measurements performed by Göteborg Energi in several buildings in 2010-2011. During these measurements tests were carried out in which the input signal from the outdoor temperature, which controls the heat supply to the radiators, was adjusted. Test cycles were designed in order to alternate between periods of charge and discharge of heat and carried out at different times of the day to avoid variations caused by the users and weather. This resulted in a pattern of eight cycles per week.

Test buildings are evaluated by the following parameters: how the indoor temperature (measured in two apartments per building) and heat supply change during test cycles; the size of these variations compared to natural variations; for how long the heat deliveries can be reduced and how different outdoor temperatures affect building behaviour.

Initial results showed that the indoor temperature was rather stable during regular heating, but alternated according to the test cycles when they were used. During testing, temperature changes during the discharge period were less than 1°C and often less than 0.5°C. Some differences between the buildings could be found, but since there were such variations between apartments within the buildings, not all of them were certain. Larger change of the control signal in the test often showed larger temperature variation, but not entirely proportional. The temperature change may have been impacted by variations in outdoor temperature, but the variations between different results may also have different causes.

The temperature variations caused by the tests were found to be in the same level of magnitude as the natural variations in the apartments. That indicated a possible decrease in power of about 10 W/m^2 for a normal-to-discharge test period and 17-21 W/m^2 for a charge-to-discharge test period.

Key words: Data analysis, demand side management, district heating, measurements, peak reduction, thermal energy storage.

Utvärdering av byggnaders lämplighet som värmelager i ett fjärrvärmesystem

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SAMMANFATTNING

När topplaster inräffar i fjärrvärmenätet används spetspannor för att täcka behovet. Dessa pannor är ofta minde effektiva än basanläggningar och drivs av fossila bränslen, vilket är sämre för miljön. Genom att använda en del av byggnaderna i fjärrvärmenätet som värmelager och på så sätt kunna jämna ut förbrukningen över dagen kan man generera mer av värmen med hjälp av basanläggningar.

Det som undersöks i detta arbete är byggaders lämplighet som värmelager i ett fjärrvärmesystem, genom att analysera mätningar utförda av Göteborg Energi i ett flertal byggnader mellan 2010 och 2011.

Under mätningarna utfördes tester där styrsignalen till värmesystemet, i form av utomhustempearatur, justerades. Testcyklerna var konstruerade så att de alternerade mellan perioder av i- och urladdning av byggnaderna, och längden på testcyklerna avvek från ett dygn för att inte användar- och vädervariationer skulle påverka resultaten. Mönstret som användes var 21 timmar långt och det gick således 8 cykler på en vecka.

I testerna utvärderades förändringar i innomhustemperatur och värmetillförsel liksom hur lång tid av urladdning byggnaderna klarade av. Det studerades också hur olika utomhustemperaturer påverkade resultaten och hur stora temperaturförändringarna orsakade av testen var jämfört med de variationer som vanligtvis förekom i byggnaderna.

De inledande resultaten visade att temperaturen normalt var ganska stabil, men att förändringar kunde ses när olika testcykler användes. Temperaturen sjönk inte med mer än 1°C under urladdningen och oftast var förändringen mindre än 0,5°C. Vissa skillnader mellan byggnaderna kunde noteras, men i vissa fall var skillnaderna mellan rum inom en byggnad större än skillnaderna mellan olika byggnader. Större justeringar av styrsignalen ledde till större temperaturvariationer, men något exakt förhållande kunde inte utläsas. Inget klart samband mellan förändringar i inomhustemperatur och utomhustemperaturen kunde påvisas, eventuellt finns de men doldes av andra variationer.

Påverkan från testerna på inomhustemperaturen var ganska liten, och i storleksordning med de variationer som orsakas av andra störningar. Potentialen för effektjustering låg i spannet 10-21 W/m^2, beroende på vilken styrning som användes.

Nyckelord: Dataanalys, efterfrågestyrning, fjärrvärme, mätningar, topplast-minskning, värmelageer, värmelagring.

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Preface

In this thesis, we have approached the problem of power peaks in district heating demand by examining the possibility to move the time of heat deliveries while sustaining a feasible temperature.

The foundations of the research were measurements in different buildings that were carried out by Göteborg Energi, as a part of their research on the subject in the years 2010 to 2011. We would like to thank Peter Hultén for supplying us with these measurements and helpful information.

We would also like to thank our supervisor at Chalmers, Johan Kensby, who has initiated the project and has come with much helpful input from this research area. At last we want to thank our examiner Anders Trüschel, who has shown support and interest.

Göteborg, June 2013

Joi Elebo

David Petersson

Notations

Roman upper case letters

A	Area	[m^2]
$A1$, $A2$	Apartment 1 and 2	[-]
C_{th}	Thermal mass of a building	[J/K]
I	Thermal inertia	[J/(m^{2}Ks$^{0.5}$)]
K_{rad}	Radiator coefficient	[W/K^n]
$P_{specific}$	Building specific heat loss rate	[W/K]
$\dot{Q}$	Radiator power	[W]
$\dot{Q}_i$	Ventilation losses	[W]
$\dot{Q}_{tr}$	Total heat loss due to transmission	[W]
T_o	Outdoor temperature	[°C]
T_r	Room temperature	[°C]
T_{var}	Temperature variation over one cycle	[°C]
$T_{RAD,forward}$	Radiator forward temperature	[°C]
$T_{RAD,return}$	Radiator return temperature	[°C]
U	Thermal transmittance	[W/(m^{2}K)]

Roman lower case letters

c_p	Specific heat capacity	[J/(kgK)]
k	Thermal conductivity	[W/mK]
n	Radiator exponent	[-]
t	Time	[s]

Greek upper case letters

ΔT	Change in (temperature) control signal	[°C]
ΔT_{lm}	Logarithmic mean temperature difference	[°C]

Greek lower case letters

ρ	Density	[kg/m^3]
τ	Time constant	[s]

Translation of names of institutes

Göteborg Energi	Gothenburg Energy

Abbreviations

CHP	Combined Heat and Power
CP	Charge Period
DH	District Heating
DP	Discharge Period
HEX	Heat Exchanger
HOB	Heat Only Boiler
NOP	Normal Operation Period
PCM	Phase Change Materials

1 Introduction

In this chapter a background for the thesis is given followed by a description of the range of the project.

1.1 Background

The heat load in a *district heating* (DH) system varies throughout the day and the season, mainly because of demand side activities and weather changes. These variations create an uneven load for the network and peak loads boilers that run on fossil fuels, typically oil or natural gas, are used for the supplementary heating (Gadd and Werner 2013).

Therefore, having more even heat generation is a goal so that use of peak load boilers can decrease (peak reduction or peak shaving). When daily peak loads are lowered a greater portion of the heat can be generated in more efficient boilers, reducing the need for less efficient fossil-fuelled boilers, which would then only be needed in case of extremely cold outdoor climate.

A potential method to reduce load peaks is to use the building mass as thermal energy storage. This is done by temporarily reducing heat supplies in selected buildings, during the most critical hours of the day. In that way a more even heat generation can be obtained in the DH system. The consequence of this, however, will be reduced indoor temperatures.

By controlling what technology is used and at what time the heat is generated, it is possible for DH companies to optimize generation so that costs as well as emission of greenhouse gases are reduced. Ability to control when heat is generated can also be utilised in cogeneration plants so that both electricity and heat is generated when electric power demand is high (COGEN Europe 2001).

The DH company Göteborg Energi has been looking into the possibilities to use buildings as thermal energy storage in comparison to investing in a heat water accumulator. It was estimated that 25% of the buildings were available as short term heat storage and the available heat power 9-54 MW depending on what the adjustment of outdoor temperature is (Ingvarsson and Werner 2008).

1.2 Purpose

The main purpose of this thesis is to evaluate different buildings' suitability to be used as thermal energy storage, and thereby reduce peaks in the DH system. This has been done by analysing measurements with the perspective of the research questions presented in the section below.

1.3 Research questions

To be investigated specifically are the following research questions:

- How much does the indoor temperature, expressed in °C, decrease during a test cycle?
- How much does the heat supply, expressed as W/m^2, change during a test cycle?

- How large are the variations that are caused by the test cycle compared to natural variations?
- For how long can the heat load be reduced and how long time do buildings need to recover?
- How do variations in outdoor temperature affect behaviour of the buildings?

1.4 Method

Measurements have been carried out by Göteborg Energi in several buildings, testing a strategy for controlling their heating system. The tests are carried out by adjusting a control signal based on the outdoor temperature, adjusted up or down at different intervals (most often 7°C). The idea is to see how this control mechanism changes the indoor temperatures and the use of energy. In this way, the sensitivity to changes in the heat input is analysed for each building.

The measurements consist of a 21 hour cycle so that there is data for every time of the day for different parts of the test cycle, creating 8 cycles every week. A sensitivity analysis of the system is carried out to see how the buildings react to changes.

The methodology is further described in section 3.1.

1.5 Limitations

The aim of this thesis is to analyse how changes in operation of energy supplies affect the indoor climate in different types of buildings. What is required for the indoor climate to be considered pleasant will not be studied more deeply. The one parameter that has been used to measure indoor climate is the indoor temperature. For further research see the Commtech Group (2003).

The geographic limitations in the project are that all buildings are located in Gothenburg, and connected to the district heating system of Göteborg Energi.

2 Theory

This chapter gives an explanation of certain expressions, phenomena and other terminology that is used further on in this thesis, as well as some that are left for further studies.

2.1 The district heating system

A *district heating* (DH) system provides heating of building spaces and domestic hot water through heat generation at a few central plants and distribution by a piping system.

The DH plants utilized by Göteborg Energi and their generated thermal energy are illustrated in Figure 1; organized by type of plant. First, to the right is waste heat from refineries, municipal solid waste and heat pumps which, since they are all cheap and abundant in energy, are used as base load plants. Next are the *combined heat and power* (CHP) plants followed by biomass fuelled *heat only boilers* (HOB) and finally fossil-fuelled HOB.

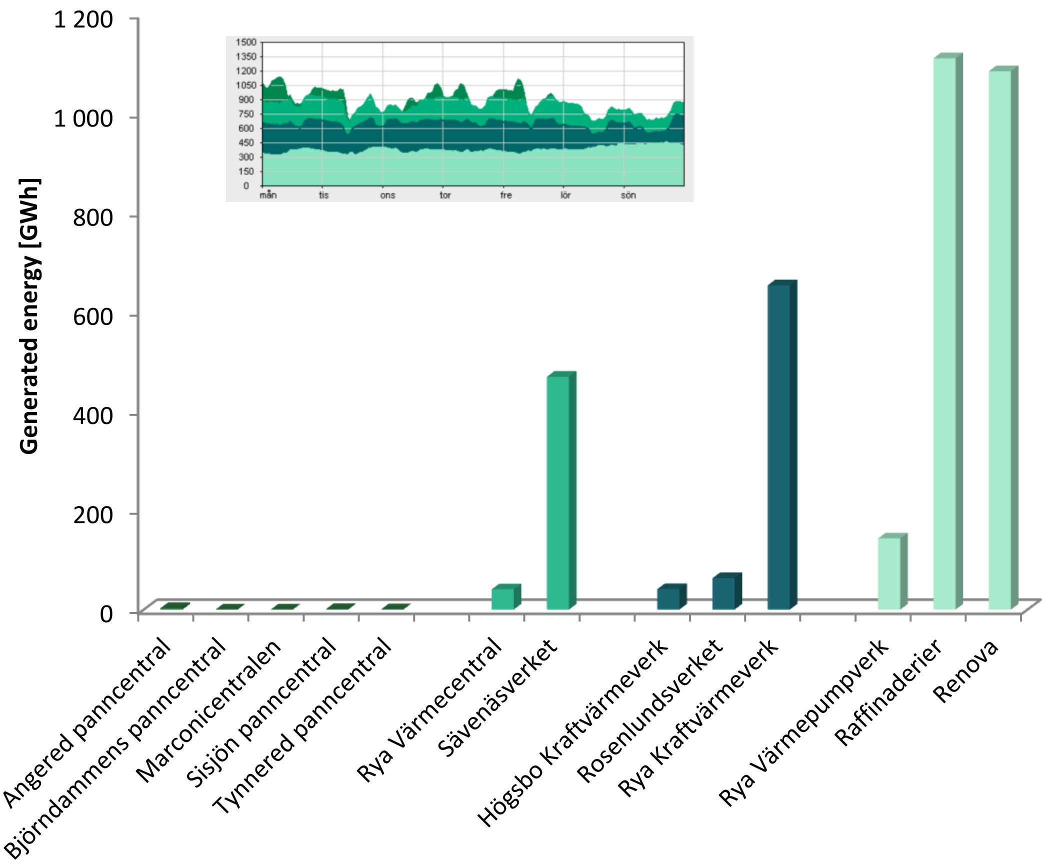


Figure 1. Thermal energy supply in the DH system of Göteborg Energi. The first 5 plants, from the left, are fossil HOBs, the next 2 bio HOBs, the next 3 CHP plants and the last 3 waste heat resources. The picture in the upper left corner is a load [MW] diagram exemplifying a high load week in March 2013 with the colours matching the categories in the energy diagram.

The annual generation of heat is 3772 GWh. The CHP plants are fuelled by natural gas, have a power-to-heat ratio < 1 and together produce 626 GWh of electricity. (Göteborg Energi 2013)

2.2 Building physics

2.2.1 Heat balance

The heat loss through the building envelope consists of transmission and infiltration losses. Transmission through the walls is described by the Commtech Group (2003):

$$\dot{Q}_{tr} = \sum UA(T_r - T_o) = K_{tr}(T_r - T_o) \tag{1}$$

To describe ventilation losses the following equation is used:

$$\dot{Q}_i = \dot{V}_i \rho c_p (T_r - T_o) = K_i (T_r - T_o) \tag{2}$$

These aspects should be considered but are not quantitatively studies in this thesis since there are no measurements of it for these particular buildings.

2.2.2 Thermal inertia of the building

Thermal inertia, I, is used for describing the ability of a material to resist temperature changes (Goulart 2004). It is calculated as the square root of the products of the material properties thermal conductivity (k), density (ρ) and specific heat capacity (c_p):

$$I = \sqrt{k \rho c_p} \tag{3}$$

As comparative values, the thermal inertia of wood, gypsum, bricks and concrete is 310, 400, 900 and 1800 J/($m^2Ks^{0.5}$), respectively (Persson and Vogel 2011).

2.2.3 Time constant

The time constant, τ , of a building is defined as the quotient between its thermal mass and its specific heat loss rate:

$$\tau = \frac{C_{th}}{P_{specific}} \tag{4}$$

It describes how fast the building adopts to temperature changes. A large time constant means that the temperature changes slowly. Standard values for typical buildings vary from 24 hours for an older light building up to 300 hours for a medium heavy building with concrete slab (Persson and Vogel 2011).

The time constant is used for determining change in room or outdoor temperature in respect of time t. The following equation is used:

$$dT_r = dT_o\left(1 - e^{-\frac{t}{\tau}}\right) \quad (5)$$

In other words, the time constant is the time for 63.2% of the transition from initial temperature to a new equilibrium.

For methods of using measurements to predict a time constant or a new equilibrium, see Measurement Specialities Inc. (2012). Further information and values are found in Antonopoulos and Koronaki (1999).

2.3 Thermal heat storage

As mentioned in chapter 1, there are certain methods to lower the peak loads. Thermal heat storage is the one considered in this thesis. It can be divided into sub-methods describing different ways and locations to store the heat in the system after it has been generated at the plants:

- Varying temperature in DH network
- Hot water storage tank
- Ground storage
- Phase change materials (PCM)
- Heat capacity in buildings

The *DH network* is used by increasing the temperature of the water in the pipes of the system, so that there is a potential to use extra heat whenever needed.

A *hot water storage tank* is installed in several DH systems. This option requires investments for instalments that could be avoided by instead using buildings as thermal energy storage.

Ground storage is using a medium placed in the ground to store thermal energy.

Phase change material is a way of storing heat inside the buildings. The building material changes phase around a designed critical room temperature. In other words, the thermal inertia of the building (see section 2.2.2) is increased. PCM is further explained by Hawes, Feldman et al. (1993) and a literature study in carried out by Burman and Johansson (2011).

Heat capacity in buildings is what is examined in this thesis. Whereas PCM uses the potential of the material, the use of heat capacity in normal building materials requires a change in surrounding temperature in order to be utilized.

2.4 Space heating

The heat supplied to a room and the mean temperature difference between the radiator and the room is estimated by a radiator constant K_{rad}:

$$\dot{Q} = K_{rad} \cdot \Delta T_m{}^n \quad (6)$$

Here n, usually values between 1.1 and 1.4, expresses the radiation. A simplification gives $\Delta T_m = \Delta T_{lm}$, the logarithmic mean temperature difference described by:

$$\Delta T_{lm} = \frac{T_{RAD,forward} - T_{RAD,return}}{\ln\left(\frac{T_{RAD,forward} - T_r}{T_{RAD,return} - T_r}\right)} \quad (7)$$

An implementation of these equations is shown in section 4.4 for one of the test buildings. (Commtech Group 2003)

Other parameters that can be considered in controlling space heating are threshold and balance temperature, heating degree days and heating indexes. For an introduction to different aspects of space heating, see Jardeby, Soleimani-Mohseni et al. (2009).

2.5 Control system

Normally the heat supply to the buildings in DH systems is controlled in one of two ways. For an area with smaller buildings the hot stream from the DH system provides heat through a *heat exchanger* (HEX) to a local area network. The idea of a substation is to lower the energy content of the flow. In the case of larger buildings, they are connected directly to the DH system (Fredriksen and Werner 2013), which make these more suitable for DH thermal energy storage.

In the building a substation is situated, where another HEX is used. Here the control system delivers water with a certain temperature to the apartment radiators. This temperature is called the radiator forward temperature ($T_{RAD,forward}$) and is decided by the prevailing outdoor temperature; a relation whose values are illustrated by a control curve and is decided in advance by testing performed in order to get a steady indoor temperature independent of the weather (Fredriksen and Werner 2013). The control curves for the buildings in this thesis are shown in Appendix B.

P-regulation, which is the most common regulation, is used to control the radiator forward temperature. It causes some over-jump in the response, so at other places a PI-regulation is used (another type of regulator which removes the remaining error by integration).

By comparing the DH thermal power delivered to a building together with the correspondent outdoor temperature the relation between outdoor temperature and power consumption can be calculated. This is illustrated in Figure 2 for a whole year's measurements of Building E.

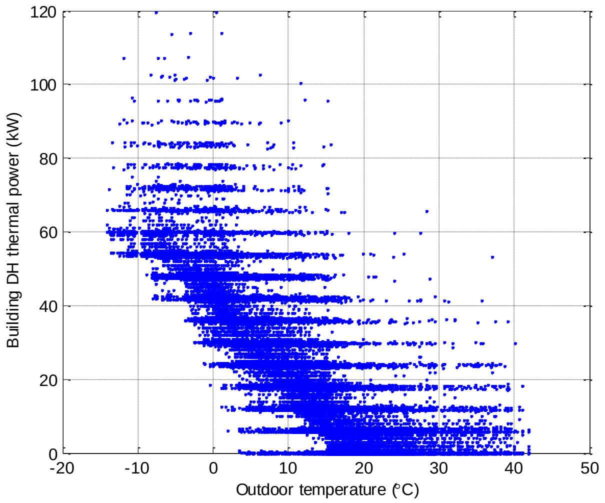


Figure 2. Thermal power, for different outdoor temperautures, in Building E.

A curve can be estimated from data points scattered around it (starting at 60 kW for -10°C and decreasing the power for higher outdoor temperatures). It has a "break point", often at 15°C as in this example. This is where the heating system shuts down. The resolution of power steps of ~1 kW is probably due to measuring equipment for the flow speed of the heating medium. Larger deviations from the expected curve can be caused by domestic hot water production.

2.6 Domestic hot water supply

Domestic hot water is used by residents for drinking, food preparation, personal hygiene etc. and is heated using the DH system. This heating energy is included in all of the measurements in this thesis and has not been altered during the tests (i.e. the domestic hot water demand is supplied as usual).

3 Literature survey

This chapter examines some earlier studies of the building as thermal energy storage.

3.1 District heating in Sweden

Introduction textbooks on district heating are rare. However, a thorough guide by Fredriksen and Werner (2013) still, at the moment of writing, awaits publishing and will soon be available. For an introduction to the particular case of DH systems in Sweden, see Werner (2010).

3.2 Earlier attempts on thermal energy storage

A larger research on DSM for different buildings was carried out by Kärkkäinen, Sipilä et al. (2004). They conclude that peak loads of 20-30% in the DH system could be avoided by using buildings as thermal energy storage. In Jyväskylä DH system with a 300 MW maximum peak load, it is assessed that a 20% reduction of daily peak demand is possible, thus avoiding starts of heat-only boilers. Using this information, an economic analysis then show that avoiding an investment of a 20 MW HOB for $1.8 \cdot 10^6$ €, can save 900 € annually per consumer.

As mentioned earlier, in Ingvarsson and Werner (2008) the possibilities of thermal energy storage in the DH system of Gothenburg is described. In particular, different buildings are assessed by their time constant in order to describe their future suitability as thermal energy storage.

3.3 Recent studies of buildings as thermal energy storage

In Myrendal and Olgemar (2010) potential of energy savings by remotely controlling vents by a technology from NODA is estimated. Available for reduction is a mean of 20-30% of the DH load demand for Linköping DH system buildings during a three hour period. The control system generates an annual saving for the buildings that on average is 5%. However, indoor climate aspects are not fully looked into.

Svedberg and Olsson (2012) investigate load control in the Trollhättan DH system. Apartment buildings with high energy usage and time constants were found suitable. It is appreciated that if the 72 top energy buildings were to use thermal energy storage, 12 MW peak load could be avoided for three hours.

In Molander and Olofsson (2012) one of two methods presented for peak reduction (the other one is using solar energy) is periodically switching the control curve during the day. Data analysis is carried out and compared for different types of buildings. The method shows potential to reduce the heating power demand, but at the cost of indoor climate. High time constant buildings give the most positive response.

4 Method

Data from tests have been used to find out how different types of buildings react to a change in the energy deliveries. The tests, which were performed by Göteborg Energi before this thesis was initiated, were carried out with a couple of different test cycles depending on what was of interest at the time.

4.1 Buildings

The buildings are connected to the DH system of Göteborg Energi and situated in the Gothenburg area. They all have in common that they are multi-family houses of suitable sizes for implementing thermal energy storage. Even though locations are confidential, data from inventorying carried out by Göteborg Energi in the winter and spring of 2010 are provided and shown in Appendix A.

4.2 Test design

The main concept of the tests is that the control signal into the system, which is normally the outdoor temperature, is some time adjusted so that it provides the system with a signal that indicates either a higher or a lower outdoor temperature.

The adjustments of the control signal are made by repeating patterns, called test cycles. All cycles starts with a period where control signal is adjusted to show a higher outdoor temperature. This leads to a heat deflect and the period is called a *discharge period* (DP). The magnitude of the discharge is described as ΔT [°C], where ΔT is the number of degrees that is added to the normal control signal. In most cycles there is also a *charge period* (CP). The charge of the building is achieved in the opposite way of the discharge, by subtracting ΔT [°C] from the normal temperature signal. All cycles end with a period where the normal control signal is used. This period is called a *normal operation period* (NOP).

The length of one cycle of temperature adjustments has been 21 hours. One week corresponds to exactly 8 cycles; therefore it is preferable to make the analysis over a number of whole weeks. The analysis of the results is based on mean values calculated over several cycles. In that way effects from natural temperature variations such as user behaviour, during the day has been reduced, because the effects will occur during different times for each cycle and therefore compensate for each other over a period of several cycles.

The goal of the study is to find out how much the thermal power delivery can be reduced during a short time period without changing the indoor climate too much. Therefore is has been interesting to analyse how the indoor temperature and the thermal power demand vary over the test cycle.

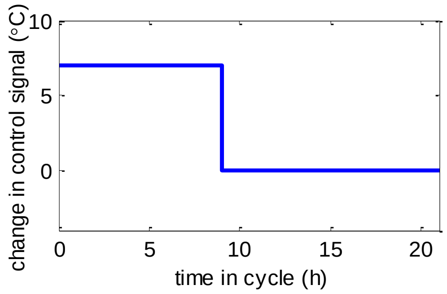
For each hour of the cycle, the mean indoor temperature for two different apartments in the buildings has been calculated, as well as the mean thermal power demand. From this data the temperature fall during heat deficit could be calculated. The change in thermal power consumption is also studied.

For all of the tests, data has been extracted by different sensors (of which the categories are displayed in Appendix C). The buildings' heat supply is regulated by their different control curves, which are presented in Appendix B.

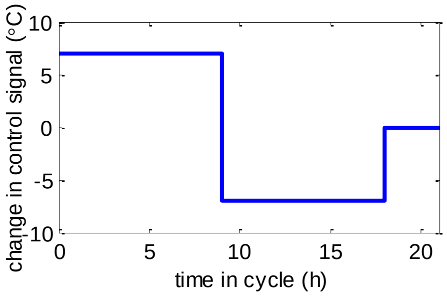
4.3 Test cycles

Tests have been performed with 5 different cycles for adjusting the temperature signal into the control system of the building. A description and illustration of the cycles is given in Figure 3.

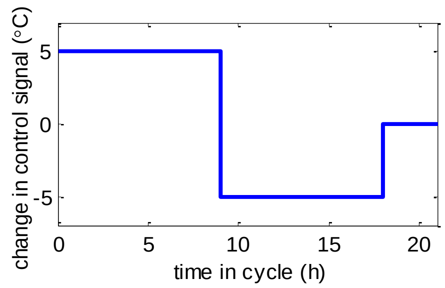
Cycle I: The first 9 hours is a DP with ΔT = 7°C. The following 12 hours is a NOP.



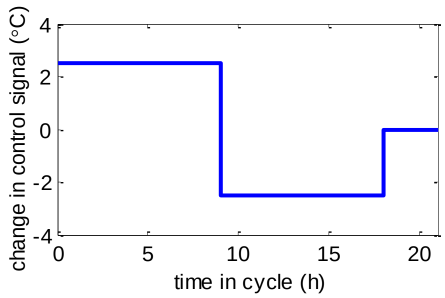
Cycle II: The first 9 hours is a DP ΔT = 7°C. This is followed by a 9 hour CP with ΔT = -7°C. The remaining 3 hours of the cycle is a NOP.



Cycle III: The first 9 hours of the cycle is a DP with ΔT = 5°C. This is followed by a 9 hour CP with ΔT = -5°C. The remaining 3 hours of the cycle is a NOP.



Cycle IV: The first 9 hours of the cycle is a DP with ΔT = 2.5°C. This is followed by a 9 hour CP with ΔT = -2.5°C. The remaining 3 hours of the cycle is a NOP.



Cycle V: The first 9 hours of the cycle is a DP with ΔT = 7°C. This is followed by a 9 hour CP with ΔT = -3°C. The remaining 3 hours of the cycle is a NOP.

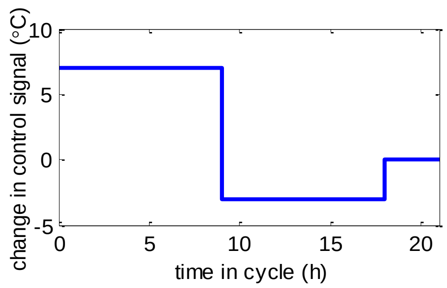


Figure 3. Description of the test cycle design.

4.4 Modelling of building heating system

This section takes a brief look at the hydronic system and the temperature measurement devices in the buildings.

4.4.1 The hydronic system

As an example of the behaviour of the hydronic system referred to in section 2.4, consider a steady outdoor temperature period where no testing is carried out, so that the transients are gone. Such is the case for Building E in the following case:

The measured energy usage for a certain period is 24 kWh. The power is the same as the measured energy consumption divided by one hour, which makes $\dot{Q}$ = 24 kW.

The radiator logarithmic mean temperature difference is calculated using equation (7), from $T_{RAD,forward}$ = 34.5°C, $T_{RAD,return}$ = 32.4°C and T_r = 23.0°C:

$$\Delta T_{lm} = \frac{34.5 - 32.4}{\ln(\frac{34.5 - 23.0}{32.4 - 23.0})} = 10.41°\text{C} \tag{8}$$

Assuming values of the radiator exponent as for a normal panel radiator n = 1.28–1.30 (Trüschel 2013) and using equation (6) with the values above:

$$K_{rad} = \frac{\dot{Q}}{\Delta T_m{}^n} = 1.1\text{–}\,1.2\ \text{W/K}^n \tag{9}$$

The actual value of K_{rad} as well as n depends on the size and design of the radiator.

4.4.2 Measurement devices

The indoor temperature sensors give values in steps of 0.25°C, which can be recognised in for example Figure 4 and 5 below. However, mean values over several test cycles will generate a smoother curve, giving more detailed information. At the same time, information about the specific patterns of each period is lost and an offset measurement might make impact on the mean values too.

4.5 Method of analysis

The method of analysis has been to answer the research questions by displaying the measurements, chose appropriate periods of time and comparing them to each other. Sometimes new aspects of the results were found more interesting and were used as supplemental research question, as they proved more informative.

Different test cycles have been used in different buildings. Some of the test cycles have been used in more than one building and some in just one of the studied buildings. Therefore the analysis does not always include all buildings or cycles.

A method in the analysis has been to isolate one parameter and see how it affects the result of the test. The studied parameters are:

- Building thermal properties
- Different test cycles
- Outdoor temperature
- Variations from tests or other sources

4.5.1 Building thermal properties

The way the temperature inside the different buildings behaves is compared in this analysis, as well as how the behaviour differs between different apartments in the same building. For example, Cycle I has been used both in Building A and E.

4.5.2 Different test cycles

The impact different test cycles have on the indoor temperature is studied. For example: in Building G Cycles II to IV have been used.

4.5.3 Outdoor temperature

For Building E Cycle I was used for a long period over which the outdoor temperature varied. Therefore the measurements from Building E could be used to see how the outdoor temperature affects the result of the test.

4.5.4 Variations from tests or other sources

For most buildings the data was mainly from test periods and not normal operation. During normal operation there were different outdoor temperatures than for the test periods. Hence, temperature data for ordinary behaviour was limited. Therefore a method was constructed for analysing the variations that occurred during the test cycles but was not caused by the tests cycles. This method uses the standard deviation.

In Figure 4 the mean indoor temperature is presented with a blue curve, and the standard deviation of it as an interval between the 2 red curves. The set of temperature data was broken down into whole weeks, in segments of 8 test cycles á 21 hours (presented as 8 thin multi-coloured curves in Figure 4, where each curve consists of 126 values).Then a standard deviation for each corresponding value in the 8 cycles was calculated (126 deviations from 8 values each).

That way, the temperature change due to tests was similar for all the analysed data points, and therefore the test cycle would not affect the calculation of the standard deviation.

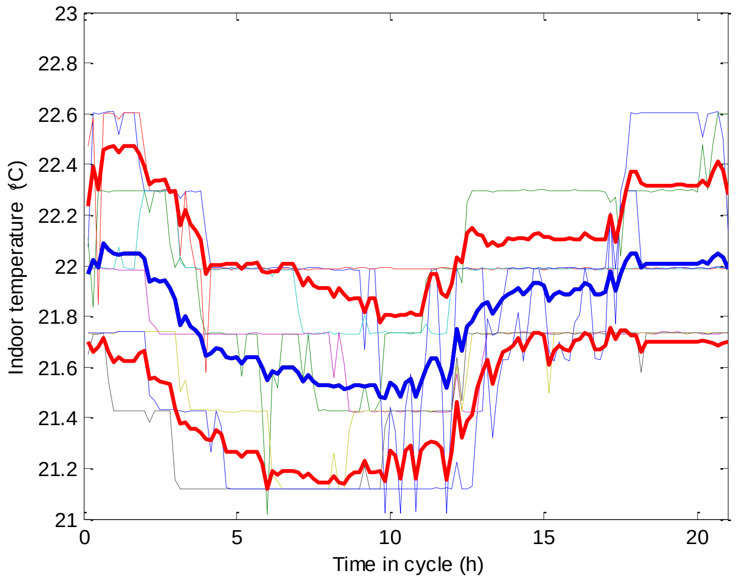


Figure 4. The mean temperature (blue) and standard deviations (red).

To get a well-defined interval to compare the temperature curve to, a mean value of the standard deviation curve was calculated (represented as black lines in Figure 5, in which the blue and background curves are the same as in Figure 4).

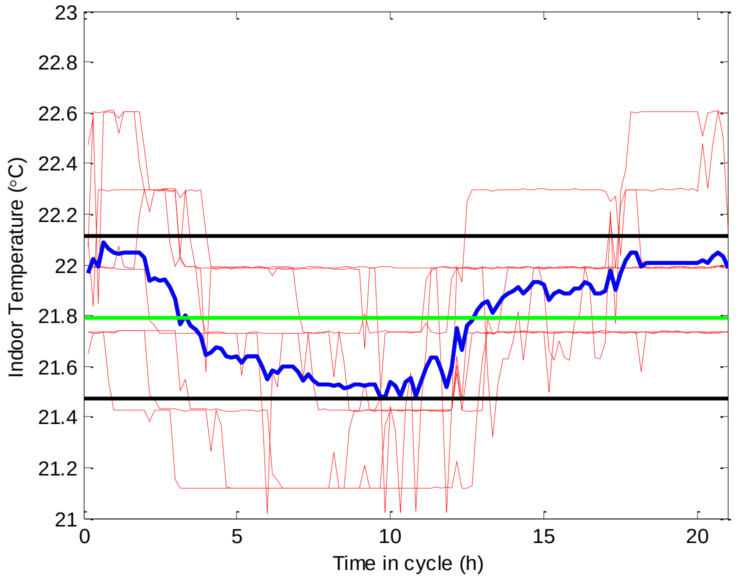


Figure 5. Mean temperature and "normalised" standard deviation.

The green line is the total mean temperature for the period. The blue line is the curve of interest for analysis, the mean temperature for each point in the cycle. The results from this analysis in presented in section 5.3.

5 Results and analysis

In this chapter there is a presentation of the results and system behaviour taken from the measurements. These results are then analysed for example by looking at mean values over several test cycles.

5.1 Initial results

5.1.1 Testing and normal operation

Variations in indoor temperature occur whether the tests are running or not. In Figure 6 a period from Building A illustrate how the test can change indoor temperature. The red curve shows the test cycle behaviour, the blue one the outdoor temperature and the green the indoor temperature.

When the red curve is horizontal (normal operation) the indoor temperature is rather stable for longer periods of time. The reasons for indoor changes during this time are probably sudden turns in outdoor temperature, which correlate with the time of the fluctuations, as well as activities inside the apartment.

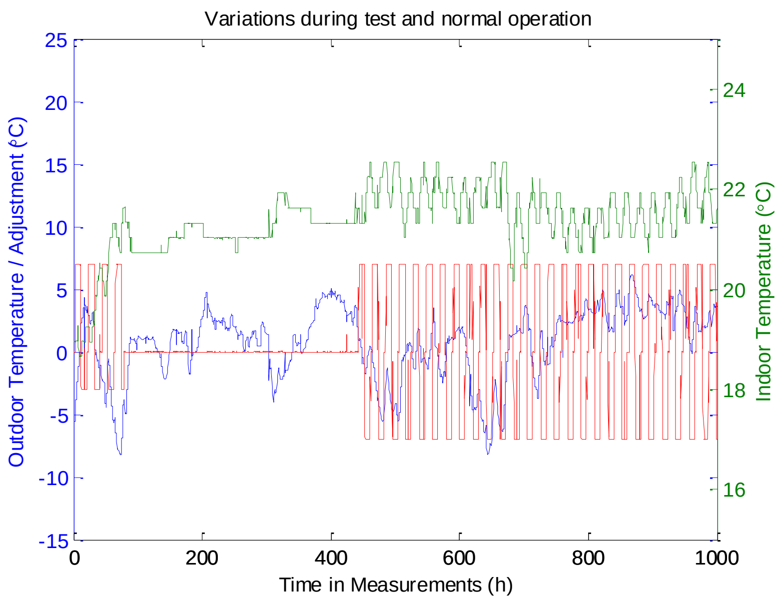


Figure 6. Variations in indoor temperature during regular control (horizontal red line) and testing (square red curve). The blue curve shows the behaviour of outdoor temperature and the green curve the indoor temperature.

However, when the control signal is modified the indoor temperature starts to oscillate in a pattern that correlates to the modification. Due to the low resolution of the temperature sensor the actual size of the variation is difficult to see in this diagram. Therefore the variations have been studied as mean values over longer periods in section 5.2.

5.1.2 Outdoor and indoor temperature

The correlation between outdoor and indoor temperature is, as expected. When the outdoor temperature is lower than 15°C there is a small correlation between indoor and outdoor temperature. When the temperature is higher the correlation is more significant. This is because around this temperature no additional heating is needed, so a higher outdoor temperature cannot be compensated by reducing the heating (see Figure 7). It should be noted that the values may be affected by the placement of the temperature sensor; some measurements indicate an outdoor temperature above 30°C, which is not common in Gothenburg.

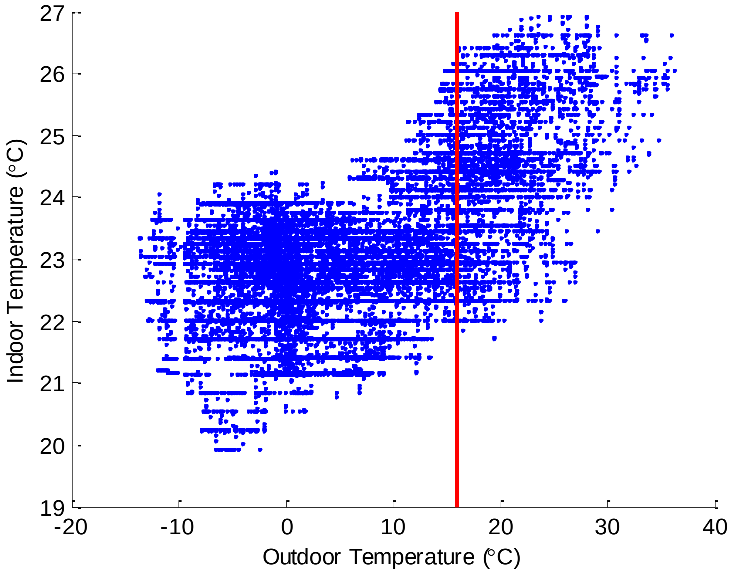


Figure 7. Correlation between the outdoor and indoor temperature for an example building. The red line indicate where the heating system stops (the values to the right are caused by outdoor temperature).

5.1.3 Different building properties and test cycles

To get an overview of the behaviour of different buildings and test cycles, a comparison of indoor temperature variations is made. The data is based on mean values over for the buildings and test cycles; it was chosen by controlling to what degree the test cycle was implemented. If the test was running correctly for at least 6 days of a week, it was included.

In Table 1 the mean values of temperature variations (T_{var}) is displayed. T_{var} is expressed as the difference between maximum and minimum values of one test cycle. The number of test weeks varies in the measurements and is indicated in the table.

Table 1. Mean values of the temperature variations (T_{var}) for different buildings and test cycles.

Test cycle	Building	T_{var} in Apartment 1 [°C]	T_{var} in Apartment 2 [°C]	Number of test weeks
I	A	0.52	-	8
	E	0.46	0.78	18
II	A	0.80	0.80	6
	B	0.57	0.58	6
	F	0.18	0.38	5
	G	0.11	0.53	1
III	G	0.22	0.44	2
IV	G	0.12	0.20	1
V	A	-	0.59	5

As can be seen, the variation in indoor temperature during testing is never more than 1°C and often less than 0.5°C. This is put into comparison of other temperature variations in section 5.3 to grasp the magnitude and significance of the tests.

5.2 Impact on indoor temperature

In this section there is only focus on the impact of the tests on the indoor temperature. The analysis is carried out for different buildings and control cycles. The results are then compared using a couple of parameters, as explained in section 4.5.

5.2.1 Building properties

A comparison was made between different buildings using Cycle I and II. The temperature was measured in two apartments in each of the buildings. The mean temperature over the test cycle can be seen in Figure 8.

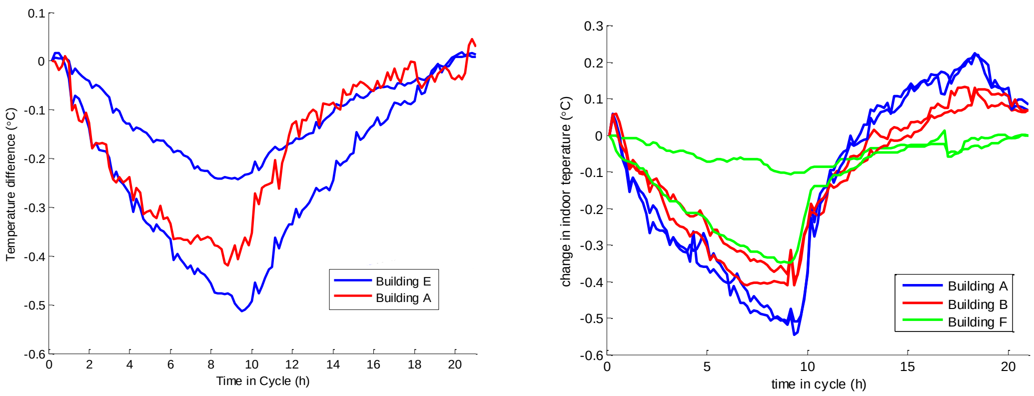


Figure 8. Temperature developmenet for different buildings using Cycle I (left) and II (right) .

During the tests with Cycle I the temperature sensor was out of order in one apartment, so there is only data for one apartment. Here it is interesting to see the large differences between the apartments in one building, but also the difference in behaviour between buildings. Even though the amplitude of the temperature changes is different for the Building E apartments the behaviour is similar. For Building A on the other hand the change appear to first go faster and then even out, during both DP and CP.

In the test with Cycle II the temperature drop and rise was similar in both apartments, except for in Building F. There might have been a problem with the temperature sensor in one of the apartments in Building F, explaining its unexpected behaviour.

It may be that there are differences between the apartments in all buildings, like in Building E, but that the choice of apartments in this test did not show it.

5.2.2 Different test cycles

In Building G Cycle II, III and IV have been used. The difference between the cycles is in how much the control temperature has been changed (ΔT = ±2.5, ±5 and ±7°C for the cycles, respectively). The adjustment curve for the outdoor temperature is presented in Figure 9a, where a positive value on the y-axis indicates that the control signal has a higher value than the actual outdoor temperature. The resulting change in indoor temperature can be studied in Figure 9b.

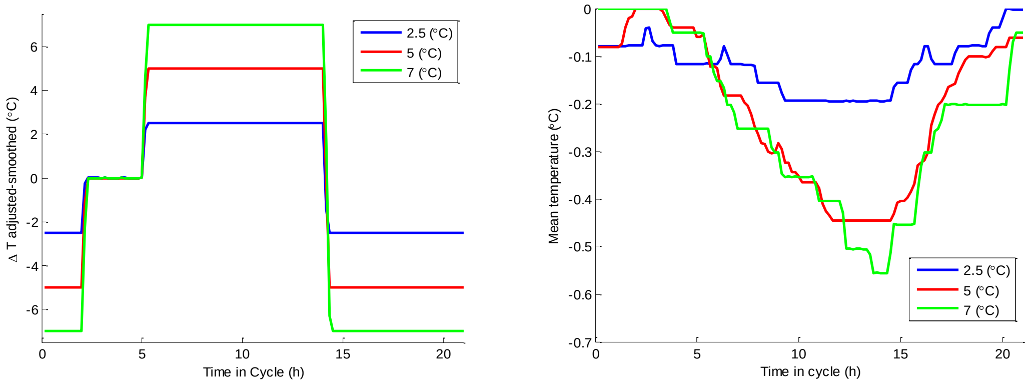


Figure 9. a) Adjustment curve and b) change in indoor temperature, for Building G.

It can be seen from Figure 9 that a larger temperature adjustment causes a larger drop in indoor temperature. However, the difference in amplitude of the temperature drop between the periods is unexpected; the expected result would be that the temperature drop for ΔT = 5°C would be slightly less than what was measured, so that the drop in indoor temperature and the amplitude of the modification had a positive but slightly decreasing correlation. This would be due to an increased heat transfer from the building material to the indoor air when the temperature difference gets larger.

In Building A, tests were made with test Cycles I, II and V. The difference between the charge temperature and the normal temperature signal was 7°C in Cycle I, and the difference between the discharge and charge temperature was 14°C and 10°C for Cycle II and V. This enabled studying the resulting indoor temperature change of 3 different adjustments for the temperature signal. The temperature curves for the test periods are seen in Figure 10.

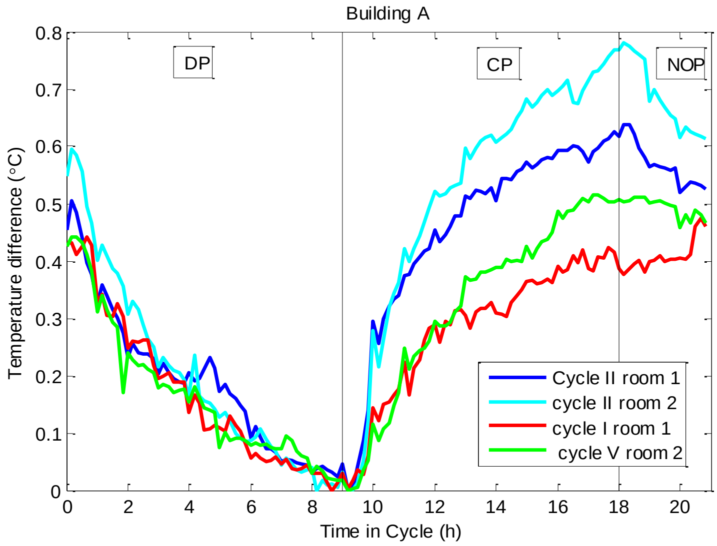


Figure 10. Temperature curves for Cycle II, I and V in Building A.

It can be seen that for Cycle II the temperature starts to decrease in the last 3 hours of the cycle; this is when the control system is changed from a CP to a NOP. For the test with Cycle V the temperature stabilizes when the NOP starts. For Cycle I where there is no CP but a 12 hour NOP instead, the temperature continues to rise.

When tests are running the indoor temperature starts to oscillate in the same way that the temperature signal is adjusted. A larger adjustment of the temperature gives a larger magnitude in the temperature oscillations, as mentioned in section 5.1.1.

When using Cycle I, the temperature is changing during the whole cycle. However, the speed of the change is largest just after the adjustment of the temperature signal, i.e. the temperature drops fast just after the change from a NOP to a DP.

This is caused by two separate mechanisms, the thermal inertia of the building (see section 2.2.2), and the difference between actual indoor temperature and the set point temperature. The adjustment of the outdoor temperature could be seen as a change of the set point indoor temperature.

In the beginning of a discharge cycle the building material in the house has a lower temperature than the air, and therefore has a cooling effect on the air. At the end of the DP, when the air has been chilled faster than the walls, the building is used as a heat bank where the walls have a heating effect on the air, and slow down the cooling rate.

To determine whether the magnitudes of the temperature oscillations were small enough they will be compared with the normal variations in temperature over the test period in section 5.3.

5.2.3 Outdoor temperature

In Building E analysis was made to see whether the variations in indoor temperature are affected by outdoor temperatures. Three different periods of length 4, 2 and 4 weeks were studied, with mean outdoor temperatures of 6.5, 1.5 and -5.0°C, respectively.

First of all, the indoor temperature drop with different outdoor temperature showed different results for the two apartments (as was also stated in section 5.2.1). The results are presented in Figure 11, where it can be seen that in both apartments the temperature drop was lowest for the highest temperature (6.5°C). In the first apartment the difference between the temperature drops in the two other studied periods was very small. In the second apartment the indoor temperature drop was similar for the period with -5°C mean outdoor temperature as for the period when the temperature was 1.5°C.

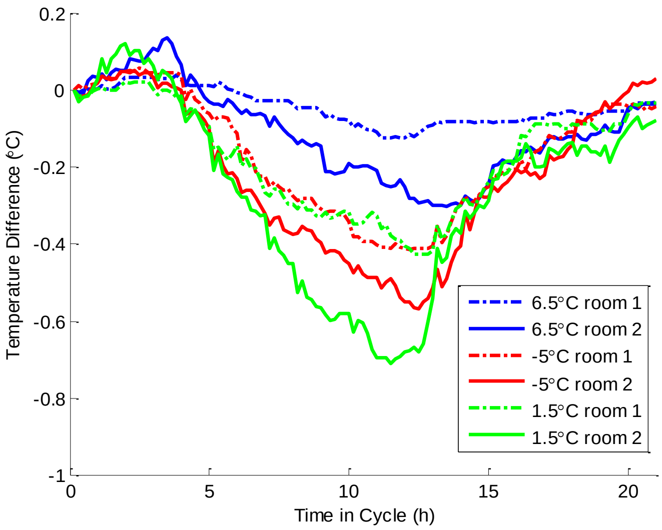


Figure 11. Temperature curve for different outdoor temperatures in Building E.

The heat consumption was measured for the whole building, and the change in heat consumption between the DP and NOP was largest in the period with 1.5°C and lowest in the period with 6.5°C. It corresponds well to the temperature change seen in the second apartment, but not as well to the temperature change in the first.

5.2.4 Temperature drop time

It was studied how long time it took for the temperature to drop 0.5 and 1 degrees respectively from the start of the DP. This differs a bit from the previous tests where the reference temperature has been the highest temperature of the cycle, which sometimes occurs at a different point in the cycle, either in the break between charge and NOP, or another point due to measurement irregularities.

In Table 2 it can be seen that for none of the periods the temperature dropped more than 1°C, this is also true for every studied week during these test periods. Only in 3 of the 10 studied periods the temperature drop was larger than 0.5°C for the total period. However, in 8 of the periods 1 week or more had a mean temperature drop that was larger than 0.5°C during the DP.

Table 2. Time for the indoor temperature to drop 0.5°C.

Building	Apartment	Test Cycle	Mean time for the 0.5°C drop [hh:mm]	Fraction of weeks with less than 0.5°C drop	Mean time for weeks with less than 0.5°C drop [hh:mm]	Maximum temperature drop [°C]
A	1	II	06:10	3/5	05:10	0.63
	2	II	07:10	4/5	05:30	0.58
	1	I	-	3/6	05:40	0.46
	2	V	-	1/5	05:20	0.46
E	1	I	-	3/17 (4/18) [1]	09:00	0.36
	2	I	06:10	16/18	06:20	0.63
F	1	II	-	0/5	-	0.11
	2	II	-	1/5	08:30	0.35
B	1	II	-	0/6	-	0.39
	2	II	-	3/6	03:10	0.41

[1] One week was excluded because the temperature was falling constantly during the whole week, so it is likely that the temperature drop was not related to the tests, also the temperature drop did not pass 0.5°C during DP, but did so in the NOP.

5.3 Variations from tests or other sources

The method for comparing different kinds of variation described in section 4.5.4 was used both on each of the weeks that the data in Table 1 is based on and in different compound test series used in the analysis. Table 1 can be extended with these values and is shown in Table 3. The full table with data for every week is found in Appendix D.

Table 3. Variations caused by the tests are expressed in terms of standard variations (std) of the indoor temperature (°C) for Apartment 1 (A1) and Apartment 2 (A2).

Test Cycle	Building	T_{var} in A1 [°C]	T_{var} in A2 [°C]	Deviation A1 [std]	Deviation A2 [std]	A1 [°C/2std]	A2 [°C/2std]
I	A	0.52		0.24		1.12	
	E	0.46	0.78	0.20	0.41	1.12	0.96
II	A	0.80	0.80	0.29	0.30	1.36	1.32
	B	0.57	0.58	0.22	0.21	1.32	1.38
	F	0.18	0.38	0.09	0.17	0.96	1.09
	G[1]	0.11	0.53	0.16	0.23	0.36	1.15
III	G[1]	0.22	0.44	0.43	0.20	0.26	1.09
IV	G[1]	0.12	0.20	0.34	0.17	0.17	0.59
V	A		0.59		0.24		1.23

When the temperature variations for one test cycle is studied it can be noticed that in an apartment with a large temperature variation due to the test cycle (column 2 and 3) the variation from other sources (column 5 and 6) are also larger (compare test Cycle II for Building A, B and F for example).

This indicates that if a building is good at preventing changes from the test cycle, it is also good at handling variations that is caused by other disturbances.

In column 8 and 9 the difference between the test induced and the normal variations is compared, for most of the studied periods the test induced variations is about as large as ±1 standard deviation of the normal temperature variations.

5.4 Impact on the heating system

A change in temperature signal will have an effect on the thermal power usage of the building. The change for different buildings and cycles are shown in Table 4. The power is expressed for the whole building in column 5-8 and as W/m^2 is column 10-13. The different columns represent the difference between the different periods in the cycle. Cycle I has only has a NOP and a DP. Therefore there is just one value for the power difference. For the other cycles three power differences are listed, one for difference between NOP-CP and one between NOP-DP. The third is the difference between CP and DP.

[1] This data is based on a shorter period than the others and may not be representative for the building.

Table 4. Power variation for different test cycles.

Test Cycle	Building	ΔT indoor [°C]		Δ Power [kW]			Area [m^2]	Δ Power [W/m^2]			Power, mean period [W/m^2]	Power [kWh/(m^{2}yr)]
		Apartment 1	Apartment 2	NOP-DP	CP-NOP	CP-DP		NOP-DP	CP-NOP	CP-DP		
I	E	0.46	0.78	13.8			1030	**13.4**			37.7	189
	A	0.52		13.7			1308	**10.5**			20.0	136
II	A	0.80	0.80	8.1	14.0	22.0	1308	6.2	10.7	**16.8**	32.6	136
	B	0.57	0.58	8.7	10.8	19.4	1029	8.4	10.5	**18.9**	44.0	209
	F	0.18	0.38	8.4	13.1	21.6	1029	8.2	12.7	**21.0**	44.4	-
V	A		0.59	9.1	5.6	14.7	1308	7.0	4.3	**11.3**	39.8	136

Due to the transition time it takes for the power to stabilize after a change between two control periods it is hard to find the level where the power would have ended up in the NOP if it was longer than three hours. Therefore the difference between CP and DP could be at better measurement of the change in thermal power use. In Figure 12 the power for three different test cycles in Building A can be studied.

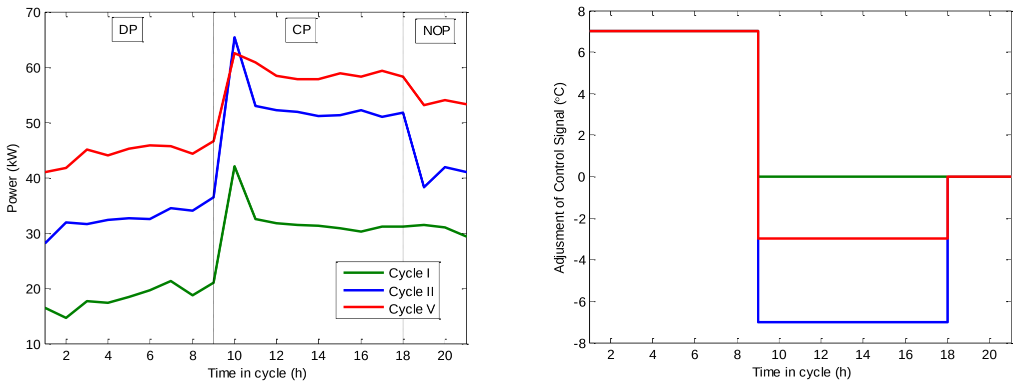


Figure 12. Power change in different test cycles (left figure) and corresponding cycle design (to the right).

The different periods is marked with dashed black lines in the left figure, and the difference between different changes in the control signal can be studied. For Cycle II, where the difference in the control signal between DP and CP is largest the power change is also largest. For Cycle I, with the same signal for CP and NOP no power change can be observed after 18 hours as in the other cycles.

6 Discussion

In this chapter there is a discussion on the measurements, results and analysis. Furthermore, there is a comparison of the different buildings.

6.1 Building control properties

Outdoor temperature variations during testing have different impact on different buildings because of the shape of their control curves. For some of the buildings the control curve slope changes over for example the interval 5-10°C. That means that an adjustment of ±7°C will put the operational point into a steeper or flatter slope, which will cause additional heat surplus or deficit. The result of this is a lack in proportionality, which could have been avoided if the tests were using control curves similar to the original ones but moved horizontally.

Other properties of the building control system that differ are that in Building E there is a compensation for the wind (during high speed wind the building heat loss increases, so more heat is supplied by regulation) and in Building G there is a decrease in set point temperature at night, so called “night time set back”.

As mentioned earlier, the temperature measurements from Apartment 1 and 2 often differ for the same time period. The location of the apartment within the building, user behaviour and insolation will cause this kind of result.

6.2 Design of test cycle

One limitation of the test is that it is just a test. The goal of the study is to test the ability of the buildings to compensate for changes in heat delivery by using the energy that is stored in the building thermal mass.

6.2.1 Impact on indoor temperature

Buildings often have time constants of over 100 hours. That means that the way a building behaves in a test like this is not only affected by the changes in heat delivery that occurs during a, in this context, short period of 21 hours. In some cases it has been noticed that the indoor temperature does not have the time to stabilize between the DPs. This will affect the results of later test cycles, partly because the start temperature of the cycle will not be the same as if the time between the tests was longer. And even if the air-temperature is restored during a cycle, the walls may not have the time to reheat.

If the desired type of control is similar to the test cycle, these factors will be present and then it is essential that the tests are made the way they were. But for other ways to control the hydronic system one must be aware that a change in power-input to a building can have different impacts on the temperature, depending on the temperature history of the building.

Using a building as thermal energy storage in a DH system can have either of two reasons. The purpose is always to avoid high peaks in the heat consumption, which causes the need for use of fossil peak boilers that are expensive to use and causes large CO_2 emissions. The difference is in the size of the peaks, and the frequency in which they occur. Either they are long peaks that come seldom or daily variations, caused by weather, or they are short peaks caused by usage patterns that last for just 3 or 4 hours, but occur two times a day. The test cycle used in the test is somewhat a combination of these two; a period of 9 hours that occur every 21 hours.

6.2.2 Response from tenants

In these tests the DP occurs on different time every day of the week. According to test performers there were not any increase in complaints from tenants while testing (Hultén 2013).

If the tests were carried out with, for example, two DPs every day, one in the morning and one in the afternoon; it is more likely that temperature difference would be noticeable for the tenants (if they are home at the time).

6.3 Measurements

As always when using measurements, there is a risk for measurement failure. The values from a temperature sensor are affected by the behaviour of the people in the apartment. Sometimes a window is opened, a radiator is turned off, there are more people than normal in the apartment or there is just a failure in the measuring equipment.

This brings uncertainty to the results. Some time periods has been excluded from the analysis if the values have been too much off from the expected.

Other things that may have impact on the temperature is the location of the apartments; are they located on the corner of the building or in the centre, which floor are they on, and which direction are the windows facing. Things like these have not been taken into account when presenting the results.

The design of the test cycle, however, helps dealing with some of these insecurities. The fact that the test cycle is 21 hours instead of 24 hours makes the living and weather patterns occur during different hours of the period for each test cycle, so when a mean value over many cycles is calculated the impacts are spread over the cycles and most likely cancel each other out.

As mentioned in section 4.4.2 the resolution of the temperature sensors was 0.25°C. This is another reason to use mean values for longer periods. To notice temperature changes that in mean was as low as 0.18°C the insecurity would be large for short periods. On the other hand, the goal is not to determine the exact variations in temperature, but to control that they are not too large, and then accuracy less than 0.25°C is not necessary.

6.4 Implementation

For all studied periods the temperature dropped most in the beginning of the DP, therefor it is probably possible to use longer DPs without the temperature dropping much more. However, the thermal power tends to increase after a while, possibly because the thermostats react and increases the flow. Another reason could be a larger temperature difference between the radiator and the air when the air temperature drops.

7 Summary and conclusions

In this study there has been focus on how a predetermined series of tests affect the indoor temperature. Most importantly, this gives evidence of possibilities for practical use of buildings as thermal energy storage.

7.1 Answer to research questions

How much does the indoor temperature, expressed in °C, decrease during a test cycle?

The results for different buildings and test cycles, presented in Table 1, indicates that for all test cycles and building the temperature drop is between 0.18 [2] and 0.8°C. Interestingly, both of these results are for Cycle II which is the cycle with the largest difference between CP and DP. This indicates that the difference between the buildings is predominant to the effects of the different cycles.

How much does the heat supply, expressed as W/m^2, change during a test cycle?

The change in thermal power during the cycle is studied in section 5.4. The results indicate that the change is larger in the test cycles that have a larger temperature difference between CP and DP.

For Cycle II the power difference is in the range of 17-21W/m^2. In Cycle I and V, where the temperature difference is smaller than in Cycle II, the power difference is in the range of 10-13W/m^2.

How large are the variation that are caused by the test cycle compared to natural variations?

The different types of variations are studied in section 5.3. The magnitudes of the natural variations as well as the test induced ones differ between the apartments and buildings, but compared to each other they are in the same range.

Generally, a larger standard deviation due to natural variations indicates that the variation due to the tests will also be over the mean value. This is probably because the mechanisms that keep the temperature balanced works for compensating both normal variations and variations due to the test cycles.

For how long time can the heat load be reduced and how long time do buildings need to recover?

To answer this question the time for the temperature to drop 1.0 and 0.5°C was analysed for 4 different buildings and 3 different test cycles (I, II and V). It resulted in a total of 10 test series of varying length (5-18 weeks).

This analysis was carried out a bit differently than the other ones; the temperature was not measured between the highest and the lowest temperature of the cycle, but between the temperature just before the DP and the following measurements. This led

[2] For one period the temperature drop was as low as 0.11°C, but since that test period only lasted for one week the result is uncertain.

to that for some weeks, even though the maximal temperature drop for the mean values was higher than 1.0°C, none of them had a temperature drop of more than 1.0°C during the DP. No test period had a drop larger than 0.6°C. The focus is therefore on how often a temperature drop of more than 0.5°C occurs, and how long time it takes.

The results are presented in Table 2. In the 10 test series the mean temperature drop was larger than 0.5°C in 3 of them. Studying every week separately, the temperature drop was larger than 0.5°C in 47% of the weeks.

Do variations in outdoor temperature affect behaviour of the buildings?

In general, a higher outdoor temperature leads to a higher indoor temperature, but it could not be shown that there were any connections between the outdoor temperature and the temperature drop during the test cycles. The study of this was performed in sections 5.1.2 and 5.2.3.

7.2 Suggestions for further studies

In this thesis an analysis has been carried out on a set of pioneer tests. It shows that there is a potential of using buildings as thermal energy storage. However, before such a system could be implemented on a larger scale further tests and analysis has to be performed in order to adjust the control strategies for each building and to find the optimal power cut that each building could provide.

7.2.1 Building data

In this project the behaviour of different buildings can be noticed, but the results have not been connected to the properties of the buildings. By going into the building structure and the difference between them (e.g. expressed as different time constants) more conclusions could be made about which types of buildings are suitable. The findings could be compared with theoretical calculations, modelling and simulations.

7.2.2 Different control strategies

Even though there are some differences in the test cycles used in this study, they all consist of the same 21 hour test cycle with a 9 hour discharge period that for most cases was a 7°C adjustment of the temperature signal. It could be interesting to look at longer cycles with more time for the building to restore the normal temperature conditions for the thermal mass as well as the air. It could also be interesting to try longer DPs, or a larger adjustment of the temperature signal.

On top of trying different cycles; which is a good way of getting large amounts of data to analyse, thus getting a more reliable overview of variations; more realistic tests on how an actual system would work could be performed.

7.2.3 Energy use

Changing the heat deliveries to a house does not only affect the momentary energy use, but could also affect the total energy consumption for a building. Therefore it could be a good idea to study how different control methods affect the overall energy performance of the building.

7.2.4 Connection to the district heating system

This study has not at all looked into how the DH system is affected by the variations in heat consumption of the buildings. There could be several aspects that affect how the interaction works, and even if the two sides of the system could be analysed separately, they will have to be coordinated if the system is to be implemented.

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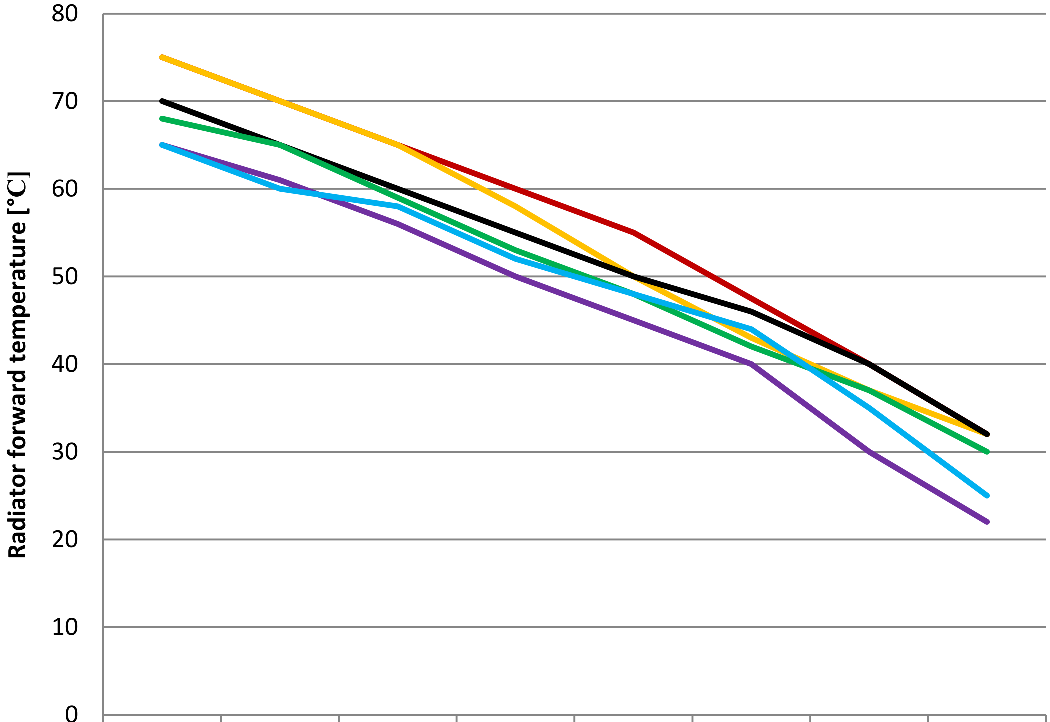
Appendix A – Building data

List of data of what is known about the 6 different buildings.

Building	**A**	**B**	**D**	**E**	**F**	**G**	**Unit**
Year of construction	1950	1939	-	1934	1939	-	-
Living area	1178	904	-	900	904	-	m^2
Common area	130	125	-	130	125	-	m^2
Number of floors	3	5	3	3	5	3	-
Basement	1	1	1	1	1	1	-
Attic	-	-	1	-	-	1	-
Number of apartments	20	24	25	19	24	25	-
Number of stairways	3	3	1	4	3	1	-
Pump. Start/stop	15/17.5	15/17	15/17	15/17	15/17	-/17	°C
Night setback	-	-	-	-	-	1.5	°C
Wind setback	-	-	-	0.5	-	-	°C
Pressure controlled pump	Grundfos UPS 40 120 F06	WILO Typ: TOP-S40/4	Wilo Typ: TOP-S50/4	-	Grundfos UPS 50-60/4 F	Wilo.	-
Circulation pump	Grundfos UP 20 – 15N 150	SMC COMMODORE 160-35B	-	UP 20- 45 N 150	Grundfos UP 20-30 N 150	Grundfos UP 20 –30 N 150	-
Type of building	Heavy	Heavy	Light	Light	Heavy	Heavy	-
Facade	Plastered	Plastered	Wood	Wood, brick	Brick	Brick	-
Window type	2 glass	2 glass	2 glass	3 glass	2 glass	2 glass	-
Balcony	Yes	Yes	No	No	Yes	Yes	-
Thermostat	Yes	Yes	Yes	Yes	Yes	Yes	-
Laundry house	Yes	Yes	-	Yes	Yes	-	-
Other information	Separate building. 2-stage consumer substation	Housing structure: Pensioners, family & lone.	Housing structure: Pensioners, family & lone.	Two alongside facades, gables adjacent other building.	Housing structure: Pensioners, family & lone.	Housing structure: Pensioners, family & lone.	-

Appendix B – Control curves

Each building has its unique control curve, according to which the heat input is regulated. It is regulated by the outdoor temperature [°C], which is displayed on the horizontal axis.



	-20	-15	-10	-5	0	5	10	15
A	65	61	56	50	45	40	30	22
B	75	70	65	60	55	47,5	40	32
D	75	70	65	58	50	43	37	32
E	70	65	60	55	50	46	40	32
F	68	65	59	53	48	42	37	30
G	65	60	58	52	48	44	35	25

Appendix C – Measurement data

Here are the data measurement categories from the tests.

	Swedish label	English translation	Unit
1.	Datum	Time [e.g. 2010-01-01 12:00]	-
2.	Effekt FJV (Medel 10 min)	DH power (average over 10 min)	kW
3.	Energi FJV Mätarställning	DH energy (meter indication)	kJ
4.	FV-GT1 Framtemp	DH forward T (sensor)	°C
5.	FV-GT2 Returtemp	DH return T (sensor)	°C
6.	GT-RUM1 Rumstemp	T in Apartment 1 (sensor)	°C
7.	GT-RUM2 Rumstemp	T in Apartment 2 (sensor)	°C
8.	RAD-GT1 Börvärde	Radiator set point T	°C
9.	RAD-GT1 Framtemp	Radiator forward T (sensor)	°C
10.	RAD-GT2 Returtemp	Radiator return T (sensor)	°C
11.	UTE-GT1 Utetemp	Outdoor T	°C
12.	Utetemp (Dämpad)	Smoothened outdoor T	°C
13.	Utetemp (Fiktiv/Justerad)	Adjusted outdoor T	°C
14.	Ventil RAD-SV1	Radiator valve	-
15.	Ventil VV-SV1 obl.	Unmixed hot water valve	-
16.	Ventil VV-SV2 bl.	Mixed hot water valve	-
17.	Volym FJV Mätarställning	DH volume (meter indication)	m^3
18.	VV-GT1 oblandat	Unmixed hot water T	°C
19.	VV-GT2 blandat	Mixed hot water T	°C
20.	VV-GT3 VVC temp	Central hot water T	°C

Appendix D – Data of change in indoor temperature

Here are the weekly results displayed as a summary for each building. Red temperatures are excluded from all analysis because they are based on measurements with obvious errors.

Building E		ΔT (°C)			Standard deviation		Quote ΔT / std dev.	
Start cell	week	R1	R2	dW	R1	R2	R1	R2
24474	25	0.27	0.54	10.30	0.14	0.30	0.98	0.91
26490	27	0.19	0.67	11.89	0.12	0.41	0.83	0.82
27498	28	0.18	0.67	10.43	0.11	0.37	0.82	0.91
28506	29	0.24	0.52	8.78	0.11	0.28	1.06	0.92
29514	30	0.28	0.75	8.80	0.15	0.37	0.96	1.03
30522	31	0.72	0.85	14.80	0.23	0.37	1.59	1.15
31530	32	0.58	0.68	17.82	0.22	0.38	1.30	0.90
32538	33	0.50	1.04	14.28	0.25	0.48	0.99	1.09
33546	34	0.63	0.64	8.97	0.25	0.34	1.25	0.96
34554	35	0.37	1.05	12.63	0.16	0.55	1.14	0.95
38587	39	0.61	0.80	15.92	0.33	0.47	0.91	0.86
39595	40	0.56	0.86	14.54	0.22	0.41	1.24	1.04
40603	41	0.47	0.96	16.45	0.18	0.56	1.29	0.86
41611	42	0.84	0.90	16.71	0.33	0.54	1.28	0.84
42619	43	0.50	0.66	14.27	0.20	0.38	1.28	0.86
43627	44	0.44	0.89	20.25	0.21	0.39	1.07	1.13
44635	45	0.38	1.01	14.94	0.18	0.42	1.04	1.19
45643	46	0.49	0.56	15.79	0.20	0.35	1.20	0.80
	Mean	**0.46**	**0.78**	**13.75**	0.20	0.41	1.12	0.96

Building A		ΔT (°C)		Power difference			ΔT out		Standard deviation		ΔT / std dev.	
Start cell	week	R1	R2	NOP-DP	CP-NOP	CP-DP	Max	Min	R1	R2	R1	R2
2016	3	0.61	0.73	6.35	12.90	19.25	7.00	-7	0.25	0.29	1.21	1.25
3024	4	0.82	0.76	7.50	14.07	21.57	7.00	-7	0.32	0.27	1.29	1.39
4032	5	0.78	0.90	8.55	12.86	21.41	7.00	-7	0.28	0.33	1.41	1.36
5040	6	0.80	0.71	7.67	12.17	19.84	7.00	-7	0.29	0.26	1.37	1.33
6048	7	0.99	0.66	8.39	12.69	21.08	7.00	-7	0.33	0.26	1.50	1.26
51408	52	0.01	1.06	9.97	19.10	29.07	7.00	-7		0.39		1.34
	Mean	**0.80**	**0.80**	**8.07**	**13.97**	**22.04**			**0.29**	**0.30**	1.36	1.32

				Power difference			ΔT out		Standard deviation		ΔT / std dev.	
Start cell	week	R1	R2	NOP-DP			Max	Min	R1	R1	R1	R2
8065	9	3.46	3.10				7.00	0				
9073	10	5.23	2.14				7.00	0				
11089	12	0.52	2.61	13.92			7.00	0	0.20		1.27	
36289	37	0.56	1.23	13.60			7.00	0	0.27		1.05	
37297	38	0.58	1.47	19.18			7.00	0	0.24		1.19	
39313	40	0.54	1.34	15.15			7.00	0	0.24		1.11	
40321	41	0.61	1.06	11.38			7.00	0	0.26		1.16	
41329	42	0.31	0.72	8.90			7.00	0	0.17		0.92	
	Mean	**0.52**	**1.71**	**13.69**					**0.24**		1.12	

				Power difference			ΔT out		Standard deviation		ΔT / std dev.	
Start cell	week	R1	R2	NOP-DP	CP-NOP	CP-DP	Max	Min	R1	R1	R1	R2
43345	44	0.04	0.76	6.78	6.43	13.21	7.00	-3		0.27		1.43
44353	45	0.00	0.57	9.01	6.34	15.35	7.00	-3		0.23		1.22
45361	46	0.00	0.48	7.60	4.76	12.36	7.00	-3		0.21		1.16
46369	47	0.01	0.42	9.99	3.46	13.44	7.00	-3		0.18		1.20
47377	48	0.01	0.73	12.06	7.23	19.29	7.00	-3		0.31		1.16
	Mean		**0.59**	**9.09**	**5.64**	**14.73**				**0.24**		1.23

Building F		ΔT (°C)		Power difference			ΔT out		Standard deviation		ΔT / std dev.	
Start cell	week	R1	R2	NOP-DP	CP-NOP	CP-DP	Max	Min	R1	R2	R1	R2
9938	10	0.22	0.30	8.49	11.58	20.1	7	-7	0.09	0.16	1.20	0.95
10946	11	0.22	0.27	9.51	13.39	22.9	7	-7	0.10	0.16	1.07	0.87
11954	12	0.14	0.42	7.50	13.79	21.3	7	-7	0.10	0.17	0.73	1.26
12962	13	0.17	0.50	8.26	13.19	21.4	7	-7	0.09	0.19	1.01	1.33
15986	16	0.14	0.40	8.50	13.63	22.1	7	-7	0.09	0.19	0.80	1.06
	Mean	**0.18**	**0.38**	**8.45**	**13.11**	**21.56**			0.09	0.17	0.96	1.09

Building G				Power difference			ΔT out		Standard deviation		ΔT / std dev.	
	week	R1	R2	NOP-DP	CP-NOP	CP-DP	Max	Min				
	14	0.11	0.53	21.6	21.5	43.1	7	-7	0.16	0.23	0.36	1.15
	11	0.12	0.20	5.7	3.2	9.0	2.5	-2.5	0.34	0.17	0.17	0.59
	12	0.25	0.46	9.9	13.9	23.7	5	-5				
	13	0.19	0.42	13.9	14.6	28.4	5	-5				
									0.43	0.20	0.26	1.09

Building B				Power difference			ΔT out		Standard deviation		ΔT / std dev	
	week	R1	R2	NOP-DP	CP-NOP	CP-DP	Max	Min	R1	R2	R1	R2
	9	0.52	0.48	9.37	10.94	20.3	7	-7	0.20	0.19	1.28	1.30
	10	0.63	0.65	7.56	12.04	19.6	7	-7	0.22	0.22	1.42	1.47
	11	0.65	0.52	10.48	7.66	18.1	7	-7	0.25	0.20	1.29	1.30
	12	0.49	0.56	6.23	12.41	18.6	7	-7	0.19	0.20	1.32	1.40
	13	0.61	0.58	9.82	10.69	20.5	7	-7	0.23	0.22	1.33	1.34
	14	0.52	0.65	8.56	10.81	19.4	7	-7	0.20	0.22	1.29	1.46
	Mean	**0.57**	**0.58**	**8.67**	**10.76**	**19.43**			0.22	0.21	1.32	1.38