THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Buildings as thermal energy storage

Pilot test and large-scale implementation for district heating systems

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Abstract

Heat loads in a district heating system can exhibit significant variations within a single day, which sets problematic conditions for efficient heat generation. Short-term thermal energy storage (TES) can decrease these daily variations and make the conditions for generating heat more favorable. This study presents the results from a pilot test in which the short-term TES capacity is tested for five multifamily residential buildings in Gothenburg, Sweden. By periodically over-heating and under-heating the buildings, causing small variations in the indoor temperature, their thermal inertia is utilized for short-term TES. The signal from the outdoor temperature sensors in the test buildings was adjusted in different cycles over a total of 52 weeks. The heat loads and indoor temperatures were measured during the test to find their correlation with the control signal. Based on the results from the pilot test, a large-scale implementation of short-term TES in buildings is simulated for the district heating system in the city of Gothenburg, Sweden. It is shown that heavy buildings with a structural core of concrete can tolerate relatively large variations in heat delivery while still maintaining a good indoor climate. Storing 0.1 $kWh/m^2_{floor\ area}$ of heat will very rarely cause variations in indoor temperatures greater than ±0.5°C in such buildings. A short-term TES in 20% of the heated floor area in Gothenburg's district heating system would decrease the daily heat load variation by 50%, hence reducing the need for (often fossil-fueled) peak heat generation and the number of starts and stops of heat-generation units. This could be a cost-efficient solution that can increase system efficiency and reduce the environmental impact from district heating systems.

Keywords: District heating, Thermal energy storage, Buildings, Demand side management, Space heating, heat demand, heat load.

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Buildings as thermal energy storage
Pilot test and large-scale implementation for district heating systems

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Sammanfattning

Värmelasten i fjärrvärmenät kan variera kraftigt under dagen, vilket skapar svåra förutsättningar för en effektiv värmeproduktion. Korttidslagring av värme kan dämpa denna variation och skapa mer fördelaktiga förutsättningar. Denna studie presenterar resultaten från ett pilot-test där möjligheten att utnyttjas som värmelager har testats för fem flerbostadshus i Göteborg, Sverige. Genom att periodvis över- respektive under-värma byggnaderna kan de nyttjas för korttidslagring av värme. Detta orsakar små variationer i byggnadernas innetemperatur. Signalen från byggnadernas utetemperaturgivare justerades i olika cykler under totalt 52 veckor. Värmelaster och inomhustemperaturer mättes under denna tidsperiod för att finna deras korrelation med justeringen av utetemperaturgivarnas signaler. Baserat på samband identifierade från pilottestet har en simulering med ett storskaligt värmelager i byggnader utförts för Göteborgs fjärrvärmenät. Resultaten visar att tunga byggnader med betongstomme kan hantera relativt stora variationer i levererad värme och ändå behålla ett tillfredställande inneklimat. Nyttjande av lagringskapaciteten 0.1 $kWh/m^2_{golvyta}$ orsakar väldigt sällan variationer i innetemperatur större än ±0.5°C i sådana byggnader. Ett storskaligt värmelager som innefattar 20% av den uppvärmda golvytan i Göteborgs fjärrvärmenät skulle minska den dagliga lastvariationen med 50%. Detta skulle minska behovet av fossila hetvattenpannor för spetsvärme och vara ett kostnadseffektivt sätt att öka effektiviteten och miljöprestandan i fjärrvärmenät.

Nyckelord: Fjärrvärme, Värmelager, Byggnader, Laststyrning, Rumsuppvärmning, Värmebehov, värmelast.

Denna licentiatuppsats har finansierats av Göteborg Energi AB för Installationsteknik vid Chalmers Tekniska Högskola.

FOREWORD

At the end of my studies in Civil Engineering, I wrote my master's thesis at the Division of Building Services Engineering. There was a position open for a Ph.D. project, which I hardly considered. But this stubborn professor kept encouraging me to apply for the position. In the last days before the application deadline, I finally read the project proposal and I was hooked. This opportunity sounded way too interesting to pass up. Thank you Jan-Olof Dalenbäck for not giving up on your efforts to persuade me!

Jan-Olof became my examiner and main supervisor for this project. Even though you have "a thousand balls in the air", you have always motivated me and made me feel important. And Anders Trüschel, my assistant supervisor – your attention to detail has greatly improved this work. But more important, you have been there to encourage me and push me when things have been tough.

The atmosphere at the Division of Building Services Engineering is very unpretentious and helpful. This is thanks to my wonderful colleagues, whom have generously shared their expertise, support and laughter.

This work has been carried out in collaboration with Göteborg Energi AB (Gothenburg Energy), where Otto Olsson has been my supervisor. The first thing you did as a supervisor was taking a full day to show me the plants, control rooms and offices. You have shown this welcoming and inspiring attitude throughout the whole project.

As a Ph.D. student you can sometimes feel lonely in your work. I am very thankful that I have had the privilege to work very closely with master thesis students within the project. Joi Elebo, David Petersson, Linus Appelgren, Henrik Erlandsson, Matheiu Dreano and Christelle Machu: you are very appreciated, both for your contribution to the project and enriching me and my colleagues' days at the office.

At last, I would like to send my thoughts to my family and friends – thank you for your patience, unconditional support and for enriching my life.

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Gothenburg, Sweden
2015

LIST OF PUBLICATIONS

This thesis is based on one peer-reviewed journal paper and one peer-reviewed conference paper:

[Paper 1] KENSBY, J., TRÜSCHEL, A. & DALENBÄCK, J. O. 2015. Potential of residential buildings as thermal energy storage in district heating systems - Results from a pilot test. *Applied Energy,* 137**,** 773-781.

[Paper 2] KENSBY, J., TRÜSCHEL, A. & DALENBÄCK, J. O. 2014. Utilizing Buildings as Short-Term Thermal Energy Storage. *The 14th International Symposium on District Heating and Cooling.* Stockholm, Sweden.

TABLE OF CONTENTS

ABBREVIATIONS, NOMENCLATURE, AND SYMBOLS

Abbreviations

AC	Air-Conditioning
CHP	Combined Heat and Power
CP	Charge Period
DC	District Cooling
DH	District Heating
DHC	District Heating and Cooling
DLS	*Swedish:* Driftledningssystem (Operation Management System)
DSM	Demand Side Management
DP	Discharge Period
HEX	Heat Exchanger
HOB	Heat Only Boiler
HVAC	Heating Ventilation and Air-Conditioning
NOP	Normal Operation Period
TABS	Thermally Activated Building Systems
TES	Thermal Energy Storage

Nomenclature

Degree hours	Time integral over a temperature difference
Demand	The amount of energy or power required to fulfill the customer's needs
Heavy building	Building with high thermal inertia, typically with a core of concrete
Light building	Building with low thermal inertia, typically with a core of wood or steel
Load	The amount of energy or power delivered to the customer
Power limitation	Maximum power that a TES can be charged or discharged with
Relative daily variation	"The relative daily variation is the accumulated positive difference between the hourly average heat load and the daily average heat load divided by the annual average heat load and the number of hours during a day. The relative daily variation is expressed with 365 values per system and year." (Gadd and Werner, 2013a)
Short-term	A time frame ranging from a few hours to a few days
Storage capacity limitation	Maximum energy that can be stored in a TES
Thermal inertia	Resistance against changing temperature
Time constant	The time it takes the system's step response to reach 63% of its final value
U-value	A measure of thermal transmittance through, e.g., a wall

Symbols

Δu	Adjustment to outdoor temperature signal	[°C]
G_d	Relative daily variation	[%]
P_h	Hourly heat load	[W]
P_d	Daily heat load	[W]
P_a	Annual heat load	[W]
$\dot{Q}$	Heating power	[W]
T	Indoor temperature	[°C]
$T_{var.21h}$	Indoor temperature variation, during test cycle (21h)	[°C]
$T_{var.24h}$	Indoor temperature variation, daily (24h)	[°C]
T_0	Indoor temperature at time 0	[°C]
T_∞	Indoor temperature approaches this value	[°C]
t	Time	[h]
τ	Time constant	[h]
u	Outdoor temperature signal	[°C]

1 INTRODUCTION

There is an ongoing change in the global climate, mainly due to excessive emissions of carbon dioxide and other greenhouse gases. Limiting this change is one of the critical challenges of our generation. Hence, it is of great importance to reduce primary energy use since it is heavily linked to the amount of greenhouse gas emissions. The final energy usage in Sweden for the year 2012 was divided among buildings, 38%; industry, 36%; transportation, 24%; and other, 2% (IEA, 2012). This makes buildings the largest energy-using sector in Sweden, which is also true for the world as a whole. Energy in buildings is primarily used for heating, ventilation, and air-conditioning (HVAC) and secondarily for electrical appliances (Oldewurtel et al., 2012). The main heat sources for HVAC purposes vary greatly between different countries. In Sweden, district heating (DH) has a market share of 60%, (Frederiksen and Werner, 2013) and every town with more than 10,000 inhabitants has a DH system (Johansson et al., 2010).

The main factor affecting the environmental impact of DH systems is the fuel mix. Since 1980, Sweden has made the transition from mostly oil-based to mostly biofuels and waste incineration (Frederiksen and Werner, 2013). Nevertheless, even in 2013, fossil fuels (oil, natural gas, and coal) had a share of 8% of the fuel mix, not including flue gas condensation (SvenskFjärrvärme, 2013). This last remaining 8% is difficult to replace since non-solid fuels, like gas and oil, are best suited to peak load heat-only boilers (HOBs) that cover peak loads in DH systems. The peak load HOBs are required since the heat load in DH systems can exhibit significant variations within only a few hours, mainly due to variations in outdoor temperature and domestic hot water usage. The reasons to use gas and oil in these peak load HOBs are that such boilers have fairly low investment costs and can be operated efficiently for short periods of time. Variations in heat loads also cause frequent starts and stops of HOBs and other heat sources. There are extra losses, costs, and wear associated with starts and stops, especially for bio-fuel boilers, since they often utilize solid fuels. An example of the situation in the DH system in Gothenburg is shown in Fig. 1.

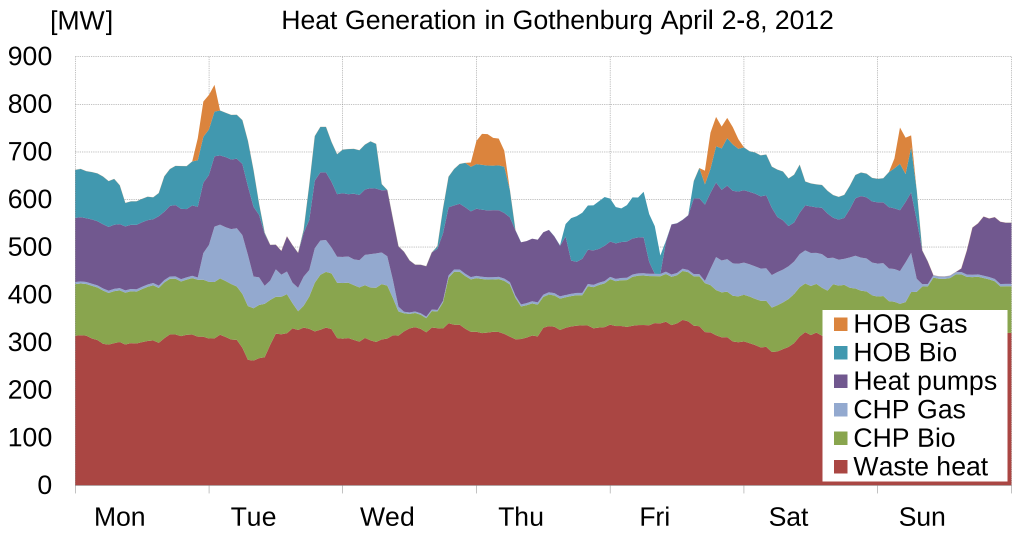

Fig. 1 Example of the heat generation in Gothenburg during one week. A total of 28 different heat sources (boilers, heat pumps, waste heat sources, etc.) are grouped into six categories. During this week, heat sources were started and stopped a total of 36 times.

Heat generation in DH systems is traditionally demand-driven. When customers increase their heat demand, the heat supplier must increase heat generation. Otherwise, temperatures in the distribution network will drop. To improve the overall system's efficiency and the environmental performance of DH systems, it is beneficial to manage heat usage more strategically. This can be achieved with short-term thermal energy storage (TES). "Short-term" implies a time frame ranging from a few hours to a few days. With access to short-term TES, it is possible to better manage heat usage and gain a number of benefits, including:

- Reduced load variation
- Better fuel economy
- Fewer starts and stops in heat generation
- Increased security of supply
- Less need for peak load heat generation
- The operation of combined heat and power plants (CHPs) according to the price of electricity
- The operation of heat pumps and direct electrical heaters in DH systems according to the price of electricity

An overview regarding possible strategies for TES, both short-term and seasonal, is available (Heier, 2013). Examples of some strategies for short-term TES that have the potential for efficient implementation in DH systems are:

- Hot water storage tanks
- Varying temperatures in the DH network
- **Utilizing building thermal inertia**, which is the main focus of this thesis

The main reasons for focusing on the utilization of building thermal inertia as short-term TES are:

- Possibility for high TES potential at low cost
- Sparse research within the area
- The possibility of evaluating a pilot test

1.1 Purpose

The purpose of this study is to survey and evaluate how building thermal inertia utilized for short-term TES can improve the system efficiency, environmental performance and economy of DH systems. The focus is on strategies that can affect heat load and generation in the short-term, ranging from hours to days. Strategies such as seasonal TES are, therefore, excluded.

The DH system in Gothenburg is used as a subject for the case studies, and the benefits of the strategies may be very different for different DH systems. Therefore, it is important to measure the benefits gained from the studied strategies in general terms that can be applied to other DH systems.

1.2 Methodology

The methodology used throughout this thesis is based on three steps: a literature review, pilot test, and large-scale implementation. The steps are briefly described in this chapter. They are described in greater detail in their associated chapters and the attached papers. The results from five master theses are also included in the study (Elebo and Petersson, 2013, Sirén, 2014, Machu, 2014, Dreano, 2013, Appelgren and Erlandsson, 2014). The author has been the main supervisor for four of these and has provided counseling for the fifth. Their methods are briefly explained, where required. Throughout this thesis, the DH system in Gothenburg is used as the case study. The reason for this is that this work is conducted in Gothenburg and is supported by Göteborg Energi AB (both financially and by supplying measurement data, feedback tutoring, and executing pilot tests).

Literature review

To survey existing strategies for demand-side management, a literature review has been carried out. This includes a more general overview of the load situation in DH systems and the possible strategies for short-term TES. The literature review goes more in-depth regarding utilizing building thermal inertia as short-term TES and how large-scale implementations can benefit DH systems. The literature review is presented in Chapter 2.

Pilot test

The pilot test was evaluated regarding the utilization of building thermal inertia for short-term TES. The measurements have been carried out by Göteborg Energi AB on five multifamily residential buildings with radiator heating systems during a full year. The outdoor temperature signal was adjusted in different cycles, which resulted in variations in the heat load and indoor temperature. The measurement data have been statistically analyzed to establish correlations that describe how the buildings function as short-term TES. There have been a few pilot tests in this subject before, but this is the first one, to the author's knowledge, with a concept and strategy that enables the findings of clear correlations between how the TES is controlled, the heat load of the buildings, and the resulting variations in indoor temperature.

Large-scale implementation

Studies of heat loads and heat generation in DH systems have been carried out in this work to analyze both the current situation and how it can be improved with short-term TES. The DH system in Gothenburg has been used as a real-world example in these studies. Several measures have been taken to make the results universal:

- Using parameters for evaluation that can easily be applied to other DH systems
- Comparing the results from Gothenburg to other studies
- Collaborating with other researchers who applied the developed simulation of the Gothenburg DH system to the DH system in Hudiksvall

The data required for these studies are mainly gathered via the operation management system used by Göteborg Energi AB: Driftledningssystem (DLS). This is a system that monitors and stores a huge number of parameters regarding heat and electrical generation, distribution, consumption, economy, etc. in Gothenburg.

This is the first study known to the author basing a full-scale simulation of a building’s short-term TES on the actual behavior of buildings in a pilot test.

1.3 Organization of this work

The introduction is followed by a literature review that gives a broad overview of the research area and insight into the different strategies possible.

The next part of the study is divided into several chapters with a similar approach. They delve a bit deeper into different aspects within the study. This starts with a chapter that surveys the load situation in DH systems (Chapter 3) and what causes it. The main chapters cover the pilot test that utilizes building as short-term TES (Chapter 4) and how a large-scale implementation could benefit a DH system (Chapter 0). Chapters 4 and 0 are structured in a similar way and include the following parts:

- A methodology part describing what work has been carried out within this study
- Key results and discussion

This thesis is rounded off with its conclusions (Chapter 0). One peer-reviewed journal paper and one peer-reviewed conference paper are also included.

2 LITERATURE REVIEW

The literature review is split into four parts: load situation, strategies for storing heat, buildings as short-term TES, and effects on DH systems.

2.1 Load situation

The main purpose of strategies for short-term TES in DH systems is to increase system efficiency and environmental performance. This is achieved by increasing the flexibility of heat load and generation. Therefore, it is important to survey the load characteristics of DH systems.

The heat loads of six Swedish DH systems are studied by Werner (Werner, 1984). A model for the heat load is presented that incorporates a steady temperature-dependent load, transient heat transmission, wind-induced air infiltration, solar gain, hot water supply, distribution losses, and additional workday load. The magnitude of each parameter's impact on the total heat load is also studied in this thesis.

Relative daily variation is presented by Gadd and Werner as an assessment method for describing daily load variations (Gadd and Werner, 2010). This assessment method has also been refined (Gadd and Werner, 2013a). The measurement is independent of system size and can be applied to any kind of system in which daily variations occur. It is used for measuring load variations throughout this thesis and will be elaborated on later in Chapter 5 – Large-Scale Implementation. Twenty Swedish DH systems of different sizes have been analyzed (Gadd and Werner, 2013a), and the annual average relative daily variation has been determined, among other parameters. The annual average relative daily variation ranges from 3% to 6% for these systems. This approach has also been used to study heat load patterns on a consumer level in 141 substations (Gadd and Werner, 2013b). The study showed a large variation in heat load patterns among various buildings, implying that a standard heat load pattern for customer substations does not exist.

2.2 Strategies for storing heat

Different strategies for short-term and seasonal TES has been comprehensively studied (Heier, 2013). The study includes both hot and cold storage, a focus on decentralized storages, and the following strategies:

- Passive sensible storage
- Passive latent storage
- Sensible storage in tanks
- Latent storage in tanks
- Latent storage in ventilation or AC (air-conditioning) equipment
- Thermo chemical storage
- TABS (thermally activated building systems) with water distribution
- TABS with air distribution
- Borehole storage
- Aquifer storage
- Snow storage
- Storage in pits, buried tanks, etc.

2.3 Building short-term TES

Utilizing building thermal inertia as short-term TES in a district heating system is not a new concept. The oldest pilot test known to the authors is from 1982 (Österlind, 1982). The main aim of this test was to increase supply security for the heat customers located farthest away from a heating plant in case of a shortage. In Stockholm, Sweden, 80 residential and office buildings participated, and their heat deliveries were remotely reduced by a control system. The magnitude and durations of the reduced heat deliveries were based on assumed *time constants* for the buildings and a maximum accepted drop in the indoor temperature of 3°C. The indoor temperature was measured in two of the buildings. The variations were at a normal level except during the test with the longest duration (48 h).

Another pilot test was conducted during the winter of 2002–2003 in two Finnish buildings with concrete structures and radiator heating systems (Kärkkäinen et al., 2003). The test revealed that the heat load could be reduced by 20% to 25% over 2 h to 3 h, causing a drop in the indoor temperature of up to 2°C. These tests were performed at outdoor temperatures of -10°C to 0°C. The same study demonstrated a smaller potential for load shifting in a building complex consisting of offices and facilities for streetcar maintenance in Mannheim, Germany. The peak load for heating was reduced by 4.1% during the tests. The main reason for the lower potential was that the building was mainly heated by an air heating system. The main aim of these tests was to evaluate the potential for the reduction of peak load generation in the district heating system. This was also the main focus of the subsequent studies presented here.

A residential area in Karlshamn, Sweden, was the subject of a pilot test in which DSM (demand side management) was implemented in the form of agent-based load control (Wernstedt et al., 2007, Wernstedt and Johansson, 2008). The control was distributed among agents on the production side, on a cluster level and on a customer level. These agents monitored and controlled the local systems. They also communicated with each other to achieve system-wide peak reduction and optimization. The system displayed the potential for reducing peaks and energy consumption by 4%, even though the thermal storage capacity was only partly utilized in this test. The average return temperatures to the district heating system were also reduced by 2°C while the system was in operation (Wernstedt et al., 2008). A subsequent larger test of this technology was performed in three major Swedish district heating systems (Johansson et al., 2010). A total of 58 substations serving one to several buildings each were included in this test. Peak load reductions of approximately 15% to 20% and energy savings of 7.5% were achieved.

The effect of the utilization of buildings for short-term TES on the indoor temperature was studied (Johansson and Wernstedt, 2010). The test was performed in an office building with a light construction and concrete slabs. The heat load was reduced during short periods of up to 1 h and longer periods of 4 to 8 h. Both single and frequently recurring heat load reductions were tested. The average deviation was chosen as the measurement for the variations in indoor temperature. During periods with load reductions, the average deviation increased to 0.29°C from the normal 0.19°C.

A study with the aim of estimating the possible thermal storage potential of different building types was conducted in Gothenburg, Sweden (Ingvarson and Werner, 2008). The heat deliveries to the different buildings were reduced over periods of 24 h, and the heat deliveries and indoor temperatures were measured. *Time constants* for each building were calculated based on these measurements. Wooden buildings reported *time constants* of 102 h, stone buildings 155 h, and tower blocks 218 h to 330 h.

2.4 Effects on DH systems

A few researchers have studied the effects of the large-scale implementation of buildings' thermal inertia as short-term TES in district heating systems. They have adopted very different approaches.

One case study revealed how the implementation of DSM would affect the fuel and operational costs of the DH system in Næstved, Denmark (Wigbels et al., 2005). Two cases were considered in which the heat load was assumed to be adjusted by 20% and 80%, respectively, toward the mean heat load. They resulted in total savings of 1% and 2.6%.

District heating systems in which a considerable number of the buildings utilize nighttime setbacks can have large peaks in heat demand in the morning hours. A simulation study regarding the DH network of Altenmarkt in Pongau, Austria, studied the effects of applying DSM strategies to buildings utilizing a nighttime setback (Basciotti and Schmidt, 2013). The buildings were controlled so they recovered from their nighttime setback at different hours. Up to 35% peak saving would be achieved if applied to the overall district heating network.

The effects of three energy conservation measures on the local energy system in Linköping, Sweden, were compared (Difs et al., 2010). The compared measures were heat load control (utilizing buildings' thermal inertia), attic insulation, and electricity savings. Heat load control showed a potential for energy savings primarily in the spring and autumn. It would also be economically profitable for both the DH provider and the residents. The analyzed installation for heat load control is described in "Deployment of Agent Based Load Control in District Heating Systems" (Johansson et al., 2010).

3 HEAT LOADS

Demands and loads are two concepts in energy systems that are in many ways similar but not equal. With the introduction of smart grids, it is important to define concepts well. This chapter will first define demands and loads for energy and power. "Demand" and "load" can be defined as follows:

Demand – The amount of energy or power required to fulfill the customer's needs.
Load – The amount of energy or power delivered to the customer.

Fulfilled demand is equal to the load in an energy system (which is often the case). Unfulfilled demands can occur unintentionally due to failures/limitations in the energy system or due to an intended active strategy. Demands and loads can also be further split into power demands/loads and energy demands/loads. They are then defined as the following:

Power demand – Maximum power required to fulfill the customer's needs.
Energy demand – Amount of energy required to fulfill the customer's needs over a given period of time.

Power load – Maximum power delivered to the customer.
Energy load – Amount of energy delivered to the customer over a given period of time.

A customer can have a high power demand but not necessarily a high power load if the outtake from the grid is limited, for example, by a fuse (electrical) or limited water flow (heat).

The individual costumer loads are aggregated in grids and contribute to the total load in the system. In addition to the customer's loads, there are also distribution losses in both electrical grids and heat grids. All energy loads can simply be added to the distribution losses to make up the total energy load. When it comes to power loads, the fact that maximum load does not occur for all customers simultaneously needs to be considered. A study of how power loads are aggregated in an electrical grid is provided (Broadwater et al., 1997).

Different types of power loads have different diversity factors and are, hence, aggregated to different extents. Heat loads caused by space heating are mainly dependent on the outdoor temperature and, therefore, occur at the same time for most customers within an area. The total thermal power load caused by space heating is then close to the sum of all individual thermal power loads caused by space heating. For domestic hot water, loads generally do not occur at the same time. This can be compensated for using a diversity factor when aggregating the individual thermal power loads. The aggregated load caused by domestic hot water usage is usually much smaller than the sum of the individual loads. How much smaller depends on the number of aggregated loads, size of the loads, customer type, etc.

A smart energy grid is an important component in efficient load management. The term “smart energy grid” includes both smart electrical grids and smart heat grids (DH systems). Before defining what a smart energy grid is, it is best to start with defining the term “smart.” “Smart” is a term commonly used in naming technologies, concepts, and products. This term, being a more informal counterpart to “intelligent,” implies that what is labeled as smart has some kind of intelligence. Some kind of logic and decision-making is, hence, implied. There are generally three steps in a decision-making process:

- Interpretation of information
- Evaluation of alternatives
- Action

This concept can be implemented as a system in the electrical and/or heat grids that gathers information about energy supply, distribution, and consumption. The system then acts on this information to improve the efficiency, economics, reliability, and/or sustainability of the energy system.

The electrical grids and DH networks of today are mainly demand driven. Customers are usually free to consume electricity and heat at any given time. They pay an energy price that is usually fixed over periods of one month or more. Demand for electricity and heat causes loads in the grids that need to be balanced by generation.

This variation in heat and electrical loads sets the conditions for generation. For example, in an electrical grid where the electricity is supplied by mainly hydro power and fossil combustion plants, it is possible to match load variation with a variation in generation without a major falloff in efficiency. It gets more complicated when intermittent electricity generation, such as wind or solar, is introduced to the system. In grids with a high share of intermittent electricity generation, problems can arise because there is little to no flexibility in the load and in the intermittent part of generation. This puts high demands on the remaining (non-intermittent part) of generation and on the grid. The plants operating on the margin can experience large variations in loads, causing them to run less efficiently and increasing the number of starts and stops. The demand for backup generators on standby also increases. They are required to compensate for sudden changes in electrical load and generation that can otherwise cause blackouts.

DH systems have some major differences compared to electrical grids. First, they are local systems that are generally not connected to other DH systems. Second, while the load and generation have to be in balance at all times in an electrical grid, this is not the case for a DH system. There is some room for time delays since the distribution network has thermal inertia and can handle some variation in supply and return temperatures. By utilizing this flexibility, the distribution network can be used as a short-term TES. This possibility is exploited today in some DH systems.

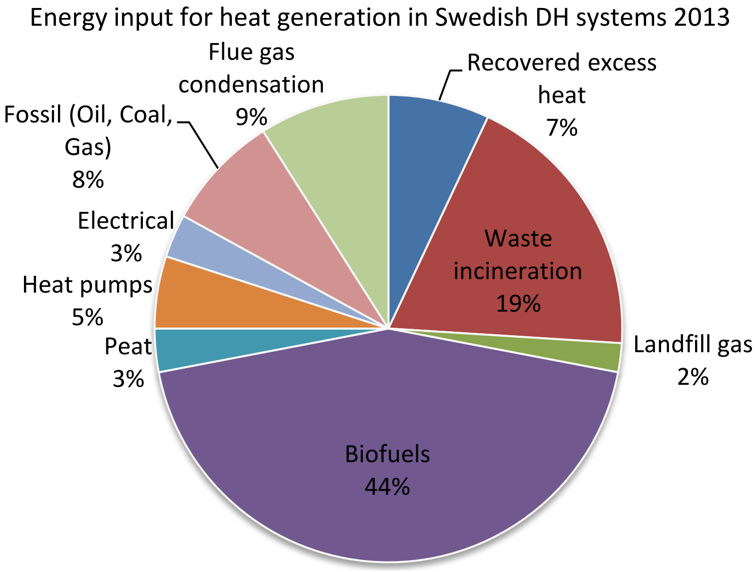

Fig. 2 Fuel mix in Swedish DH systems (SvenskFjärrvärme, 2013).

The heat source diversity in DH systems has increased during recent decades. This is due to the fuel change from mainly oil to mainly biofuels and waste incineration over time (Frederiksen and Werner, 2013). The Swedish fuel mix in 2013 can be seen in Fig. 2. Biofuel boilers and waste incineration are less flexible than oil boilers because they often utilize solid fuels and are, therefore, more affected by extra losses, costs, and wear associated with starts and stops. Reducing the load variation and decreasing the number of starts and stops are, thus, becoming more important for increasing the system efficiency and environmental performance of DH systems.

4 PILOT TEST

The pilot test and a study of how a large-scale implementation can benefit a DH system are well documented in the two included papers, [PAPER 1] and [PAPER 2]. The data have also been analyzed in a master's thesis (Elebo and Petersson, 2013). These three studies have had different foci:

- (Elebo and Petersson, 2013) – A broad analysis quantifying the effects on heat load and indoor temperature in all the tested buildings.
- [PAPER 1] – A deeper analysis focusing on finding relations between control signal, heat load, and indoor temperature variation.
- [PAPER 2] – A focus on how the results from the pilot test can be extrapolated to study how a building's short-term TES can benefit a DH system.

4.1 Test setup

This description of the methodology is based on [PAPER 2]. More details on how the data are analyzed can be found in [PAPER 1].

During 2010 and 2011, the ability of five buildings to function as TES in a district heating system was tested in Gothenburg, Sweden. The five buildings that were included in the analysis are all residential buildings with three to five stories. A summary of the building data is presented in Table 1. There are some differences in the buildings, and they can be grouped into two categories: light and heavy. This classification is based on the thermal mass of the building. A light building typically has a core of steel or wood, which results in a low capacity for storing heat. A heavy building typically has a core of concrete, which results in a higher capacity for storing heat. One of the buildings can be classified in the light category. All of the buildings were constructed between 1939 and 1950 and have a yearly heating demand of approximately 150 $kWh/m^2_{\text{floor area}}$ per year. This is a normal energy performance for these types of buildings in the city of Gothenburg, Sweden, which has a yearly average temperature of 8°C. A major portion of the large public housing stock that was built in the 1960s and 1970s is similar to the buildings tested in this study regarding energy performance (Energimyndigheten, 2013). More recently constructed buildings generally have lower heat demand.

Table 1 Building Data.

Building	A	B	C	D	E
Year of construction	1950	1939	1934	1939	No info.
Living area [m^2]	1,178	904	900	904	No info.
Stories	3	5	3	5	3
Apartments	20	24	19	24	25
Estimated	Heavy	Heavy	Light	Heavy	Heavy
Facade	Plastered	Plastered	Wood, brick	Brick	Brick

The heat deliveries to the buildings were increased and reduced during specified periods, and the indoor temperature, *T*, was measured in two apartments in each building. Temperature sensors were placed on a wall in the hall in each apartment. All buildings were connected to district heating and had a radiator heating system.

All of the buildings in the pilot test adjusted the heating power by controlling the supply temperature to the radiator system using a conventional feedback controller. The supply temperature was set based on the outdoor temperature and a control curve. A fine adjustment of the heating power within each individual apartment was performed via thermostats on the radiators. To control the heating power delivered to the buildings in this test, the signal from the outdoor temperature sensor, *u*, was adjusted in different cycles, as shown in Fig. 3. This affected the set point for the water supply to the radiators in the feedback controller. For example, to discharge a building, 7°C was added to the outdoor temperature signal. The real outdoor temperature was 3°C, but the control system receives the signal 10°C (3°C + 7°C). According to the control curve, this resulted in a lower supply temperature to the radiator system. The apartments then received radiator water with a lower temperature than they needed to maintain their indoor temperature, *T*, at the current outdoor temperature. The indoor temperature, *T*, slowly started to drop in the apartments, and the building affected the district heating system, similar to discharging a hot water storage tank. This test setup was similar to the one used in “Heat load reductions and their effect on energy consumption” (Johansson and Wernstedt, 2010).

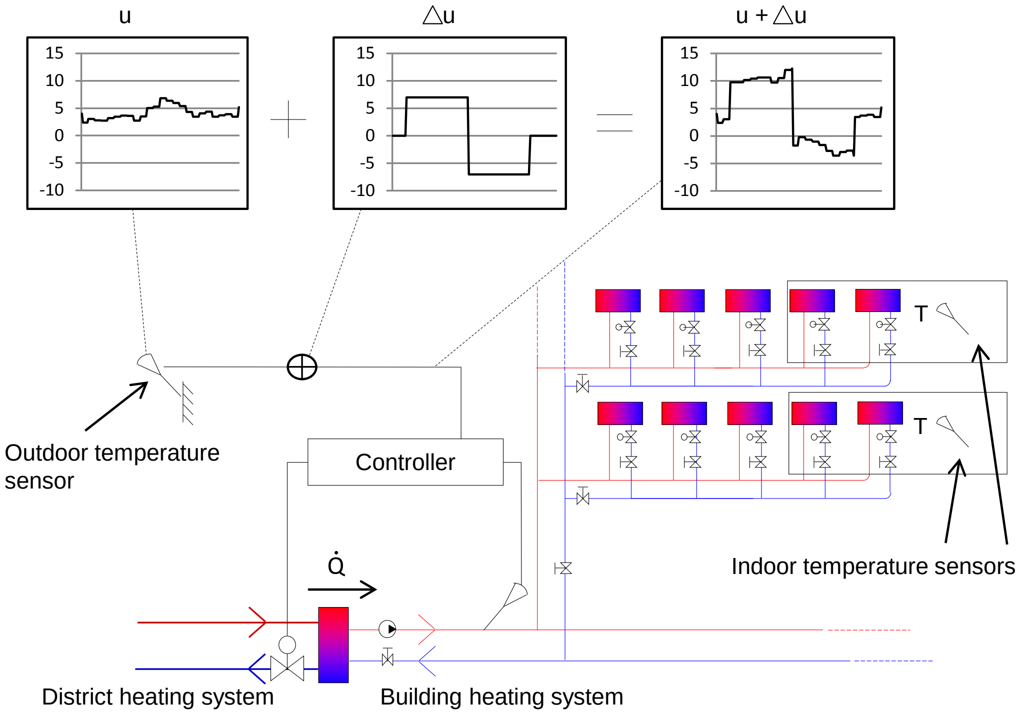

Fig. 3 Schematic of how the control was implemented in the pilot test.

In this test, the adjustments to the outdoor temperature signal were performed in 21-h cycles. Most of the tested control cycles contained one 9-h period of discharging, one 9-h period of charging, and one 3-h period of normal operation. The reason to use a test cycle that was 21 h (and not 24 h) was that this caused the charging and discharging to occur at different times each day. This made it possible to separate variations in indoor temperature caused by the test from normal variations caused by, for example, sunlight and the tenants' behavior. Eight cycles of 21 h make one full week.

Five different cycles of charging and discharging were tested; they are shown in Fig. 4. The following notations are used to describe them:

CP – Charge period; the building receives more heat than it normally would at the current outdoor temperature.

DP – Discharge period; the building receives less heat than it normally would at the current outdoor temperature.

NOP – Normal operation period; the building's heating system operates as it normally would.

Δu – Adjustment to outdoor temperature signal.

Cycle II was the most extensively tested. It was tested in all five buildings and produced 19 complete weeks of measurement data without any obvious measurement errors. Cycle II is also the cycle with the largest variation in Δ*u* and, therefore, should be the cycle that provided the largest utilization of the building's thermal energy storage capacity and produced the largest variations in indoor temperatures.

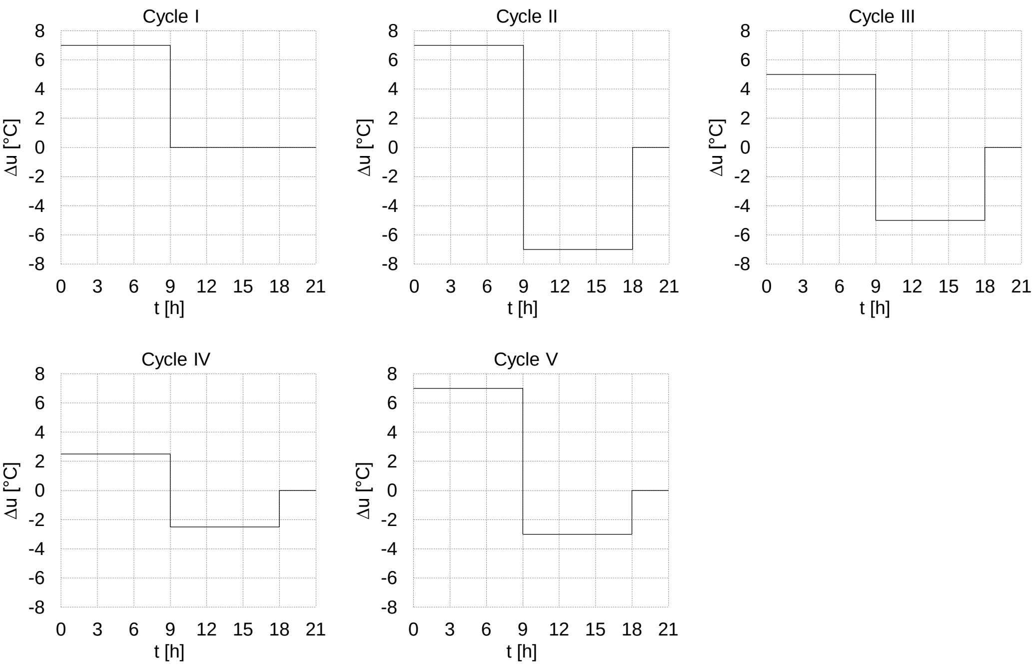

Fig. 4 The five test cycles used in the pilot test.

4.2 Heat deliveries in tested buildings

The relation between the heat delivered to the buildings, $\dot{Q}$, and the adjustment to the outdoor temperature signal, Δ*u*, has been studied in [PAPER 1 and PAPER 2]. This has been done by separating the variations caused by the test from the normal variations occurring every day. An average profile for each test week has been created from the eight weekly 21-h cycles. This causes the normal variations to cancel out each other since they will occur at different times in each cycle. An example of a heat delivery profile is presented in Fig. 5.

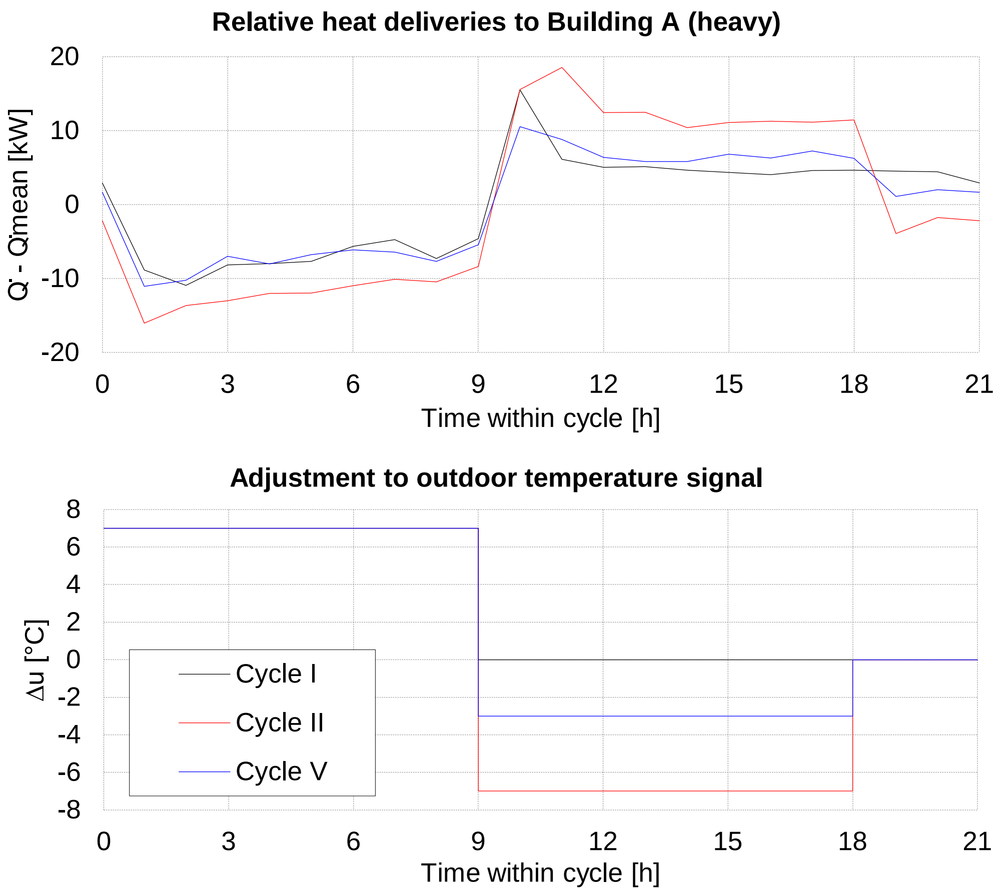

Fig. 5 Heat delivery profiles relative to the control cycle average for Building A. Each profile is based on five to eight weeks of measurements.

The heat stored in the buildings is depicted in Fig. 5 by the area between the graphs and the 0 kW line. For Cycle II (the strongest cycle tested), this area is about 110 kWh. With a living area of 1,178 m^2, the heat stored per floor area is about 0.1 $kWh/m^2_{floor\ area}$, and all the tested buildings showed similar results. Given that the variations in indoor temperature are acceptable, this value can then be used as a rule of thumb for estimating thermal storage capacity for similar buildings. It has also been shown in [PAPER 1] that the amount of stored heat has a close-to-linear relation to the magnitude of the control signal. This indicates that the thermal storage capacity can be utilized both for short and large adjustments to the heat deliveries as well as long and small.

One concern that needs to be raised is if a control method that changes Δu is counteracted by the thermostats. This is briefly elaborated on in [PAPER 1]. The reason why it can occur is best explained with an example: A Building is charged with decreasing Δu; hence, the supply temperature to the radiators is increased. After some time, the indoor temperature rises, which causes the thermostatic valves on the radiators to close. This reduces the heating power from the radiators and counteracts the charging of the building. The effect is displayed in Fig. 5 by the slow recovering trend of the heat load, especially during discharging. This effect could be seen to different extents in some of the tested buildings, but not in all of them. The reason is probably the varying and often bad functionality of thermostatic valves (Johansson et al., 1989). The counteraction of the heat load adjustment peaked at about 30% after nine hours of charging in Building A, which was the building that showed the strongest load recovery. This is about what would be expected in a rough theoretical model with a thermostat using a P-band of 2°C and a change in indoor temperature of 0.6°C. This should, then, have a fairly small impact on the performance of such a control system. However, it might be a problem in systems where the P-band is smaller.

4.3 Indoor climate in test buildings

Most standards and practices for thermal comfort have emerged from the works of P.O. Fanger. The most well-known article regarding this topic is probably "Assessment of man's thermal comfort in practice" (Fanger, 1973). This study finds the relations between clothing, activity, and the most comfortable indoor temperature. At the most comfortable indoor temperature, it is expected that about 5% of people are dissatisfied. With a 0.5°C deviation from this temperature, about 10% is expected to be dissatisfied. This is important to keep in mind when designing a building's short-term TES, but what is more relevant is to take into account how variations in indoor temperature affect thermal comfort. This has been considered in more recent standards. A change in indoor temperature of up to 1°C has been shown to have no impact on thermal comfort (ISO7730, 2005). This value has been used as a guideline for what variations in indoor temperature are acceptable as a result of utilizing buildings as short-term TES.

Indoor temperatures exhibit a natural variation in residential buildings. This occurs because of variations in weather and tenant activities such as cooking, using electrical appliances, and emitting body heat. All of these factors can be considered as disturbances that need to be compensated for by a control system to keep a comfortable indoor climate. The only disturbance that is normally measured is the outdoor temperature, which is compensated for by adjusting the supply temperature to the radiators. All other disturbances are compensated for by the thermostatic valves on the radiators, tenants opening windows, etc. The thermostatic valves need a change in the indoor temperature before they react; hence, significant variations in the indoor temperature can occur on a normal day.

The effect of utilizing a building as short-term TES is that it adds an extra variation to the indoor temperature. This variation may coincide with or counteract the natural variation, thus increasing or decreasing the total variation depending on when the variation occurs.

4.4 Indoor temperature variations in test buildings

To separate variations in indoor temperature, *T*, caused by the test from the normal variations, an average indoor temperature profile for each week has been created based on the eight cycles. These profiles were created in the same manner as the profiles for relative heating power in Fig. 5. An example of these profiles in one of the heavy buildings is presented in Fig. 6. For details on how these profiles are generated, see [PAPER 1].

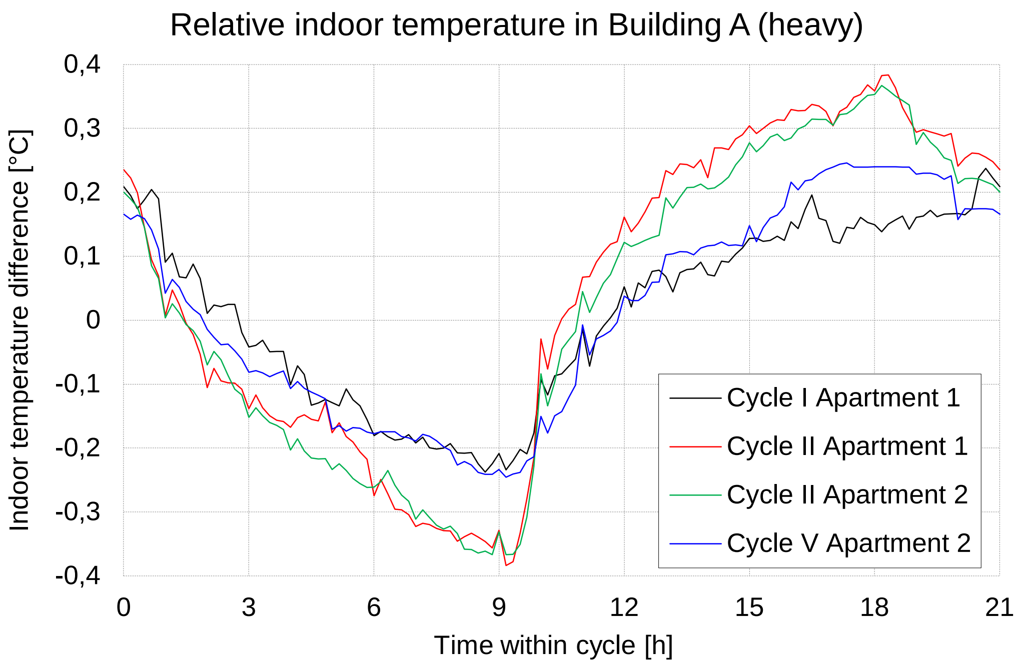

Fig. 6 Indoor temperature variations caused by the pilot test. Each curve is based on average values over a period of four to six weeks.

For each week in each apartment in each building, the indoor temperature variation, $T_{var.21h}$, caused by the pilot test was calculated. $T_{var.21h}$ is defined as the difference between the maximum and the minimum temperature for a weekly 21-h profile divided by two. A summary of the variations is presented in Table 2.

Table 2 Average variation in indoor temperature caused by the pilot test.

Test cycle	Building	$T_{var.21h}$ Apartment 1 [°C]	$T_{var.21h}$ Apartment 2 [°C]	Number of test weeks
I	A—heavy	±0.26	-	8
	C—light	±0.23	±0.39	18
II	A—heavy	±0.40	±0.40	6
	B—heavy	±0.29	±0.29	6
	D—heavy	±0.09	±0.19	5
	E—heavy	±0.06	±0.27	1
III	E—heavy	±0.11	±0.22	2
IV	E—heavy	±0.06	±0.10	1
V	A—heavy	-	±0.30	5

As shown in Table 2, all four heavy buildings experienced average variations in indoor temperature of ±0.40°C or less when exposed to Cycle II. This is within the allowed 1°C change in indoor temperature, which be translated into a variation of ±0.50°C. If one looks at each individual week, there is only one week in one of the apartments in one of the buildings that caused variations in indoor temperature larger than ±0.50°C, that is, ±0.53°C. Comparing the indoor temperature variations caused by the pilot test to allowed variations is not enough to fulfill the requirement since the possibility of coincidences with the normal variation needs to be taken into account. The normal variation has been studied in [PAPER 1]. For the two apartments in Building A, the average was ±0.21°C and ±0.16°C, and the maximum was ±0.33°C and ±0.25°C. These values cannot be added to the variations caused by the pilot test since the two variations may partly coincide or partly cancel each other out. Which scenario occurs depends on how the demand for thermal storage in the DH system coincides with the normal indoor temperature variations in the utilized buildings. It is, however, unlikely that buildings utilized as short-term TES (with restrictions similar to those in the pilot test) will frequently experience indoor temperature variations larger than ±0.5°C, hence affecting thermal comfort. This is further confirmed by the landlords for the tested buildings who reported that the frequency of complaints regarding the indoor climate were at a normal level during the pilot test. To ensure a good indoor climate or to open the possibility of utilizing more thermal storage capacity, continuous measurements of the indoor temperature can be implemented in the control of the TES.

4.5 Thermal storage potential

It has been shown in [PAPER 1 and PAPER 2] that buildings similar to those in the pilot test can be utilized as short-term TES with the restrictions from Cycle II and still provide a comfortable indoor climate. To transfer this concept to other buildings, parameters describing thermal storage capacity have been established. What is interesting from an energy supplier's perspective is the *storage capacity limitation* and *power limitation* of the storage. Thanks to the close-to-linear dependency of Δu, $\dot{Q}$, and T, the results from the pilot test can be simplified into these two parameters: [PAPER 1]. The *storage capacity limitation* is the amount of energy that can be in thermal storage, measured in, for example, MWh. The *power limitation* is the maximum power that the storage can be charged or discharged with, measured in MW, for example. These values for Building A with regard to the demands on indoor climate can be derived from [PAPER 1]:

- Power limitation: 12.3 kW
- Storage capacity limitation: 110.5 kWh

The other heavy buildings in the test all showed a higher potential for storing heat since they experienced smaller variations in indoor temperature at similar adjustments to Δu and $\dot{Q}$ [PAPER 1](Elebo and Petersson, 2013). Due to the relatively small number of tested buildings, the results from Building A have been selected to define the parameters for a larger short-term TES.

Three methods for scaling the results from the pilot test and transferring them to other buildings have been considered:

- Stored heat per floor area [Wh/m^2]
- Degree hours [°Ch]
- Time constant [h]

The *stored heat per floor area* is the *storage capacity limitation* divided by the floor area that still gives an acceptable indoor climate. For Building A, this is 110.5 kWh / 1,178 m^2 = 94 Wh/m^2. Assuming this value is valid for other similar buildings, it can be used to estimate their thermal storage capacity. An analogue is the *power limitation per floor area*: 12.3 kW / 1,178 m^2 = 10.4 W/m^2.

The *degree hour* measurement is directly related to the control signal, Δu, used in the pilot tests. It is, simply, the largest Δu multiplied by the longest time it can be applied while still maintaining a good indoor climate. It can be translated into an energy quantity by multiplying a building's (or group of buildings') heating power signature. The heating power signature is the dependency of the heat demand on the outdoor temperature. The thermal storage capacity for Building A measured in *degree hours* is 63°Ch. The *power limitation* relates analogously to the maximum-allowed Δu in °C.

The *time constant* can also be used for describing a building's ability to store heat. It can be decided by a step response test in which the control signal, in this case Δu, is adjusted in one step and the temperature in the building is measured over the following hours. The *time constant* can then be calculated according to Eq. 1.

Eq. 1 $$T(t) = T_0 + (T_\infty - T_0) \times e^{\frac{-t}{\tau}}$$

$T(t)$ = Indoor temperature at time t
T_0 = Indoor temperature at time 0
T_∞ = Indoor temperature approaches this value
t = Time
τ = Time constant

For this application, it is assumed that: $(T_\infty - T_0) = -\Delta u$. This assumption implies that an adjustment of the outdoor temperature signal of 1°C will cause the drop in the indoor temperature to approach 1°C after a long time. This assumption is only true for shorter periods of time and smaller changes in indoor temperature since a number of secondary effects will become significant with a larger change in indoor temperature. For example, the cooling effect from the ventilation will change. Since the change in indoor temperature is much smaller than Δ*u* in this pilot test, such secondary effects are ignored, and the assumption is true.

Defining *time constants* for the buildings in the pilot test has been attempted in [PAPER 1]. It showed that the resulting *time constant* was heavily dependent on the length of the measurement; hence, a simple *time constant* was not enough to describe the building's thermal storage properties. This is illustrated in Fig. 7. A deeper analysis of the thermal behavior of the building can be found in [PAPER 1].

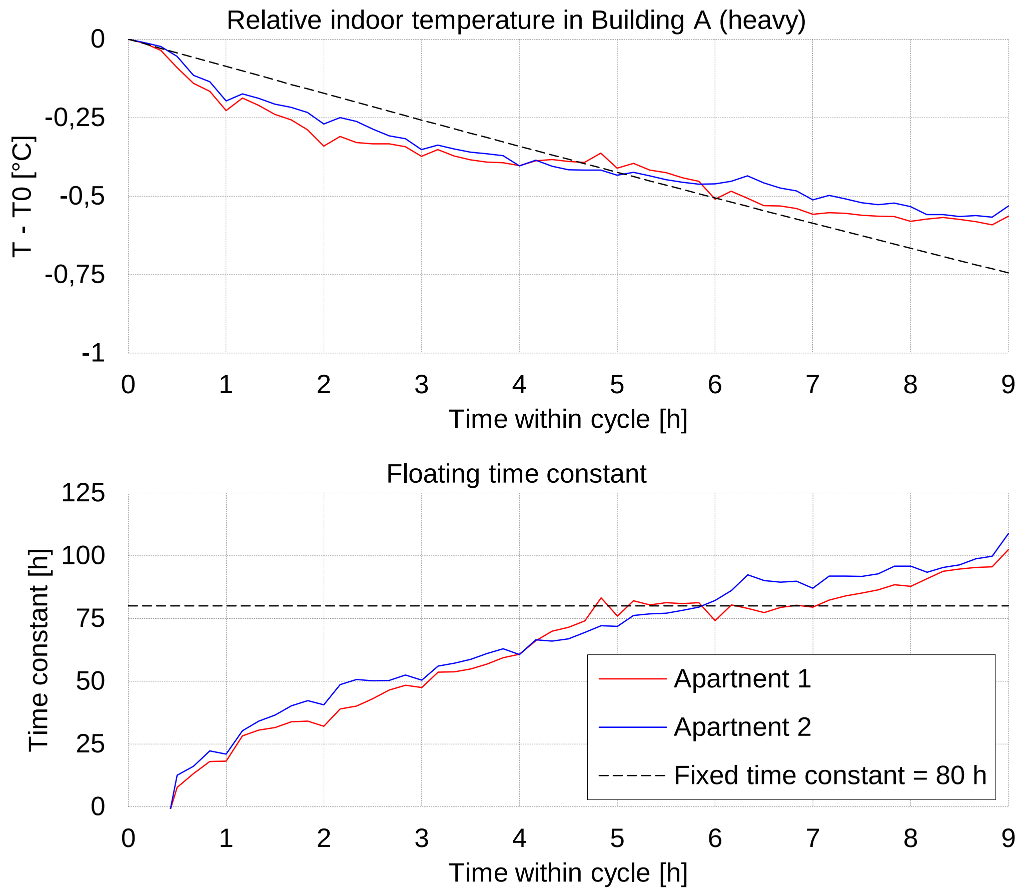

Fig. 7 Top graph: Average indoor temperature profile during DP. The *fixed time constant* has a slightly rising concave shape. Bottom graph: *floating time constant* based on the temperature profile from the top graph.

It is important that the selected method is accurate while still requiring as little data and simulations as possible for the buildings that are evaluated for usage as short-term TES. This is of extra importance when estimating the thermal storage capacity for buildings that are not similar to those in the pilot test in one or more aspects. The *power limitation*, *storage capacity limitation*, and the parameters defined for the different methods are all affected by several properties in the buildings. These effects are summarized in Table 3. It should be noted that the proportions of the effects are very rough and they are only used to visualize how the parameters relate. For example, doubling the insulation's U-value will not halve the heat demand for space heating since the heat demand is also affected by air leakage, ventilation, internal heat gains, etc. The ratios would, however, be fairly accurate for a very simple building without ventilation and inhabitants.

Table 3 Rough estimates of how the measurements for storage capacity limitation are affected by different parameters in simple buildings.

Changed parameter	**Yearly heat demand [Wh]**	**Storage capacity limitation measured in:**			
		Amount of stored heat [Wh]	**Stored heat per floor area [Wh/m2]**	**Degree hours [°Ch]**	**Time constant [h]**
Accessible thermal inertia x 2	Unchanged	x 2	x 2	x 2	x 2
Allowed temp. variation x 2	Unchanged	x 2	x 2	x 2	Unchanged
Insulation x 2	x 0.5	Unchanged	Unchanged	x 0.5	x 2

Increasing the allowed variation in temperature will increase the storage capacity measured in *stored heat per floor area* and *degree hours,* but the *time constant* will remain unaffected. The *storage capacity limitation* is independent of the insulation level of a building. Hence, so is the *stored heat per floor area* measurement. *Degree hours* and the *time constant* differ here from the *storage capacity limitation,* which needs to be compensated for in the scaling of the storages.

Required data about a building to estimate its *storage capacity limitation* can also be summarized. With *stored heat per floor area*, the required parameters are:

- Floor area
- Thermal inertia in relation to Building A

For the *degree hour* method:

- Heating power signature
- Yearly heat demand
- Thermal inertia in relation to Building A

All these data are fairly easily obtainable except for thermal inertia, so the choice between *stored heat per floor area* and *degree hours* should only depend on what is most practical for each application. For this study, *degree hours* has been used since the required data were available for parts of the studied DH system as well as for the whole studied DH system. It is assumed that the large number of residential buildings similar to the buildings in the test have the same thermal inertia as the tested buildings.

One question that needs to be addressed is the validity of the results from the pilot test regarding the thermal storage capacity of buildings in climates other than those in Gothenburg. Since the thermal storage capacity of a building is mainly dependent on the thermal mass of a building, the results should be valid regardless of what climate the building is located in. What is affected is how much the thermal storage capacity can be used. This is because using a building as TES requires that the building has a demand for space heating. The heat demand for space heating cannot be reduced below zero. Buildings similar to those in the pilot test can be utilized to some degree if the outdoor temperature is below 15°C and to its full capacity at outdoor temperatures below 8°C. Buildings in other climates and periods of time will probably have different levels of insulation that affect these two values.

5 LARGE-SCALE IMPLEMENTATION

The DH system in Gothenburg is used as the main case study throughout this chapter. The methodology developed for this thesis has also been applied in a master's thesis on the DH system in Hudiksvall (Sirén, 2014). The results from that study are also summarized here.

To study a large-scale implementation of short-term TES in buildings, a group of buildings suitable for implementation need to be analyzed. For this purpose, Västra Gårdsten, a residential area in Gothenburg, was selected. The area has 13 substations, each supplying heat to a group of two to three buildings. There is a total of 1,000 apartments in the area with an average living area of 76 m^2. The average annual heat consumption for the area is 12.1 GWh. The buildings are all residential except for one small dental practice and one office for about 20 persons. All buildings are three to five stories and have a core of concrete. They are very similar to the heavy buildings in the pilot test. This building type is also very common in Sweden, as many large residential areas similar to Västra Gårdsten were built in the 1960s and 1970s.

Due to their similarities, it is assumed in this study that the buildings in Västra Gårdsten will perform identically to the heavy buildings in the pilot test with regard to the ability to function as short-term TES. To scale the results from the pilot test to Västra Gårdsten, the heating power signature is used. The heating power signature is the heat demand dependency on the outdoor temperature. It is determined by finding the linear dependency with the smallest squared error based on three years of measurements of the delivered heat and the outdoor temperature.

How a large-scale implementation of building TES can benefit DH systems has been studied within the context of this work. This has been done by scaling the results from the pilot test and simulating the effects on the heat generation in DH systems. A simulation program has been developed for this purpose and is described in [PAPER 2]. The simulation has been used in several studies related to this work with somewhat different approaches:

- [PAPER 2]: Focuses on scaling the results from the pilot test to find how much the variation in heat load can be reduced depending on how many buildings are utilized as short-term TES in the Gothenburg DH system.
- (Dreano, 2013): Studies how the reduced variation in heat load found in [PAPER 2] will affect the fuel mix and number of starts and stops in the Gothenburg DH system.
- (Sirén, 2014): Serves as a case study for the DH system in Hudiksvall (Sweden), where utilizing building thermal inertia is compared economically to the alternative of constructing a hot water storage tank.
- (Machu, 2014): Investigates how a hot water storage tank could benefit the DH system in Gothenburg. Two operational modes have been analyzed: using the hot water storage tank to maximize income from sold electricity from CHP or to reduce the load variation and improve fuel economy.

To evaluate the results, the relative daily variation was studied for four different sizes of TES. Relative daily variation is defined (Gadd and Werner, 2013a) as follows:

"The relative daily variation is the accumulated positive difference between the hourly average heat load and the daily average heat load divided by the annual average heat load and the number of hours during a day. The relative daily variation is expressed with 365 values per system and year."

Eq. 2 $$G_d = \frac{\frac{1}{2}\sum_{h=1}^{24}|P_h - P_d|}{P_a \cdot 24} \cdot 100\ [\%]$$

P_h – hourly heat load
P_d – daily heat load
P_a – annual heat load
G_d – relative daily variation

The relative daily variation is also graphically illustrated in Fig. 8.

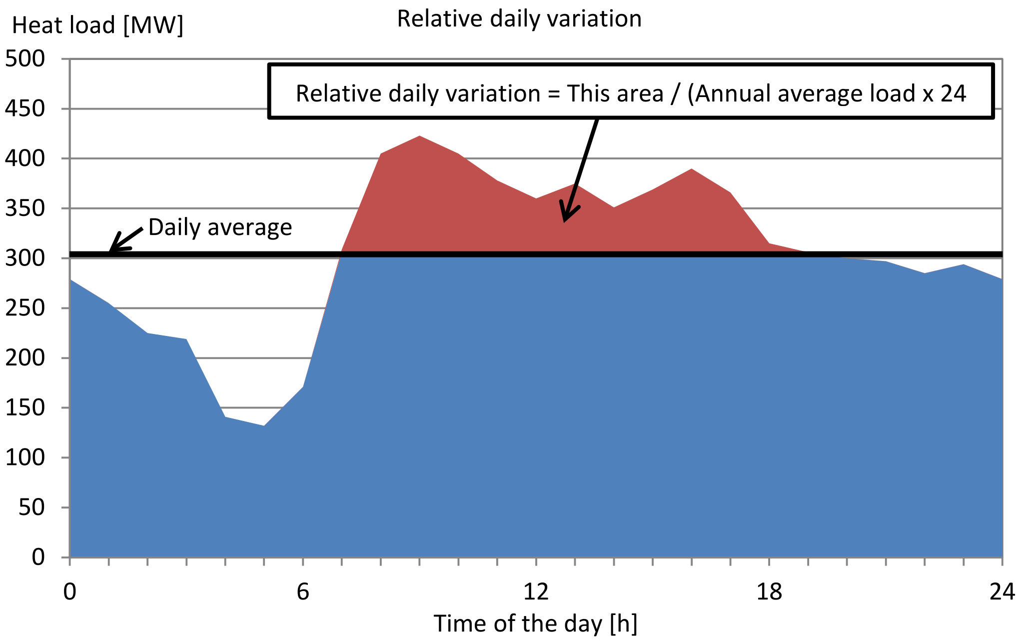

Fig. 8 Graphical representation of relative daily variation, G_d.

5.1 Simulation of Gothenburg's DH system

To find the *power limitation* and *storage capacity limitation* for a large-scale, short-term TES, we need to combine the results from the pilot test with the heating power signature for the intended building stock. The heating power signature for Västra Gårdsten, which has an average annual heat consumption of 12.1 GWh, is shown in Fig. 9.

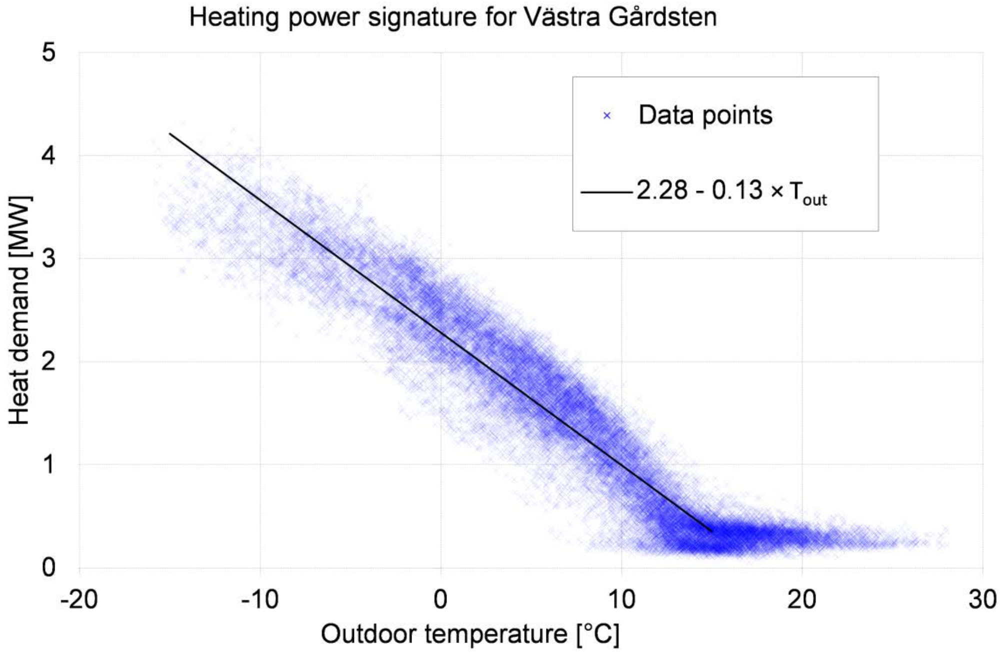

Fig. 9 The inclination of the trend line is the heating power signature for the residential area of Västra Gårdsten, Gothenburg.

Fig. 9 shows that an increase in the outdoor temperature of 1°C would result in a decrease in the heat delivered to the area of 0.13 MW. Hence, an increase in Δ*u* of 1°C would result in a decrease in the heat delivered to the area of 0.13 MW. With the limitations of |Δ*u*| < 7°C and 63°Ch of thermal storage capacity, this area could be utilized as thermal storage with a *power limitation* of 0.13 MW/°C × 7°C = 0.91 MW and a *storage capacity limitation* of 0.13 MW/°C × 63°Ch = 8.19 MWh. There are many areas similar to Västra Gårdsten in Gothenburg (and in other cities), so it is possible to scale these results for a city-wide implementation.

Since the cost of implementing building short-term TES is proportional to the number of substations that need adjustments, it is better to utilize the substations with the largest yearly heat demand first. During 2010–2012, the DH system in Gothenburg had an average annual heat generation of 4.26 TWh. The total amount of delivered heat to customers was 4.04 TWh, of which 2.12 TWh was delivered to the 4,457 substations in multifamily residential buildings. The heat deliveries to these substations are sorted in Fig. 10 to find the required number of substations for each case presented in Table 4.

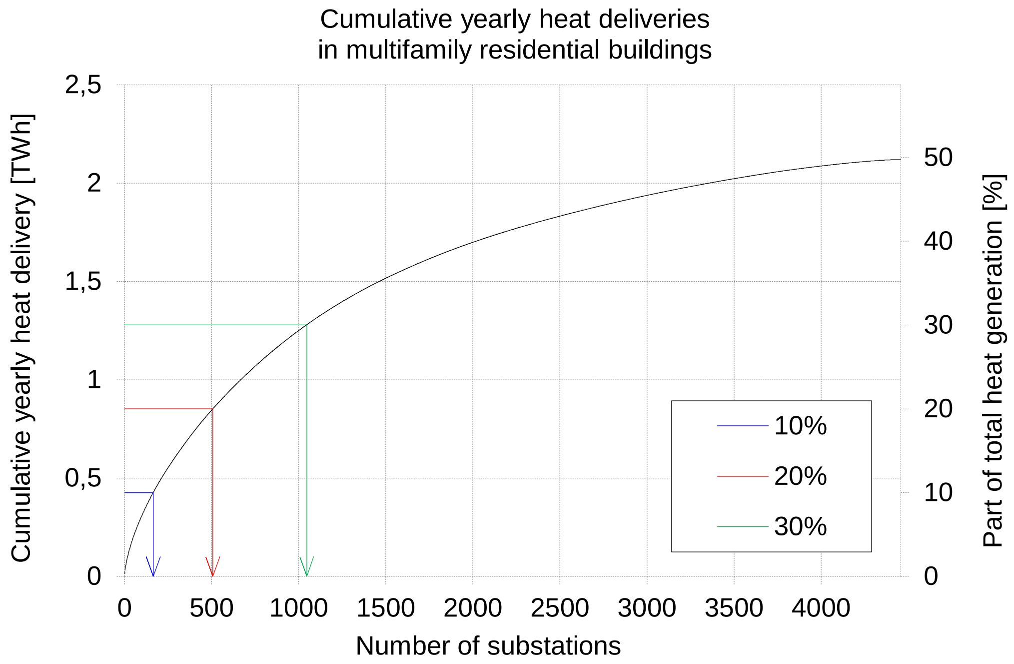

Fig. 10 Cumulative yearly heat deliveries to all substations in multifamily residential buildings in Gothenburg, Sweden.

Based on the data from Fig. 10 and the parameters found from the study of Västra Gårdsten, the four simulation cases can now be summarized in Table 4.

Table 4 Summary of the four simulation cases.

Case	Yearly heat delivery to utilized substations [GWh]	Number of utilized substations	Power limitation [MW]	Storage capacity limitation [MWh]
0% (ref)	0	0	0	0
10%	426	165	32	285
20%	852	507	63	571
30%	1,279	1,046	95	856

Based on the data from Table 4 and the hourly heat generation data for Gothenburg from 2010–2012, a full-scale simulation was performed. An example showing how the heat load in the seven-day period from the introduction chapter could be improved with the 20% case is shown in Fig. 11. During this week, there would be no need to use the gas HOB to cover the peak loads. The reduced variation in heat load would also reduce the number of starts and stops of heat generating units, increasing system efficiency. More results on how the storage is operated and how the indoor temperature will vary in the most affected buildings can be found in [PAPER 2].

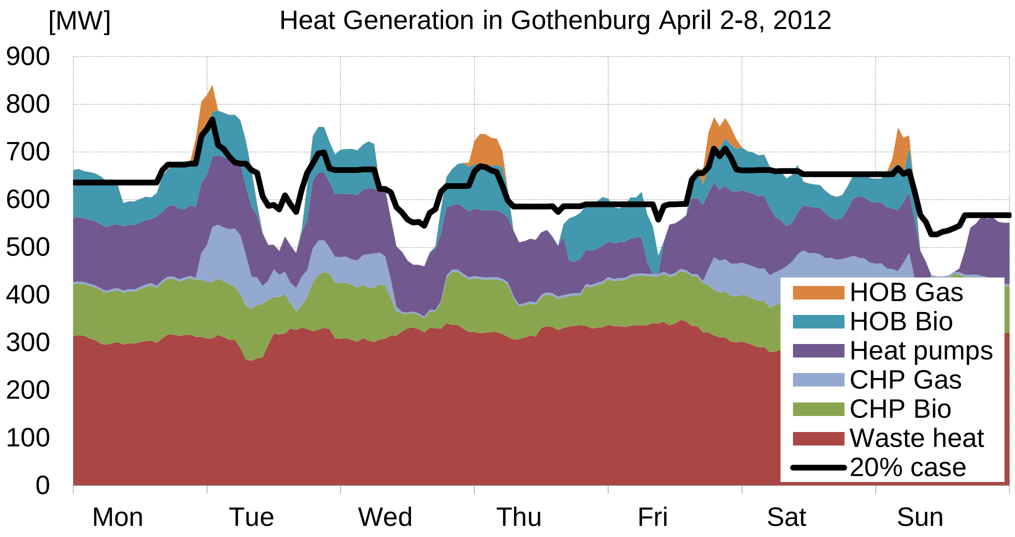

Fig. 11 Example of the heat generation in Gothenburg during one week with a possible load curve from the 20% case as an overlay.

5.2 Evaluation

The relative daily variation, G_d, has been calculated for each day for all simulation cases. The values over the three-year simulation period are presented in Fig. 12.

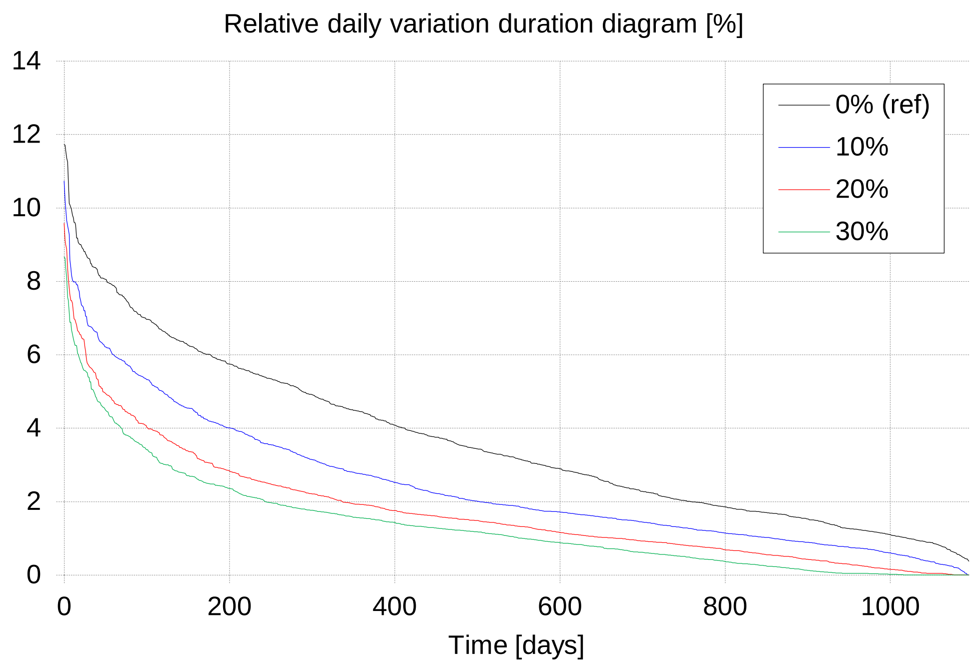

Fig. 12 Relative daily variation cumulative distribution function for three years (2010–2012).

It can be clearly seen in Fig. 12 that the variation in heat generation has decreased and that the conditions for generating heat are more favorable with a building's short-term TES. The decrease from no storage to 10% is larger than the decrease from 10% to 20%. This is because, in some cases, 10% is enough to cut a peak, and there is no need for larger storage. Then, the utilization is larger for the smaller storage of 10%.

If one looks at the average values for G_d, one obtains a simple measurement for comparing the four cases:

TES Size	G_d
0% (reference):	3.63%
10%:	2.44%
20%:	1.74%
30%:	1.38%

In the 20% case, the average relative daily variation is reduced by 50% compared to the reference case. This comes at the cost of increasing the variation in indoor temperature in the customers' buildings in most cases by less than ±0.5°C and the investment in adjusting the substations. This should be compared with the value of reducing the variations in heat generation and other storage options.

5.3 Comparison with hot water storage tank

The main alternative to storing heat in buildings for short-term TES in DH systems is hot water storage tanks. The behaviors of these storages are similar in many ways, but there are some important differences:

- Storing heat in buildings requires space heating; hot water storage tanks do not. This is because the heat transfer from the DH system to the buildings is one way. There cannot be a negative heat load in a building. The consequence of this is that a building's short-term TES (in buildings similar to those in the pilot test) can only be discharged at its full *power limitation* when the outdoor temperature is lower than about 8°C.
- The location of the storage in DH grids differs, and its functionality is affected by transfer limitations in the grid. Hot water storage tanks are generally located close to a CHP plant (or other heat source), and building short-term TES is distributed on the demand side. This makes the two types of storages better suited for somewhat different roles. Hot water storage is better for reducing variations in the heat supply, and building short-term TES is better for reducing variations in the heat load. These effects are neglected in this thesis. How the location of storage affects its usefulness is studied in the e-hub project: "The potential of distributed storage for active control of District Heating grids" (Vanhoudt, 2014).
- Building short-term TES affects the return temperature in DH networks. When a building is discharging (the heat load is temporarily reduced), the flow in the distribution network is decreased as well as the return temperature. The reduced flow will immediately reduce the need for heat generation, but part of the reduction has to be "paid back" when the colder return temperature front reaches the plants.

For the specific case of Gothenburg, the 20% case would require adjustments in about 507 substations. This can be compared with investing in a hot water storage tank with a storage capacity of 576 MWh and a *power limitation* of 64 MW. With a supply temperature of 80°C and a return temperature of 45°C, this would result in a hot water storage tank of 14,200 m^3 with a maximum flow of 0.44 m^3/s. Such a storage tank would have an investment cost of roughly 3 M€ to 6 M€. This estimation includes all related costs required to get the storage tank in operation and is based on interviews with three Swedish district heating companies. Assuming that the required adjustments to the substations can be made cheaper than 6,000€ to 12,000€ per substation, utilizing buildings as short-term TES can be a more economical alternative than hot water storage tanks. It should, however, be noted that this is a very rough economic comparison that only includes the investment cost.

The decreased variation in heat loads will have positive effects on fuel economy and will reduce the number of starts and stops of HOBs. The 20% case will reduce the heat generation in oil and gas HOBs in Gothenburg by 10% to 20% (Dreano, 2013).

The effects of installing a hot water storage tank in the Gothenburg DH system have been further studied (Machu, 2014). Results from that study should be fairly applicable to building short-term TES as well, but the three points above should be kept in mind. The main difference, that building short-term TES is not usable in the summer months, is mostly neglected because there is little need for short-term thermal storage in the summer since the heat load is fulfilled by waste heat. Two different applications for storage were studied:

- Using storage to reduce the heat load variation in the DH system.
- Using storage to maximize income from selling the electricity of a major CHP plant (Rya CHP).

A hot water storage tank with a volume of 23,000 m^3 was considered. Such storage would have a *power limitation* of 130 MW and a *storage capacity limitation* of about 1,000 MWh. Compared to the studied cases presented in Table 4, this would be comparable to a 35% to 40% case.

The results showed that using storage to maximize income from electricity sales from a major CHP plant would result in a yearly revenue of 4.8 MSEK (520 k€). Using storage to reduce the variations in heat load in the DH system would result in yearly savings in fuel costs of 3.5 MSEK (380 k€), which is about 0.7% of the yearly fuel cost for the Gothenburg DH system (based on market fuel prices and not counting the price of bought waste heat). It should be noted the savings from reducing the number of starts and stops of boilers is not included in these calculations. The study also showed that there was no need for the storage in the summer months for either of the two applications. Thus, the results should be fairly representative for a building's short-term TES with similar power and storage limitations.

5.4 Hudiksvall's DH system

The simulation developed for this study has also been adjusted for and applied to the DH system in Hudiksvall (Sirén, 2014). The DH system in Hudiksvall is considerably smaller than the system in Gothenburg, with yearly heat sales of 130 GWh (compared to 4,000 GWh); 92.6% of the yearly heat generation is produced in a CHP plant powered by solid bio fuels. Peak loads are covered by two HOBs fueled by pine pitch and oil. They cover 5.4% and 2.1% of the yearly heat generation respectively. The aim with this study was to find the potential for load-shifting from the peak load boilers to the base load plant by utilizing buildings as short-term TES. The economical profitability of the storage has been emphasized in this study.

The results showed that building short-term TES with a size corresponding to a 20% case for Hudiksvall would reduce the consumption of oil in heat generation by 15%. A simple payback time for storage of that size would be 7.5 years. Larger storages showed even larger economic benefits; storage sizes corresponding to 40%, 60%, and 80% cases all showed simple payback times of 5.5 to 6 years. This can be compared to Gothenburg, where a more economic optimal storage size would be around the 30% case (Machu, 2014).

There is some evidence that relatively larger TES is generally more favorable in smaller DH systems. Due to smaller load and geographical diversity in smaller DH systems, the variations in heat load are expected to be larger. This trend is weak but is demonstrated for larger systems (Gadd and Werner, 2013a). Another major factor affecting the viability of TES is the diversity of the heat supply. The DH system in Gothenburg has a total of 28 different boilers and other heat sources with a large variation in operational cost, etc. A smaller DH system might have a base load plant with low operational cost and a peak load plant with high operational cost. This can make TES very valuable when the heat load is close to the limit of when the peak load plant needs to be started and less valuable in other cases. The economic viability for TES is highly individual for every DH system. However, the results regarding load variation can easily be transferred to other DH systems. This is because relative daily variation is a generic parameter that can be applied to any system with a daily variation.

5.5 Practical implementation

The focus in this study has been on the potential for utilizing buildings as short-term TES and what benefits that can bring to a DH system. If buildings as short-term TES are to be implemented, there needs to be a business model and a method to control the TES. This can be solved in many ways that can be grouped in two categories: direct control and indirect control.

Direct control

With a direct control system, the heat supplier has direct control over the heat load in the utilized buildings. Such solutions can be simple to implement since the buildings can use the already existing control system for the radiator system and the TES control can be implemented by adjusting Δu. A data connection or some other method for the heat supplier to adjust Δu is required for such a solution.

Even if the technical solution is fairly simple, there are organizational obstacles to overcome. The heat supplier and the building owner need to have a contract that covers several areas:

- How large adjustments can be made to the heat load
- How often the heat load can be adjusted
- Who is responsible if there is a problem with the indoor climate in the building
- How the building owner is compensated.

The first three of these points can be overcome if the indoor temperature is continuously measured and implemented in the control, or if there at least is a fairly accurate model of the building's thermal properties. But such measures come with a cost and will impact the profitability of short-term TES. It might be more beneficial to have more narrow adjustments to Δu on a larger amount of buildings and avoid implementing the suggested measures.

The last point about how the building owner is compensated can be solved in several ways. Economic remuneration in the form of fixed compensation or reduced heat prices is possible. It is also possible to compensate the building owner for each time the building is used as short-term TES.

Indirect control

With indirect control of building TES, the building's owner makes adjustments to the heat usage, resulting in a more favorable heat load profile. Some kind of incentive from the heat supplier is required for the building's owner to make these adjustments. The incentive can be a price model that makes it favorable for the building to use heat when it is favorable from a system perspective. A favorable solution would be to have hourly pricing of heat based on what type of heat generation is on the margin. This would give building owners an incentive to use heat when it is generated in the most economically favorable way, which is often the most efficient and environmentally friendly way.

A solution with hourly heat pricing circumvents the organizational obstacles associated with a direct control approach. The interaction between the heat supplier and the building owners is simple, and all control in the buildings is voluntary and the responsibility of the building's owner. The obstacles to overcome are more technical with this strategy. The heat distributer needs to have a model (and preferably a forecast) for the cost of heat generation and some way of communicating the hourly heat prices to the consumers. The consumer, on the other hand, needs to have a control system that can take the cost of heat and the thermal inertia of the buildings into account. This could open a new market section in building automation systems or expand the existing market section for weather forecast control. The infrastructure to implement hourly heat pricing is already in place in buildings with weather forecast control since there is already a model for the building's thermal properties and an Internet connection that can receive weather forecasts. It should be cost effective in these systems to supplement them with hourly heat prices and change the target function to be minimized from total energy usage to total energy cost.

6 CONCLUSIONS

The pilot test in this study has shown that heavy buildings with a structural core of concrete can tolerate relatively large variations in heat deliveries and still maintain a good indoor climate. Storing 0.1 kWh/m^2 floor area of heat will very rarely cause variations in indoor temperature larger than ±0.5°C in the heavy buildings most sensitive to temperature variation. This corresponds to adjusting the outdoor temperature signal, Δu, by 7°C over 9 h. Most heavy buildings will have even smaller variations in indoor temperature and could possibly be used to store larger quantities of energy than the more sensitive buildings.

Both *degree hours* and *stored heat per floor area* can be used as tools to estimate the *storage capacity limitation* and *power limitation* of buildings or areas that can potentially be used as short-term TES. Which one of these parameters is more favorable depends on what data are available. The third alternative tool, *time constant,* is less suitable as a measurement for said purpose.

The greatest uncertainty from the pilot test is the small number of tested buildings. The buildings had a fairly large spread in the variation in indoor temperature, while the spread in stored heat was much more consistent. This is why the “safe side” assumption for a larger scale TES is based on the most sensitive of the heavy buildings in the pilot test. If a building’s short-term TES on a large scale is to be implemented, it would involve many buildings. Such a solution would be fairly costly if many buildings need to be extensively tested. The results from this pilot test can be used in similar buildings without much testing since the indoor temperature variation will be well within acceptable values in most buildings.

Variation in heat loads in DH systems can be greatly reduced by utilizing buildings as short-term TES. Using about 500 substations for short-term TES in large residential buildings would provide a capacity for storing heat equivalent to constructing a hot water storage tank with a volume of 14,200 m^3 for the city of Gothenburg. The yearly heating energy load for these 500 substations corresponds to 20% of the heat generation. Such a TES could decrease the daily variations in heat load by 50%, reduce the need for peak heat generation, and reduce the number of starts and stops of heat generation units. This can result in reduced heat generation in oil and gas HOBs in Gothenburg by 10% to 20%. Assuming that the required adjustments to the substations can be made cheaper than 6,000€ to 12,000€ per substation, utilizing buildings as short-term TES can be a more economical alternative than hot water storage tanks.

REFERENCES

APPELGREN, L. & ERLANDSSON, H. 2014. *Reduction of Peak Heating Power in Commercial Buildings Connected to District Heating.* Chalmers University of Technology, Gothenburg, Sweden.

BASCIOTTI, D. & SCHMIDT, R. R. 2013. Demand side management in district heating networks: Simulation case study on load shifting. *Euroheat and Power (English Edition),* 10**,** 43-46.

BROADWATER, R. P., SARGENT, A., YARALI, A., SHAALAN, H. E. & NAZARKO, J. 1997. Estimating substation peaks from load research data. *IEEE Transactions on Power Delivery,* 12**,** 451-456.

DIFS, K., BENNSTAM, M., TRYGG, L. & NORDENSTAM, L. 2010. Energy conservation measures in buildings heated by district heating - A local energy system perspective. *Energy,* 35**,** 3194-3203.

DREANO, M. 2013. *The possibilities with thermal storage in buildings in a district heating system.* Chalmers University of Technology, Gothenburg, Sweden.

ELEBO, J. & PETERSSON, D. 2013. *Evaluation of buildings' suitability as thermal energy storage in a district heating system.* Chalmers University of Technology, Gothenburg, Sweden.

ENERGIMYNDIGHETEN 2013. Energistatesik för flerbostadshus 2012 (Energy statistics for multi-dwelling buildings in 2012). Eskilstuna, Sweden.

FANGER, P. O. 1973. Assessment of man's thermal comfort in practice. *British Journal of Industrial Medicine,* 30**,** 313-324.

FREDERIKSEN, S. & WERNER, S. 2013. *District Heating and Cooling,* Lund, Sweden, Studentlitteratur AB.

GADD, H. & WERNER, S. Daily heat load variation in Swedish district heating systems. The 12th International Symposium on District Heating and Cooling, 2010 Tallinn. 199-201.

GADD, H. & WERNER, S. 2013a. Daily heat load variations in Swedish district heating systems. *Applied Energy,* 106**,** 47-55.

GADD, H. & WERNER, S. 2013b. Heat load patterns in district heating substations. *Applied Energy,* 108**,** 176-183.

HEIER, J. 2013. *Energy Efficiency through Thermal Energy Storage - Possibilities for the Swedish Building Stock.* KTH School of Industrial Engineering and Management, Stockholm, Sweden.

IEA. 2012. *Energy Balance Sweden 2012* [Online]. http://www.iea.org/Sankey/index.html#?c=Sweden&s=Final. [Accessed 2015-04-10].

INGVARSON, L. C. O. & WERNER, S. 2008. Building mass used as short term heat storage. *The 11th International Symposium on District Heating and Cooling.* Reykjavik, Iceland.

ISO7730 2005. Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

JOHANSSON, C. & WERNSTEDT, F. Heat load reductions and their effect on energy consumption. The 12th International Symposium on District Heating and Cooling, 2010 Tallinn, Estonia. 244-249.

JOHANSSON, C., WERNSTEDT, F. & DAVIDSON, P. 2010. Deployment of Agent Based Load Control in District Heating Systems. *First Agent*

Technology for Energy Systems Workshop, Ninth International Conference on Autonomous Agents and Multiagent Systems. Toronto, Canada.

JOHANSSON, G., KOLEHMAINEN, M. & WALDNER, L. 1989. Långtidsegenskaper hos radiatortermostatventiler. *Statens råd för byggnadsforskning.*

KENSBY, J., TRÜSCHEL, A. & DALENBÄCK, J. O. 2014. Utilizing Buildings as Short-Term Thermal Energy Storage. *The 14th International Symposium on District Heating and Cooling.* Stockholm, Sweden.

KENSBY, J., TRÜSCHEL, A. & DALENBÄCK, J. O. 2015. Potential of residential buildings as thermal energy storage in district heating systems - Results from a pilot test. *Applied Energy,* 137**,** 773-781.

KÄRKKÄINEN, S., SIPILÄ, K., PIRVOLA, L., ESTERINEN, J., ERIKSSON, E., SOIKKELI, S., NUUTINEN, M., AARNIO, H., SCHMITT, F. & EISGRUBER, C. 2003. Demand side management of the district heating system. *VVT Research Notes 2247.* Espoo, Finland.

MACHU, C. 2014. *Optimization of a district heating system with thermal energy storage.* Chalmers University of Technology, Gothenburg, Sweden.

OLDEWURTEL, F., PARISIO, A., JONES, C. N., GYALISTRAS, D., GWERDER, M., STAUCH, V., LEHMANN, B. & MORARI, M. 2012. Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings,* 45**,** 15-27.

SIRÉN, T. 2014. *Utvecklingsmöjligheter för fjärrvärmens affärsmodell - Genom användning av byggnader som värmelager.* Linköping University, Linköping, Sweden.

SVENSKFJÄRRVÄRME. 2013. *Statistik Fjärrvärme - Tillförd Energi* [Online]. Svensk Fjärrvärme. Available: http://www.svenskfjarrvarme.se/Statistik--Pris/Fjarrvarme/Energitillforsel/ [Accessed 2015-04-10].

VANHOUDT, D. The potential of distributed storage for active control of District Heating grids, e-hub project. The 14th International Symposium on District Heating and Cooling, 2014 Stockholm, Sweden.

WERNER, S. 1984. *Heat load in district heating systems.* Chalmers University of Technology, Gothenburg, Sweden.

WERNSTEDT, F., DAVIDSSON, P. & JOHANSSON, C. Demand side management in district heating systems. 6th International Joint Conference on Autonomous Agents and Multiagent Systems, AAMAS'07, 2007 Honolulu, HI. 1383-1389.

WERNSTEDT, F. & JOHANSSON, C. 2008. Intelligent distributed load control. *The 11th International Symposium on District Heating and Cooling.* Reykjavik, Iceland.

WERNSTEDT, F., JOHANSSON, C. & WOLLERSTRAND, J. 2008. Sänkning av returtemperaturer genom laststyrning (Decreased return-temperatures through heat load control), report no. 2008:2.

WIGBELS, M., BOHM, B. & SIPILÄ, K. 2005. Dynamic Heat Storage Optimisation and Demand Side Management. *IEA Annex VII I 2005:8DHC-05.06.*

ÖSTERLIND, B. 1982. Effektbegränsning av fjärrvärme: Försök med centraliserad styrning av abonnenternas effektuttag. *Rapport / Byggforskningsrådet, 0349-3296; 1982:63.*