THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

SMART ENERGY GRIDS
Utilization of Space Heating Flexibility

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ABSTRACT

Buildings are the largest energy-using sector in the world. Since the generation of energy is highly associated with greenhouse gas emissions, contributing to climate change, there is a large focus on reducing energy use in buildings. However, reducing the end use of energy is not an end goal in itself: it is also important to take into consideration how the energy used in buildings is generated. In most district heating systems, the conditions for generating heat are constantly changing, and the marginal cost and environmental impact can vary greatly within a single day. It is therefore of interest to take a step back and study the energy use in buildings with a system boundary that includes the energy supply system, e.g., a district heating system.

The objective of this work is to study how the control of space heating in buildings can be adapted to a system boundary that includes the energy supply system in order to gain a total cost improvement. Heat use flexibility is therefore important, and two types of flexibility are studied: First, the thermal inertia in buildings can be used as short-term thermal energy storage for shifting heat use from hours with high cost of heat generation and environmental impact to more favorable hours. Second, in buildings with both district heating and heat pump as heat sources, the heat load can be shifted between them to favor the heat source with the lowest cost of generation at any given time. In order to utilize these flexibilities, there needs to be some type of control system with integration towards the energy supply system. For this purpose, hourly heat prices based on the marginal cost of heat generation in a district heating system are used as a control input.

The methods used include pilot tests, building modeling, energy systems modeling, and literature review. One pilot test is focused on quantifying the thermal storage capacity that can be utilized in buildings' thermal mass while still maintaining good thermal comfort. A second pilot test in 19 multi-family residential properties focused on using hourly heat prices, based on the marginal cost of heat generation in the district heating system, as input to the space heating control system in buildings. Modeling work includes creating linear and dynamic models for thermal energy storage in buildings based on measurements from the pilot tests. These models are used in energy systems modeling to quantify the benefits of using buildings as thermal energy storage in a district heating system. The benefits of heat source shifting between district heating and exhaust air heat pump are evaluated based on a study of heat load profiles in residential buildings, hourly heat prices in a district heating network, and hourly electricity prices from the spot market.

The main results include linear and dynamic models for energy storage in building thermal inertia. A rough estimate is that a multi-family residential building with a structural core of concrete can be utilized as thermal energy storage with a storage capacity of 0.1 $kWh/m^2_{\text{heated area}}$, while keeping the indoor temperature variation within ±0.5°C. A potential large-scale implementation can have a major impact on the heat load in district heating systems. Simulation results show that utilizing buildings accounting for 20% of the heat load can reduce daily heat load variations by 50% in a DH system. This also comes with significant cost savings. In the district heating system in Gothenburg, Sweden, the cost of heat generation associated with heating the controlled buildings can be reduced by at least 5.5–11.0% (only counting fuel cost and net bought electricity). The second pilot test, where hourly heat prices were used as a control input to the heating systems in the buildings, showed that the control method worked, and all test buildings reduced their average price per purchased unit of heat. The achieved savings in the test are hard to evaluate due to the short test length, but if it is assumed that the test period is representing average conditions, the savings are of the same magnitude as the results from theoretical studies.

Heat source shifting with hourly prices can be an economically viable method of controlling the heating system in buildings with district heating and heat pump as heat sources. Whether this is viable depends on whether there is a situation where the heat source that is cheapest shifs during periods when both heat sources are available (if the same heat source has the lowest heating cost at all hours, there is no point in heat source shifting). This mainly depends on how high the electricity price is, how much it fluctuates, the coefficient of performance of the heat pump, and how all these factors correlate to the marginal cost of heat generation in a district heating system.

Keywords: District heating, smart, demand side management, thermal energy storage, thermal storage in buildings, demand response, heat price control, heat source shifting, heat pump, exhaust air heat pump.

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

Göteborg, April 2017

Johan Kensby

The currents before us are ever-changing.
We must adapt and press forward if we
are to see our journey's end.

Sean Bean

List of Publications

This thesis is based on one peer-reviewed journal article, two peer-reviewed conference papers, and two articles submitted for journal publication, which are appended and cited as follows:

Paper I 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 II 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.

Paper III KENSBY, J., TRÜSCHEL, A. & DALENBÄCK, J. O. 2016. Heat source shifting in buildings supplied by district heating and exhaust air heat pump. *The 15th International Symposium on District Heating and Cooling.* Seoul, Republic of Korea (South Korea).

Paper IV ROMANCHENKO, D., KENSBY, J., ODENBERGER, M. & JOHNSSON, F. 2017. Thermal energy storage in district heating: a comparison of centralised storage and thermal energy storage via inertia in the building stock. *Submitted for journal publication*.

Paper V KENSBY, J., TRÜSCHEL, A. & DALENBÄCK, J. O. 2017. Heat price control of thermal energy storage in building thermal inertia – Results from a pilot test in a district heating network. *Submitted for journal publication*.

I (the author of this thesis) am the first author of Papers I, II, III and V. I have performed the studies behind the papers and written the papers. The second and third authors, respectively my supervisor and examiner, have contributed with feedback and comments during the studies and the writing process. For Paper IV, I am the second author. My contribution is the model for thermal energy storage (TES) in buildings. I have written most of Chapter 2.2 BITES Model Adaptions and contributed with feedback and ideas for the other parts of the study.

CONTENTS

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NOMENCLATURE

Symbols

K	Heat transfer coefficient	[W/m^2; °C; W]
r	Pearson correlation coefficient	[-]
P	Price	[-]
Q	Thermal energy	[Wh]
T	Temperature	[°C]
t	Time	[h]
τ	Time constant	[h]
u	Outdoor temperature signal	[°C]
Δu	Adjustment to outdoor temperature signal	[°C]
$\dot{V}$	Ventilation flow rate	[l/m^{2}s]

Subscripts

balance	Balance
cap	Capacity limitation
ch.cap	Maximum charge rate
d	Daily
disch.cap	Maximum discharge rate
DOT	Design outdoor temperature
end	Last hour of test period
h	Hourly or hour
in	Indoor
loss	Heat losses to the ambient environment
mean	Average value (over one test cycle)
out	Outdoor
rel.var	Relative variation
set-point	Indoor temperature set-point
stored	Stored energy in thermal node
var.21h	Variation for weekly 21h profile
w	Weekly
yr	Annual

Superscripts

Building n	Parameter associated with building n
Shallow	Parameter associated with the shallow storage
Deep	Parameter associated with the deep storage
DH	Parameter associated with the district heating system

Abbreviations

BITES	Building Inertia Thermal Energy Storage
CHP	Combined Heat and Power
COP	Coefficient Of Performance
CP	Charge Period
DH	District Heating
DHC	District Heating and Cooling
DP	Discharge Period
DOT	Design Outdoor Temperature
EAHP	Exhaust air heat pump
HOB	Heat Only Boiler
HP	Heat Pump
HPC	Heat Price Control
HVAC	Heating, Ventilation, and Air-Conditioning
HWT	Hot Water Tank
NC	Normal Control
NOP	Normal Operation Period
PI	Price Index
TES	Thermal Energy Storage

1 INTRODUCTION

Limiting changes to the global climate is one of the critical challenges of our generation. Since energy generation is highly associated with greenhouse gas emissions, which contribute to climate change, there is a large focus on energy efficiency measures. Buildings account for the largest energy-using sector in the world. This is specifically true for Sweden as well, where the final energy use (consumption) for the year 2014 was divided as follows: residential and commercial buildings, 35%; industry, 34%; transportation, 24%; non-energy use, 6%; and other, 1% (IEA, 2014). Energy in buildings is primarily used for heating, ventilation, and air-conditioning (HVAC) and secondarily for electrical appliances (Oldewurtel et al., 2012). There is a large focus on reducing the energy use in buildings, and building codes in many countries are being updated with stricter requirements. But reducing the end use of energy is not an end goal in itself: it is also critical to reduce the cost of energy usage (both environmental and economic). It is therefore of great importance to take into consideration how the energy used in buildings is generated.

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). Since 1980, heat sources in Swedish DH have made the transition from mostly oil-based heat-only boilers (HOBs) to a much more diversified mix of heat sources (Frederiksen and Werner, 2013). The fuel mix for 2015 is presented in Figure 1.1.

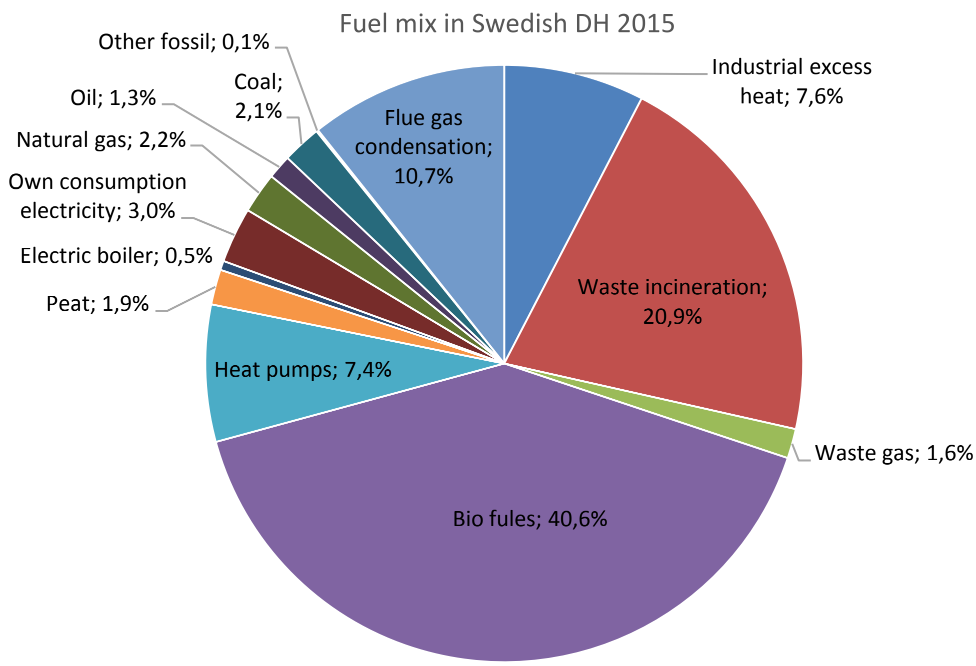

Figure 1.1 Fuel mix in Swedish DH 2015. Based on statistics from Svensk Fjärrvärme (2017)

The fuels shown in Figure 1.1 differ greatly from each other in terms of cost and environmental impact. Many Swedish DH systems use some type of bio-fuel, garbage incineration, and/or industrial excess heat to cover the base load, and fossil fuels are mostly used to cover the peak loads. This is true for the DH system in Gothenburg, Sweden, and a yearly dispatch for that DH system is shown in Figure

1.2. On top of diversified fuels, a fair share of the heat is generated in combined heat and power (CHP) plants and heat pumps (HPs), and the heat cost of these units is hence heavily dependent on the electricity price for the present hour. These factors cause the cost and environmental impact of heat generation to be highly dependent on when the heat is used. It is therefore not only important to reduce the heat use in buildings but also to control the buildings so that they use heat when it is most favorable to generate.

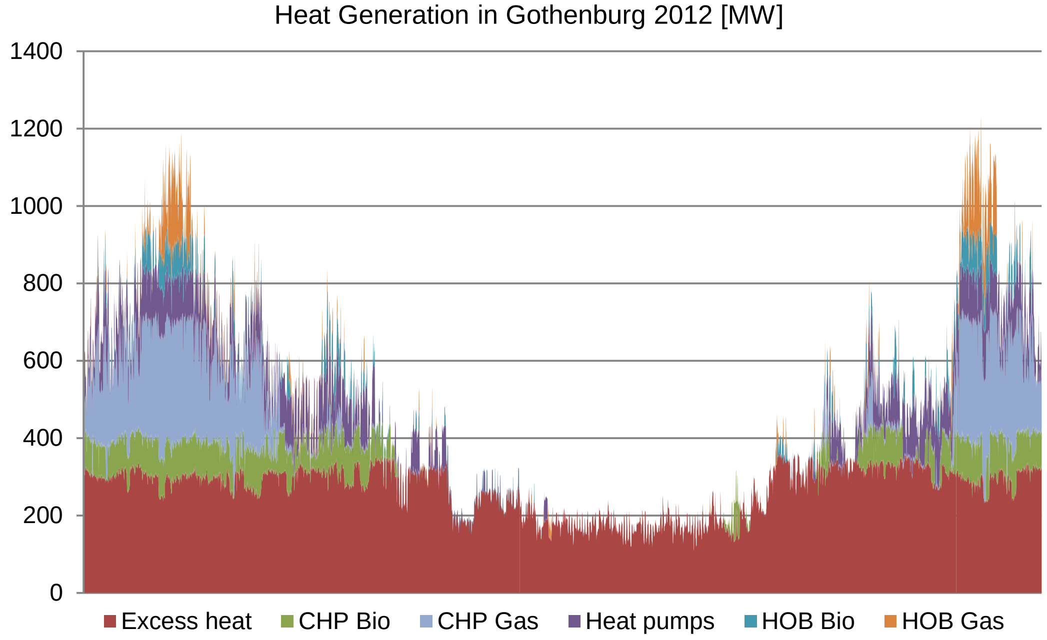

Figure 1.2 Heat Generation in Gothenburg DH system during one year

Currently, there are several commonly used control methods for reducing the heat use in buildings. Most focus only on reducing total heat use, without taking varying costs of heat into consideration. There are, however, possible methods for controlling the space heating in buildings that take varying costs into consideration. These methods rely on utilizing flexibility in the heat load, and one example of flexibility that can be utilized is storing heat in the thermal inertia in buildings. This allows heat loads to be shifted in time from hours with large costs of heat generation to hours when the heat generation is more favorable. This can be seen as a method of adding flexibility to the DH system (or any other energy supply system). Flexibility in DH systems is desirable since it provides opportunities to better optimize the generation of heat. There are currently several sources of flexibility that are being utilized in some DH systems, e.g., thermal energy storage (TES) in hot water tanks (HWT) and using the water in the distribution pipes as a TES. These flexibilities have their limitations (e.g., a HWT requires a substantial investment cost, and using a distribution system as TES has limited potential and affects generation efficiency), and it is therefore of interest to study new methods of adding and utilizing flexibility in DH networks. This work covers two methods for adding flexibility to energy supply systems:

Utilizing thermal inertia in buildings as TES is based on the idea that there is already large thermal inertia in buildings' mass and hydronic heating systems that can be utilized to store heat. By periodically over- and under-heating buildings, heat loads can be shifted in time while causing a variation in indoor temperature that is small enough to not negatively impact the thermal climate. This is referred to in this work as building inertia thermal energy storage (BITES).

Heat source shifting in buildings with DH and HP is based on the idea that the cost of generating electricity and the cost of generating heat in a DH network are not heavily correlated. In a building with both a HP and a DH connection, the heat source with the lowest cost in a system perspective is constantly shifting. If the buildings are offered hourly heat and electricity prices (or are controlled as if they were), it can be beneficial to constantly shift which heat source in the building is prioritized to cover the base load.

The reason for focusing on these two methods is that they are expected to potentially have a very favorable ratio between impact and implementation cost. The potentially low cost is because these methods are simply improved control methods that utilize already existing equipment and assets. In the best suited buildings, these methods require only adjustments to the software in the control equipment, but some buildings may require supplementary control equipment, sensors, and/or IT-infrastructure. However, the required investments are still very small compared to, for example, construction of a HWT.

Simply adding flexibility to DH networks (and other energy networks) is of no good if there is no control system that can utilize it. This is why a smart energy grid is required. "Smart" is one of the top buzz-words of this decade and, in this context, it implies that a system is able to interpret information, evaluate alternatives, and take action. Such systems are required in order to best utilize flexibilities to achieve increased economic and environmental preference. This includes some method of integrating the control systems in the buildings with the optimization in the energy supply system. The goal is to optimize control systems in the buildings together with the entire energy supply system to minimize the total system cost. A fully centralized control system that optimizes the local control systems in all connected buildings in, e.g., a DH system is probably neither a realistic nor a desirable solution. A method of integration that is as close to a total cost optimization as possible while still being practical is therefore desirable. For this purpose, using heat price control (HPC) as a method of integration is tested and evaluated. This control solution is a type of demand response that utilizes hourly heat prices that are based on the marginal cost of heat generation. The control system in each building is given the task of minimizing the total heating cost with individual heat prices for each hour. The same principle works whether the heating system has the possibility to utilize building thermal inertia to shift heat loads in time or if the building has the possibility of heat source shifting between two heat sources, e.g., DH and HP (both with hourly prices). These control methods should utilize the available flexibility in the buildings to minimize cost in a system perspective without the drawbacks of a fully centralized control system.

1.1 Objectives and Methods

The objective of this work is to study how flexibility in space heating can be utilized to achieve cost savings in the energy supply system. The energy supply systems considered in this work include the DH systems in all the studies as well as the electrical grid in some of the studies. The considered control methods are HPC, utilizing the thermal inertia in buildings as a TES and heat source shifting with DH and HP. For both BITES and heat source shifting, the study is carried out in three steps with linked objectives.

- **Building level:** The objective is to evaluate how and to what extent typical buildings can contribute to flexibility in their energy supply system(s). This should result in scalable parameters and models that can be used to study large-scale implementations.
- **System level:** The objective of this step is to evaluate the value of flexibility in buildings on a system level. The focus is on optimizing the flexibility in buildings to achieve cost saving in DH systems and electrical grids. All studies are optimized towards minimizing cost, but the environmental performance is also evaluated in some of the studies.
- **Implementation of control:** The objective in this step is to find a practical method for controlling heating systems in buildings to minimize the operational cost in DH systems and electrical grids. HPC is tested as a control method for BITES, and it uses hourly heat prices based on marginal cost of heat generation as a control signal.

The general method includes literature reviews, pilot tests, building modeling and energy system modeling. The central concepts are briefly discussed in this chapter, and more detailed descriptions can be found in each of the main chapters in this report as well as in Papers I–V. Parts of this study have also been carried out in the form of a master's thesis. The author of this doctoral thesis has been the main supervisor for eight master's theses within (or at least highly related to) this research project (Dreano, 2013, Machu, 2014, Elebo and Petersson, 2013, Appelgren and Erlandsson, 2014, Carlsson, 2016, Holm and Ottosson, 2016, Jangsten, 2016, Siiskonen, 2015). The author has also collaborated on one other master's thesis related to this research project (Sirén, 2014). All these master's theses are frequently referenced in this work.

Two pilot tests have been carried out within this project. The first is referred to as the Thermal Response Pilot Test and was designed to evaluate to what extent building thermal inertia can be used for short-term TES while still maintaining good thermal comfort. The measurements have been carried out by Göteborg Energi AB on five multifamily residential buildings with radiator heating systems during a full year. The second pilot test is referred to as Heat Price Control (HPC) of Building Inertia Thermal Energy Storage (BITES). Hourly heat prices are used as input to a control system that utilizes the thermal inertia in buildings. This test is carried out in collaboration with Göteborg Energi AB, and the control system is provided by NODA Intelligent systems AB. It includes three months of testing in 19 residential properties with a total of 1,800 apartments.

Based on the results from the Thermal Response Pilot Test, models for BITES have been established. They are used to study how a large-scale implementation would impact heat generation in DH networks. Simulations are performed in a Matlab program (coded by the author) with the target to minimize heat load variation as well as in a model of Gothenburg DH network in the modeling language GAMS with the target to minimize total system operating cost.

The study of heat source shifting is based on measured heat loads in residential buildings in Gothenburg. The studied buildings currently have DH as their only heat source. A simple model of an exhaust air heat pump (EAHP) is added to the system where the coefficient of performance (COP) is a function of the temperature in the radiator system. The size of the EAHP is based on a survey of Energy Performance Certificates for similar buildings.

Generally, the system boundary in the studies includes the DH system the buildings are connected to, but in the studies where HPs are considered, the system boundary also includes the electrical grid. There is a major difference in the system boundary regarding DH systems and the electrical grid. When studying the effects of flexibility on the DH system, the interaction is two way, i.e., the control in the buildings affects the total heat load and cost in the DH system and vice versa. The interaction with the electrical grid is one way, i.e., the cost of electricity only affects how the buildings are controlled, not the other way around.

1.2 Limitations

Most of the studies are carried out in the context of the DH network in Gothenburg. This is a fairly large DH network, with 4 TWh yearly heat generation and a total of 22 heat sources with high diversity. Measures have been taken to make the results of this work general and applicable to other DH systems. Emphasis is put on using relative parameters that can easily be scaled and applied in other systems, e.g.:

- BITES model parameters are measured in degrees and degree-hours, which can be translated to power and energy with a energy signature.
- Heat load variations are measured with relative daily variation that can be scaled and applied to other DH systems.
- Economic savings and heat-/electricity- cost/price are presented as fractions or relative values.

The two methods for adding flexibility are solely applied to multi-family residential buildings. No other buildings, such as commercial, industrial, or single family homes, are considered. There are a number of reasons for this imposed limitation:

- Multi-family residential buildings are by far the largest customer segment in most DH systems. In Gothenburg, over 50% of all generated heat is used in multi-family residential buildings (not counting two-family houses or mixed commercial and residential buildings).
- Multi-family residential buildings are fairly homogenous in their heating systems configuration: Heating is by radiator systems with circulating water, cooling is non-existent, etc.
- Many multi-family residential buildings are well suited as BITES since they are made of structural material with large thermal mass and radiator heating systems with high thermal inertia.

All studies are optimized towards lowest cost, and the resulting environmental impact is studied in some parts of the work. The reasoning behind this is that energy operators optimize their daily operation towards lowest cost. Environmental impact is somewhat "included" in the cost through, e.g., taxes on less favorable sources of heat, but perhaps more on a strategic level, e.g., deciding what heat sources to invest in. Nevertheless, at least in Sweden, there is a strong correlation between operational cost and environmental impact for the heat sources in DH systems.

1.3 Previous Research

The literature review is split into three parts:

- Heat Loads in DH Networks
- TES in Buildings
- Heat Source Shifting

1.3.1 Heat Loads in DH Networks

A main purpose of adding flexibility to DH networks is to affect the heat load profile so that the required heat can be generated with higher system efficiency and environmental performance. Therefore, it is important to survey the load characteristics of DH networks.

The heat loads of six Swedish DH systems are studied by 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 (2010) as an assessment method for describing daily load variations. This assessment method has also been refined by 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 and price variations throughout this thesis and will be elaborated on further in 2.1. Twenty Swedish DH systems of different sizes have been analyzed, and the annual average relative daily variation has been determined, among other parameters. The annual average relative daily variation ranges from 3–6% for these systems. This approach has also been used to study heat load patterns on a consumer level in 141 substations by 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.

1.3.2 TES in Buildings

TES in buildings is one of the methods for increasing flexibility in energy networks studied in this thesis. The studied method uses the already present thermal inertia for sensible heat storage. There are, however, other methods possible for TES in buildings. A good overview of them these methods is presented by Heier et al. (2015). Heier refers to the method of TES in buildings that is studied in this thesis as Passive storage – Sensible thermal mass.

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, by Österlind (1982). The main aim of this test was to increase security of supply for heat customers located farthest from a heating plant in case of a heat 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 by Kärkkäinen et al. (2003). The test revealed that the heat load could be reduced by 20% to 25% over 2–3 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.

A residential area in Karlshamn, Sweden, was the subject of a pilot test presented by Wernstedt et al. (2007) and by Wernstedt and Johansson (2008) in which demand side management was implemented in the form of agent-based load control. The control was distributed among agents on the generation 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 peak load and energy use 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, as presented by Wernstedt et al. (2008). A larger subsequent test of this technology was performed in three major Swedish district heating systems by 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 15–20% 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 by 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 4–8 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 by Olsson 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, 218–330 h.

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.

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

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

The effects of three energy conservation measures on the local energy system in Linköping, Sweden, were compared by 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 by Johansson et al. (2010).

A control approach similar to HPC with hourly heat prices has been tested in a simulation study by Van Deventer et al. (2011). A variable heat price was used, and the indoor temperature set-point was set as a function of the heat price each hour. The results showed a reduction in daily peak load by 20% and variation in indoor temperature of 1°C during a period with outdoor temperature of -15°C.

1.3.3 Heat Source Shifting

EAHPs constitute a growing segment in the Swedish heating market since this solution can provide a good ratio between performance and investment cost compared to other HP solutions. In most applications, it is impossible or uneconomic to design an EAHP that covers the entire heat demand in, e.g., a residential building. EAHPs are therefore often combined with DH. No study that includes heat source shifting between EAHP and DH has been identified, but one study that includes heat source shifting between ground source HP and DH have been found. The combination of EAHPs and DH without heat source shifting has been studied more thoroughly.

A study of potential energy conservation measures in Swedish multi-family residential building stock by Bröms and Wahlström (2008) examined the impact that installing EAHPs would have on DH demand. The results show that if EAHPs are added to buildings heated with DH, the DH heat load will have a reduced base load, and a larger share of the load will be peak loads. The added electrical load will be fairly constant during the heating season.

A more detailed study of the impact that installing EAHP and other energy conservation measures will have on system efficiency and greenhouse gas emissions of DHSs has been carried out by Lundström and Wallin (2016). The authors conclude that the results are heavily dependent on the choice of assessment factors, but the case of shifting from DH to a combination of DH and EAHP increases the CO_2 emissions for all sets of assessment factors studied. The results regarding primary energy use are more mixed but indicate that installing EAHP in DH heated buildings increases the primary energy use.

Heat source shifting with an approach similar to that in Paper III (using hourly heat and electricity prices) has been studied in a simulation study by Borg (2015). The heat source shifting aspect was part of a more advanced energy solution in a residential building with solar photovoltaic, electric vehicle charging, battery storage, ground source HP, DH, and HWT. The results show that it is beneficial to have both DH and HP in the building when hourly prices are considered, although it cannot be concluded how beneficial the actual heat source shifting is, since no comparison is made with the case when the HP is always used for base load.

1.4 Disposition

This thesis is divided into seven chapters, and versions of the five journal articles and conference papers are included in the appendix. **2 Basic Concepts** provides some basic knowledge about DH systems that is fairly specific to this work. **3 Smart Energy Grids** describes interaction between the usage and the generation side in energy supply systems and defines the hourly heat and electricity prices that are used in this work. **4 Thermal Energy Storage In Buildings** presents a summary of the results from Papers I, II, IV, and V. This includes a thermal response test, two simulation studies, and a pilot test where hourly heat prices are used as control input to a BITES. **5 Heat Source Shifting** presents a summary of the results from Paper III, which includes a survey of buildings with several heat sources and a simulation study of heat source shifting between DH and EAHP in multi-family residential buildings. **6 Conclusions** summarizes the main conclusions and further elaborates on some aspects of the work. This chapter also includes suggestions for future work.

2 BASIC CONCEPTS

This chapter provides some basic knowledge about DH systems, electrical grid, and heat use in buildings. It is by no means a full theory chapter but aims to provide knowledge and definitions that are fairly specific for this work. For a more thoroughly theoretical description, please read *District Heating and Cooling* by Frederiksen and Werner (2013).

This work focuses on the space heating of buildings in the most cost efficient way, where the system boundary is expanded beyond the buildings to also include the energy supply systems that generate and transfer the energy. In Swedish conditions, the energy to be used for heating purposes in buildings is most often transferred to the buildings as electricity in the electrical grid or as heat in DH networks (Frederiksen and Werner, 2013). These are the two energy supply systems that this work focuses on. From the European and global perspective, heating buildings with natural gas from a gas grid is also very common.

2.1 Heat Load

Heat is used in buildings mainly for two purposes: space heating and hot tap water. Space heating is mainly dependent on outdoor temperature (environmental load), and hot tap water is mainly dependent on the behavior of the tenants (social load). The individual customer loads are aggregated in energy supply systems and contribute to the total system load. In addition to the customer loads, there are also distribution losses which can be seen as a load. Loads can further be split into power loads and energy loads and are defined as follows:

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

All energy loads can simply be added to the distribution losses to make up the total system 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 by Broadwater et al. (1997). Different types of power loads have different diversity factors and are, hence, aggregated to different extents. 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 maximum power load caused by space heating is then close to the sum of all individual maximum 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, but how much smaller depends on the number of aggregated loads, size of the customers, customer type, etc.

Relative daily variation is used as a measurement for variations in heat load (and other parameters) throughout this work and is as defined by Gadd and Werner (2013a). The reason for choosing this measurement is that it is independent of system size and can be applied to describe variations in any time-dependent parameter. This makes the results from this study applicable to other DH systems than the one in Gothenburg that this particular study uses as the main object of research. The relative daily heat load variation is defined as:

$$Q_{d.rel.var} = \frac{\frac{1}{2}\sum_{h=1}^{24}|Q_h - Q_d|}{Q_{yr} \cdot 24} \cdot 100\ [\%] \tag{2.1}$$

where Q_h is the heat load during hour h, Q_d is the daily average heat load, Q_{yr} is the yearly average heat load, and $Q_{d.rel.var}$ is the relative daily heat load variation. The relative daily heat load variation is also graphically illustrated in Figure 2.1.

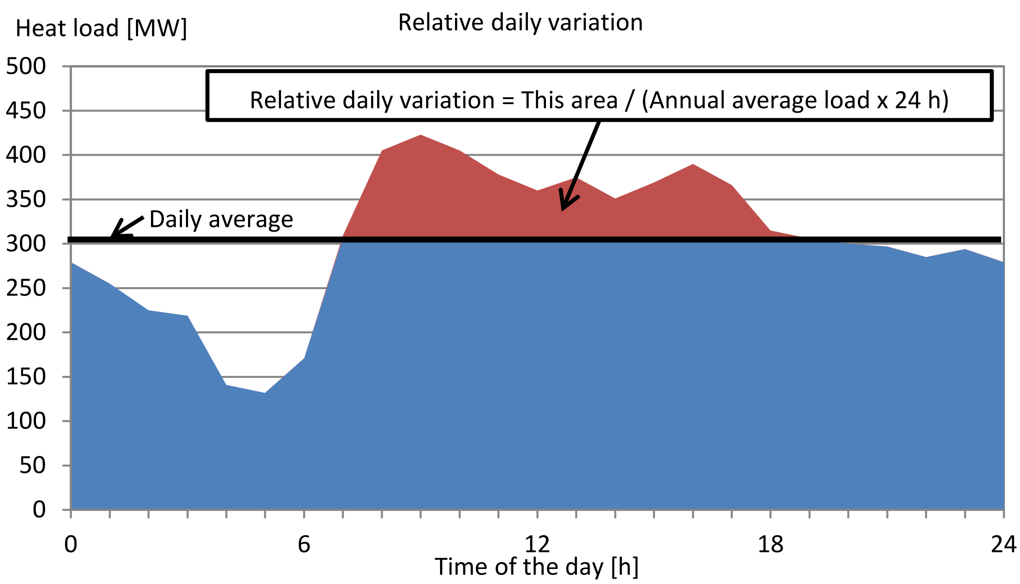

Figure 2.1 Graphical representation of relative daily variation, $Q_{d.rel.var}$

In Paper IV, the relative weekly variation is also used as a parameter for evaluation. The definition is analogous with relative daily variation, but the heat load each hour is instead compared to the weekly average heat load and can be expressed as:

$$Q_{w.rel.var} = \frac{\frac{1}{2}\sum_{h=1}^{24 \cdot 7}|Q_h - Q_w|}{Q_{yr} \cdot 24 \cdot 7} \cdot 100\ [\%] \tag{2.2}$$

where Q_w is the weekly average heat load and $Q_{w.rel.var}$ is the relative weekly heat load variation.

2.2 Electrical Grid and DH System Interaction

The two energy supply systems considered in this work are DH systems and the electrical grid. They should not be viewed as two separate systems since they interact with each other in several ways. The most straightforward interaction is through the heat generation in DH systems since many DH systems utilize CHP and/or HPs. In Swedish DH systems, 42% of the supplied heat was generated in CHP and 6% was generated in HPs in 2015 (Werner, 2017). CHP couples heat generation with electricity generation while HP couples heat generation with electricity use. These couplings causes the operation of CHP and HP to be dependent on the value of both electricity and heat. A consequence of this is that adding flexibility to either DH systems or the electrical grid indirectly adds flexibility to the other energy system as well. One example of this is that TES in DH systems allows for decoupling of heat demand and heat generation, adding flexibility to the operation of CHPs and HPs. This allows for CHPs and HPs to better fit their electricity generation and usage to the conditions in the electricity grid.

Another connection between DH systems and the electrical grid that exists but is not actively utilized is buildings with both DH and some type of electrical heating, e.g., a HP. Currently, such combined heating systems most often use the HP to cover base load and DH to cover peak load. If incentives are given to the building owner (e.g., hourly heat and electricity prices) and a control system that can handle heat source shifting is installed, this flexibility can benefit both DH systems and the electrical grid. Such solutions could allow for operating HPs in buildings as if the HP was a part of the DH system, but with the restriction that the HP (generally) cannot provide its excess capacity to the DH network.

There are also some major differences in flexibility in DH systems and electrical grids that needs to be kept in consideration throughout this work. First, DH systems 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 a 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 currently exploited in some DH systems. In an electrical grid, load and generation needs to be balanced at any given time. This causes the variations in electrical load to set the conditions for the generation. In an electrical grid where the electricity is supplied by mainly hydro power and combustion plants, it is possible to match load variation with a variation in generation. It gets more complicated when intermittent electricity generation, such as wind or solar, is introduced to the system. In electrical grids with a high share of intermittent electricity generation and load share of balancing electricity generation (e.g., hydro), problems can arise because there is little to no flexibility in the load or in the generation. This puts high demands on the 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.

2.3 Gothenburg DH System

Throughout this work, the DH system in Gothenburg, Sweden, is used as an example of application in simulations and environment for pilot tests. The conditions in this DH system are therefore of importance since they may affect how applicable the results from this study are on other DH systems. The DH system in Gothenburg has a yearly heat generation of about 4.2 TWh and supplies heat to roughly 20,000 substations. The heat supply is covered by 22 heat sources, presented in Table 2.1. The DH network is also connected to four neighboring DH networks from where heat is both imported and exported.

Table 2.1 Heat sources in the Gothenburg DH system. Where several heat sources are grouped, their total capacity (heat output) is presented.

Type	Unit(s)	Primary fuel	Capacity [MW]
Excess heat	Renova CHP	Municipal waste	185
	Preem	Industrial excess	60
	ST1	Industrial excess	85
CHP	Sävenäs CHP	Wood chips	110
	Rya CHP	Natural gas	295
	Högsbo CHP	Natural gas	85
HP	Rya HP 1-4	Electricity	160
HOB	Rya HOB 1-2	Wood pellets	100
	Angered HOB 1-3	Bio oil	105
	Sävenäs HOB 1-2	Natural gas	150
	Rosenlund HOB 1-3	Bunker oil	420
	Rosenlund HOB 4	Natural gas	140
	Tynnered HOB	Fuel oil	20

The most unique aspect of Gothenburg's DH system is the very high share of excess heat, covering about 55% of the heat supply on an average year. The excess heat has a very low cost and, in the summer months, it can cover almost the entire heat demand. In all studies in this work, the cost of excess heat has been set to zero. About 30–35% of the yearly heat generation is covered by CHP, and 7–10% by HPs that utilize sewage water as a heat source. The peak loads are covered by HOBs, and their yearly share of the heat generation is therefore heavily dependent on the weather conditions, but a magnitude of 5% is fairly common. The large diversity in heat sources and the interaction with the electrical grid through HPs and CHPs causes the conditions for generating heat to constantly shift in this DH grid. This makes the DH system in Gothenburg an interesting test environment for this project, but it should also be kept in mind that all results might not be directly applicable to other DH systems with, e.g., only a CHP plant and a HOB for peak loads.

3 SMART ENERGY GRIDS

Traditionally, electrical grids and DH networks have had a low level of information available and there have been a limited set of available flexibilities. This is because traditional electrical grids and DH networks are mainly demand driven. Customers are usually free to use electricity and heat at any given time. They pay an energy price that is usually fixed over periods of one month or more. Electrical and heat demand causes loads that need to be balanced by generation. The electrical grid needs to have balanced load and generation at all times while there is some built-in flexibility in DH networks if the temperatures are allowed to vary. The introduction of smart energy networks is meant to facilitate the utilization of flexibility.

3.1 "Smart"

"Smart" is one of the most frequently used buzzwords of this decade, but what does it really mean in the context of energy grids? The term is 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

Recent technological advances and policies by the European Commission (2009) have drastically increased the amount of available information in energy grids, e.g., through the rollout of smart meters. At the same time, the amount of usable flexibility is increasing. This combination enables smart energy grids that have the potential to evaluate energy systems with their flexibility and control them in a way that meets given demands at the lowest possible cost (economical, environmental, or any arbitrary cost function). This work primarily studies two methods for increasing flexibility in energy grids, but there are many possible methods, including but not limited to:

TES in buildings

By storing heat in buildings, consumers' heat demand becomes flexible and the flexibility can be utilized in the energy supply system if there is some connection between the building's control system and the energy supply system. One method for TES in buildings is covered in detail in this work: BITES. Other methods are presented in 1.3.2 and they are described in more detail by Heier et al. (2015).

Buildings with several heat sources

In buildings where the energy used for heating can be supplied from several systems, there is an available flexibility that can be utilized by actively shifting heat source to the most favorable at each hour. This possibility is covered in this work for shifting heat load between DH and EAHP, but can generally be applied to any heat sources.

Network storage in DH

There is a built-in thermal storage capacity in the water volume in DH networks. This TES can be utilized by varying the supply temperature from the heat generation. A control technique utilizing this TES capacity is presented by Basciotti et al. (2011).

Hot water tank (HWT)

The most utilized technology for TES in DH systems is HWT. In Sweden, 104 of the 167 larger DH systems utilize this type of TES (Eriksson, 2016). Since this technology is so commonly used, it is of great interest to compare TES in buildings with HWT. This is done in this work in Paper IV and in a master's thesis by Holm and Ottosson (2016). The impact of different sizes of HWTs in the DH system in Gothenburg have also been covered in a master's thesis by Machu (2014).

Seasonal TES

There are several technologies available for seasonal TES, e.g., pit storage, cavern storage, and borehole storage. These types of TES can add flexibility to, e.g., a DH system on a seasonal scale. Case studies for two seasonal TES solutions in the DH system in Gothenburg have been carried out in the form of two master's theses within this study: low temperature borehole TES by Siiskonen (2015) and cavern TES Holm and Ottosson (2016).

User flexibility

There is also some flexibility in social heat loads, and end users can interact with the control of heating systems in buildings. This flexibility can be utilized through the usage of, e.g., "smart home technology." A study on enabling residents to be informed of the status and in control over their heating system has been carried out by Renström (2016).

Diversified heat sources in DH networks

Having diversity in available heat sources can also been seen as a flexibility. This flexibility can be utilized when the total heat demand and distribution limitations in a DH grid do not fully restrict which heat sources need to be in operation at the given time. This can be especially useful if the merit order of the heat generation is constantly changing, e.g., caused by dependency on electrical price by CHP and HPs.

3.2 Integration and Control

In order to utilize flexibility to improve the economic and environmental performance of energy systems, there needs to be some method for optimization and control. Optimization of energy systems should be performed on three time horizons:

Strategic

Strategic optimization is about making the right investments in energy systems. The time horizon is usually years and the decisions should preferably be based on accurate modeling of the energy network or some other tool for evaluation. How flexibility is provided by large-scale implementations of BITES and how heat source shifting affects DH systems have been evaluated in the work, using several methods: studying load variation (Paper II), marginal cost study (Papers III & V) (Carlsson, 2016) and energy system modeling (Paper IV) (Holm and Ottosson, 2016).

Operational Planning

On a shorter time horizon (the coming hours and days), the conditions for an energy system are set. The operation of the DH system should be planned so that all heat demands will be fulfilled at the lowest possible cost. To plan the operation in advance is important, e.g., since electricity (generated by CHPs and used by HPs) is traded one day in advance on Nordpool (2017). In a traditional DH system with few degrees of freedom, the planning is a relatively "simple" task. If heat demand is known (through forecasts) and there is no flexibility considered (e.g., no TES or heat source shifting) the heat generation must match the demand at all times. The heat generation is planned according to the heat sources' merit order (utilizing cheaper sources first). As soon as flexibility is added, the optimization becomes exponentially more complex, thus putting higher demand on software and personnel. The pilot test (presented in 4.6 and Paper V) is controlled on the operational planning time horizon by heat price control (HPC), i.e., the control system uses hourly heat prices based on forecasted marginal costs of heat generation as input.

Real Time Control

The real time control of DH networks (heat generation, pumps, etc.) is handled by operative personnel in a control room. They base their control on operational planning but adjust the actual operation if forecasts are not accurate or any other situation occurs. Allowing flexibility in DH networks to be controlled at this level would provide better opportunities for optimizing DH systems. The control can be automatic (a certain parameter in the DH system, e.g., total heat load or pressure in a pipe causes an action, e.g., a building switches heat source from DH to HP) or performed manually by the operator. The control system used in the pilot test presented in Paper V has these capabilities but it is not utilized during the test since such control could interfere with the goal of the test, which is to evaluate HPC.

3.3 Marginal Cost and Price

Marginal cost and prices based on the marginal cost (for both heat and electricity) is used as an input for the control system and as a tool for evaluation throughout this work. An hourly resolution for marginal cost/price is used since this is the resolution used on the Nordpool electricity spot market (2017), and it is a very common resolution for data in DH networks.

3.3.1 Hourly Heat Price

In order to optimize the control of BITES (in Paper V) and heat source shifting (in Paper III), hourly heat prices are used as a control signal from the DH network operator to the buildings' control systems. In Paper III, hourly heat prices are used together with hourly electricity prices to simulate control of heat source shifting. For both studies, the prices are equal to the marginal cost of heat generation in the DH system in Gothenburg, but the prices for Paper III are based on historical values from 2013–2014, while the prices for Paper V are based on forecasts. For both studies, the prices are provided by the operational management group at Göteborg Energi AB (the DH provider in Gothenburg). The process of calculating the hourly heat prices is preformed in four steps, where only the last two are required for the historical prices (since the heat generation of each unit is known):

1. **Forecasted prices:** A heat load forecast for the coming 72 hours that is created at least once a day based on weather forecasts and historical heat loads.
2. **Forecasted prices:** Based on the heat load forecast, a heat generation forecast is created by a dispatch model that matches heat generation to heat load each hour based on a merit order for the heat sources. The merit order is decided by the operational cost of each heat source, which is primarily based on fuel costs (and the price of electricity from Nord Pool Spot (2017) for CHPs and HPs). Factors such as minimum load, ramp time, and startup costs are also considered when heat sources are dispatched.
3. **Forecasted and historical prices:** The marginal cost of heat generation is calculated for each hour. This is most often the variable cost per MW of heat output from the most expensive heat source each hour. However, if the plant with the highest variable cost is running on minimum load, then the plant with the second highest operational cost determines the marginal cost. In the model, marginal cost should be the extra cost associated with generating, for example, 1 MW of extra heat in the DH system.
4. **Forecasted and historical prices:** A heat price is set for every hour based on the marginal cost of heat generation. In this work, the hourly heat prices are always equal to the marginal cost of heat generation, but in a more general case, this is not necessarily true.

For the study of heat source shifting in Paper III, historical hourly heat prices have been calculated for the years 2013 and 2014, and they are used in simulations and for evaluation. The prices are presented in Figure 3.1.

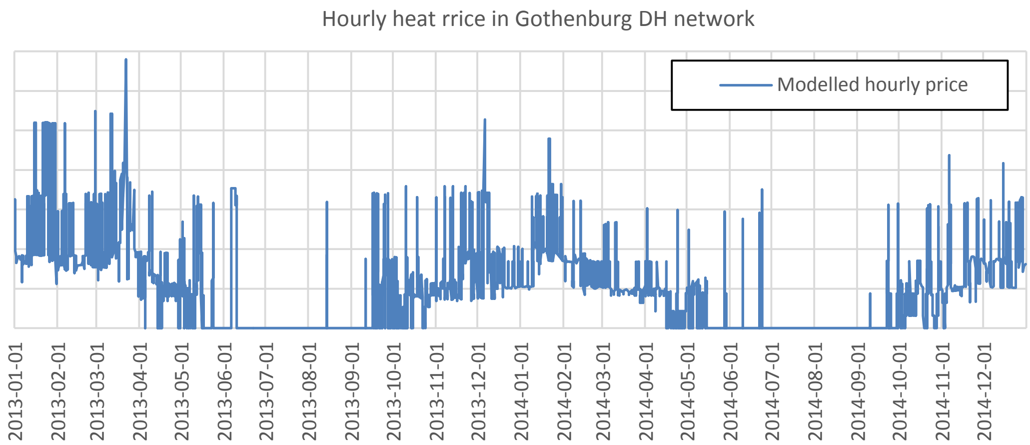

Figure 3.1 Hourly heat price based on marginal cost of heat generation in Gothenburg 2013–2014

Figure 3.1 shows that the modeled hourly price has a large variation, not only seasonally but also within short periods of time. It is not uncommon that there is a factor of 2–3 in price difference within the same day. It can also be noted that, during some hours, the marginal heat generation is zero, such as when industrial excess heat is on the margin or when there is an excess of heat in the DH system that needs to be cooled, e.g., in a river, as in Gothenburg.

3.3.2 Hourly Electricity Price

The hourly electricity cost used in this study is based on the Nordpool electricity spot market (Nordpool, 2017). The electricity trading is split on a day-ahead market, an intraday market, and a balancing power market, with the vast majority of the electricity traded on the day-ahead market. The function of the intraday market is to correct the mismatch in supply and demand that occurs due to imperfect predictions. As a customer, if you have an agreement with hourly electricity prices, they are based on the day-ahead market. This is therefore the data used in this study. Due to transfer capacity limitations in the national and international electricity grid, Nordpool is divided into 16 geographical areas. These areas will share the same prices when the transfer capacity in the grid is not limiting, and the prices will differ when the transfer capacity is limiting. Since most of the applications in this work are located in Gothenburg, the prices from the associated area SE3 are used. The price a customer with hourly electricity prices pays consists of five components:

- Nordpool elspot SE3 day-ahead price
- Electricity tax (294 SEK/MWh)
- Electricity certificate (varies ~35 SEK/MWh for the studied time period)
- Premium to the provider
- Value added tax (VAT) (25%)

Throughout this work, premium to the provider and VAT are not considered in electricity prices (nor in district heat prices). This decision is made since this work is about optimizing the heating in buildings from a system perspective, where the target is to minimize costs with a system perspective. A consequence of this decision is that there is most often no difference between cost and price.

3.3.3 Price Correlation

Figure 3.2 shows a comparison of the modeled heat price and electricity price in Gothenburg for the years 2013–2014. It is clear from Figure 3.2 that the variation in heat price is greater than the variation in the electricity price. The heat price has a strong seasonal variation that is not present in the electrical price. There are a few hours when the heat price is higher than the electricity price. During these hours, it would even be beneficial to generate heat with electrical heaters in the DH network. These hours currently number very few, but in the future, with intermittent renewable electricity generation, they may become more common. It should also be noted that electricity prices were at a historically low level during 2013–2014 (and were still low during 2015–2016), due to a number of circumstances in the Swedish electricity market, such as increased end user efficiency and a recent expansion of wind power. Forecasts of future electricity prices are highly dependent on the rate of decommissioning of nuclear power.

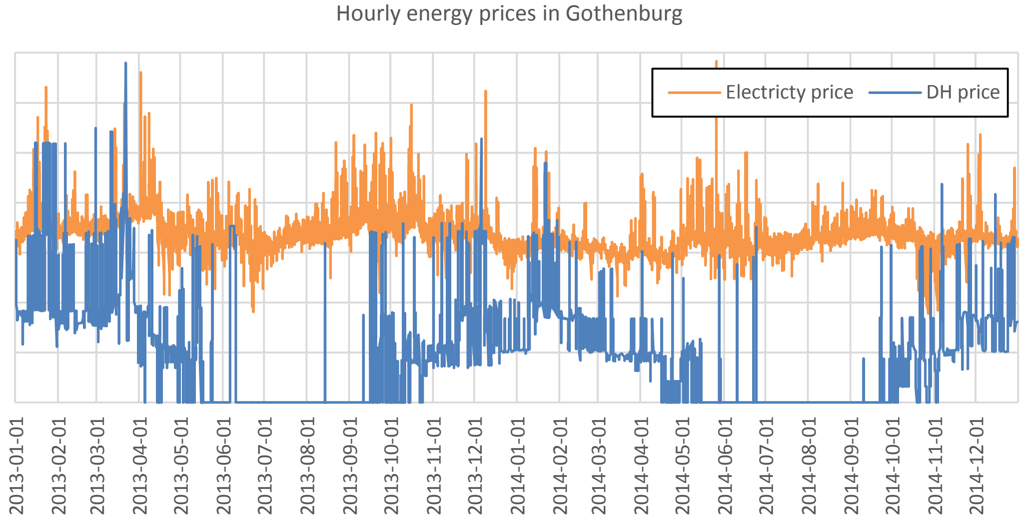

Figure 3.2 Hourly elecricity price and district heat price based on marginal cost of heat generation in Gothenburg 2013–2014

The Pearson correlation coefficient, *r*, is calculated for the heat price and electricity price. The formula is presented in:

$$r(a, b) = \frac{\sum(a-\bar{a})(b-\bar{b})}{\sqrt{\sum(a-\bar{a})^2 \sum(b-\bar{b})^2}} \tag{3.1}$$

where a and b are two arbitrary sets of data (in this case, electricity price and heat price), $\bar{a}$ and $\bar{b}$ are the average values of the data sets. The Pearson correlation coefficient, *r*, has a value between -1 and 1. If one data set can be expressed as a linear function of the other data set, then *r* = 1 or -1 (depending on if the realtion is positive or negative). If the data is completely random, then *r* = 0. The Pearson correlation coefficient for the hourly heat and electricity prices for 2013–2014 is 0.18, which indicates that there is some correlation but that it is not significant. This is further highlighted in Figure 3.3, which shows a scatter plot of hourly heat and electricity prices for 2013–2014. There is a very large spread in heat price regardless of electricity price. The only clear correlation that can be observed is in the highlighted area. The reason for the highlighted data points to correlate is that, during those hours, HPs were operating on the margin in the DH network. A likely reason for the low correlation between heat price and electricity price is that they are driven by different factors. Heat demand is a highly important factor for heat price, and it is mainly affected by outdoor temperature. Electricity price is more affected by factors such as industrial usage and appliances in homes.

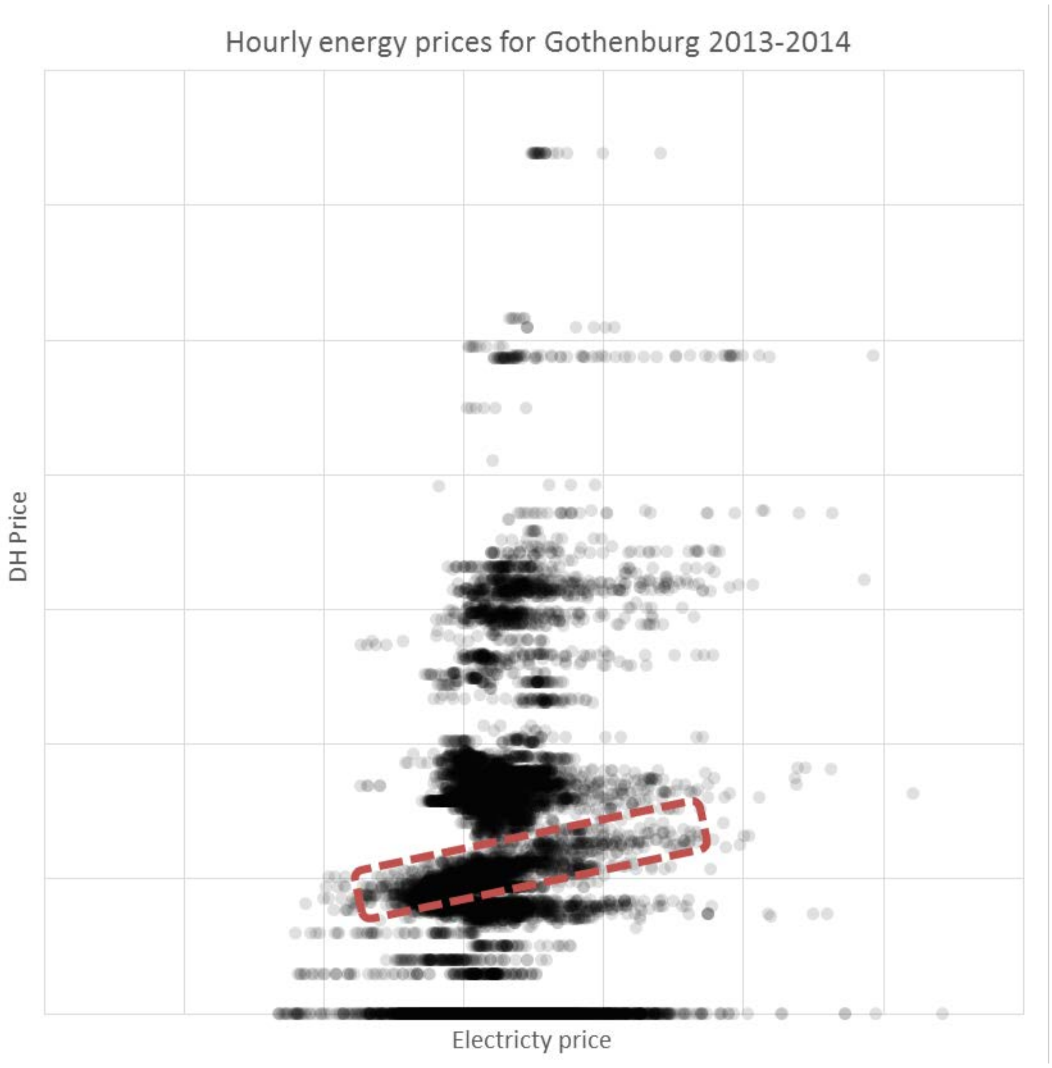

Figure 3.3 Elecricity and district heat price in Gothenburg 2013–2014. Each marker in the scatter plot represents one hour, and the markers are partly transparent, so a darker color indicates a common combination of heat and electiricy price. The highlighted area marks hours when HPs are operating on the margin in the DH system.

4 THERMAL ENERGY STORAGE IN BUILDINGS

The utilization of thermal inertia in buildings as TES with the purpose of load shifting has been studied in this work:

- Paper I evaluates a thermal response pilot test in five buildings utilized as TES. The relation between control signal, heat load, and indoor temperature variation is analysed. Based on these relations, parameters for a linear model of BITES are created. A broader, more statistical analysis of the thermal response test was also performed in the form of a master's thesis by Elebo and Petersson (2013).
- Carlsson (2016) expands the linear model to a dynamic model with two thermal nodes. The dynamic model is also used to simulate the building with a control system and hourly heat prices with the target to minimize heating cost. The hourly heat prices used are the historical heat prices based on marginal cost of heat generation (described in 3.3.1).
- Paper II uses the linear model from Paper I to study how a large-scale implementation of BITES can reduce the daily heat load variation in DH systems.
- Paper IV uses the dynamic model by Carlsson (2016) and further develops it to model how a large-scale implementation of BITES can affect the heat generation in a DH system in Gothenburg. The results are compared to a set up with a hot water tank (HWT). A similar study in the same DH system, but for an assumed future scenario in 2032, is also carried out by Holm and Ottosson (2016).
- Paper V presents the results from a large-scale pilot test where buildings with a total of 1,800 apartments are utilized as TES. The buildings utilize HPC with the target of reducing heating cost, i.e., heat use is shifted from hours with high heat price to hours with low price. The hourly heat prices used are the forecasted heat prices based on the marginal cost of heat generation (described in 3.3.1).

4.1 Thermal Response Pilot Test

During 2010 and 2011, the ability of five buildings to function as TES was tested in Gothenburg. The five buildings that were included in the analysis are all residential buildings with 3–5 stories. A summary of the building data is presented in Table 4.1. 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 1934 and 1950 and have a yearly heating demand of approximately 150 $kWh/m^2_{floor\ area}$ per year. This is normal energy performance for these types of buildings in the city of Gothenburg, 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 4.1 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 thermal mass	Heavy	Heavy	Light	Heavy	Heavy
Façade	Plastered	Plastered	Wood, brick	Brick	Brick

4.1.1 Test Setup

The heat deliveries to the buildings were increased and reduced during specified periods, and the indoor temperature, T_{in}, 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 Figure 4.1. 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 as 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_{in}, at the current outdoor temperature. T_{in} 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 by Johansson and Wernstedt (2010).

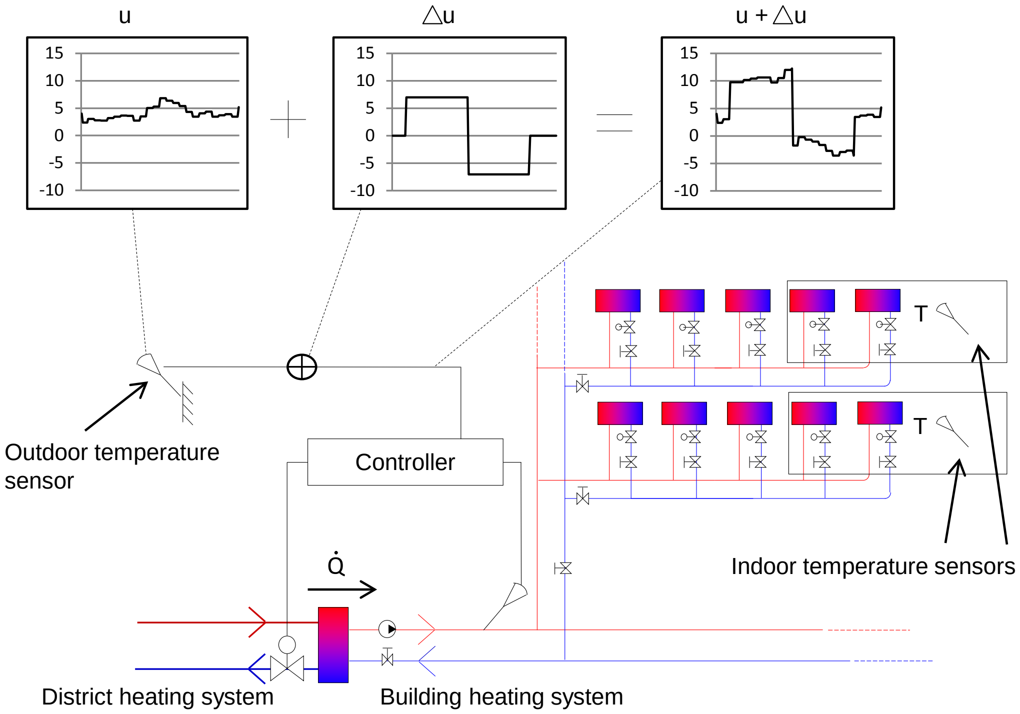

Figure 4.1 Schematic of how the control was implemented in the pilot test

In this test, the adjustments to the outdoor temperature signal, Δ*u*, 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 for using 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 Figure 4.2. 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 the outdoor temperature signal.

Cycle II was the most extensively tested. It was tested in all five buildings and it 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, it 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.

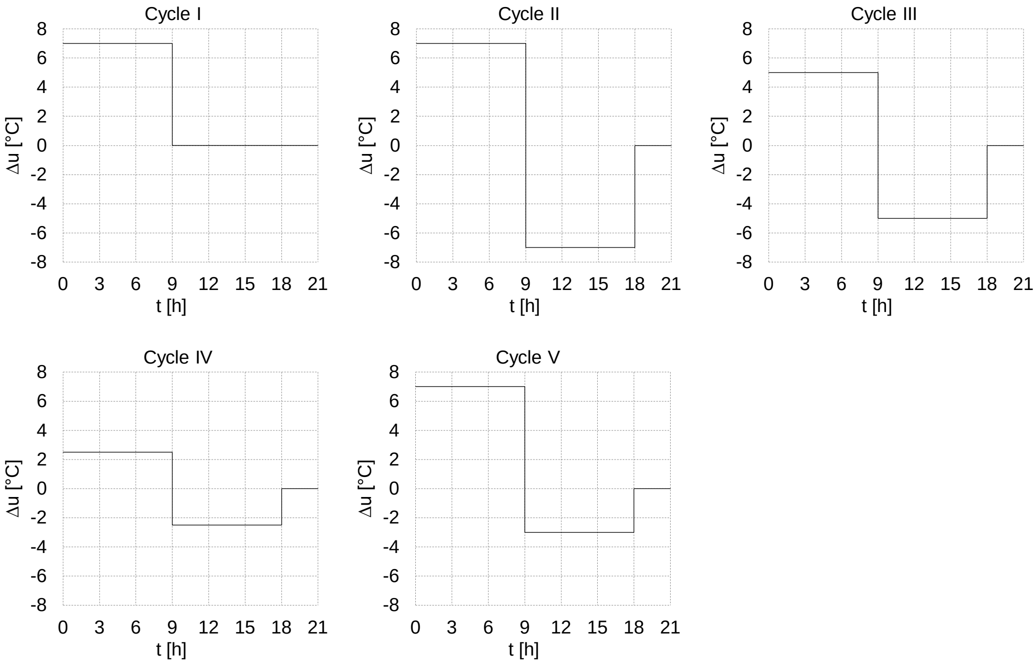

Figure 4.2 The five test cycles used in the pilot test

4.1.2 Heat Load

The relation between the total thermal flow to the buildings from the DH system, $\dot{Q}$, and the adjustment to the outdoor temperature signal, Δu, has been studied in Papers I & II. This has been done by separating the variations caused by the test from the climate compensation and 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 each other out since they will occur at different times in each cycle. An example of a heat delivery profile is presented in Figure 4.3.

The heat stored in the buildings is depicted in Figure 4.3 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$^2_{\text{floor area}}$, 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 I 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.

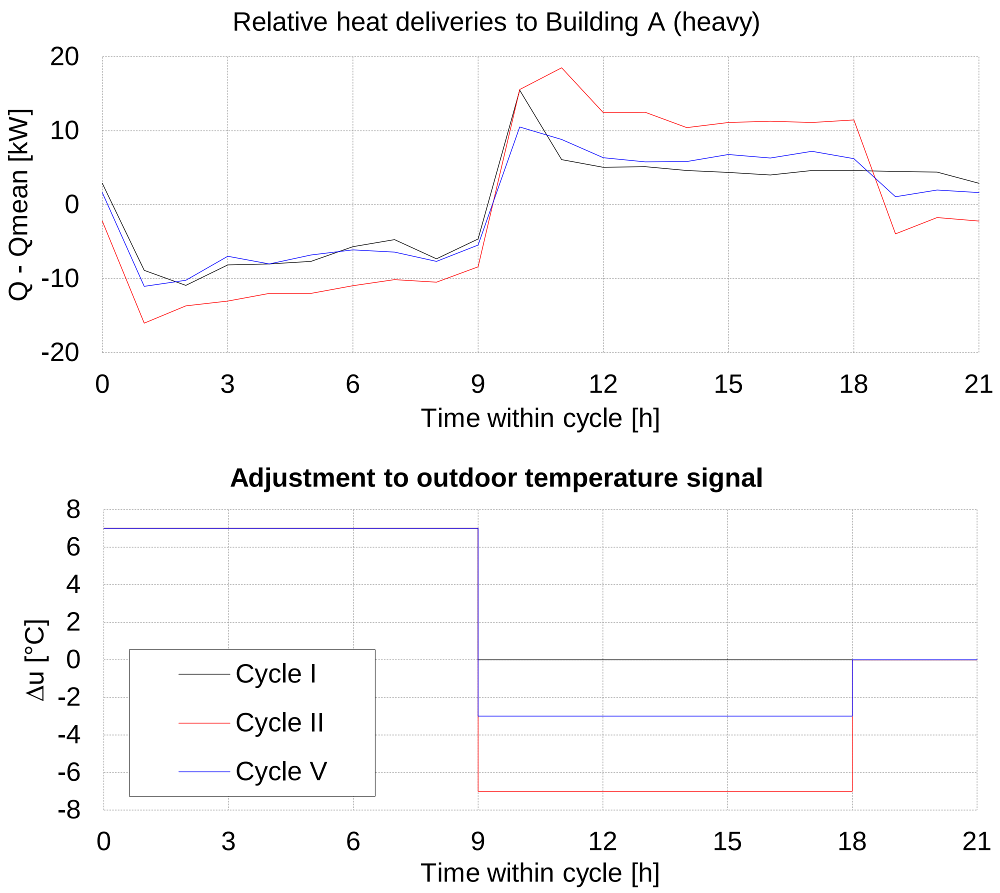

Figure 4.3 Heat use profiles relative to the control cycle average for Building A. Each profile is based on 5–8 weeks of measurements.

One concern that needs to be raised is if a control method that changes Δ*u* is counteracted by thermostat activity. This is briefly elaborated on in Paper I. The reason why it can occur is best explained with an example: A Building is charged with decreasing Δ*u*; 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 Figure 4.3 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.

4.1.3 Thermal Comfort

Most standards and practices for thermal comfort have emerged from the works of P.O. Fanger. The most well-known paper 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% are 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 fluctuations in indoor temperature affect thermal comfort. This has been considered in more recent standards. An amplitude in indoor temperature variation 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 acceptable indoor temperature variations 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 in order to maintain 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.

To separate variations in indoor temperature, T_{in}, 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 Figure 4.3. An example of these profiles in one of the heavy buildings is presented in Figure 4.4. For details on how these profiles are generated, see Paper I.

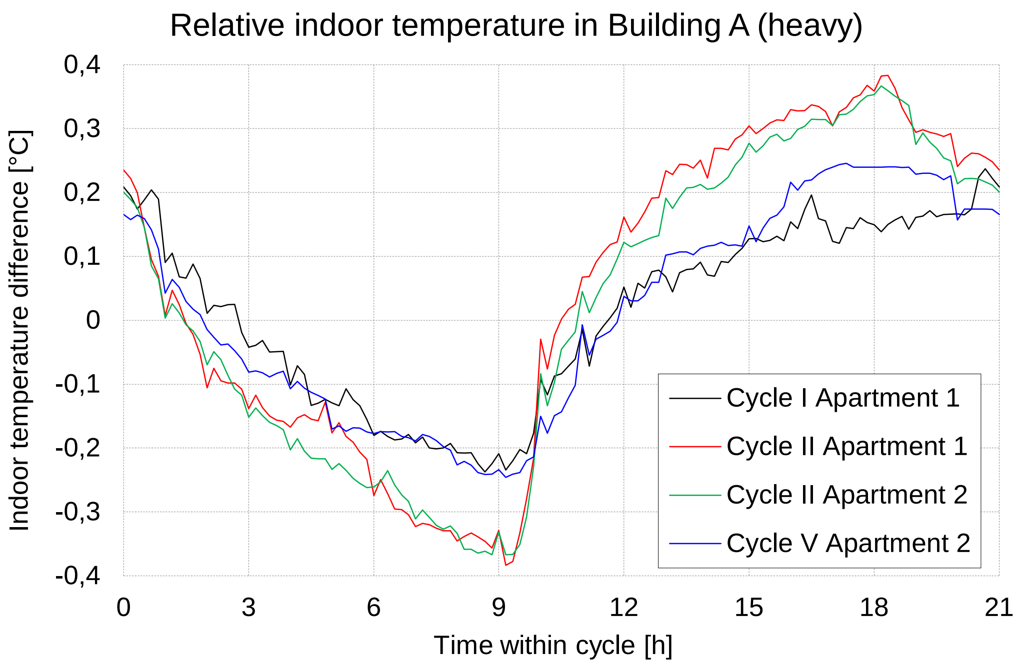

Figure 4.4 Indoor temperature variations caused by the pilot test. Each curve is based on average values over a period of 4–6 weeks.

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 4.2.

Table 4.2 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 4.2, 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 can 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 the 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 I. 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 BITES.

4.2 Modeling BITES

Based on the results from the thermal response pilot test, two models have been created for BITES: a linear model and a dynamic model. What is common for both models is that the part of the buildings' heat load that is required to keep the indoor temperature at a set-point is excluded. This part of the heat load is reflected in the DH system heat load when the models are used in simulations. Only the deviations from this heat load are handled in the BITES models. This approach is also used by Hedbrant (2001) and by Hagentoft and Kalagasidis (2015) for modeling BITES.

4.2.1 Linear Model

It has been shown in Papers I & II that buildings similar to those in the pilot test can be utilized as short-term TES with the restrictions from Cycle II and can 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, TES_{cap}, maximum charge rate, $TES_{ch.cap}$ and maximum discharge rate, $TES_{disch.cap}$. Thanks to the close-to-linear dependency of Δu, $\dot{Q}$, and $T_{var.21h}$, the results from the thermal response pilot test can be simplified into these three parameters. These values for Building A, with regard to the demand of not causing indoor temperature variations larger than ±0.5°C, can be derived from Paper I and are summarized in Table 4.3. All three modeling parameters can be expressed both in terms of energy and as corresponding Δu, and the relation between the two measurements is the buildings energy signature, i.e., the relation between outdoor temperature, T_{out}, and heat demand. $T_{balance}$, is the balance temperature, i.e., the outdoor temperature at which the entire demand for space heating can be fulfilled by internal heat gains.

Table 4.3 Linear modeling parameters expressed both in terms of energy and as corresponding Δu.

Storage capacity: TES_{cap}	94 Wh/m^2 63°Ch
Max charge rate: $TES_{ch.cap}$ (Min at $T_{out} \geq T_{banlace}$ + 7°C; Max at $T_{out} \leq T_{balance}$)	0 – 10.4 W/m^2 0°C – 7°C
Max discharge rate: $TES_{disch.cap}$ (Min at $T_{out} \geq T_{balance}$; Max at $T_{out} \leq T_{balance}$ - 7°C)	0 – 10.4 W/m^2 0°C – 7°C

These parameters should be seen as a safe-side assumption. This is because the rate at which the indoor temperature changes decreases with time. Thus, a control with TES_{ch} (expressed as Δu) = 3.5°C over 18 h will have a smaller impact on the indoor temperature than a control with TES_{ch} = 7°C over 9 h. If a building similar to those in the thermal response pilot test is controlled with the limitation of these parameters, it is highly unlikely that it will experience variations in indoor temperature caused by the TES control that are larger than ± 0.5°C.

The other heavy buildings in the thermal response pilot test all showed a higher potential for storing heat since they experienced smaller variations in indoor temperature at similar adjustments to Δu and Q. Due to the relatively small number of tested buildings, the results from Building A have been selected to define the parameters for the linear model.

4.2.2 Dynamic Model

Although it has been shown in Paper I that the relation between Δu and $T_{var.21h}$ is close to linear, it is evident from Figure 4.4 that the progression of T_{in} is not linear during charging or discharging with a constant Δu. A dynamic model can more accurately model the relations between Δu, Q, and T_{in}, allowing for higher utilization of the TES capacity. Such a model has been created in a master's thesis (Carlsson, 2016), and some adjustments to the model are made in Paper IV, where the model is also applied to a large-scale implementation of BITES in the DH system in Gothenburg in a GAMS model.

The dynamic model created by Carlsson (2016) is an on-line adaptive gray-box model, which is constructed with the possibility to mimic physical real life systems, i.e., using the same inputs that the real system experienced, the model can mimic the system's behavior and produce similar outputs that the system had in reality. The model splits the building into three thermal nodes with internal homogeneousity: Hydronic radiator system, Shallow storage, and Deep storage.

Energy flow in and out of each of these storages is described by a linear first order differential equation, with restrictions regarding flow directions and magnitudes. All parameters (such as heat storage capacities, heat transfer coefficients, etc.) for the model are optimized so that a cost function is minimized. The cost function describes how well the model mimics the measurements in Building A when exposed to the same control input. A large weight is put on the dynamic behavior, i.e., how well the model describes heat load variations and indoor temperature variations during charging/discharging cycles. For more details on the model, please see *Marginal Price Control of Buildings Utilised as Thermal Energy Storage - Optimising the Heating Cost of a Modelled Residential Building with Respect to the District Heating Network Marginal Generation Cost* by Carlsson (2016).

In Paper IV, the dynamic model of BITES by Åberg et al. (2012) is applied to a possible large-scale implementation of BITES in the DH system in Gothenburg. Two changes have been made to the model:

- Heat losses from the buildings due to their utilization as TES are modeled.
- The radiator system is included in the shallow storage.

The reason for including the radiator system in the shallow storage is to improve the computational performance and make it possible to run the model in the General Algebraic Modeling System (GAMS). Shallow storage and deep storage are then defined as:

- Shallow storage – The indoor air and all components that have a very low resistance for transferring heat to the indoor air, such as furniture, internal wall coating, and the hydronic radiator heating system. The amount of heat stored in the shallow storage is assumed to be directly proportional to the indoor air temperature.
- Deep storage – The structural elements in the building, in this case mostly concrete.

A schematic representation of the dynamic model for BITES is shown in Figure 4.5.

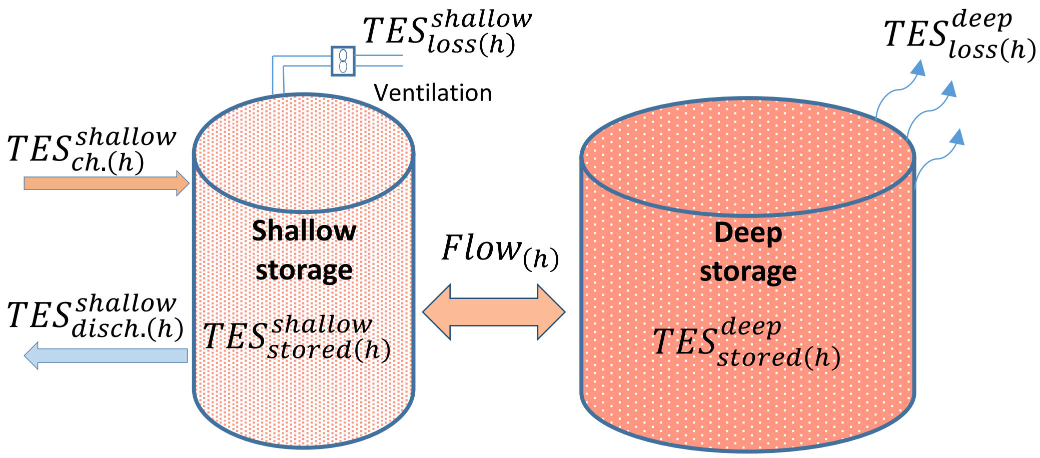

Figure 4.5 Schematic representation of dynamic model for BITES

The energy balance for the shallow storage and deep storage can then be expressed as:

$$TES^{shallow}_{stored(h)} = TES^{shallow}_{stored(h-1)} + TES^{shallow}_{ch.(h)} - TES^{shallow}_{disch.(h)} - Flow_{(h)} - TES^{shallow}_{loss(h)} \tag{4.1}$$

$$TES^{deep}_{stored(h)} = TES^{deep}_{stored(h-1)} + Flow_{(h)} - TES^{deep}_{loss(h)} \tag{4.2}$$

where $Flow_{(h)}$ is the heat exchange between the shallow and deep storage in a given hour h and is calculated according to:

$$Flow_{(h)} = \left(\frac{TES^{shallow}_{stored(h)}}{TES^{shallow}_{cap}} - \frac{TES^{deep}_{stored(h)}}{TES^{deep}_{cap}}\right) \cdot K \tag{4.3}$$

where $TES^{shallow}_{cap}$, TES^{deep}_{cap} are the maximum energy capacities of the shallow and deep storage, respectively, and K is the heat transfer coefficient, defined by Carlsson (2016).

Since the radiator system is a part of the shallow storage, only the shallow storage interacts with the DH system and can be directly charged or discharged. In contrast to the linear model (presented in 4.2.1), no limits are put on maximum charge/discharge rate ($TES_{ch.cap}$ and $TES_{disch.cap}$) except for physical limitations. In the linear model, the limitations to $TES_{ch.cap}$ and $TES_{disch.cap}$ are required to not charge the storage too fast and overheat the indoor air before the heat has time to buffer into the structure. Since the dynamic between the shallow and deep storage is modeled in the dynamic model, these restrictions are no longer required. $TES_{ch.cap}$ and $TES_{disch.cap}$ are still physically limited so that:

- The charge rate cannot be higher than the installed heating capacity in the building minus the heat load required to keep the indoor temperature at the set-point.
- The discharge rate cannot be higher than the heat load required to keep the indoor temperature at the set-point.

The extra heat losses caused by the utilization as TES are included in the dynamic model. It is assumed in the dynamic model that the allowed temperature span of 1°C is from the building set-point to the set-point plus 1°C. The heat required to keep the indoor temperature, T_{in}, at the set-point is already included in the building's heat load profile. The consequence of only allowing the BITES model to increase the indoor temperature from the set-point is that all utilization as TES will cause extra heat losses from the utilized buildings. The reasoning behind defining the allowed temperature span as only positive from the set-point is to separate the heat losses associated with utilizing buildings as TES from the energy saving potential by using an advanced control system for heating in buildings. This energy saving potential stems from reducing variations in indoor temperature by incorporating feedback from indoor temperature and weather forecasts and/or using a dynamic building model. The reduced variation in T_{in} allows for a reduction in set-point for T_{in} that can save space heating energy in the magnitude of 10% (Olsson, 2014). It is highly recommended to have such an advanced control system in buildings that are to be utilized as TES (if the thermal comfort is to be maintained) and the chosen definition of allowed temperature span excludes the energy saving potential associated with such control systems from this study. The heat losses from the

BITES in this model should therefore be seen rather as a reduction in energy saving potential for an advanced control system than as added heat losses.

The heat losses from the buildings utilized as TES are modeled as a function of the charge level of the shallow storage and deep storage. Keeping both storages charged to their full storage capacity and at steady state corresponds to keeping T_{in} 1°C above a set-point, hence, corresponding to the heat flow associated with Δu = 1°C. For Building A, this heat flow is about 1.49 $W/m^2_{heated\ area}$. Since this is the total heat loss from the BITES, an assumption is needed to be made regarding how the heat loss is split among the shallow and deep storage. The assumption is made that all ventilation losses come from the shallow storage and all transmission losses from the deep storage. The reasoning behind this assumption is that ventilation losses occur from the constant replacement of indoor air by fresh outdoor air, and the shallow storage consists of the indoor air and all components in the building that have a low resistance for transferring heat to the indoor air. The transmission losses go through the walls and roof, which are parts of the deep storage. The ventilation flow rate, $\dot{V}$, is assumed to follow the Swedish building code requirements of 0.35 L/m^2s (Boverket, 2010), and the specific heat loss from the shallow storage can then be calculated by the formula:

$$TES^{shallow}_{losses(h)} = \dot{V} \cdot \rho_{air} \cdot Cp_{air} \cdot \left(T_{in} - T_{set-point}\right) \tag{4.4}$$

where ρ_{air} is the density of air, Cp_{air} is a specific heat capacity of air, and $T_{set\text{-}point}$ is the indoor temperature set-point. When the shallow storage is fully charged (+1°C from a set-point), the specific heat loss is then 0.42 $W/m^2_{heated\ area}$. The remaining heat loss of 1.07 $W/m^2_{heated\ area}$ (1.49 minus 0.42) is assumed to be transmission losses from the deep storage when it is fully charged. Note, that this distribution of losses between the shallow and deep storage is only valid when both storages are fully charged. The heat losses can also be expressed as loss coefficients, K_{loss}, which refers to the heat loss at fully charged storage divided by the storage capacity. The losses from both the shallow and deep storage decrease linearly with decreasing charge level and are assumed to be zero when the storages are fully discharged, and these can be expressed as:

$$TES^{shallow}_{loss(h)} = TES^{shallow}_{stored(h-1)} \cdot \left(1 - K^{shallow}_{loss}\right) \tag{4.5}$$

$$TES^{deep}_{loss(h)} = TES^{deep}_{stored(h-1)} \cdot \left(1 - K^{deep}_{loss}\right) \tag{4.6}$$

where $K^{shallow}_{loss}$ and K^{deep}_{loss} are the heat loss coefficients of the shallow and deep storage, respectively. The heat loss coefficients are $K^{shallow}_{loss} = 0.9913$, $K^{deep}_{loss} = 0.9963$.

The heat loss coefficients can also be expressed with the help of time constants, τ; this is a common parameter used in the thermal modeling of buildings, and the relation will be as follows:

$$K_{loss} = exp\left(\frac{-1}{\tau}\right) \tag{4.7}$$

Thus, the time constants of the shallow and deep storage in this work are found and are equal to $\tau^{shallow}$ = 115 h and τ^{deep} = 267 h, respectively. Time constants for multi-family buildings, presented as two thermal nodes, with the shallow and deep parts represented as in this work, were not identified in previous studies. However, previous studies by Olsson Ingvarson and Werner (2008) and Karlsson (2012) show that time constants for residential multifamily buildings can vary within the range of 100–350 h (for light and heavy buildings, respectively), which is in line with the constants derived in this study.

All parameters for the dynamic model of BITES are summarized in Table 4.4. The model parameters can be expressed in both terms of energy and as corresponding Δu, and the relation between the two measurements is the building's energy signature, i.e., the relation between outdoor temperature and heat demand.

Table 4.4 Linear modeling parameters expressed in both terms of energy and as corresponding Δu.

Parameter	Shallow storage	Deep storage
Storage capacity: TES_{cap}	46 Wh/m² 31°Ch	291 Wh/m² 195°Ch
Max charge rate: $TES_{ch.cap}$ (Min at $T_{out} \leq T_{DOT}$; Max at $T_{out} \geq T_{balance}$)	0 – 46 W/m² 0°C – 31°C	n/a
Max discharge rate: $TES_{disch.cap}$ (Min at $T_{out} \geq T_{balance}$; Max at $T_{out} \leq T_{DOT}$)	0 – 49 W/m² 0°C – 31°C	n/a
Loss coefficient: K_{loss}	0.9913 /h	0.9963 /h
Losses range: TES_{loss} (Min at TES_{stored} = 0; Max at TES_{stored} = TES_{cap})	0 – 0.42 W/m² 0 – 0.28°C	0 – 1.07 W/m² 0 – 0.72°C
Internal heat transfer: K -K < Flow < K; Positive flow direction is from Shallow to Deep	→ 30 W/m² → → 20°C →	

4.3 Large Scale Application Models

Both the linear model (presented in 4.2.1) and the dynamic model (presented in 4.2.2) have been up-scaled for large-scale application models in this work. In this work, the models are applied to the DH system in Gothenburg (described in 2.3). Generally, the models can be applied to any DH system, as exemplified by Sirén (2014), who applied the linear model from this work to the DH system in Hudiksvall, Sweden.

To study a large-scale implementation of short-term TES in buildings, a group of buildings suitable for implementation have been analyzed in Paper II. 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 apartment area of 76 m². The average annual heat use 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 3–5 stories and have a core of concrete. They are very similar to the heavy buildings in the thermal response test presented in Table 4.1. 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 energy signature is used. The energy 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.

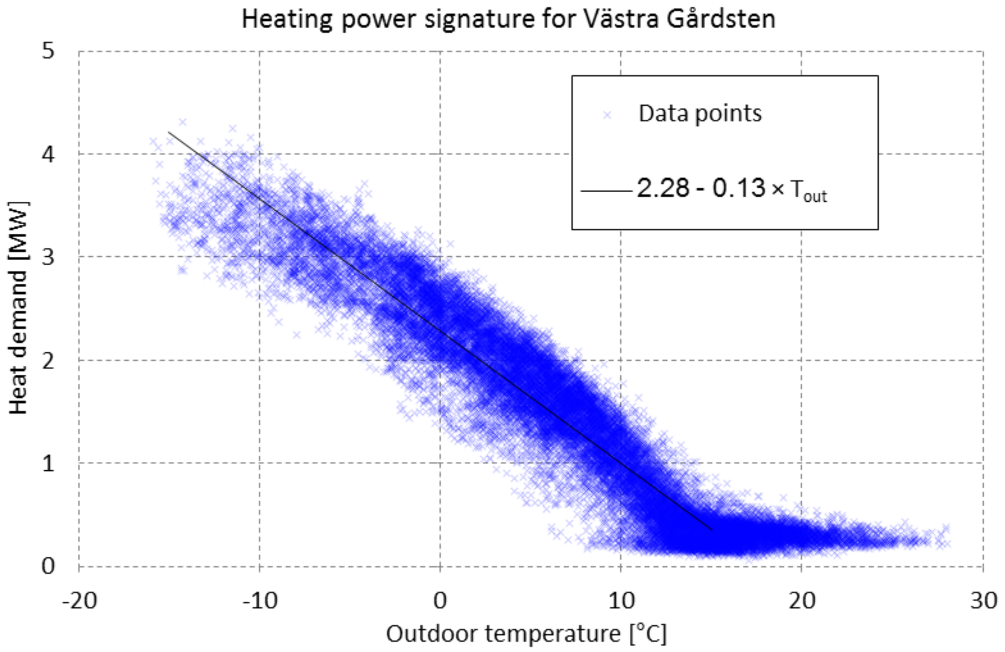

Figure 4.6 The inclination of the trend line is the energy signature for the residential area of Västra Gårdsten, Gothenburg

Figure 4.6 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, 0.13 MW/°C can be multiplied with the °C and °Ch parameters from Table 4.3 and Table 4.4 to create a linear or dynamic BITES model of this residential area. Even though Figure 4.6 shows a slight concave shape, a linear relation between heating power and outdoor temperature is assumed. This is because there are other factors than the actual outdoor temperature dependency that causes the concave shape. Such factors include, but are not limited to:

- Higher probability of cloudy, rainy, and windy weather at temperatures in the middle of the span.
- Higher probability that the coldest temperatures occur at nighttime when domestic tap water usage is low.

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 use by these substations are sorted with the substations with largest heat use first and their cumulative heat use is plotted in Figure 4.7.

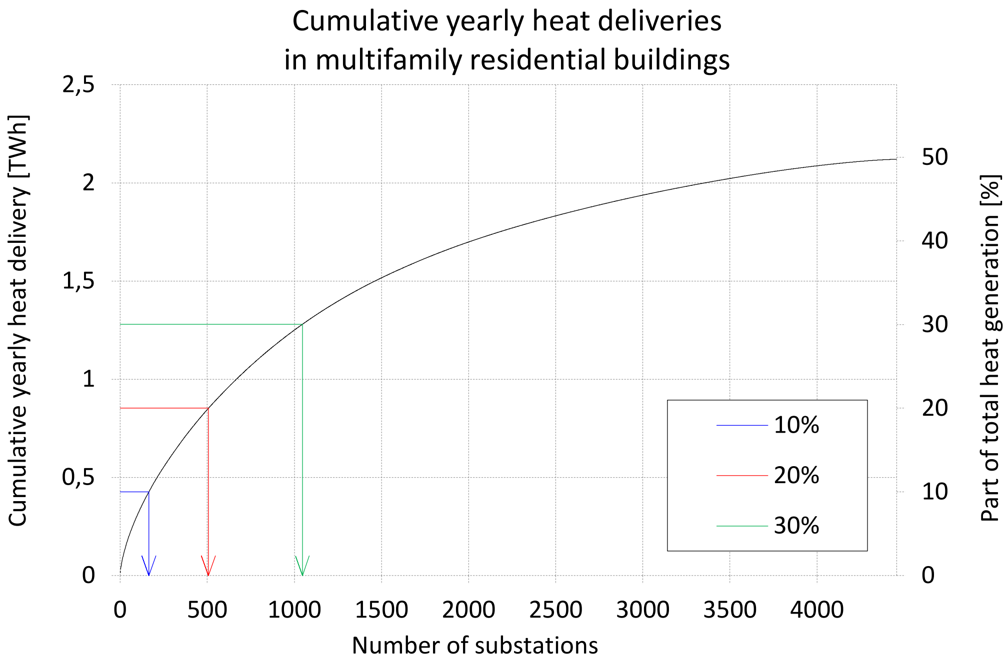

Figure 4.7 Cumulative yearly heat deliveries to all substations in multifamily residential buildings in Gothenburg

An assumption is made that there are a sufficient number of properties in Gothenburg that are similar to those in Västra Gårdsten (and the heavy buildings in the thermal response test). That is, they have similar thermal behavior and ratio between yearly heat deliveries and energy signature. This allows the modeling parameters from Table 4.3 and Table 4.4 to be scaled to large-scale application models. The linear model is scaled for three simulation cases corresponding to the 10%, 20%, and 30% cases from Figure 4.7. The parameters are presented in Table 4.5.

Table 4.5 Summary of modeling parameters for the linear model applied to the Gothenburg DH system

Case	**10%**	**20%**	**30%**
Number of utilized substations	165	507	1,046
Storage capacity: TES_{cap}	285 MWh	571 MWh	856 MWh
Max charge rate: $TES_{ch.cap}$ (Min at $T_{out} \geq T_{banlace} + 7°C$; Max at $T_{out} \leq T_{balance}$)	0 – 32 MW	0 – 63 MW	0 – 95 MW
Max discharge rate: $TES_{disch.cap}$ (Min at $T_{out} \geq T_{balance}$; Max at $T_{out} \leq T_{balance}$ - 7°C)	0 – 32 MW	0 – 63 MW	0 – 95 MW

The dynamic model is scaled using the same methodology, but it is only applied to the 20% case, which corresponds to a large proportion of the public housing in Gothenburg. The parameters are presented in Table 4.6.

Table 4.6 Summary of dynamic modeling parameters for the 20% case in the Gothenburg DH system

Parameter	**Shallow storage**	**Deep storage**
Storage capacity: TES_{cap}	278 MWh	1,758 MWh
Max charge rate: $TES_{ch.cap}$ (Min at $T_{out} \leq T_{DOT}$; Max at $T_{out} \geq T_{balance}$)	0 – 279 MWh	n/a
Max discharge rate: $TES_{disch.cap}$ (Min at $T_{out} \geq T_{balance}$; Max at $T_{out} \leq T_{DOT}$)	0 – 279 MWh	n/a
Loss coefficient: K_{loss}	0.9913 /h	0.9963 /h
Losses range: TES_{loss} (Min at TES_{stored} = 0; Max at TES_{stored} = TES_{cap})	0 – 2.4 MW	0 – 6.6 MW
Internal heat transfer: K -K < Flow < K; Positive flow direction is from Shallow to Deep	→ 180 MW	→

4.4 Linear Model Application

In Paper II, the linear model is applied to the DH system in Gothenburg, with the target to minimize variations in heat load. All three cases from Figure 4.7 and Table 4.5 are simulated and compared to a reference case with no TES. The total heat generation in Gothenburg (minus exports, plus imports) for the years 2010–2012 with an hourly resolution is used as input in this application. This should equal the total heat load for customers plus the heat losses to the ground (distribution network dynamics is disregarded). The linear model has also been applied to the DH system in Hudiksvall, Sweden, in the master's thesis by Sirén (2014), and the results from this study are summarized in 4.4.3.

4.4.1 Optimization Algorithm

An optimization problem was formulated with the aim of minimizing the variation in heat load. With a resolution in time of 1 h and a heating power of 1 MW, the number of solutions is small enough to be solved with a brute force iteration approach, testing all possible solutions.

The progression for the iterative solution is to first split the data set into periods of 200 h each to speed up the simulation. For each time period, the highest hourly heat load in the DH system, $Q_{DH}(t)$, is reduced by one step (1 MW), and the lowest hourly heat load $Q_{DH}(t)$ is increased by one step (1 MW). A check is performed to see if the storage limitation is violated at any point in time ($0 \leq TES_{stored} \leq TES_{cap}$). If the check passed, the test was started over, and if not, the program proceeded to test all combinations of decreasing Q_{DH} in descending order, where $Q_{DH}(t) > Q_{DH}(t-1)$ and/or $Q_{DH}(t) > Q_{DH}(t+1)$ and of increasing Q_{DH} in ascending order where $Q_{DH}(t) < Q_{DH}(t-1)$ and/or $Q_{DH}(t) < Q_{DH}(t+1)$. The iteration continued until no further improvements could be made. This method is quite computation heavy (solving at about 10,000 times real time) but guarantees a solution with the maximum possible peak reductions. To avoid boundary constraints from the 200-h periods influencing the results, the full iteration was performed a second time with overlapping time periods.

4.4.2 Evaluation

An example of the results showing how the heat load in a seven-day period could be improved with the 20% case is shown in Figure 4.8. During this week, there would be no need to use 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 can be found in Paper II.

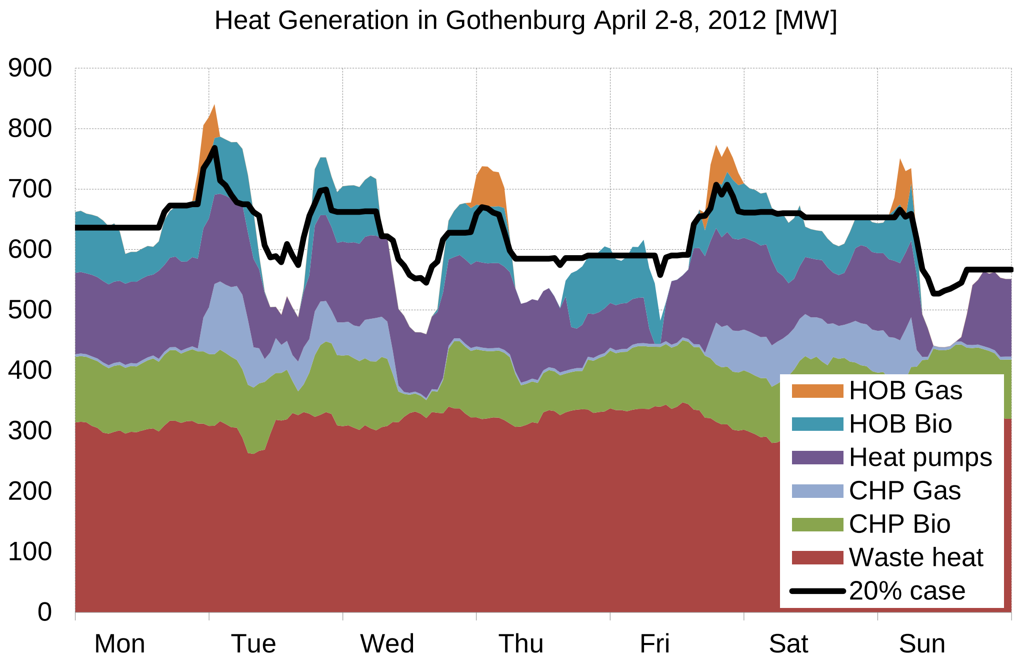

Figure 4.8 Example of the heat generation in Gothenburg during one week with a possible load curve from the 20% case as an overlay.

The relative daily variation, $Q_{d.rel.var}$, defined in (2.1) has been calculated for each day for all simulation cases. The values over the three-year simulation period are presented in Figure 4.9.

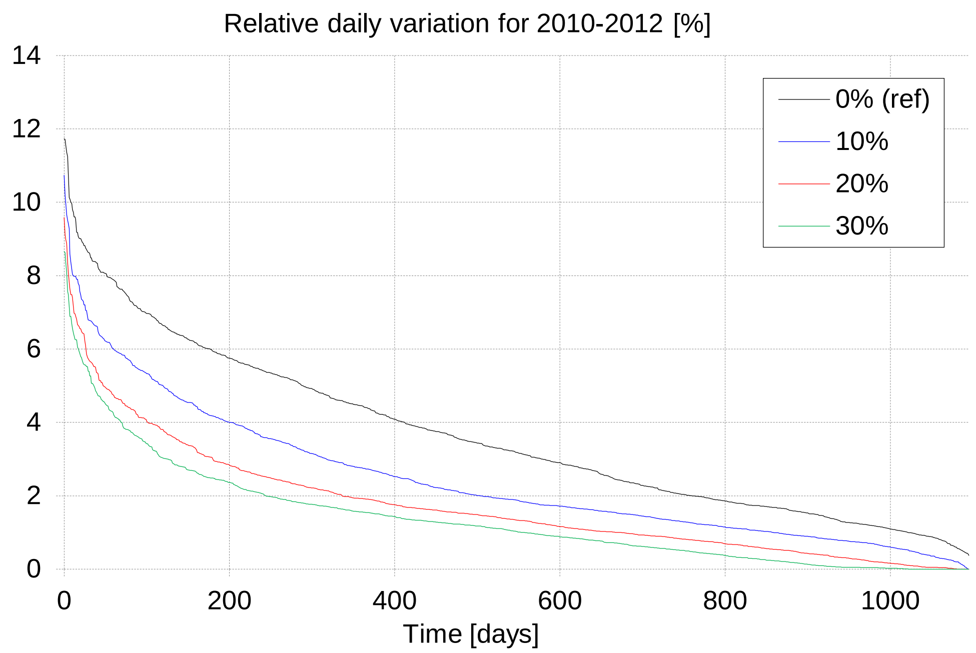

Figure 4.9 Relative daily variation cumulative distribution function for three years (2010–2012)

It can be clearly seen in Figure 4.9 that the variation in heat generation has decreased and that the conditions for generating heat are more favorable with BITES. 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.

If one looks at the average values for relative daily heat load variation, $Q_{d.rel.var}$, one obtains a simple measurement for comparing the four cases:

- 0% case (reference): 3.63%
- 10% case: 2.44%
- 20% case: 1.74%
- 30% case: 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. How the decreased variation in heat load would affect the heat generation has been examined in a master's thesis by Dreano (2013), which showed that the 20% case would reduce the heat generation by oil and gas HOBs in Gothenburg by 10–20%.

4.4.3 Hudiksvall DH System

The simulation developed for this study has also been adjusted for and applied to the DH system in Hudiksvall in a master's thesis by 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). Of the yearly heat generation, 92.6% is from 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 of this study was to find the potential for load-shifting from the peak load HOB 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 BITES with a size corresponding to a 20% case for Hudiksvall would reduce the use of oil in heat generation by 15%. A simple payback time for a BITES 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 5.5–6 years. This can be compared to Gothenburg, where the impact of different sizes of TES have been compared in a bachelor's thesis by Machu (2014). Although the thesis compared sizes of HWTs, the results should be applicable since the linear model is very similar to HWT models. Increasing the TES capacity above a corresponding 20–30% BITES case brings very small benefits.

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. It is far from a strong correlation, but a trend is demonstrated for larger systems by 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.

4.5 Dynamic model application

The dynamic model (described in 4.2.2) has been applied in the DH system in Gothenburg in two studies:

- (Paper IV) A comparison of BITES and hot water tank (HWT) in the DH system in Gothenburg, based on historical data from 2012.
- (Holm and Ottosson, 2016) A comparison of BITES, HWT, and seasonal storage in the DH system in Gothenburg, for an assumed 2032 case. Also includes a study of heat source shifting, which is further elaborated on in 5 Heat Source Shifting.

Both studies uses the 20% case with parameters from Table 4.6, with the exception that heat losses from BITES are excluded in Holm and Ottosson's work (Holm and Ottosson, 2016).

4.5.1 Optimization Model

Both studies uses a techno-economic optimization model that is a further development of the dynamic unit commitment optimization model presented in more detail by Romanchenko et al. (2017b). The model uses mixed-integer linear programming to minimize the objective function, which in these studies is the total system operational cost. Sold electricity from CHP contributes to lowering the system operational cost. The model is developed with the focus to optimize a unit commitment and a dispatch of the heat generation units, available in the DH system investigated, for a period of up to a year. Thus, investment costs are not included in the modeling. The model also has a perfect foresight, i.e., hourly heat demand, electricity prices, fuel costs and fees are exogenously given to the model. The model is formulated in the modeling language GAMS and uses the optimization software package CPLEX as a solver. For further details on the model, please read Paper IV.

4.5.2 HWT Model

As an alternative to BITES, sensible heat storage in a hot water tank (HWT) is modeled in Paper IV. A non-pressurized HWT with a supply water temperature of 80°C and return water temperature of 45°C is modeled. The capacity of the HWT is chosen to be equal to the total storage capacity of the shallow and deep storage in the BITES, presented in Table 4.6. The HWT capacity and supply/return temperatures give an HWT volume of around 50,000 m^3. Charge and discharge rates are based on the condition that the HWT can be fully charged or discharged in 10 hours. Due to the mixing of hot (at the top) and cold (at the bottom) water inside the HWT during the charge/discharge cycles, respective charge and discharge efficiencies of 98% are applied. Heat losses of 0.01% per hour are also applied. A more detailed description of the HWT model is provided in Paper IV.

4.5.3 Utilization Patterns of HWT and BITES

One of the aims of Paper IV was to study the principal differences in utilization patterns between HWT and BITES in a DH system. To answer this question, the optimization model is run for the year 2012 with BITES, HWT, and a reference case with no TES. Two measures for the utilization of TES, the number of full load charge cycles and the average storage level, are also defined as:

$$Full\ load\ charge\ cycles = \frac{\sum_{h=1}^{H} TES_{ch.(h)}}{TES_{cap}} \tag{4.8}$$

$$Average\ storage\ level = \frac{\sum_{h=1}^{H} TES_{stored(h)}}{8760} \tag{4.9}$$

Figure 4.10 shows the number of full load cycles a) and the average energy level of the HWT and the BITES (b), as obtained from the modeling for one full year. The HWT is on average kept charged at a level more than twice of the average charge level of the BITES, whereas the number of full load charge cycles is only 10% higher for the HWT (45 and 50 cycles, respectively). The charge level of the HWT is higher due to the lower energy losses to the outdoor air, as compared to the losses from the BITES, and, consequently, longer periods of time when the HWT is kept charged.

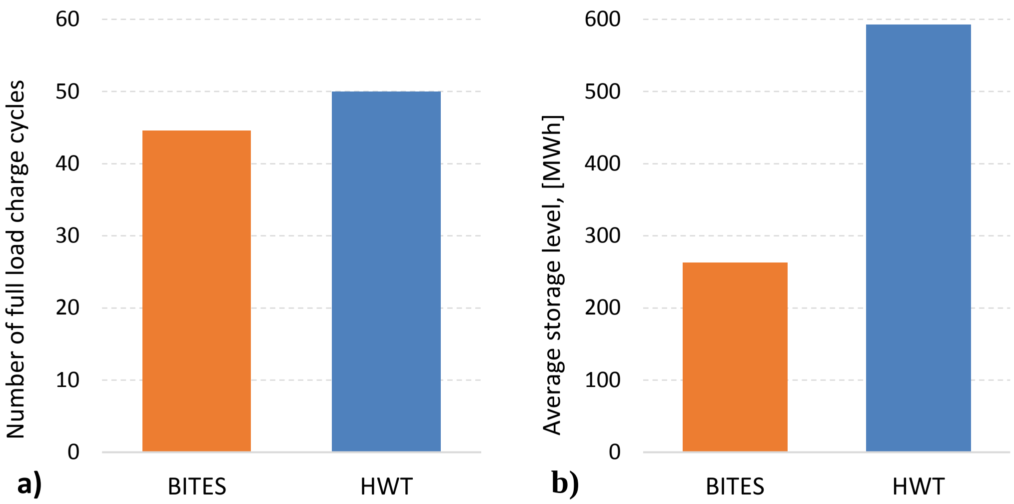

Figure 4.10 The number of a) full load charge cycles and b) the average energy level in the HWT and the BITES over the year

Figure 4.11 gives the number of occasions over the year when the HWT and the BITES store 1,000 MWh of heat (50% of maximum capacity) or more for the number of consecutive hours, which are aggregated in duration segments. The results show that both TES types investigated are equally good at storing large amounts of heat over a period of up to two days, but if large amounts of heat are to be stored for a longer time, only the HWT is chosen by the model. As shown in

Figure 4.11 the HWT is used 16 times to store 1,000 MWh or more heat for periods longer than 50 consecutive hours, whereas the BITES is used only 3 times. The analysis of the operation of the heat generation units in the DH system investigated (elaborated on in more detail in the next section) shows that the heat stored for longer than two-day periods is mainly used to prevent or delay start-ups of the heat generation units. This characteristic of the HWT can be particularly useful in the future if the heating and electricity systems become more integrated, requiring higher flexibility in the operation of DH systems. A more detailed analysis on how the two types of TES are operated can be found in Paper IV.

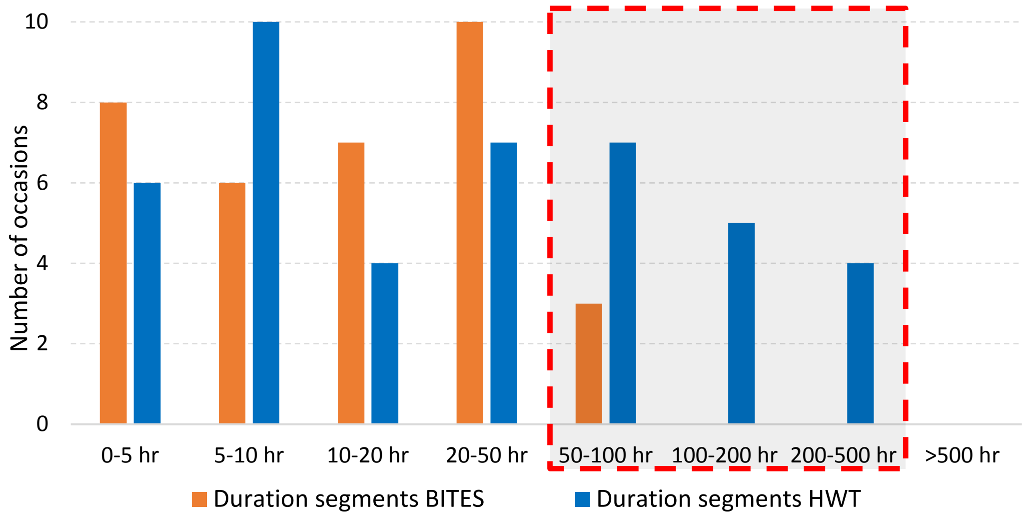

Figure 4.11 The number of occasions classified in duration segments when the HWT and the BITES remained charged at a level higher than 1,000 MWh, as obtained from the modeling

4.5.4 Benefits of HWT and BITES

Another focus of Paper IV was to study the benefits to a DH system of an active use of TES, in the form of either HWT or BITES. Figure 4.12 shows the relative daily net load variations (a) and the relative weekly net load variations (b), in both cases, organized in descending order for the reference, HWT, and BITES scenarios. The results show that both TES types investigated provide benefits to the DH system investigated by smoothening daily heat load variations equally well. Yet, the HWT performs better in that it can smoothen the weekly load variations. In the BITES and HWT scenarios, the average relative daily heat load variations reduced in total by 19% and 20%, respectively, compared to the reference scenario, while the relative weekly heat load variations decrease by 10% and 17%, respectively. The results indicate that even though rapid charging and discharging of the BITES is limited by the capacity of the shallow storage, the two TES solutions are still equally good at moderating short-term heat load variations. The higher ability of the HWT to smoothen weekly heat load variations is further elaborated on in Paper IV and can in short be explained by its lower heat losses to the surroundings.

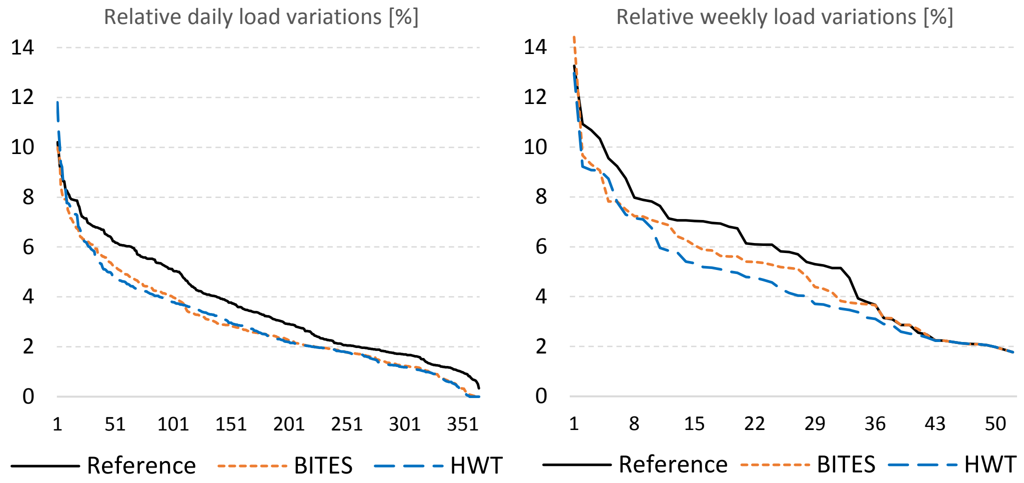

Figure 4.12 The a) relative daily heat load variations and b) relative weekly heat load variations for the reference, BITES, and HWT, in descending order

It should be noted that some values of both relative daily and relative weekly heat load variations cannot be reduced by TES and, in some cases, can even be higher than the values in the reference scenario. This is due to the fact that the objective of the modeling is not to minimize heat load variations but to minimize the total system operating cost. The most noticeable effects on the heat generation is that the amount of heat generated in gas HOBs is reduced by 25% and 30%, respectively, for the BITES and HWT cases, compared to the reference case, while the amount of heat generated in HPs is increased by 5% for both cases. A more detailed study of the effects of TES on the heat generation, including number of starts and stops, can be found in Paper IV.

Figure 4.13 shows the total system operating cost, total heat and electricity generation, and total electricity use within the DH system in the BITES and HWT cases compared to the reference scenario. The results show that there is an economic advantage of having TES in the DH system investigated. The total system operating cost is reduced by 1.1% for the BITES case and by 2.0% for the HWT case. For the BITES case, this can also be seen as the cost of heat generation associated with heating the utilized buildings, as TES is reduced by 5.5% (1.1%/20%). Further, neither the BITES nor the HWT give a significant increase in the total yearly heat generation. Yet, as can be seen from Figure 4.13, BITES leads to a slightly higher increase in total heat generation, indicating that the heat losses from buildings used as TES are higher than the combined effect of the energy and charge/discharge losses from the HWT. Note that in the model, it is only allowed for the buildings used as TES to increase their indoor temperature from the set-point, leading to increased heat losses.

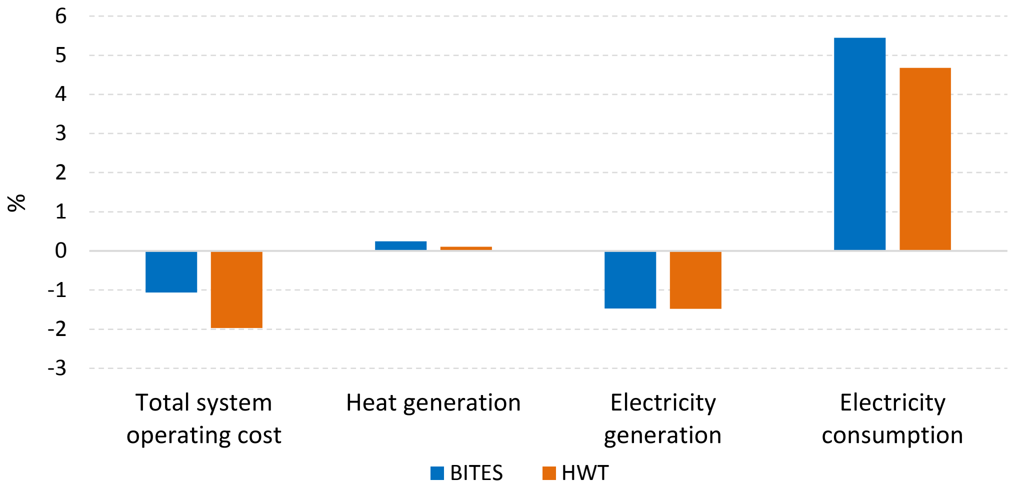

Figure 4.13 The total system cost, the total heat and electricity generation, and the total electricity use for the cases with the BITES and the HWT, as obtained from the modeling and compared in percentages to the reference case with no TES

Availability of TES also results in lower electricity generation (from the CHP plants available) and higher electricity use (by the HPs) in the scenarios investigated. This is because the electricity prices for the modeled year, 2012, were low enough to place HPs before CHPs in the merit order of the modeled DH system in Gothenburg. Note that, in a future with high electricity prices, the merit order of HPs and CHP plants can change and lead to the opposite outcome.

4.5.5 BITES and HWT in 2032 scenario

BITES has also been evaluated for a possible 2032 scenario for the DH system in Gothenburg in a master's thesis by Holm and Ottosson (2016). The dynamic BITES model uses the parameters presented in Table 4.6 with two exceptions:

- The heat losses are not modeled
- The stricter limitation for charging/discharging is used from Table 4.5

The study used the optimization model described in 4.5.1, and the main differences in the DH system is that all natural gas is replaced with bio gas, and a new bio-fueled CHP is built. These changes are currently planned for the DH system, and the target is to be fossil free by 2030. A model for hourly electricity cost for 2032 is included and three different scenarios for the electricity sector are considered.

The results show that a large-scale implementation (20% case) of BITES would reduce total system cost by 1.8–2.2%, depending on the electricity scenario. This can also be seen as a reduction in the heat generation cost associated with heating the buildings utilized as TES by 9–11% (1.8–2.2%/20%). The cost reductions are about twice as high as those found for the 2012 case (presented in 4.5.4). There can be two reasons for this:

- TES is more favorable in 2032 due to factors in the DH system and electricity prices.
- The difference in how the BITES is modeled has a major impact on how it is operated.

Most likely, the truth is a combination of both points, although there are good arguments for the first point being more important:

- Holm and Ottosson (2016) also modeled a HWT in 2032, half the size of the one modeled for the 2012 case in Paper IV, while still achieving equal reductions in system operational cost.
- The total heat losses from the BITES in Paper IV are small (0.24% of the total heat generation) compared to the extra system cost reduction achieved in the 2032 case (Holm and Ottosson, 2016).

A study of a seasonal storage using a cavern TES is also included in (Holm and Ottosson, 2016) as well as a study of large-scale implementation of heat source shifting between EAHP and DH (further elaborated on in 5.4).

4.6 Heat Price Control of BITES

Paper V presents a test where heat price control (HPC) is evaluated as a method of integrating the control of BITES with the heat generation optimization at a DH company. HPC is a type of demand response where a control system is given hourly heat prices control the heating in buildings in order to minimize the heating cost. The reason for testing HPC is that the main goal with TES is to reduce the total system operational cost. Using hourly heat prices based on the marginal cost of heat generation as input should provide a control system with better conditions to achieve this goal than, e.g., using the heat load in the DH system as input. The heat prices used in this study are the forecasted prices (described in 3.3.1).

4.6.1 Test Buildings

A total of 19 properties were used in this pilot test, each connected to the DH system by a separate substation. Each property consists of 1–3 multi-family residential buildings with a total of 1,800 apartments. All properties are primarily used for residential purposes, but a few of them house minor non-residential tenants, such as kiosks. They were all built in the 1960s and 1970s as part of a major Swedish public housing development program called the Million Homes program. Thus, the type of building is very common in Sweden (and many other countries). All buildings are 3–8 stories with a structural core of concrete, and they are heated by radiator systems with circulating water. They are ventilated by either exhaust only systems or natural ventilation (i.e., there is no supply of pre-heated air). Hence, the buildings are also very similar to the building in the thermal response pilot test (presented in 4.1). The yearly heat load for space heating and hot tap water is 16.6 GWh for all the test buildings, or about 150 $kWh/m^2_{heated\ area}$.

Another 30 properties with similar characteristics were used as references. Their total yearly heat load is 25.5 GWh, or about 150 $kWh/m^2_{heated\ area}$. The reference buildings are located in the same part of Gothenburg in order to minimize the risk that the buildings will be exposed to different weather conditions (Gothenburg is in a coastal, hilly region).

4.6.2 Control System

The test buildings kept the existing control systems for space heating, and the TES control was used to adjust the input to these control systems. All buildings control space heating by varying the supply temperature to the radiator system. Normally, the supply temperature is about 60–65°C at design outdoor temperature (DOT) (-16°C in Gothenburg) (Jangsten, 2016) and decreases toward room temperature, in line with Kärkkäinen's equation (Kärkkäinen, 2010), at an outdoor temperature of 15–17°C. The trimmed average indoor temperature (excluding outliers) for all apartments in each building is compared to the buildings' indoor temperature set-point, and if deviation is identified, the supply temperature to the radiator system is increased or decreased. There are thermostats located on the radiators in all apartments, but they usually only reduce the flow in individual apartments when the internal heat increases (e.g., due to high occupancy, solar irradiation, or cooking), causing the room temperature to exceed the set-point, which is normally 21°C. However, if the temperature is high in all apartments, the feedback from the indoor temperature sensors will have already reduced the supply temperature to the radiator system. It is also common for thermostats to have no or poor functionality, due to age, wear and tear (Johansson et al., 1989).

The supply temperature to the radiator systems in the test buildings is set as a function of the outdoor and indoor temperatures by the existing control system. The control system for TES connects to the existing control system in the buildings by adjusting the input from the indoor temperature sensors. In the thermal response test (presented in 4.1), adjustments were made based on signals from the outdoor temperature sensors. Since the radiator supply temperature in these buildings is a known function of both temperature signals, the one that is adjusted is chosen based on the ease of access. In order to be consistent with earlier work, all control signals are here expressed as adjustments corresponding to signals from an outdoor temperature sensor, Δu. The TES control system was developed by NODA Intelligent Systems (NODA, 2017), and it is described and evaluated by Johansson et al. (2012), Johansson and Wernstedt (2010), Johansson et al. (2010), and Wernstedt et al. (2007). For this study, the control system was further developed to perform HPC with hourly heat prices as input parameters and to minimize the following cost function:

$$Cost\ function\ = \sum_{h=h_0}^{h=h_{end}} P_h \times Q_h \tag{4.10}$$

where time has an hourly resolution, h_0 is the hour the period starts, h_{end} is the hour the period ends, P_h is the price of heat at hour h, and Q_h is the heat used during hour h. This cost function should be minimized while maintaining a good indoor climate, which requires the indoor temperature variation to be kept +/- 0.5°C from the set-point, in line with ISO7730 (2005). The indoor temperature considered here is the trimmed average (excluding outliers) of each building. Discharging power is limited so that the supply temperature to the radiator system is never allowed to be lower than what it would be if the outdoor temperature were 12°C higher

(Δu = 12°C). No active charging (Δu < 0°C) was allowed during this test. A supplementary limitation was added to the control system to act as a fail-safe and guarantee a good indoor climate in case there were any problems with the control during the test. During any 24 h period, the integral of Δu and time had to be less than 40°Ch (50°Ch for HPC period 3). This limited the amount of heat that could be discharged from the buildings each day.

4.6.3 Evaluation Methodology

The evaluation focus is on using hourly heat price as a control signal. It should be stressed that the TES control system is not evaluated in detail since it is already a commercial product and has been sufficiently covered in other studies by Johansson et al. (2012), Johansson and Wernstedt (2010), Johansson et al. (2010), and Wernstedt et al. (2007). It has only been checked that the TES control system manages to keep the trimmed average indoor temperature within +/- 0.5°C from the set-point.

When evaluating a test in real buildings with tenants, it is impossible to compare the results of the test with what would have happened if no test was performed. Even an "identical" building located nearby is a questionable reference since similar buildings are seldom truly identical and may differ greatly in tenant behavior. In the previous thermal response pilot test (Paper I), this dilemma was handled by exposing the buildings to the same control signal many times (evenly distributed over different times of day) and studying the average effects on indoor temperature and heat load. This method proved successful for evaluating the performance of the TES control system, building dynamics, and effect on the indoor temperature. However, this approach is not possible when the control signal is dependent on the marginal cost of heat generation in a DH system. For this study, the evaluation uses reference buildings and compares how much the average price of heat is decreased when some buildings are utilized as TES compared to periods when no buildings are utilized as TES.

The TES control system was installed in the test buildings in October and November 2016. During the test period, the TES control system underwent improvements, parameter adjustments, and bug fixes. The total test period is therefore split into several test periods, referred to as HPC periods. Periods in which no HPC was performed in any building served as references and are referred to as NC (normal control) periods. The NC periods include the same dates as a previous heating season to minimize the impact of variations in tenant behavior during different seasons. The dates for all HPC periods and NC periods are presented in Table 4.7. The hourly heat prices for the NC periods are the historical heat prices from 2013–2014 and the heat prices for the HPC periods are the forecasted heat prices (both described in 3.3.1).

Table 4.7 Dates for HPC periods and NC periods. All dates formatted as YYYY-MM-DD.

Period	Start date	End date	Length [days]
HPC period 1	2016-11-26	2016-12-11	16
HPC period 2	2017-01-01	2017-02-04	35
HPC period 3	2017-02-13	2017-02-27	15
NC period 1	2013-11-26	2013-12-11	16
NC period 2	2014-01-01	2014-02-04	35
NC period 3	2014-02-13	2014-02-27	15

For each HPC and NC period, the cost function (4.10) is calculated and divided by the total heat use to determine the average price per purchased unit of heat. This is performed individually and collectively for all test and reference buildings. This value is then divided by the corresponding average price per unit of heat for the total heat load in the DH network, and 1 is subtracted. This results in a price index (PI) for each building/aggregate group of buildings:

$$PI^{Building\ n} = \left(\frac{\sum_{h=0}^{h=h_{end}} P_h \times Q_h^{Building\ n} / \sum_{h=0}^{h=h_{end}} Q_h^{Building\ n}}{\sum_{h=0}^{h=h_{end}} P_h \times Q_h^{DH} / \sum_{h=0}^{h=h_{end}} Q_h^{DH}} - 1 \right) \times 100\ [\%] \qquad (4.11)$$

This returns PI = 0% for a building with a heat load profile that is directly proportional to the DH system as a whole. A calculation performed for a building with relatively higher heat use during hours with high prices would result in a positive PI. PI can also be seen as the price per unit of heat a customer pays relative to the average if all customers paid the hourly heat prices. It is hypothesized that the test buildings will have lower PIs during the HPC periods compared to the NC periods, while the reference buildings will show no difference.

4.6.4 Test Results and Evaluation

In order for HPC to be beneficial, there must be variation in the price of heat. Since the thermal properties of residential buildings make them best suited for TES on a daily basis, as shown in Paper IV, the relative daily price variation, $P_{d.rel.var}$, is used to determine whether this prerequisite is fulfilled. The relative daily price variation, $P_{d.rel.var}$, is calculated like the relative daily heat load variation (described in 2.1), but the heat price is considered each hour, instead of the heat load. The average $P_{d.rel.var}$ values for all days within each period as well as the average outdoor temperatures for each period are presented in Figure 4.14. All periods show positive average $P_{d.rel.var}$ values, indicating that PI may be reduced by utilizing HPC. In addition, the average $P_{rel.var}$ values and outdoor temperatures are similar in all periods, indicating that they represent fairly normal heat generation conditions in the DH system during the heating season. Whether the average $P_{rel.var}$ value (4–7%) is relatively high or low is hard to tell. At least a full year of studying $P_{d.rel.var}$ and comparing those values to other DH networks is required to answer that question. HPC Period 3 has higher price variations than the other periods, indicating that the potential for HPC is higher in this period.

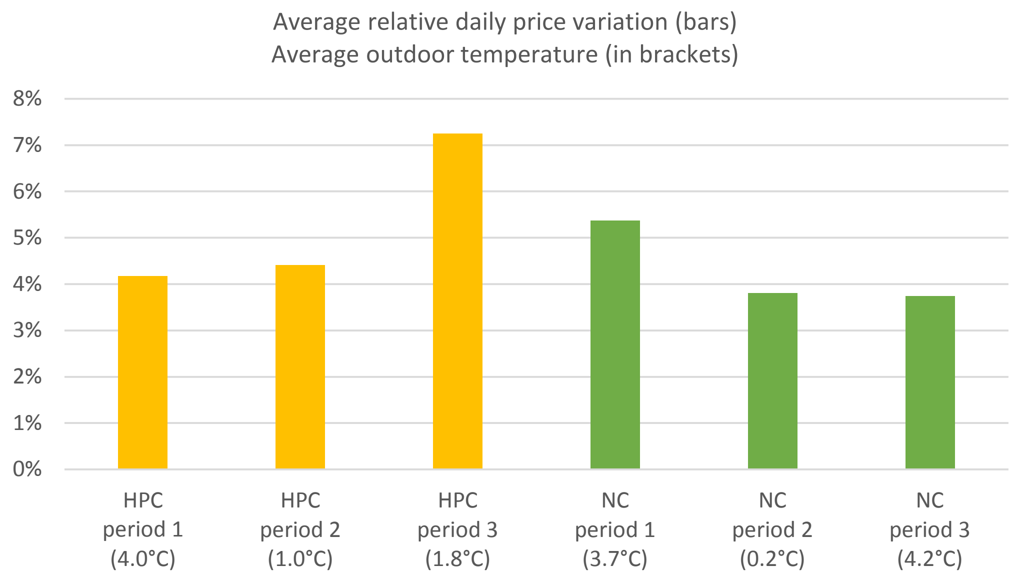

Figure 4.14 Average relative daily price variation and outdoor temperature for each HPC and NC period

During the three selected NC periods (when no HPC was performed in any building), both the test and reference buildings' aggregate PI was close to 0%, indicating that their heat load profiles were similar to that of the entire DH system, as shown in Figure 4.15. The test buildings had slightly higher PIs than the reference buildings for all NC periods, meaning that they have heat load profiles with relatively higher heat use during times at which the price is high. Over all three NC periods, the test buildings had an aggregate PI of -0.1%, while the corresponding PI for the reference building was -0.7%. The PI of the total heat load in the DH system (including distribution losses) is 0%, per definition.

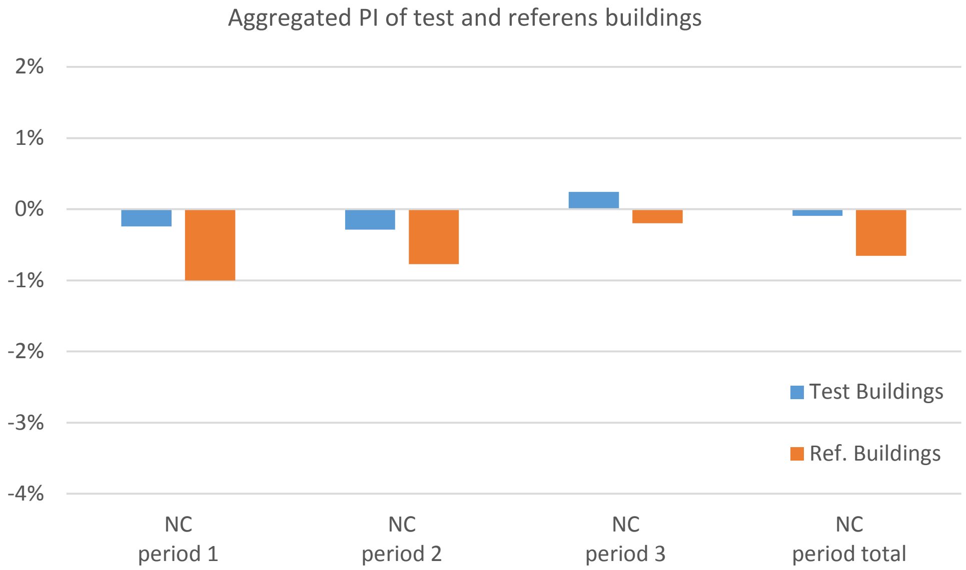

Figure 4.15 Aggregate PI for all test buildings and reference buildings during the NC periods (no HPC was performed in any building)

PI is calculated for every building during the three HPC periods (HPC control implemented in test buildings only), and the aggregate results are presented in Figure 4.16, with the overall results from the NC periods for comparison. The first important result is that, during all three HPC periods, the test buildings had lower PIs than the reference buildings. Second, this difference is significant only during HPC Period 3. This aligns with the fact that HPC Period 3 had the highest average $P_{rel.var}$ value of the MPC periods, indicating that the potential for MPC is highest in this period. However, a more likely explanation for the improved results in HPC Period 3 is that the optimization algorithm for the HPC has undergone improvements and bug fixes between HPC periods. If we compare the results for HPC Period 3 to the overall results of the NC periods, the PI for the test buildings is decreased by 2.2%, while the PI for the reference buildings is increased by 0.6%. This indicates that if the test buildings purchased heat at a price proportional to the marginal cost of heat generation, the average price paid per kWh would be 2.8% (2.2% + 0.6%) lower than if no HPC was performed. For more details on how the PI is affected on a building level, see Paper V.

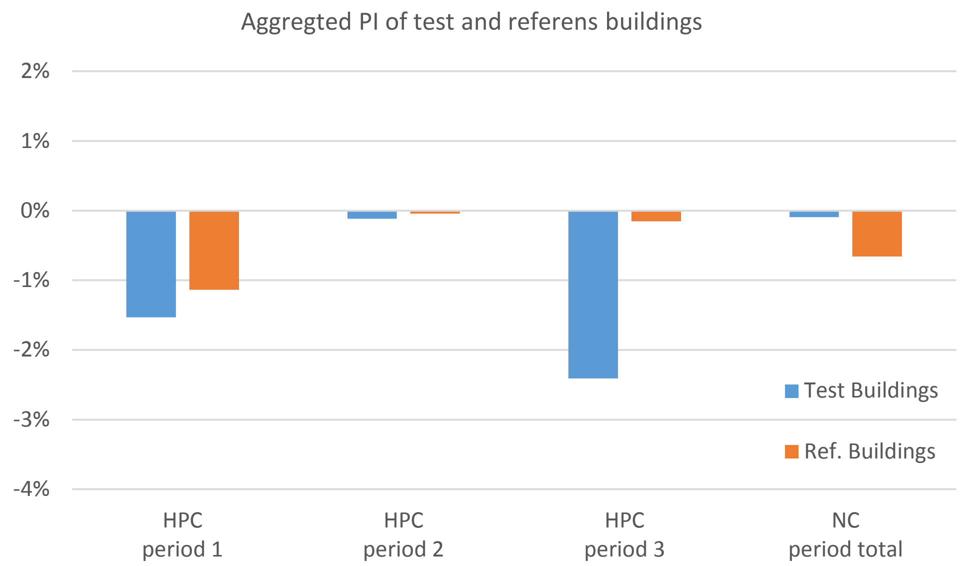

Figure 4.16 Aggregate PI for all test and reference buildings during each HPC period and the NC periods

This test result should be seen as proof of the concept that heat price control can be used to control TES in buildings supplied by DH and not as a comprehensive evaluation of the economic potential of HPC. There are two main reasons for this:

- First, this is the first implementation of HPC for TES in buildings. The system is under continuous development, and thus there is a large difference in performance from the start to the end of the test. Improvements in the control logic and tuning of parameters are expected to further improve future performance.
- Second, the total test period is 66 days, but the system showed desirable performance only during the last 15 days. Since the economic potential of the system is heavily dependent on variations in the marginal cost of heat generation, which varies with season, at least a full year of operation is needed to properly assess the economic potential.

That said, there are still some points to be made regarding the economic potential of heat price control of BITES. During HPC Period 3, all test buildings showed reduced PI, while the PI for the reference buildings slightly increased. This proves that the control method worked and achieved savings in the energy system. It should also be pointed out that reductions in PI do not directly correlate to the total cost savings of heat generation, because only a part of the heat generated in a DH system shares the marginal cost. That is, if 10% of the buildings in a DH system reduce their PI by 10%, the reduction in total heat generation cost in the DH system is greater than 1% (10% × 10%). How much greater the reduction is depends on the ratio between the cost of heat generation if all generated heat shares the marginal cost and the actual total cost of heat generation. This factor was calculated as 1.5 for both 2013 and 2014 in Gothenburg. If we assume that the 2.8% reduction in PI in HPC Period 3 is representative of an average year and that the results can be scaled to 20% of customers, the reduction in total heat generation cost would be 0.84% (2.8% × 1.5 × 20%). This result can be compared to the results presented in 4.5.4 that is a simulation of this exact scenario in the same DH system (Gothenburg, Sweden), which showed a 1.1% reduction in total system operational cost. Even though this is a very rough comparison, it still shows that the real and theoretical savings are of the same magnitude.

During this HPC of BITES pilot test, ensuring the robustness of the controls and maintaining a good indoor climate were of higher priority than cost savings. The control logic was therefore kept simple, and the parameters were set conservatively. This allows for several measures to improve the control system and achieve larger reductions in PI. Three such measures are identified and described in more detail in Paper V:

- Allow active charging of the BITES
- Use feedback from the indoor temperature as the main limitation for the storage capacity, instead of the integral of Δu and time
- Improve the HPC logic with, e.g., a solver

5 HEAT SOURCE SHIFTING

The conditions for generating district heat and electricity are constantly shifting, and therefore so is the cost of these commodities. The correlation between electricity cost and district heat cost is low (r = 0.18), as shown in 3.3.3. This is because the conditions for generating heat and electricity are affected by different factors and, therefore interaction between the energy networks can be beneficial. Such interaction is possible not only by CHP and HP in DH systems but also by switching heat supply on the consumer side; this is referred to as Heat Source Shifting in this work. The concept of heat source shifting is introduced in Paper III and is defined as switching between two heat sources so that the one with lowest operational cost is prioritized at any given moment in time. "Cost" in Paper III is the economic cost, but generally any cost function can be used (e.g., marginal CO_2 emissions). This chapter about heat source shifting is based on Paper III and a master's thesis by Holm and Ottosson (2016) and is disposed as:

- Survey of residential buildings with several heat sources (Paper III)
- Modeling heat source shifting between DH and exhaust air heat pump (EAHP) with performance representable of present installed stock. Time period: 2013–2014 (Paper III)
- Modeling large-scale implementation of heat source shifting between DH and EAHP with performance of state-of-the-art EAHPs from 2016. Time period: 2032 (Holm and Ottosson, 2016)

It should be stressed that these studies are not a comparison of which one is the more economical alternative between HP and DH. Such a study would need to take into account investment costs, maintenance, etc. These studies assume that the investments are already made and focuses on optimizing the control of the combined space heating system from a total system perspective.

5.1 Survey of Buildings with Several Heat Sources

In Paper III, a survey of residential buildings with several heat sources is performed. The aim is to find what heat sources are most often combined with DH and thus what combination of heat sources to further focus on. For this purpose, a database covering Energy Performance Certificates for Swedish properties was used. The database covers the vast majority of multi-family residential properties in Sweden and is further described by Mangold et al. (2015) and Johansson et al. (2016).

During the year 2013, there were 20,056 properties that were customers of the DH system in Gothenburg. Out of these properties, 4,457 were multi-family residential properties, although they represent 50% of heat use. This only includes properties with the main application area as "residential" and which house at least three families. Villas, semidetached houses, and properties where only a minor part of the area is used for residential purposes are thereby excluded. One property can include several buildings, which is fairly common; usually, buildings that share the same yard belong to the same property. Of the 4,457 multi-family residential properties, 170 also have at least one other heat source. These are presented in Table 5.1.

Table 5.1 Multi-family residential properties in Gothenburg supplied by DH and at least one other heat source. The DH share is the share of DH of the total energy for heating purposes delivered to the building. The average heat load is converted to an average year using the degree day method.

Extra heat source (all properties also have DH)	Number of properties	Average heat load [MWh/year]	DH share (of bought energy for heating)	Average year of construction
Combination of 2 heat sources				
EAHP	119	591	87%	1956
Electric (air distributed)	16	910	91%	1967
HP (air/water)	7	429	78%	1965
HP (ground source)	6	260	34%	1962
HP (air/air)	4	418	95%	1935
Electric (water distributed)	2	2940	97%	1973
Natural gas	1	292	81%	1924
Combination of 3 heat sources				
Electric (direct) & EAHP	8	617	79%	2010
Firewood & Elec. (direct)	3	241	99,7%	1934
Natural gas & Elec. (water distributed)	2	211	89%	1933
Pellet & Elec. (water distributed)	1	45	44%	1902
Electric (water distributed) & HP (air/air)	1	432	83%	1916

From Table 5.1, it is clear that by far the most common combination of a second heat source in DH-connected buildings is with EAHP. This heating combination is present in 2.7% of the multi-family residential properties in Gothenburg. This can be compared to Sweden as a whole, where this combination is present in 2.2% of multi-family residential properties with DH. It might seem surprising that the DH share of the heat load is on average 87% in these properties, but that is because property owners only report the input electricity to their HPs (not the output heat). Assuming seasonal performance factor (SPF) = 3.0 for this category, the average coverage of DH instead becomes 69% of the yearly heat load. Furthermore, in these 119 properties, 21% of the total heat output is used for domestic hot water. Assuming that only DH is used for domestic hot water, on average 61% of the yearly heat use for space heating is covered by DH for the buildings in Gothenburg. For Sweden as a whole, this value is 56%. However, the share of DH is unevenly distributed among the 119 properties in Gothenburg, as shown in Figure 5.1. It is therefore of interest to study several system configurations in a sensitivity analysis.

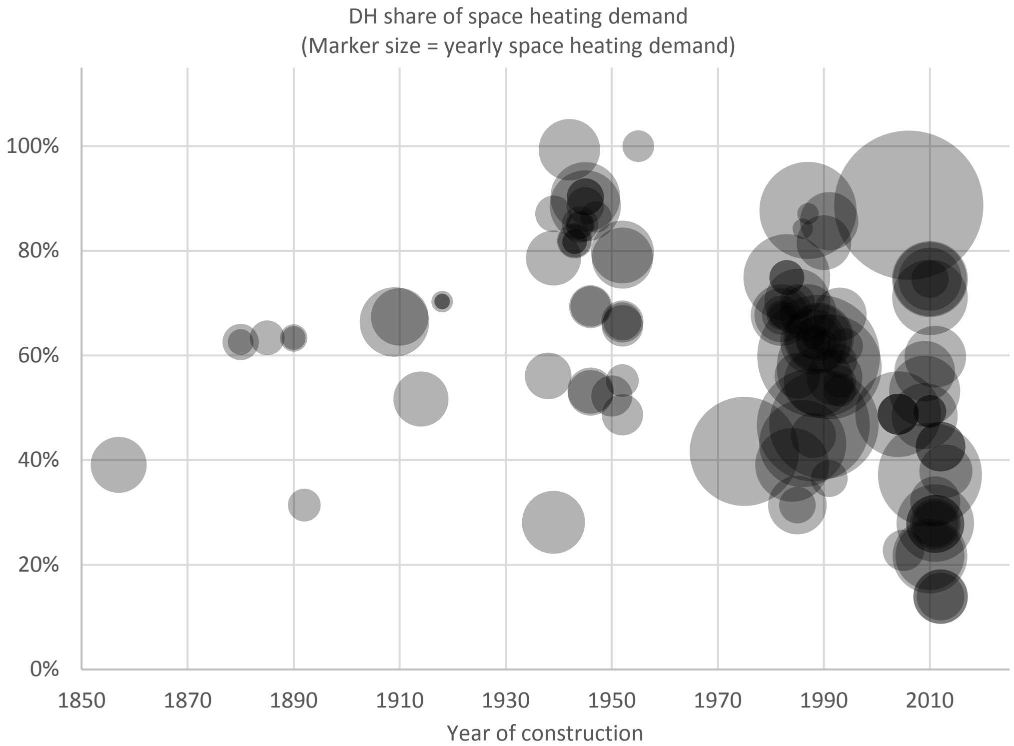

Figure 5.1 DH share of space heating demand in buildings with DH and EAHP (SPF = 3), assuming all domestic hot water is provided by DH. Markers are transparent, and darker color indicates higher concentration of properties.

5.2 EAHP Model

It is important to have a model configured with the heating system that represents systems that are actually installed in buildings today. Some of the required parameters can be extracted from the energy performance certificate database presented in 5.1. Yearly electrical input to the heat pumps, yearly bought heat from the DH system, and the division of heat use between space heating and domestic hot water are examples of parameters that can be found this way. However, there are other parameters more difficult to find representative data for. One is system configuration. Here, practices can vary among different companies, cities, and countries. The system configuration used in Paper III and by Holm and Ottosson (2016) is based on the regulations from the DH provider in Gothenburg and on the experiences of consultants working with such solutions in the city. Two main things stand out that could be different in other cities due to local conditions:

- The EAHP is only used for space heating (not for domestic hot water). The reason is that there is a large share of low-cost industrial excess heat in the Gothenburg DH system, and customers pay a seasonal price that is very low in the summer. It is therefore not economically viable to have the EAHP generate domestic hot water, and the consultants design it this way.
- The heat pump is assumed to be connected in parallel with the district heating substation. This is a part of the customers' contract with the DH provider; if they are to install a second heat source, it should be connected in parallel, so it does not increase the return temperatures to the DH network. The heat pump can still supply heat to the same radiator system as the DH network, and the flow will be split between the two heat sources as system configuration 4.2.2 defined by Boss (2012).

With these constraints, a model for the EAHP is established. The temperature levels are based on a radiator heating system, with 60°C supply temperature at DOT -16°C, and decreasing at higher outdoor temperatures, following Kärkkainen's equation (Kärkkäinen, 2010). A survey of radiator temperatures in Gothenburg by Jangsten (2016) shows that this is a very common supply temperature profile in multi-family residential buildings. According to consultants, a common design for an EAHP is to allow cooling of the exhaust air down to 5°C to avoid the need for defrosting, so this condition is used in this study. The amount of exhaust air is set to 0.35 L/m^{2}s (Boverket, 2010). More details on how the COP is calculated can be found in Paper III and *The Future Development of District Heating in Gothenburg* by Holm and Ottosson (2016). The model results in a seasonal performance factor (SPF) of 3.2 for the study of the 2013–2014 case presented in Paper III. This is in line with surveys of SPF in existing systems by Maivel and Kurnitski (2015), Ottosson et al. (2013), and Lundström and Wallin (2016). For the 2032 case by Holm and Ottosson (2016), a SPF of 4.3 is used.

5.3 Heat Source Shifting in Present Systems

In this section, it is assumed that a building with both DH and EAHP for space heating is provided with hourly prices of electricity and heat that are equal to the cost of electricity and heat for 2013–2014 (presented in 3.3). Heat source shifting is applied with the target of minimizing the heating cost of the building that is analyzed for several cases.

The space heating demand in the simulated building is based on measurements from 2013–2014 in a multi-family residential building, because it is the most common customer in the DH system, accounting for more than 50% of the heat load. For other building types, the heat load profile might be different. The selected building is located in Västra Gårdsten, Gothenburg. This is one of the buildings that the energy signature in 4.3 is based on. The building is typical of the time period when a large part of the buildings with DH and EAHP were built. It is a three-story building with a structural core of concrete and only tenancy apartments.

The simulations are run in two modes: EAHP prioritized and shifting priority. EAHP prioritized should represent how the systems installed currently operate, where the EAHP always delivers as much heat as it is capable of doing, and DH fills the remaining demand when the heat output of the EAHP does not meet the total demand. Shifting priority means that the cheapest heat source has load priority each hour. When the DH price is lower than the electricity price divided by COP for the present hour, DH is prioritized, and the EAHP is turned off. The size of the EAHP is chosen so that, when it is prioritized, it covers 39% of the yearly space heating demand like the average building from 5.1 Survey of Residential Buildings with Several Heat Sources. This corresponds to an EAHP that can cover 9.9% of the heat load that occurs at the design outdoor temperature (DOT) of -16 °C. Results from the simulation are presented in Table 5.2.

Table 5.2 Results from the base simulation case and a reference case with only DH and no EAHP in the building

Case	Prioritized heat source	DH yearly share	SPF	DH price average [SEK/MWh]	El. price average [SEK/MWh]	Heating cost [kSEK]
Reference (Only DH)	-	-	-	328	-	400
Base (DH and EAHP)	EAHP	61.0%	3.2	375	642	374
	Shifting	75.0%	3.0	324 (-14.0%)	642 (±0.0%)	362 (-3.2%)

From Table 5.2, we can see that the change from prioritizing EAHP to having a shifting priority in heat sources has a big impact on how the system operates. The share of DH increases from 61% to 75%, and the average DH price drops by 14%. This is a consequence of turning the EAHP off during the summer and in daytime in spring/autumn when the DH price is very low. The savings achieved by enabling heat source shifting are 3.2%. This may seem small, but these savings can also be compared with the savings from installing an EAHP without heat source shifting compared to the case with only DH, which are 6.5% (374 kSEK compared to 400 kSEK). Heat source shifting has in this case increased the savings from installing an EAHP by 46%. An example of how the system with heat source shifting operates during a typical spring week is shown in Figure 5.2.

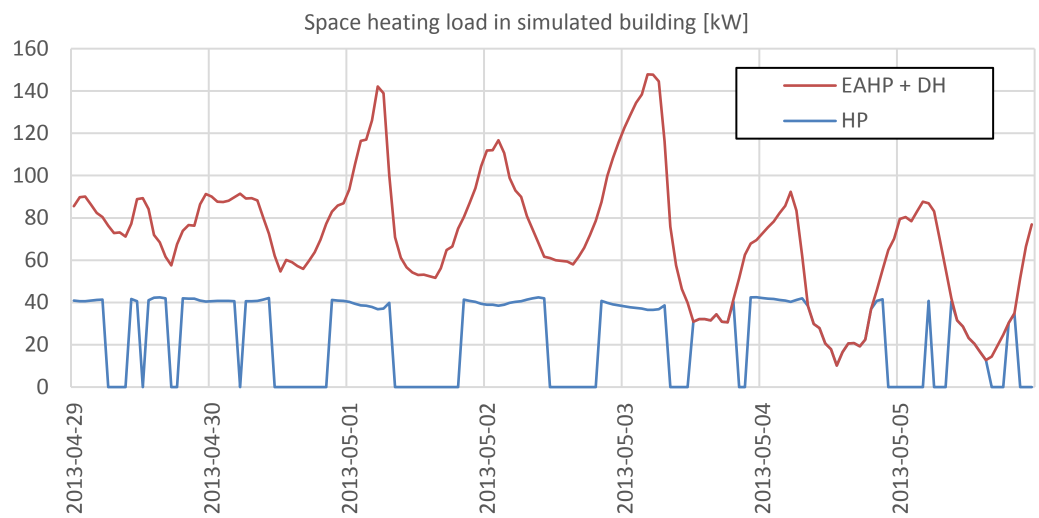

Figure 5.2 Operation of the base case heating system with shifting load priority during one spring week (warm days and cold nights)

From Figure 5.2, we can see that the EAHP is often turned on during the nights and off during the days. This is a consequence of the DH price usually being high when the load in the DH system is high (cold nights) and low when the load in the DH system is low (warm days). The decrease in SPF from 3.2 to 3.0 occurs because the EAHP is turned off for many of the hours when the COP is high. It is still economical to do so, since these hours often coincide with very low (or even zero) DH prices. This correlation is further shown in Figure 5.3.

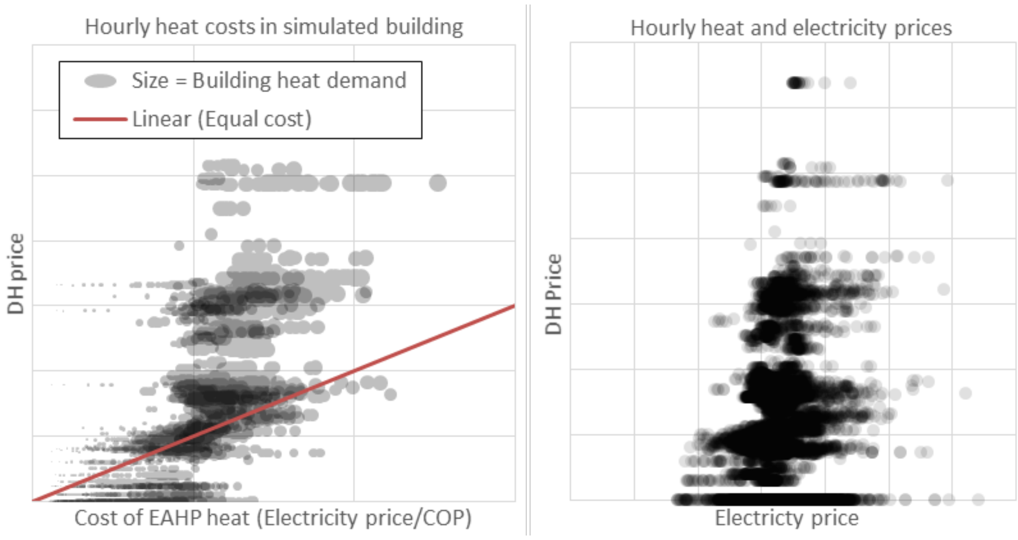

Figure 5.3 Left figure: Comparison of heat cost from the two heat sources where the COP of the EAHP is considered every hour, 2013–2014. Points below the line indicate that heat from DH is cheaper than heat from the EAHP. Right figure: Figure 3.3, scatter plot of hourly heat and electricity prices 2013–2014.

If we compare Figure 5.3 to Figure 3.3 (included here to the right as well), we can see that the data is "tilted clockwise" in Figure 5.3. This indicates that there is a correlation between COP and the DH price. This pushes many of the points closer to the line of equal cost, reducing the incentives for heat source shifting. The incentives for heat source shifting could be much more prominent in markets with a more volatile and/or higher electrical price and in systems with less variation in COP (e.g., ground-coupled HP). Since there are a number of uncertain parameters and parameters that can have a high impact, a sensitivity analysis is presented in Paper III.

5.4 Large Scale Implementation in 2032 Scenario

A possible large-scale implementation of EAHPs for a 2032 scenario has been studied in a master's theses completed within this research project by Holm and Ottosson (2016). A large proportion of the multi-family residential buildings in Gothenburg were built in the 1960s and 1970s. Many of these buildings are in need of refurbishment in the near future. The total heated area in buildings that need refurbishment is approximated to 5.0 million m^2. A possible refurbishment measure in these buildings is installing EAHPs. An estimation is also made that there will be an addition of 5.7 million m^2 in new constructed buildings before 2032. This adds up to 10.7 million m^2 of heated area where it might be suitable to install an

EAHP before 2032. The study includes several cases with varying share of the 10.7 million m^2 refurbished buildings installing EAHP, and it evaluates the savings from using heat source shifting.

The optimization is run in the GAMS-model presented in 4.5.1 for the 2032 case of the DH network in Gothenburg. Simulations are performed for cases in which 10%, 20%, 30%, 50%, and 100% of the 10.7 million m^2 in buildings potentially suited for EAHP install an EAHP. As in Paper III, a comparison is made between two operational modes:

- EAHP is prioritized as base load
- Heat source shifting with the cheapest heat source as base load each hour

Figure 5.4 shows how the heat generation in Gothenburg would be affected if 100% of the potential buildings installed EAHP and prioritized the EAHP for base load. This measure would reduce the operational cost of the DH system (counting the electricity to the EAHPs as a cost) by 12.2–15.4% depending on how the future electricity price develops. The reason the EAHP generate so little heat in the summer months (even though they are prioritized) is that they only provide space heating and no domestic hot water.

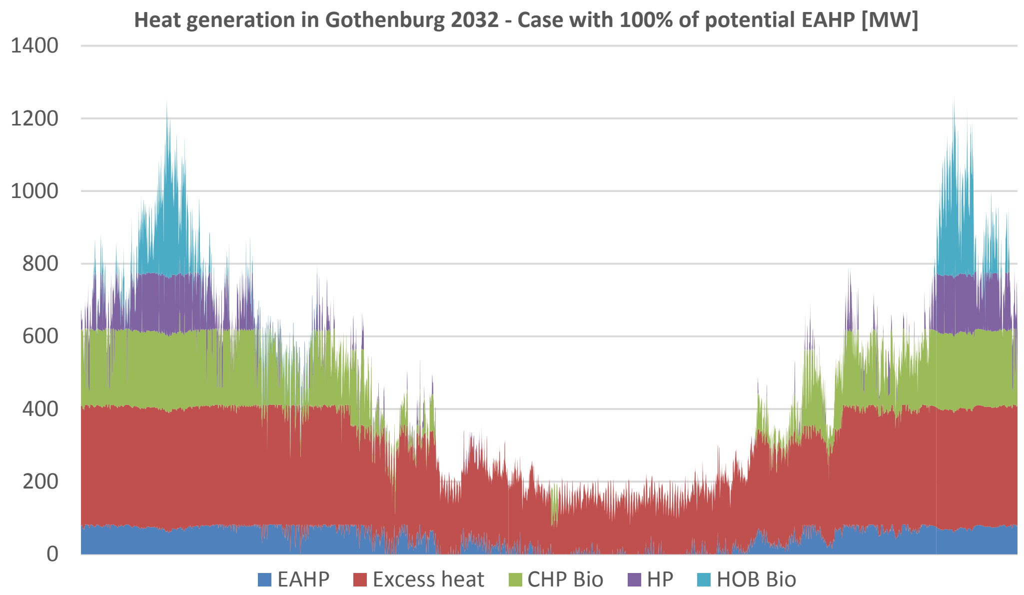

Figure 5.4 Heat generation in Gothenburg 2032 with EAHP prioritized for base load. 100% of renovated and newly constructed multi-family residential buildings have EAHP. Based on data from (Holm and Ottosson, 2016).

There is a diminishing return of installing many EAHPs. The 10% case shows savings of 1.5–1.8% compared to the 12.2–15.4% of savings in the 100% case, i.e., each EAHP is about 15–20 % less valuable in the 100% case. This is because when more EAHPs are installed, they start to replace lower-cost heat generation. However, installing EAHPs is still probably a good investment from a system perspective (when the total cost of generating heat and the electricity cost for the EAHPs are regarded). A rough calculation for a 88 kW EAHP with an investment and installation cost of 300,000 SEK gives simple payback times of 3.4–4.5 years for the 10–30% cases.

If heat source shifting is enabled, the savings in the 10% case increase from 1.5–1.8% to 1.6–1.9%. For the 100% case, the savings increase from 12.2–15.4% to 13.6–16.0%. This increase in savings translates into increasing the value of each EAHP by 4–11%. This value can be compared to the findings in Paper III where enabling heat source shifting has increased the savings from installing an EAHP by 46%. This major difference can be explained by Figure 5.4. In the 2032 scenario, the EAHPs have an SPF of 4.3, which means that they are the heat source with the lowest cost most of the hours when they are available. The exceptions are when industrial excess heat is on the margin and the few hours with very high electricity prices. From Figure 5.4, it is clear that, under these conditions, there are few occasions where it would be beneficial to turn off the EAHPs though heat source shifting. In the 2013–2014 case, the EAHPs have a lower SFP of 3.2, which during many hours places an EAHP after other heat sources (such as bio-fueled CHP) in the merit order. It is therefore much more beneficial to enable heat source shifting. This boils down to the very fundamental and simple prerequisite that heat source shifting can be beneficial, but for it to be so, there must be a situation in which the heat source that has the lowest cost actually shifts during hours when both sources are available.

6 CONCLUSIONS & DISCUSSION

In this chapter, the main conclusions are summarized and some aspects of the work are further discussed. The chapter ends with some suggestions for future work.

6.1 Main Conclusions

This work has shown through pilot tests that the thermal inertia in buildings can be used as TES for the purpose of load shifting. The thermal energy is stored in the heating system, indoor air, objects, and building structure. A multi-family residential building with a structural core of concrete can be utilized as a TES with a capacity of roughly 0.1 $kWh/m^2_{heated\ area}$ without negatively impacting the thermal comfort of the residents. This measurement is a good rule of thumb when estimating the possibilities with a BITES. For more detailed analysis, a dynamic model is also provided that better describes the interaction between the heating system, indoor air, and building structure (Paper IV).

Utilizing the thermal inertia in buildings as TES can be a very cost effective method for reducing operational costs in DH systems. In the DH network in Gothenburg, Sweden, the cost associated with generating heat for buildings utilized as TES has the potential to be reduced by at least 5.5–11.0%. This is based on a case where residential buildings representing 20% of the total heat load are utilized as TES, and all cost reductions are allocated to these buildings. Only fuel cost and net bought electricity in the heat generation are accounted for in these savings. On top of these savings there are also expected but not quantified benefits from several sources, including but not limited to:

- Reduction of starts and stops of boilers
- Better handling of bottlenecks in the distribution networks, which reduces usage of distributed less efficient heat sources due to limited capacity in pipes
- Better handling of bottlenecks, which can delay or avoid investments in DH infrastructure
- Improved ability to fairly distribute heat in the case of a heat shortage caused by, e.g., boiler failure
- BITES, which requires a more advanced control systems that can also be utilized for incorporating indoor temperature feedback and/or more weather parameters in the control and for reducing heat use for space heating to the magnitude of 10%

Even though none of the studies in this work have optimized a BITES to reduce environmental impact (e.g., CO_2 emissions), the results points towards BITES having a positive environmental impact since the use of fossil fueled HOBs have been reduced. Utilizing buildings representing 20% of the heat load as TES in Gothenburg would reduce the use of fossil HOBs by 25%. In Gothenburg and many other DH networks, fossil fueled HOB heat sources have the highest environmental impact, highest operational cost, and are hence last in the merit order regardless of whether the operation is optimized with economical or environmental criteria. The effects on environmental impact from the utilization of HPs and CHP in DH systems have not been covered in this work. The effects on environmental impact are heavily dependent on the model used for environmental impact of electricity.

BITES has been compared to HWT as alternatives for TES in a DH system in a simulation study. The results show that both TES solutions provide equal reductions to the daily heat load variations while the HWT has a better capability to reduce weekly heat load variations. The consequence of this is that the reductions in total system operating cost achieved by the HWT are almost double of those achieved by BITES. Although this result is based on a perfect heat load forecast, and forecasts are more accurate the closer they are in time, the real difference between the two TES alternatives is likely smaller. The BITES also has a significantly lower investment costs than the HWT alternative.

The first pilot test, where hourly heat prices based on marginal cost of heat generation is used as control input for BITES, is presented (Paper V). All buildings in the test reduced their average price per unit of heat by shifting heat load from high price to low price hours. The control system is still in development, and several possible improvements are identified and presented. Even though the test period is short, the results indicate that the potential savings are in the same magnitude as those found in the simulation study.

Heat source shifting based on hourly heat and electricity prices can be an economically viable method of optimizing heating of buildings with several heat sources. If it is viable, how beneficial it is depends on the fundamental prerequisite that there is a situation in which the heat source that is cheapest actually shifts during periods when both heat sources are available. This mainly depends on the electricity price level, how much the electricity price fluctuates, the COP of the HP, and how all these factors correlate to the marginal cost of heat generation in a DH system.

6.2 TES Capacity in Buildings

It has been shown in this work that the thermal inertia in buildings can be utilized for TES. To quantify to what extent a building can be utilized as TES is a difficult task and depends on many variables, such as:

- Type of heating system
- Type of ventilation system
- Accepted variation in indoor temperature
- The building's thermal properties
- Tenant activity

These factors makes each building unique, and it is impossible to have one model for thermal storage that fits all buildings. For this reason, the focus in this work has been on a building type that is common and well suited for BITES: residential buildings with a structural core of concrete, hydronic radiator systems, and exhaust only or natural ventilation. Even within this building type, the results vary between the tested buildings. For the models used in this work, the measurements from Building A were chosen for two reasons:

- Of the four "heavy" buildings in the thermal response pilot test, Building A showed the smallest capacity for TES
- Building A had the best quality in the measurement data and was tested for the widest variety of charge/discharge cycles

Even though only four heavy buildings were tested, the fact that the models are based on the worst performing of the test buildings indicates that they are "safe side" assumptions. The largest uncertainty in the models is the properties of the deep storage in the dynamic model. The reason is that the state of this thermal node was not measured during the thermal response test. Its properties are fitted to best match its interaction with the shallow storage. Since the longest charging/discharging periods were 12 h in the test, the model has a larger uncertainty for longer charging/discharging periods. However, as shown in Paper IV, BITES is best suited and is most frequently used to store heat over shorter periods of time, so this uncertainty will probably have a limited effect on the results.

If the models are to be used in a control system, it is recommended that the control incorporates feedback from the indoor temperature in the controlled buildings. This has two benefits:

- The TES potential can be utilized to a higher degree, since no safe side assumptions have to be made
- The indoor temperature can be guaranteed

Incorporating feedback from indoor temperature is not only useful directly as control input, but it can also be used to constantly improve the building model. This can be done either manually through conducting a thermal response test in the buildings or continuously with a building model that incorporates adaptive machine learning.

A prerequisite for large-scale BITES is that the thermal comfort of the tenants can be guaranteed. The thermal comfort depends on more factors than the indoor air temperature. The most noticeable parameter that is affected by the utilizations as TES (except for indoor air temperature) is the radiative heat transfer from the radiators. In the thermal response pilot test and the linear model, Δu is limited to ±7°C, which roughly translates into a change in radiator supply temperature of ±8–10°C (Jangsten, 2016). The HPC pilot test limited Δu to +12°C (≈ radiator temperature reduction of 14–16°C), and this control system is commercially used. The dynamic model puts no limits on Δu except the physical limitations, but $\Delta u >$ ±10°C was very seldom used due to the limitations on the shallow storage. How the variations in radiator temperature affect the thermal comfort of residents is not covered in this work but is of great interest for future studies, e.g., tests and/or literature reviews of radiative heat transfers affecting thermal comfort. It is essential to take this effect in consideration when further developing BITES.

Another important factor to take into consideration is that the indoor air temperature normally exhibits relatively large variations even when a building is not utilized as TES. This is because control systems normally use the outdoor temperature as the only input, and the heat demand depends on many other factors, such as solar radiation, wind speed, and tenant activity. Installing a control system that incorporates feedback from the indoor temperature and/or other weather parameters can therefore reduce energy used for space heating to the magnitude of 10% and can also provide a more stable indoor air temperature (Olsson, 2014). Such control strategies should preferably be combined with BITES, but the energy saving should not be credited to the utilization as TES. Whether the utilization of buildings' thermal inertia as TES increases, decreases, or does not affect the energy use for space heating depends on the allowed indoor temperature variations. The most restrictive condition (only allowing positive variations from the set-point) was used in Paper IV and resulted in 1% extra energy use for space heating if all extra heat use is allocated to the 20% of the buildings that are utilized as TES. Only allowing negative variations from the set-point, as in Paper V, will likely have a similar but reductive effect on the energy use. Regardless of how the temperature span is defined, the effect on total heat use allocated to BITES can be seen as small.

6.3 BITES Impact on DH Systems

The effect BITES can have on a DH network has been covered in several studies in this work. The effect BITES can have on heat load variations and the heat generation is well covered, but there are also several other effects that are not studied in detail.

One such effect occurs from BITES being a decentralized TES, compared, e.g., to HWT, which is a centralized TES. In all simulations in this work, no transfer limitations were considered and hence the location of the TES therefore did not matter. However, in many DH systems (including Gothenburg's), bottlenecks in the distribution limits both operation and expansion of the network. A decentralized storage can help with levitating these bottlenecks since the heat load variation for the customers can be leveled. This can reduce usage of distributed, less efficient heat sources due to limited capacity in pipes. On the other hand, a centralized storage can be more efficient for increasing the flexibility in the heat generation. This flexibility can be used to shift the operation of a CHP plant to the hours with highest electricity prices during a day. Why a centralized storage would be more useful in this case is less clear, but this can occur when the connection from the CHP plant (and HWT) to the distribution network is the limiting factor.

Another aspect that is unique to BITES that has not been taken into account in this work is how charging and discharging interacts with the DH distribution system. In this work, it has been assumed that a decrease or increase of heat load in a building has an immediate and equal effect on the heat generation. This is only partly true. When a building is charged by supplying extra heat, the flow in the DH network is increased, which has an almost immediate effect (flow and pressure changes in the distribution spreads at the speed of sound in water) on the heat generation. Charging a building by supplying extra heat through a heat exchanger also increases the return temperature to the DH system. This is the result of two effects in the heat exchanger: First, a larger heat transfer immediately results in a higher temperature on the DH side. Second, after some time, the return temperature of the radiator system increases, which causes an increase in the DH return temperature. These factors likely vary depending on the dimensioning of the heat exchanger, the circulation time in the radiator system, and other unique factors in each building. Modeling their effect on a DH system probably adds more complexity than accuracy to the results. However, these effects probably make BITES more favorable. This is because charging/discharging a building also simultaneously charges/discharges the return pipe in the DH network.

6.4 Practical Implementation of BITES

There are several factors to take in consideration in the practical implementation of BITES in DH systems. HPC has been tested as a control method for BITES, but it could also be used as part of the business model. Both these aspects are elaborated on here and compared to their alternatives.

When controlling a BITES in a DH environment, there needs to be some kind of control logic that decides the hours in which the heat load should be increased and decreased. This can be handled in several ways:

- The system for heat generation planning at the DH operator sends inputs (e.g., hourly prices or heat load forecasts) to the BITES control system that handles the optimization.
- The BITES control system sends inputs (e.g., available heat load flexibility) to the system for heat generation planning at the DH operator that handles the optimization and sends back signals for when the buildings should be charged and discharged.

The first alternative is tested in Paper V with hourly heat prices based on the marginal cost of heat generation as input to the BITES control system. The novelty with this study is the usage of hourly prices as input. Since the most common goal of TES is to reduce the total system operational costs, a price signal based on marginal cost should be an improvement from using, e.g., total DH system heat load as an input. The benefit stems from using the parameter that the end goal is to reduce as input to the control system. There are, however, a number of circumstances that cause hourly heat price to be a more complicated control input than, for example, the total DH system heat load. The main problem is that, if TES in buildings is used on a larger scale, the control of the TES might affect which heat source is operating on the margin and, hence, the marginal cost that the price is based on. This creates an unsolvable loop that arises due to the lack of information in the control input (i.e., the hourly heat price contains no information regarding the quantities of heat that are available at certain prices).

Instead of increasing the amount of information in the control input, it might be better to more closely integrate the control system of the BITES with the heat generation planning and energy trading systems of the DH provider, like the second presented alternative. This setup can be more complicated and requires the BITES control system to send information regarding, e.g., the maximum allowed adjustment to Δu each hour, current "charge level" (integral of Δu and time), and maximum cumulative allowed adjustments to Δu for the coming hours. This information can then be used during heat generation planning to optimize the use of the BITES. The DH provider then sends a plan with the Δu for each hour to the BITES control system. Such a solution requires software for heat generation optimization that is able to handle this input, which is far from standard in these systems. There are also simpler solutions possible, but they come with a compromise. In a parallel test in a Gothenburg DH system that is part of Celsius Smart Cities (2017), a solution is used where the optimization of the BITES is handled by a server that uses the hourly heat prices as input but receives no feedback from the buildings. Instead, the server maintains a model of the buildings, and the buildings have a fail-safe which turns off the BITES control if the indoor temperature drops too low. This can be a very easy and cost-efficient solution, but it is difficult to utilize the TES capacity to its full potential without feedback control.

Another question to be answered is whether it is feasible to go one step further than using the hourly heat price as a control input and to actually charge hourly prices based on the marginal cost of heat generation. This would allow each building owner to make their own improvements to their control systems and save costs based on their performance. Even though this study has shown that hourly heat price can be used as a control signal in DH systems, it is uncertain whether it is desirable to offer customers hourly heat prices based on marginal costs, like the electrical grid. In Northern Europe, where electricity is traded by Nord Pool, the market is deregulated and plants are owned by many different operators. This creates a situation in which it is desirable for every plant operator to minimize their costs and sell electricity every hour when their marginal cost is lower than the price on Nord Pool. A DH network, however, is a much smaller system, and all plants usually have the same owner. Using hourly prices based on marginal cost in DH systems would therefore create a strange situation in which it is beneficial for the operator to not reduce peak loads, in order to keep prices high. Such a price model would also increase the risk for the customers, since not only heat use but also heat price are higher during, for example, a relatively cold winter. Hourly heat prices might therefore only be desirable for customers who have access to an alternative heat source, such as a heat pump, and are interested in practicing heat source shifting. Nevertheless, since using hourly heat price as a control signal has been shown to help optimize BITES, a model that involves sharing value with the building owners is essential. Possible alternatives to using hourly prices are:

- Fixed compensation or discount on energy/power tariff as compensation for utilizing buildings as TES.
- "Auction system" where the DH operator requests flexibility each time it is required, and buildings bid with their available flexibility until a price equilibrium is reached.
- "Trust model" where the savings achieved by the BITES each year are evaluated and shared between the building owner and DH operator.
- DH companies have the right to use any building in the system as TES, and all customers are indirectly compensated by lower prices.
- BITES control can be combined with other benefits from the same control systems, such as energy saving, thanks to indoor temperature feedback, which can be seen as the building owners' compensation for leasing their TES capacity to the DH provider.

Which business model is best depends on local conditions. Factors like fairness, transparency, and simplicity need to be evaluated, and all involved parties need to gain from the agreement. At the same time, the tenant must not be forgotten, and it should be made clear who is responsible for the indoor climate in the buildings utilized as TES.

6.5 Heat Source Shifting

It has been shown in this work that heat source shifting with DH and EAHP can be beneficial, but how beneficial it is depends heavily on a number of factors, mainly:

- Electricity price level and variation
- Heat generation mix in the DH system
- Performance of the EAHP

This all boils down to the fundamental criteria that, in order for heat source shifting to be beneficial, the heat source that has the lowest cost needs to actually shift. Heat source shifting was studied in two cases: a 2013–2014 case with average existing EAHP, which showed fairly good potential, and a 2032 case with new EAHP, with higher SPF that showed almost no potential. These studies have been carried out from an energy system perspective, where the prices used in the simulation have been based on the marginal cost of generation, but the incentives for and the value of heat source shifting may be different from a building owners' perspective. There are also power tariffs and network tariffs in price models, which might influence the value of heat source shifting. Heat source shifting might also be a component in more advanced system solutions for heating buildings. Borg (2015) has studied a residential property (now under construction) where heat source shifting is part of an energy solution with solar photovoltaic, electric vehicle charging, battery storage, ground source HP, DH and HWT. These technologies are all growing, and it is highly likely that some combinations of these technologies will become common in future buildings. If such buildings are connected to a DH network, heat source shifting can be an important control strategy that reduces costs and environmental impact.

6.6 Future Work

In this chapter, various suggestions for future work are presented.

- Pilot tests of BITES in other buildings types than those tested in this work. More modern multi-family residential buildings with lower heat use and/or heating/ventilation solutions are of interest. Offices and other commercial buildings can also be of interest, especially if heated by hydronic heating systems.
- Study of how thermal comfort is affected in buildings utilized as TES.
- Evaluation of business models for BITES and heat source shifting.
- Study of how BITES dynamically affects DH distribution, i.e., charging/discharging buildings temporarily increases/decreases return temperatures.
- Study of the implications of BITES being a decentralized TES, e.g., effect on bottlenecks in DH distribution.
- Evaluation of environmental benefits with BITES and heat source shifting.
- Pilot test of heat source shifting with HP and DH. Such a test is now underway in an office building in Gothenburg with ground source HP and DH.
- Standardization of integration between BITES and heat source shifting control systems and energy systems operators.
- Study the impact of BITES and heat source shifting in energy supply systems with different conditions than in Gothenburg, Sweden

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