Demand Response in District-heated Buildings

Sonja Salo
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Aalto University
School of Engineering
Department of Mechanical Engineering
Energy Efficiency and Systems
Abstract

Heating and cooling account for approximately half of the total energy consumption in the European Union. That is why the European Commission in its strategy for the heating and cooling sector is emphasising ways to develop energy-saving and greenhouse gas-reducing solutions in buildings. District heating is one of the most efficient heating methods, especially in colder and densely populated areas. The challenges of district heating are large fluctuations in daily and seasonal consumption that are difficult to mitigate in the inflexible centralised production system. Additionally, district heating is mainly produced with fossil fuels and, thus, it is facing a shift towards low-carbon as well as more cost-effective systems.

On the other hand, attention is being paid to the indoor air conditions in properties. The latest indoor air classifications focus on the thermal comfort of individuals in buildings that promote not only a healthy environment but also increased work efficiency. Therefore, heating control systems in buildings give priority to the comfort of people.

This dissertation investigates the addition of flexibility to the district heating system by using the thermal inertia of building structures, as well as the thermal comfort of individuals during periods of demand response. In this dissertation, demand response refers to control measures for space heating in water-circulating radiator networks as a response for external requirements in demand. This dissertation develops rule-based control algorithms for room-level temperature control via water-circulating radiator thermostats connected to a cloud service. These control algorithms are applied in district-heated office buildings. The system allows for individual thermal comfort while performing optimised and targeted heating control. In addition, a district heating system with dynamic heating pricing was modeled for evaluating demand response by shifting loads in time on the building level and by utilising a centralised thermal energy storage.

The results of the dissertation show that individuals report poorer thermal comfort than previously anticipated on days of demand response. Additionally, the modeling results also show that the demand flexibility of district heating utilising the thermal mass of buildings is of little benefit to the district heating company. Thus, demand response itself does not bring savings to the property owner either. However, field studies show that room-based control enables individual heating, which can save energy even in highly energy-efficient office buildings.

Keywords District heating, Energy efficiency, Demand response, Internet of Thing, Flexibility, Thermal comfort

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Writing this dissertation in the middle of a pandemic has motivated me to focus on enabling healthy indoor conditions when optimising energy consumption. I want to thank several people who have made this dissertation possible. First, I want to thank Professor Sanna Syri for supervising my dissertation and supporting me during the final process. I want to also thank Professor Risto Kosonen for his kind and determined advise and listening ear. Many thanks belong also to my co-authors from Aalto University: Juha Jokisalo, Aira Hast, Janne Hirvonen and Kristian Martin. I received constructive and important feedback from my pre-examiners Professor Xingxing Zhang from Dalarna University and Professor Natasa Nord from Norwegian University of Science and Technology for which I am thankful of. I am also privileged to get Professor Zhang as my opponent. In addition, I am grateful for all reviewers of my publications who gave valuable feedback on my work.

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during life’s absurdities. Many thanks also to Andreas Holm for proofreading my dissertation and being there for me in all situations. Credits for the great cover image go to Inkeri Virtanen.

Let us all stay healthy and strong for future challenges!

Helsinki, January 17, 2021,

Sonja Salo
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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.


Author’s Contribution

Publication I: “The Effect of Demand Response on Perceived Thermal Comfort in a District-heated Office Building”

Sonja Salo initiated the article and carried out the literature review, research methodology development, building up the test environment, development of the control algorithms, result analysis, writing of the article and responding to comments of the editors and reviewers. The co-author Juha Jokisalo contributed to research methodology development, building up the test environment and review of the article. Professor Sanna Syri and Professor Risto Kosonen contributed to the development of the research idea, selection of the research methodology, and provided supervision and revision for the research article.

Publication II: “Individual Temperature Control on Demand Response in a District Heated Office Building in Finland”

Sonja Salo initiated the article and carried out the literature review, research methodology development, building up the test environment, development of the control algorithms, result analysis, writing of the article and responding to comments of the editors and reviewers. The co-author Juha Jokisalo contributed to research methodology development, building up the test environment and review of the article. Professor Sanna Syri and Professor Risto Kosonen contributed to the development of the research idea, selection of the research methodology, and provided supervision and revision for the research article.
**Publication III: “The Impact of Optimal Demand Response Control and Thermal Energy Storage on a District Heating System”**

Sonja Salo initiated the article and contributed by methodology development, literature review, analysing and validating the results and writing of the original draft of the article as well as reviewing and editing the article and responding to comments of the reviewers. Co-author Aira Hast performed the energy model simulation and contributed to analysing the results and writing the article. Co-author Juha Jokisalo contributed to methodology development, providing building simulation data and writing the article. Sanna Syri and Risto Kosonen contributed to the development of the research idea, selection of the research methodology, validation of the results and provided supervision and revision for the research article. Janne Hirvonen contributed to the validation of the results and reviewing the article. Kristian Martin contributed to the data preparation.

**Publication IV: “Smart City Resilience with Active Citizen Engagement in Helsinki”**

The article was a joint effort of the authors from different affiliations. Sonja Salo wrote, as the second author, the sections regarding intelligent heating control. Mikko Martikka as the principal author wrote the 3D Helsinki Model sections. Kristiina Siilin wrote the E-bike Charging Station and photo voltaic panel crowdsourcing sections. Timo Ruohomäki wrote the Carbon Neutral Me-App sections. Pekka Tuomaala wrote the sections regarding thermal comfort control. Esa Nykänen provided supervision and revision for the article. All authors contributed to initialising and reviewing the article.
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Abbreviations

4GDH 4th Generation District Heating
AHU Air Handling Unit
API Application Programming Interface
BMS Building Management System
CHP Combined Heat and Power
CO₂ Carbon Dioxide
DH District Heating
DR Demand Response
EU European Union
EUA European Emission Allowance
ICT Internet and Communication Technology
IoT Internet of Things
HOB Heat-only Boiler
HVAC Heating, Ventilation and Air Conditioning
HWT Hot Water Tank
PMV Predicted Mean Vote
PID Proportional Integral Derivative
PPD Predicted Percentage of Dissatisfied
TLS Transport Layer Security
TRL Technology Readiness Level
Abbreviations

**TRV**  Thermostatic Radiator Valve  
**SME**  Small and Medium-sized Enterprise  
**VAT**  Value-added Tax
Symbols

\( \tau \) time constant [s]

\( C_t \) total heat capacity of indoor air and structures [J/K]

\( CS \) Control Signal

\( G_t \) total conductance of the room [W/K]

\( SP \) Setpoint

\( t \) cooling time [s]

\( T \) final temperature [°C]

\( T_a \) indoor air temperature [°C]

\( T_{out} \) outdoor temperature [°C]

\( T_0 \) initial room temperature [°C]
1. Introduction

1.1 Background

The built environment has expanded globally by approximately 50 billion square metres of new floor area over the last decade (IEA 2018). While an increasing number of properties are built, advancements in the energy efficiency of buildings are proceeding at a tedious pace. As the level of greenhouse gas emissions from the building segment correlates with the level of demand, supply, and source of energy, it is demanding to develop energy-saving and greenhouse gas emissions mitigating strategies. Placing more effort to drive investments and research into energy efficiency can lead to enormous potential to reduce rapidly greenhouse gas emissions.

From the perspective of the European Union (EU), the heating and cooling sector represents half of the energy consumption, which is produced up to 75% by fossil fuels (European Commission 2016). Space heating is the single most significant factor in this sector (Patronen et al. 2017). EU member state Finland is characterised alongside other Nordic countries with a high share of renewable electricity production (46% in 2018) and a noteworthy district heating (DH) sector (46% market share) (Statistics Finland 2018, Leskelä et al. 2018). To further enhance the use of the renewable energy share and building performance in the heating sector, existing building automation needs to adapt new technologies.

DH is currently experiencing development on both system and technology levels, moving towards implementation of the concept referred as 4th generation district heating (4GDH) (Lund et al. 2014). 4GDH is a framework that integrates district heating and cooling systems with the surrounding energy system. In the past, DH production was guided by consumption, and only a small number of consumers could control consumption according to market needs. Alternatively, buildings can participate in a flexible energy system by demand response (DR). DR utilises the demand-side resources to shift heat loads in time from hours with high costs or emissions to more favourable hours. In a connected energy
system as described in the 4GDH framework, energy optimisation should not be solely based at the property level, but on the system level (Lund et al. 2014, Wernstedt et al. 2007).

Higher energy performance in buildings will put more demanding requirements for heating, ventilation and air conditioning (HVAC). An ordinary consumer can influence energy efficiency by manually controlling consumption via target temperatures in environments of which she has control over, such as homes. However, as many consumers are not either prepared or are not able to actively pursue energy conservation, sustainable consumption must be made simple and automatic. There are also a variety of building types in which occupants typically have a limited amount of control, such as office buildings, commercial premises and other public spaces. These spaces are of interest for a variety of reasons: They are professionally managed, have economic and often environmental performance indicators, and occupants do not typically claim ownership on these spaces and hence the decision-making process can be streamlined.

Simultaneously, adequate thermal conditions must be considered and, thus, indoor comfort and energy efficiency shall not be mutually exclusive. Hence, concepts in the smart system control sector, such as the Internet of Things (IoT) (Kevin Ashton 2009), adds granularity to the control of buildings and can contribute to autonomous and user-centric building control for enhanced energy efficiency and comfort. The emergence of the IoT can allow technology providers to generate highly granular data, which can be utilised for optimising HVAC systems and enabling individual thermal comfort (Kim et al. 2018). This dissertation refers to IoT as a concept framework, i.e., a methodology to transfer data over the internet without human interaction. IoT devices on the other hand are internet-connected objects as described in Section 3.1.

Equipping buildings with intelligent control devices might reduce energy consumption as controllers balance indoor room temperature, lower the temperature during absence, and deliver more desired levels of comfort. Using automated cloud computing and individual room-based controllers, this dissertation presents room-level control to simultaneously enhance thermal comfort and optimise heating consumption. With cogent need for fast actions to mitigate climate change, this dissertation investigates the opportunity to control consumption on building level in order to decrease thermal energy generation with fossil fuels.

1.2 Research Questions and Objectives of the Dissertation

The objective of this dissertation is to examine the effects of DR measures in DH connected buildings focusing on thermal comfort and individual room control. These actions are reflected in case studies in office buildings in Southern Finland and in a simulated DH system. The dissertation focuses on control
systems in office buildings that can be either implemented in smart control schemes in building management systems (BMSs) or act as independent systems. Specifically, the dissertation demonstrates how room-based control is utilised to control space heating for the individual consumer demand and to facilitate space heating loads for DR. From these aspects, three research questions are formulated. First, the effect of demand side interventions in DH connected office buildings has been examined:

Q1: How is thermal comfort affected by decentralised demand response in office buildings?

The next question considers a large roll-out of demand-side interventions in a typical Finnish DH system:

Q2: How is a typical Finnish DH system impacted by demand-side interventions?

Finally, as technical proof-of-concepts are crucial for an economic roll-out, the last research question focuses on how to achieve DR with IoT devices and room-based control in a DH connected building. It is formulated as follows:

Q3: From the perspective of DR and flexible heating, what tools can a municipality implement in the built environment to promote climate resilience?

These questions serve to highlight technical feasibility and economic viability of DR and smart devices for different stakeholders. The dissertation examines IoT in buildings for the energy company, for the owner of the building and for the users. The results of the dissertation help to build a model that serves all parties.

1.3 Research Novelty and the Structure of the Dissertation

This dissertation consists of four publications. It summarises previous research on the topic, presents methods used and analyses the results of the associated publications. The research questions and the interrelations between publications are depicted in Figure 1.1.

The dissertation provides new information on DR and building energy flexibility in DH networks. Digitisation of buildings and their connection to an efficient energy system is central to this research. In the dissertation, many disciplines are applied to investigate state of the art technology to meet requirements in building controls and energy systems. The novelty of each publication is stated as follows:

Publication I: The novelty of the publication is to demonstrate room-level DR actions in a real office setup. It demonstrates the capabilities of IoT devices in
space heating control by leveraging algorithms that use hourly price signals from a DH company in a highly decentralised manner. In addition, a feasible number of individuals in the studied space took thermal comfort surveys.

Publication II: This publication further extends features in individual space heating control with IoT devices and introduces the concept of maximising DR capacity in buildings by categorising each zone into areas with different DR potential. The publication applies a method to calculate the power output of water-circulating radiators and discusses limitations in DR through feedback from thermal comfort surveys.

Publication III: As DR in heating grids has received a lot of public attention, this publication quantifies the effect of DR in a typical Finnish thermal energy system with a comprehensive study of whole building simulation and system simulation. This publication compares the monetary and CO₂ emission reduction potential between a hot water storage and different building DR strategies. Additionally, the publication investigates how these storage types work together.

Publication IV: This publication shows current proceedings in technology adaptation in Helsinki, Finland. The publication presents how the city can be leveraged to test novel technologies that are developing towards a technology readiness level (TRL) that is ready for system integration (European Commission 2017). In this publication, control systems and infrastructure tested in Publication I and II are implemented in a large district-heated office building. Consequently, the publication presents DR interventions and control logic in an operating building.

The dissertation is a result of two research projects: The Business Finland funded REINO project and the EU-funded H2020 mySMARTLife project. Fourdeg Ltd has been project partner of both research projects and main provider of the technology in this dissertation. Research presented in Publication I, Publication II and Publication III are conducted as part of the REINO project. In REINO, intelligent control algorithms for flexible energy utilisation in residential and office buildings were developed together with Finnish companies and
Aalto University. The project combined Aalto University’s energy, HVAC and industrial internet laboratories. The energy company Fortum PLC provided data for research. Publication IV is part of the H2020 project MySMARTLife in which technological solutions were used in the built environment focusing on building retrofits, on-site renewable energy sources, clean transport and supporting ICT solutions.
2. Building Demand Response in District Heating Grids

This chapter provides literature review on current steps towards a carbon neutral DH system. It also summarises advances in internet-connected devices for data-driven energy systems, thermal comfort and building applications.

2.1 Decarbonisation of District Heating

Human activities have likely caused 1.0 °C of global warming above pre-industrial levels (Masson-Delmotte et al. 2018). Climate models presented in the Intergovernmental Panel on Climate Change's report in 2018 show that global warming is estimated to reach 1.5°C before 2050 if it continues to increase at the current rate (Masson-Delmotte et al. 2018). Global warming increases the likelihood of, amongst other things, regional changes in mean temperature, extreme weather conditions, heavy precipitation and high probability of draught. According to the report, limiting global warming to 1.5 °C can be reached by achieving net-zero CO₂ emissions globally by 2050. The Paris Agreement establishes a process to combine nationally regulated contributions to limit global warming. Most mitigation pathways include lowering energy demand, electrifying energy services, decarbonising the power sector and decarbonising fuel usage (Kriegler et al. 2018). The European Commission also set targets to integrate efficient and sustainable heating and cooling in buildings (EUR-Lex 2016).

The challenges facing the Nordic Countries' future energy systems include the increasing volume of variable and inflexible wind power production, which is expected to double in the 2020s in Finland (Pöyry 2018). Due to the low market prices of electricity, flexible condensate production has already dissipated from Finland (Pöyry 2018). In addition, end-of-life combined heat and power (CHP) plants have been replaced with heat-only boilers (HOBs) for DH networks, which has exacerbated the capacity for flexible and peak power generation. Compared to individual heat boilers in buildings, producing DH can be advantageous through economies of scale in investment costs, fuel procurement and emission control (Koskelainen 2006).

DH companies have a large market share in the Finnish heating sector. DH
competes with alternative heating solutions, such as direct electric heating, heat pumps, and individual boilers (Leskelä et al. 2018). Cost effectiveness is essential for each heating system because once the customer has invested in one system, she is in a lock-in situation at least for the lifetime of the equipment. In case of DH, the DH provider has secured income for approximately 20-30 years. In recent years, DH companies have been pressured to increase energy fees and, thus, other heating methods have gained foothold in the market. The industry has also pressure to remain competitive with regard to its invested infrastructure. As buildings' heating demand decline due to energy efficiency procedures and a milder climate, the current system is challenged by smaller revenue streams. As a result, cost components in DH pricing have increased, with an emphasis on load cost (also referred as water flow fee, base fee etc.). In the past, the load cost has been determined based on the contract power, but currently, an increasing amount of Finnish DH companies are shifting towards a pricing strategy based on the measured maximum power (Sarvaranta et al. 2012). The energy fee has also faced a change as an increasing amount of DH companies have introduced a seasonal pricing strategy. The most advanced pricing strategies, such as ‘Open DH’, enable buildings to become suppliers of excess heat to the network (Syri et al. 2015, Helen 2020, Stockholm Exergi 2020).

Fossil fuels have commonly been the most cost-efficient source for producing district heat, and it is strongly linked to the price of electricity in most cases. The increased cost of fossil fuels (partly due to the increase in CO₂ emission costs), and national climate policies have provided favourable market environments for the roll-out of renewable energy sources. In addition, carbon-neutral heating is the single most important factor in reducing greenhouse gas emissions in most cities in the Nordic countries. These market trends can contribute to a more efficient DH system as well. Renewable heat can be produced with e.g. biomass, solar, geothermal or electricity sources with a low CO₂ factor.

Large heat pumps offer an interesting alternative for DH production allowing utilisation of different heat sources (Hast et al. 2017, Rämä & Wahlroos 2018, Kontu et al. 2019) and lower temperature level in DH system that, together with on-site heat pumps, could allow more active consumers with waste heat to enter the DH market (Brange et al. 2016). DH companies promote decarbonisation strategies, for example, by utilising waste heat e.g., from data centres, sewage water, two-way DH, geothermal heat, heat storage and increasing the share of renewable fuels (Fortum 2018).

The current trend in future energy system design is to combine different energy production methods, distributed production, and demand-side management to promote a climate neutral energy system in a flexible and cost-efficient manner. DH systems bring sources of flexibility into the energy system since energy transformation and storage can be adjusted to demand (Lund et al. 2014). Hence, smart energy systems can bring cost-efficient flexibility when shifting toward carbon neutral production methods and, at the same time, give consumers the
opportunity to choose energy services despite the lock in pricing model.

2.2 Demand Side Management in the District Heating Grid

A consumer is typically connected to the DH network indirectly via a heat exchanger at the substation (Koskelainen 2006). At present, heat accumulators are rare in buildings so that consumption is projected directly to the heating network. The heat supply is controlled by the differential pressure control and the supply temperature (Gadd & Werner 2013a) whereas demand is controlled by domestic hot water taps and valves in radiators and ventilation air heating systems, the valves controlling the flow temperature depending on outdoor temperature.

Seasonal and temporal weather relations are assessed by Gadd & Werner (2013b) in Swedish DH networks and in an additional study (Gadd & Werner 2013a), daily and annual heat load patterns in different buildings were evaluated. The results show that inside-outside temperature differences during winter lead to larger heat loads. During intermediate season, i.e., autumn and spring, heat load peaks are characterised by sharper spikes due to relatively larger variation in outdoor temperature and solar radiation (illustrated in Figure 2.1). During summer, the heat demand is dominated by domestic hot water consumption and, thus, very small differences in heat load patterns are observed.

Figure 2.1. Typical weekly profile (counting for 168 hours) of a Finnish DH system (modified from Salo (2016)).

This variability can be confronted with flexible production units and different storage types. Adding a production unit to the system can increase variable costs, which is incorporated in the marginal costs. In energy systems, the marginal cost represents the cost for the last unit of heat production and is regarded as ‘efficient resource-allocation’ (Sjödin & Henning 2004). It considers, amongst others, fuel cost, allocation of joint costs, price of electricity, system capacity and
Building Demand Response in District Heating Grids

period term (Sun et al. 2016). Pricing schemes based on marginal costs can give actionable pricing information to the customers, which could take advantage of varying DH prices.

Hot water storage tanks are suitable not only for the optimisation CHP production but also, more generally, for balancing local peaks and valleys in DH demand (Hast et al. 2017). Such storage types enable capturing thermal energy both on an hourly level, daily level, or even for longer times, and thus, increasing flexibility in the grid (Hast et al. 2017, Paiho et al. 2018). Although investments in storage capacity are required, hot water storage tanks are relatively common in Finnish DH systems (Koskelainen 2006). More comprehensive discussion about hot water storage tanks on load control is further discussed in Publication III.

Varying the supply temperature in the DH network is already widely utilised in DH systems. The idea is to utilise the heating network’s inertia, i.e., the time delay when hot water is transferred from a heating plant and to the substation (Koskelainen 2006). DH networks are utilised as short-term energy storage especially in times when demand is predicted to increase. However, the network has only a limited storage capacity and is prone to changes in weather conditions (Basciotti et al. 2009). Furthermore, a temporary increase in supply temperature will decrease the efficiency of network equipment, including boilers and heat pumps, and can increase the risk of fatigue of distribution pipes.

The last form of storage discussed in this section is the exploitation of the building stock’s thermal inertia for load shifting purposes. Controlling the demand can be implemented in several stages of building HVAC control and, generally, requires investments in equipment. However, it has been argued that modern monitoring and controlling devices can have low investment costs and provide additional benefits via advanced indoor air monitoring and control, BMS monitoring, predictive maintenance, and increased energy efficiency.

This dissertation focuses on utilising the building thermal inertia as a short-term thermal energy storage in a DH system and thereby adding flexibility to the system. This strategy is commonly encompassed by the term demand side management (DSM). The basic idea of DSM is to make consumer interventions in power and energy usage. There are various approaches that can affect the consumer’s traditional consumption profile, including peak shaving, valley filling and load shifting. DR, on the other hand, can be defined as interventions in consumer profile based on a market signal. Hence, DR measures can mean all of the aforementioned approaches.

These interventions have been researched substantially in the power grid sector. In the power grid sector, DR can be roughly divided into dispatchable DR, which characteristically involves up- and/or downward alternations of power ordered by the system operator in the range of seconds to a few hours, and non-dispatchable resources, which rely on voluntary adjustments of demand, typically in response to price signals notified several hours or days in advance (Alimohammadisagvand 2018). In this perspective, DR measures in the heating
sector follow more the characteristics of non-dispatchable DR strategies. In these, the end-user can be charged time-varying tariffs, which motivate them to make changes in demand patterns.

A German review of field studies on power grid integration of residential thermal power storage concluded that existing field tests did not meet the flexibility challenges of smart grids with high share of variable renewable power generation (Kohlhepp et al. 2019). This indicates that DR can only moderately replace flexible conventional supply technologies in the provision of balancing power and energy (Olkkonen 2019). While DR can be utilised in limited appliances, such as in electrothermal storage appliances, to balance short-term variations in residual demand, higher integration of variable renewable power can be limited by technical and economic restrictions of the storage capacity. Therefore, the 4G DH system integration can partially solve constraints in variable renewable energy integration.

In contrast to DR in power grids, the control of DH networks has lower time intervals due to, amongst other things, lags in heat transmission in distribution networks. Depending on the size of the network, the effects of changes in supply water temperature conducted at the heating plant can be only tracked a few hours later on the demand side (Koskelainen 2006).

Because of the strong connection between supply and demand, it has been claimed that implementing heating DSM measures for DH grids could be feasible (Finnish Energy and Valor Partners 2016). DSM in heating grids has been subject of interest in recent years, such as in consultancy papers (Finnish Energy and Valor Partners 2016, Rinne et al. 2018) and master's theses (Carlsson 2016, Salo 2016, Martin 2017, Sarasti 2017, Mäki 2019), journal articles (Lund et al. 2014, Kensby et al. 2015, Le Drea et al. 2016, Paiho et al. 2018), and companies’ newsrooms (Fortum 2019a,b, Granlund Consulting 2019, Fortum 2020). These references claim that increasing flexibility in thermal systems via DSM helps to increase the share of variable renewable energy sources, decrease costs, and engage customers. The customer benefits mainly from lower cost of energy, renewed pricing strategies and the acknowledgement of different customer types (Kontu et al. 2018). Benefits for the DH company include mainly optimisation of DH production, cutting peak loads and eliminating bottlenecks in the DH network. However, these effects can require additional assistance of heat pumps (Kensby et al. 2017). DR in DH systems is currently tested in shopping centres, schools and apartment buildings in Finland (Fortum 2019a,b, Granlund Consulting 2019).

Instead of placing DR as the central element, it can be placed as a feature in a broader optimisation service of thermal loads (Timonen 2018). This service can include, amongst others, indoor monitoring, targeted heating control, decrease in total energy consumption, predictive maintenance and limiting load during peak hours. Peak hour can denote for a peak either in cost, system load, building load or emission intensity relative to the day’s or year’s average. These control schemes are enabled by using Information and Communication (ICT) methods...
between the heat supplier and the control interface in buildings when the latter is equipped e.g. with a wireless sensor network.

### 2.3 Demand Response in Buildings

The evaluation of DR strategies in buildings is considered as challenging as many approaches require modification to the building system components, which can be expensive in actual building settings. Hence, the majority of the references available use modelling to understand cause and effect of DSM in the built environment, such as work from Rinne et al. (2018), van Deventer, Jan and Gustafsson, Jonas and Delsing, Jerker (2011), Difs et al. (2010), Guelpa et al. (2017), Dominković et al. (2018) and Publication III. Although building and energy system modelling is a well-established and extensively exploited approach, many challenging effects of the control strategies might not be captured.

Furthermore, differences in building components, occupant patterns and other unpredictable conditions related to buildings could affect indoor conditions in a way that is challenging to model accurately. On the implementation side, studies with limited floor area in a building, such as Mishra et al. (2019) as well as Publication I and II. Field studies with a limited number of buildings, including work from Wernstedt et al. (2007), Österlind (1982), Kensby et al. (2015), Sweetnam et al. (2019), Kärkkäinen et al. (2003) and Publication IV are commonly exploited for validating those strategies.

In the European context, several field studies have been conducted in which the control of heating energy usage and the thermal resistance of buildings have been exploited for DR purposes. Utilising the thermal inertia of buildings as short-term thermal energy storage for load control in a DH system has been subject to research since the 1980s. The oldest pilot test by Österlind (1982) had the intention to increase the security of supply for DH customers located furthest away from a heating plant. DH delivery of 80 residential and office buildings in Sweden were remotely reduced by a one-way communicating control system. The maximum drop in indoor temperature was constrained to 3°C and the magnitude and duration of the reduced DH supply depended on an estimation of the buildings’ time constants. Measured indoor temperature showed that the variations were on a regular level except during the test with the longest duration, i.e. 24 hours. Another investigation from 2003 of two high-mass office buildings accomplished a heat load reduction of 20-25% for a duration of 2-3 hours (Kärkkäinen et al. 2003).

In a field study on a typical residential area in Sweden, DR measures were implemented in the form of an agent-based control algorithm (Wernstedt et al. 2007). The control was distributed among agents on an DH substation level, on a cluster level (i.e. local optimisation of consumer-level agents), and on the DH supplier level. These agents monitored DH substations and communicated with each other to achieve system-wide peak reduction and fuel optimisation.
The system displayed a potential of 10% reduction of total energy consumption, depending on building characteristics. Difs et al. (2010) noted that load control via a software program controls the substations of residential premises affects mostly the DH demand during spring and fall, and, hence, has a smaller effect on peak loads during colder seasons.

2.4 Control Strategies for Buildings

In order to describe the heat exchange dynamics between the indoor environment and the building structure, empirical investigations suggest an energy balance model that approximates building inertia as a thermal energy storage with several thermal nodes (Kensby et al. 2015, Karlsson et al. 2013). This storage type can be significant, as showed by Le Dreau & Heiselberg (2016). In their study, the thermal mass stored heat for more than 24 hours while maintaining indoor temperature variations within 2°C in two single-family residential buildings in Denmark. The thermal mass of a building can have a significant impact on heating flexibility. The time constant is defined as the amount of time spent until the indoor temperature drops to 36.8% of the maximum possible temperature drop after cutting off heating (Seppänen et al. 2006). The time constant for a given zone or a building and the time that room air temperature declines to a particular value are calculated according to equation 2.1 and 2.2, respectively.

\[
\tau = \frac{C_t}{G_t} \tag{2.1}
\]

and

\[
t = -\tau \ln \frac{T - T_{out}}{T_0 - T_{out}} \tag{2.2}
\]

where

- \(\tau\) is the time constant [s],
- \(C_t\) is the total heat capacity of the indoor air and building structures [J/K],
- \(G_t\) is the total conductance of the room [W/K],
- \(t\) is the cooling time [s],
- \(T\) is the final temperature [°C],
- \(T_{out}\) is the outdoor temperature [°C] and \(T_0\) is the initial room temperature [°C].

Most building control algorithms are rule-based, i.e. if-then-else based rules (Alimohammadisagvand et al. 2018). Currently, numerous advanced control techniques exist, including fuzzy logic control (Ghahramani et al. 2014), agent-based control (Johansson & Davidsson 2010), neural network control (Liang
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& Du 2005), genetic algorithm-based control (Nassif et al. 2004), and model predictive control (Freire et al. 2008, Chen et al. 2015) in building control applications. Still, rule-based applications are advantageous for their reliability and model simplicity. Rule-based applications entail linear regression models, which are especially suitable in colder climates as demand in heating energy has a strong linear dependency on outdoor temperature (Fang & Lahdelma 2016).

2.5 Internet-connected Devices

As many models rely on physical dependencies, it is also vital to obtain abundant information directly from the demand side. Therefore, internet-connected devices are reliable tools for collecting information at zero marginal cost. Currently, energy systems are significantly restricted by closed-system environments due to management and technical issues. However, this is changing with ongoing projects that standardise semantic data models and web services (Haystack 2018) and semantic descriptions of the physical, logical and virtual assets in buildings (BRICK 2020).

The usage of ICT to improve the operation of energy networks forming a smart grid is a topic, which deploys a distributed computing technology that can automatically shape energy demand and provide network benefits. Further applications of IoT are the creation of heterogeneous data environments that can be applied to building information models, grid models, and geographical information systems. Many of the techniques that have been discussed with reference to electrothermal energy storage and DR are equally applicable to buildings connected to DH networks, and vice versa. Current studies are dependent on such real-time internet-connected sensing and control technologies. For example, Sweetnam et al. (2019) used wireless sensing technologies to reduce simultaneously space heating and domestic hot water demand in English residential homes. The total weather-corrected energy consumption increased but the system led to reductions in peak demand.

Generally, the concept of IoT includes any physical device featuring a microcomputer that is connected to the Internet (Kevin Ashton 2009). IoT is not a single technology but rather a convergence of heterogeneous technologies relating to different engineering domains, which will be utilised to connect objects for remote sensing and control.

One of the largest limitations of IoT roll-outs involves Internet connectivity of the sensor nodes (Medina et al. 2017). Hence, the IoT industry has developed several connectivity solutions, leading to significant contributions to building HVAC monitoring and controls, but also creating complexity in connectivity standards and interfaces (Al-Fuqaha et al. 2015, Song et al. 2017). In IoT, devices communicate either with an Internet platform or directly with each other through a wireless network. In cloud communication, data security can be ensured via internet security protocols. The internet protocol suite, commonly
known as TCP/IP, includes layers of application, transport, network and network access (Oppliger 2009). This stack ensures that communication protocol operations occur at the end points of a communication system, ensuring that intermediaries process data correctly. These intermediaries might be unaware of the context of the communication, which applies also to the network devices that are discussed in this section.

An additional benefit of internet-connected communicating devices is the possibility of giving consumers more control in managing various services. Thus, consumers can increasingly make decisions on their heating consumption based on their individual needs and values. Adding these features might retain DH as a viable option in the future. One of these service types include thermal comfort and indoor environment reporting, which is further discussed in the following section.

2.6 Thermal Comfort

In the modern industrial society, a large part of the population spends the greater part their life indoors. People are spending more than 20 hours a day in an artificial environment, such as at home, at the workplace, at shops, and during transportation. Therefore, the character of the indoor environment is of great significance for people’s well-being. One part of well-being involves thermal comfort, which has been defined as the “condition of mind, which expresses satisfaction with the thermal environment” (ASHRAE Standard 55 2017). It is affected by different indoor environmental and human related variables, which makes it a complex variable to quantify for individual users and makes it an interesting area for artificial intelligence applications. Key characteristics of internal (occupant data) and external (environmental data) components in thermal comfort are illustrated in Figure 2.2.

![Figure 2.2. Key parameters affecting thermal comfort (Holopainen 2012).](image)

As Seppänen et al. (2006) concludes in their study, energy savings or consumption control must not have an impact on indoor air quality, otherwise a decrease in productivity will depress cost savings. Furthermore, understanding the individuals’ states of comfort becomes interesting in the context of creating wider ranges of setup temperature control in space heating.

Thermal comfort models embodied in, for example, the ASHRAE Standard 55 (2017), ISO 7730:2005 (2005) and ISO 15251:2007 (2007) are based on heat
budget models, which try to express the relation between internal and external components on thermal comfort. The PMV-PPD (Predicted Mean Vote-Predicted Percentage of Dissatisfied) is the prevalent thermal comfort model that has been used by these standards since its introduction by Fanger (1970). As the heat budget models account for some of the human related factors (i.e. clothing and metabolic rate), these are difficult to estimate and, hence, can lead to unsatisfactory results (Becker & Paciuk 2009). Additionally to the steady state model by Fanger, adaptive models developed by de Gear & Brager (1998) in ANSI/ASHRAE Standard 55 and Nicol & Humphreys (2002) in EN 15251 account for a person’s inherent ability to adapt for variable environment conditions by means of the human thermoregulation system. Although both models have their limitations and other representations exist (Kim et al. 2018), they are implemented into international standards and widely used in the building industry.

Generally, two categories of data acquisition methodologies exist: survey-based approaches, which intend to quantify perceptions based on user feedback, and physiological approaches that intent to obtain user preferences based on physiological measurements. There are various survey designs in the literature, including the ASHRAE Standard 55 (2017) scale, the Bedford scale (Bedford 1950), the comfortable-uncomfortable scale (Zhang & Zhao 2008) and the Human Building Interaction framework for Thermal Comfort (Jazizadeh et al. 2013).

Surveys are a popular way to develop an accurate representation of the environmental conditions perceived by the occupants compared to the defined criteria in the standards. These include post-occupancy surveys and right-now surveys. As post-occupancy surveys are a representation at a point-in-time, right-now surveys can be performed to show variations in thermal comfort over time. One aspect in question setting is the thermal satisfaction, which relies less on general thermal sensations and specific environmental factors, but rather on an individual’s level of satisfaction with a 7-score range (from -3 denoting for ‘very dissatisfied’ to +3 denoting for ‘very satisfied’) in the occupied space. The term ‘acceptability’ has many determinations in literature, with one being determined by the percentage of respondents who expressed an overall ‘neutral’ or ‘satisfied’ opinion, i.e. 0, +1, +2, or +3, in the room (Peretti et al. 2010).

For providing satisfactory indoor thermal conditions, HVAC operational settings are usually determined based on the recommendations of industry standards. In the simplest form, these standards recommend satisfactory temperature ranges for different seasons. ISO EN 7730:2005 recommends an indoor environment within the temperature range 23.5°C-25.5°C for achieving 94% satisfied occupants in the summer and temperatures of 21.0°C-23.0°C in the winter (ISO 7730:2005 2005). The Finnish standard RT 07-11299 (Rakennustieto 2018) for ‘good’ indoor air quality (S2) an operative temperature between 20.5°C and 23.0°C for 90% of the operation time when the ambient temperature is below 0°C. However, building controls often fail to include occupant feedback in the controls. Former field studies with DR measures claim to strive for oc-
cupant comfort with only feedback on indoor environmental data, neglecting crucial insights on thermal comfort.

In this chapter, issues around building control for DH market signals with the angle on thermal comfort have been discussed. Heating and cooling power supply can be reduced in individual apartments in a well-argued and controlled way such that agreed minimum criteria for thermal satisfaction can be obtained even during DR. Key research gaps are the lack of using latest IoT infrastructure for DR purposes in DH connected buildings, evaluating the effect of room-based control with DR and pursuing a satisfactory indoor temperature based on occupant feedback.
3. Methods

In the first two publications, controlled field studies are described in which rule-based control algorithms were developed for conducting DR. The analysis was performed on the spreadsheet program Microsoft Excel and the software R (version 3.5 with packages "tidyverse", "readr", "lubridate", "ggplot2", "magrittr", "formattable", "chron", "skimr" and "scales") for statistical computing (R Core Team 2013). Matlab and Simulink version R2018a (MathWorks 2019) were used for modelling efforts.

Publication III focuses on evaluating the effect of DR on a thermal energy system from the economic and environmental perspective. In this publication, Microsoft Excel and the modelling tools energyPRO (EMD 2019) and IDA-ICE (Moosberger 2007) were used. Publication IV presents a full-scale deployment of IoT control devices into a commercial building, and the analysis was performed with Microsoft Excel.

3.1 Demand Response Control in a District-heated Office Building in Finland

In this section, the methods used in Publication I and Publication II are presented. Both publications discuss the thermal comfort and indoor air temperature shift in an office building with a decentralised control strategy. Publication I focuses on the building’s room-based DR and on thermal comfort assessments. In Publication II, the aim is to assess how DR can be optimised through rule-based categorisation and individual heating at the room level.

Earlier in the REINO project, whole building simulations of different control strategies were conducted in two district-heated office buildings in Finland (Martin 2017, Martin et al. 2018). One building was controlled, from a DR perspective, in a centralised manner, i.e. alternating circulating water temperature at the substation level. The other building was controlled in a decentralised manner, i.e. controlling the water flow via thermostatic radiator valves (TRVs) on room level. Based on the simulations with an artificial hourly price signal for DH, a decentralised DR strategy combined with night-time setbacks and the control...
of the constant-air-volume air handling unit (AHU) resulted in cost savings of 11.9% for the property owner. The centralised approach resulted in a maximum cost decrease of 1.6%.

In order to conduct a centralised control scheme, load reductions are estimated by using a radiator heat transfer calculation model under constant-flow condition. However, in actual hydronic radiator networks with TRVs, the flow rate is not constant, which causes higher heat transfer at radiators in which TRVs open due the declining indoor air temperatures (Kärkkäinen et al. 2003).

A field study methodology is selected as research methodology for Publication I and II because the literature represented in Section 2.6 showed under-representation of measured data. Through field studies it is possible to evaluate, amongst others, the current state-of-the-art of communication technology, cloud server requirements, data security, and control devices, but also apply control schemes to existing, physical systems, as illustrated in the following block-diagram of a generic dynamic system model that evolves in time $t$ (Figure 3.1).

![Figure 3.1. Graphical representation of the feedback loop between the physical and mathematical model (Luenberger 1979).](image)

The system is characterised by a set of state variables $x(t)$ that are influenced by the input variables $u(t)$ that represent the action of the environment on the system. The output variables $y(t)$ represent the observable or measurable aspects of the system’s response. The corresponding variables of the model are represented by $\hat{x}(t)$ and $\hat{y}(t)$, respectively.

To demonstrate the usage of decentralised DR control, one floor of a district-heated office building in Southern Finland has been equipped with internet-connected radiator thermostats and environmental sensors (illustrated in Figure 3.2). Constructed in the 1960s and lastly renovated in the 2000s, the building is heated by hydronic radiators and constant air volume AHUs. Based on building model simulations of the investigated building by Martin (2017), the supply air temperature was lowered so that the hydronic radiator control contributed more to space heating than in the initial setting in which the AHU had a dominant effect on heating as the it uses supply air temperature compensation according to the measured exhaust air temperature. With a 586m² heated net floor area and a window to wall ratio of 11.5%, the total U-value has been estimated to reach 0.43W/(m²K) based on the weighted average of walls above the ground, roof, windows and thermal bridges (Martin 2017). However, the original structure
drawings of the particular building were not available and hence each element has been estimated based on a nearby building with similar building style and construction year. Inlet/outlet temperatures of the heating distribution system were 70/40°C and DH is utilised for the building’s space heating and heating coils in the AHU.

Figure 3.2. The test area’s floor plan in the study. The red dots denote TRVs and the blue dots denote indoor air temperature measurement devices.

3.1.1 The Test Area Control System

Figure 3.3 outlines the general concept of the cloud control system. The model for the architecture has been described by Theodoridis et al. (2013): The sensing layer involves TRVs with IoT capabilities and data through open access Application Programming Interfaces (APIs) of meteorological weather forecasts from Finnish Meteorological Institute (2018b). Additionally, indoor air sensors (Gemini Data Loggers 2018) without internet connection were deployed in the test area. In the communication layer, the TRVs are connected directly to the cloud server by WLAN using the Transport Layer Security (TLS) protocol (Oppliger 2009) as described briefly in Section 2.5. While the hardware was off-the-shelf, the WLAN ship and setpoint control logic were still under development (TRL 7) by the project partner Fourdeg Ltd.

The data layer involves information repositories, databases, servers and storage with enough processing power to calculate simultaneously the thermal resistance of each zone, resulting in future changes in the dependent variable, i.e. thermostat heating setpoint. Settings can be accessed in the application layer, although this opportunity was not available to the users in the research.

The DR control was executed by a rule-based control algorithm. The decision-making in the control algorithm was based on the incoming control signal $u(t)$ from the dynamic price information, the outdoor air temperature $T_{out}(t)$ and the indoor air temperature $T_a(t)$ at the radiator level at any given time $t$. The digital TRVs are steered with a rule-based proportional–integral–derivative
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Figure 3.3. Concept of the cloud control system.

(PID) controller, which is a control loop mechanism employing feedback. A PID controller continuously calculates an error value as the difference between a desired indoor air temperature setpoint $SP(t)$ and a measured indoor air temperature $T_a(t)$ and applies a correction based on PID terms, and, thus, targeting an optimal response.

The control signal with the dynamic price data is defined as follows. First, the thermal comfort constraint is defined by specifying heating setpoints, denoted by $SP$, with a buffer to prevent short cycling. If the indoor temperature is low ($T_a(t) < SP(t) - buffer$), a PID control is applied to increase the indoor temperature to the heating setpoint. The model in the cloud algorithm has a rule-based deterministic approach on calculating the future $SP$s at each time step. The setpoint temperature-change amplitude $\Delta T$ was constant across all zones in Publication I and changed based on a room characteristics categorisation method in Publication II. The $SP$ is alternated based on a price signal received by the local energy company Fortum PLC. The price signal shown in Figure 3.4 is a representation of the future marginal DR price, but it should not be perceived based on the energy company as the actual marginal DH price. Based on the moving 12-hour price signal, lower and upper price thresholds are calculated. The hourly low and high price limits were defined as follows:

\[
\text{Low price} < 1^{st} \text{ quartile of the moving 12-hour price signals.}
\]

\[
\text{High price} > 3^{rd} \text{ quartile of the moving 12-hour price signals.} \quad (3.1)
\]

Using these constantly updating thresholds, the control signal, $CS$, is calcu-
lated for each price, \( p \), on hour, \( t \), as follows:

\[
CS(t) = \begin{cases} 
  +1 & \text{if } p < \text{Low price} \\
  -1 & \text{if } p > \text{High price} \\
  0 & \text{if } p = \text{Medium price}
\end{cases}
\]  

(3.2)

This signal indicates if the setpoint temperature \( SP \) should be changed as follows:

\[
SP(t) = SP(t_0) + CS(t)
\]  

(3.3)

Figure 3.4 shows an example on marginal price variations and the formation of CS signals.

Figure 3.4. (a) DR price and conversion into the signal for setpoint moderation. (b) Control signal variations (upward and downward) during the measurement period.

In Publication II, a night-time set-back mode was added to the control strategy. Although it is not a form of DR, decreasing the indoor air temperature during times with no occupation can lead to significant energy and cost savings in buildings given that the study focused on an office space. The recovery time for achieving adequate indoor air temperatures during occupancy times is calculated based on the weather forecasts of the outdoor temperature and has been incorporated in the cloud computing system.

There are frameworks in the literature with user-led decentralised thermal comfort control systems that compute dynamic environmental and human-related variables to current BMSs to achieve better thermal comfort (Jazizadeh et al. 2014). In Publication I, the users were provided accurate indoor air temperature control with the digital TRVs. However, they were not allowed to change the setpoints in the rooms. This feature was not enabled since the scope of the study was to implement the DR control signals and to measure the thermal comfort effect of those measures on the office workers’ thermal comfort.

In Publication II, on the other hand, a more granular DR measure was implemented. Since the decentralised approach enables a room-based DR control, the users could set up individual target temperatures for their work environment. The DR implications were adjusted around the initial setpoint. In addition,
the amplitude of the setpoint change was determined based on the room usage type and estimation of thermal resistance. The effect of thermal resistance on maintaining comfortable indoor temperature has been extensively studied (Karlsson et al. 2013, Kensby et al. 2015), but building zones have not been utilised as independent resistance nodes in connection with DR control.

The hydronic radiators’ heat emissions were calculated based on the manufacturer’s heat models for each individual radiator (Purmo 2018). Most rooms contained two hydronic radiators (see Figure 3.2). Generally, the radiators had a heat output of 980-1540W (Martin 2017) with average dimensions of 300x1600mm.

3.1.2 User-led Decentralised Rule-based Control

Considering the aforementioned restrictions on thermal comfort, the proposed user-led DR control has the following objectives: 1) thermal comfort is sustained by even indoor temperatures and minimisation of temperature drift; 2) indoor temperatures are fluctuating in a controlled manner; and 3) the solution can be implemented in existing water-circulating radiator systems with minimum intrusion. The field studies were performed during three two-week periods in the autumn of 2017 (for Publication I) and a three-week period in the spring of 2018 (for Publication II).

The target was to restrict indoor air temperature variation within the range 20-24.5°C based on the standards discussed in Section 2.6. Hence, it was estimated that the chosen temperature ranges are fulfilling the design recommendations for operative temperature within offices based on the indoor environmental standard EN15251:2006 (2006), class S2, i.e. 20-26°C. In Publication II, employees could adjust setpoint temperatures in the rooms in a manner that meets their individual requirements. However, these rooms were typically occupied by two people and, thus, full individual control was not provided. Although room-based temperature control could enable perspective ‘individual’ indoor air quality (S1) target from the thermal comfort, this standard has not been pursued in this dissertation but rather performing DR measures without affecting occupant comfort. However, pursuing the S1 target increases the value proposition for room-based heating control and thus provides an additional feature for service providers.

Additionally, the temperature drift was minimised. Temperature drift is a discomfort metric related to non-steady-state thermal environments. It is defined as a steady, non-cyclic change in operative temperature of an enclosed space. The maximum allowed drift varies from 2.2°C/h in the ASHRAE Standard 55 (2017) restricted to within 2.6°C/h during any quarter of an hour period and 2°C/h in the ISO 7730:2005 (2005). In the publications of this dissertation, the latter was targeted.

For thermal comfort surveys, a right-now satisfactory survey, as discussed in Section 2.6, has been chosen to represent the overall satisfaction in the
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workspace during the measurement periods. Employees were sent daily questionnaires regarding their thermal satisfaction in the space. The users did not know on which days alterations to the heating system were performed. Thus, the psychological bias on changing indoor temperatures could be reduced.

Users’ consciousness of opportunities to control their environment could affect their experiences of thermal comfort (Toftum 2010). Consequently, usability and active feedback loops have been considered in Publication II to increase user satisfaction on indoor thermal comfort. Some research suggests the usage of various user interfaces, such as physical buttons (Zhao et al. 2014) or phone applications (Jazizadeh et al. 2013, 2014), web-based surveys (Sweetnam et al. 2019) and even wearable sensing technologies (Liu et al. 2018) that affect users’ thermal preference vote for determining HVAC control parameters. However, it was concluded that the most expedient feedback is given through the established mechanics of switching thermostats, i.e. by increasing or decreasing the temperature screened at the digital display of the thermostat.

3.2 Evaluating Demand Response in District Heating Systems

Using buildings’ thermal inertia to increase flexibility in the thermal grid has been actively discussed by stakeholders in the field. Throughout the 2010s (see Section 2.2), research in the topic have found only trivial increases in system efficiency. In a cost evaluation study by Difs et al. (2010), load control had a significant effect on the total costs paid by the DH customers but only a minor cost reduction for the DH company. Also, other system simulations (Wernstedt et al. 2007, Guelpa et al. 2017, Johansson & Davidsson 2010, Johansson et al. 2012) have shown interesting findings in the potential of DR to the local thermal system. In comprehensive studies that consider hourly values from both whole-building simulations and system optimisation models have found small enhancement in operational costs (Dominković et al. 2018, Kontu et al. 2018, Romanchenko et al. 2018).

Dominković et al. (2018) found that economic savings in operational costs of a medium-sized DH system via DR measures were in the range of 0.7%-4.6% without taking investment costs in smart controls into account. The study was performed in residential buildings in a municipality in Sweden with different time constants and U-values in the building envelopes. The results indicate that heat losses determined by the U-value have a greater effect on the flexibility potential than the building’s heat capacity or its thermal mass in a cold climate. Kontu et al. (2018) showed that increasing building flexibility affects primarily medium loads but annual peak load reduction remained insignificant. In the study, the researchers implemented DR strategies in different building types and analysed the effect on heat production in different DH systems. The results showed that the value of DSM for DH companies results in cost savings of less than 2%. Romanchenko et al. (2018) found, in a comprehensive building and...
system level model, that the DH system’s yearly operating costs decrease by approximately 1% when DR applied in buildings are utilised, and correspondingly by approximately 2% with a large thermal water storage when compared to a scenario without any storage. These economic findings are rather moderate and do not meet the expectations of media reports described in Section 2.2. Hence, the following subsection gives a more insights on the economics of DR in DH systems.

### 3.2.1 Dynamic pricing

To design a pricing structure that gives correct pricing information to the customers, the variable heating cost should be based on the factual marginal DH costs. Such a price structure would give the customers the opportunity to take advantage of varying DH prices. Based on this assumption of future pricing strategies, input data was gathered to a Microsoft Excel spreadsheet, which was originally generated by S. Rinne. The spreadsheet considers, amongst other things: heat production facility characteristics, fuel prices, electricity prices, heat demand, ambient temperature, and DH network temperatures. Additionally, the value-added tax of 24% is considered in the final prices. Alterations in demand and supply curves are done by adding an artificial price for heat when different DR strategies were implemented in a simulated building environment by K. Martin (see Section 3.1).

The demand curve is formulated based on the weather data from the Finnish reference year TRY2012 for Southern Finland (Jylhä et al. 2012). The hourly DH load curve is shown in Figure 3.5.

![Figure 3.5. Hourly DH demand of a representative year used in the simulation.](image)

DH production facilities can be divided to CHP facilities and auxiliary HOBs. From these options, the cheapest heat generation technology is selected for
each hour. During high electricity prices, DH can be produced particularly in the CHP plant. Approximately 15% of the Finnish electricity production is covered with high-efficient CHP plants (Sarvaranta et al. 2012). In the model, the wood and peat fired CHP plant covers 50% of the maximum capacity but approximately 80% of the energy production, which was adapted from Koskelainen (2006). The electricity price plays a significant role in the economic viability of heat generation in CHP plants. Hence, the marginal cost of electricity for the investigated period is generated based on the Nordic electricity market Nord Pool’s spot prices (Nord Pool 2019). The component scheme of the simulated DH network is illustrated in Figure 3.6. More details on the implemented modelling framework, including the input data used in the energy system modelling are found in Publication III.

![Figure 3.6. From left to right: biomass-fired CHP plant, oil-fired HOB, hot water tank and a variety of building types connected to the grid.](image)

The CHP’s usage in the transmission system operator’s balance and reserve power marketplaces, balance capacity markets or other potential marketplaces has not been considered. Production subsidies for biomass-based energy production or additional taxation of peat have not been considered. For demand peaks, during inexpensive electricity hours and low demand during summer time, the model considers heat generation with either the CHP’s heat-only-mode or with a separate oil-fired HOB. A separate artificial load balance fee has been added in order to balance the fluctuation in heat load. The economic values presented in Table 3.1 show that the HOB has on average the most expensive marginal production price.

<table>
<thead>
<tr>
<th></th>
<th>Economic values of the simulated power plants.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{th,\text{CHP}}$</td>
<td>$P_{el,\text{CHP}}$</td>
</tr>
<tr>
<td>MW$_{th}$</td>
<td>MW$_{el}$</td>
</tr>
<tr>
<td>196.7</td>
<td>106.9</td>
</tr>
</tbody>
</table>

Figure 3.7 presents the dynamic spot price for DH for each hour of the representative year. During the off-heating season (i.e. April to middle November) the prices are relatively stable with an average value of 40.5€/MWh and a standard deviation of 7.7€/MWh. From the end of November to the end of March, the average price and standard deviation are 68.0€/MWh and 29.7€/MWh, respectively. The price fluctuations are according to expectation as energy consumption
increases during colder periods of the year.

![Hourly dynamic price for DH in a representative year including VAT 24%.](image)

**Figure 3.7.** Hourly dynamic price for DH in a representative year including VAT 24%.

### 3.2.2 Demand Response Strategies in Buildings

The price shown in Figure 3.7 was utilised in the dynamic multi-zone simulation software IDA Indoor Climate and Energy 4.7.1 (IDA-ICE) by K. Martin (Martin 2017). IDA-ICE is a commercially available software in which the thermal indoor climate and the energy consumption of the entire building can be modelled and studied (Moosberger 2007). Demand profiles of the building are created with an hourly resolution by utilising self-build macros and detailed algorithm components. The simulated building has been described in Section 3.1. Martin developed optimal DR control algorithms from a property owner’s point of view. The developed rule-based algorithms used a dynamic DH price to control space heating and ventilation. In addition, Martin investigated the effects of peak power cutting of DH loads on indoor temperature and thermal comfort.

The simulation in Publication III took advantage of one reference scenario and five DR scenarios as building demand profiles. These profiles were scaled to the DH system’s size, resulting in an hourly demand profile for the DH system. The algorithms had future price information as described in Section 3.2.1 available for 24 hours forward. The trend of future hourly DH price was defined as rising, steady or falling by using an algorithm developed by Alimohammadisagvand et al. (2018). It has to be noted that hourly variable DH prices are not yet implemented in the market, but they are highly coveted (Kontu et al. 2018). Additionally, simulations were used in which a flexibility factor was introduced. The flexibility factor “illustrates the ability to shift heating use from high to low price periods” (Dréau 2016). Lastly, peak DH demand limiting algorithms were chosen as they have a large cost-saving potential for the property owner.

### 3.2.3 District Heating Network Modelling

The commercial software EnergyPRO was used for simulating a typical Finnish DH system. The software tool enables to conduct a techno-economic analysis in a system with both CHP plants, HOBs, and large heat tanks (Hast et al. 2017,
Methods

EMD 2019). EnergyPRO is an input-output model that solves the optimal DH operation strategy by minimising the total variable costs while meeting hourly demand.

In EnergyPRO, the same plant characteristics were utilised as in the spreadsheet. The optimal DH operation strategy is calculated in EnergyPRO by minimising the total operational costs of heat production for existing plants in the system. The sales from electricity generated by CHP plants are considered by EnergyPRO similarly as in the dynamic pricing spreadsheet, which reduce the total operational costs. Within EnergyPRO, a linear programming model optimises DH and electricity production in regional and national energy systems (EMD 2019). The system cost takes into account the total cost of meeting the demand for heat, which includes plant investment costs, fuel and maintenance costs, fuel taxes, European Emission Allowances (EUAs), along with income from electricity generated in the CHP plants. Additional data inputs are time-division, efficiency, power-to-heat ratio, heat demand, as well as the technical and economic lifetime of the plants.

The model outputs the system cost, plant operations, and marginal DH costs. In this study, the marginal costs were used as DH prices for the building stock. The simulation included hot water tanks, i.e. a large thermal storage, as a variable factor. This can bring, in addition to the aforementioned flexible elements in the energy system, further economic enhancements, such as enabling the CHP unit to increase electricity generation revenues (Hast et al. 2017).

In Publication III, hot water tanks are particularly investigated as a favourable factor in DR measures. Romanchenko et al. (2018) compared hot water tanks and the thermal inertia of buildings as sources for DH management. They simulated the system efficiency with one technology at a time and found that the hot water tank stores significantly more heat over the modelling period, while the cycles of charging and discharging are similar for both DH management categories. Hence, Publication III takes a new angle by combining both storage types for short- and long-term heat demand optimisation.

3.3 Climate Resilience in Helsinki

In order to achieve carbon neutrality by 2035, the city of Helsinki is making progress in continuous climate work. Helsinki has reduced its greenhouse gas emissions by 24% from 1990 to 2017 even though the city has grown with 150,000 inhabitants. Per resident, the emissions were calculated to be approximately 42% smaller in 2017 than 1990. However, for reaching the carbon neutrality goal, emissions have to be reduced even faster (City of Helsinki 2019).

One central target is to reduce the local DH provider Helen Ltd’s carbon intensity. Helen supplies heat to 90% of the building stock in Helsinki and accounts for approximately 20% of total DH produced in Finland (Helen Ltd 2015). According to one estimate, Helsinki’s CHP production needs to decrease
from current 1300MW to 300MW to acquire a 100% fossil fuel free Helsinki (Rinne et al. 2018).

Therefore, ICT tools are assessed in Publication IV on the one hand for raising awareness amongst citizens towards climate actions and on the other hand for developing automated building systems, which are commercially viable products for city-wide integration. Publication IV describes a set of actions that were implemented in Helsinki, Finland, within the EU-funded Horizon 2020 mySMARTLife project (mySMARTLife 2019) that lies under the European Union’s Lighthouse consortium umbrella (SCIS - EU Smart Cities Information System 2019). It focuses on optimizing space heating demand by implementing internet-connected TRVs with the DR control system developed in Publication I and Publication II in a district-heated office building. This system is described in the following section. Further examples of data-driven business practices under the Lighthouse umbrella are studies in autonomous, electrical busses (Rutanen & Åman 2019), battery energy storage (Hellman & Laasonen 2017), urban platforms and 3D city models (Ruohomäki et al. 2018) and integration of heat pumps and solar thermal collectors (Rämä & Wahlroos 2018).

3.3.1 Viikki Environmental House

This section focuses on the proceedings of utilising DR in an energy efficient office building called Viikki Environmental House. The DR control system and the telecommunication system between the cloud computing environment and the TRVs was developed by the project partner Fourdeg Ltd. Through the study, the European TRL level 8, i.e. system complete and qualified (European Commission 2017), was pursued. This means, amongst others, that the technology’s final state has been proven to function in the relevant environment and that full compliance with “obligations, certifications and standards of the addressed markets” is completed (European Commission 2017).

Viikki Environmental House has been qualified as an energy efficient office building with a measured energy index of 90kWh/m² (Helsinki Urban Environment Division 2011). The energy demand can be divided into 60% heat and 40% electricity. The building was constructed in 2011 and its gross floor area is 6,800m², and gross volume is 23,500m³. With five floors, its mean occupant density is 25m²/person on average, and its annual occupied hours are estimated to be 2,600h. Because of the building’s energy efficient nature, reducing space heating demand was regarded as challenging. On the other hand, the tight envelope raises inertia, which makes it suitable for DR, as noted in many previous studies, see for further references in Section 2.3.

The TRVs implemented in the building are connected through a separate WLAN network to the cloud environment with a similar methodology described in Section 3.1. The cloud receives through APIs weather forecasts from the Finnish Meteorological Institute and DR signals from the local DH provider Helen Ltd.
The control period lasted from December 2017 to May 2018. The heating program includes night and weekend setbacks and it is synchronised with the building’s AHU system. The synchronisation serves for decreasing the difference between inlet and exhaust air temperature. The setpoint temperature in each zone, i.e. individual room, is shifted according to a direct signal from the DH operator. The objective is to shift the heating loads away from expensive hours without abandoning thermal comfort.

Additionally, volunteering building occupants gave feedback on thermal comfort, which is further processed in a thermal comfort control tool developed by the project partner VTT (Holopainen 2012). The tool uses measured body composition of each participant and thermal perception feedback for calculating an individual setpoint temperature for each room. The questionnaire could be accessed via a QR code at the workstation whenever participants wanted to give feedback.

The building automation system initially received indoor air temperature measurements. Additionally, the project partners installed measurements devices, including indoor air relative humidity and surface temperatures of windows, radiators, chilled beams and external and internal walls, for VTT’s thermal comfort tool. These devices collected data in approximately 5-minute intervals. Air velocity was assumed to remain constant in an occupied zone and the internal wall surface temperature is estimated to be approximately the same as the floor and ceiling temperatures. The thermal comfort tool calculates based on the optimal individual thermal sensation value new heating setpoints that were sent to the TRVs’ cloud system every 15 minutes via an API.
This chapter presents central results of the publications included in this dissertation. First, research question Q1 is answered through analysing thermal comfort and indoor air temperature variations during DR events in two controlled field studies. Next, research question Q2 is answered by modelling a DH system with building DR and a large thermal energy storage tank. Finally, research question Q3 is answered by presenting a case study on DR interventions in an office building.

4.1 Demand Response Control in a district-heated Office Building

This subsection presents results in Publication I and II. The effect on thermal comfort, indoor air temperature and measured load shift on the radiator level are discussed.

4.1.1 Effect of Different Amplitudes in Heating Setpoint Change

In Publication I, three different DR control setpoint amplitudes were tested (i.e. $\Delta T = \pm 1^\circ C; \pm 1.5^\circ C; \text{and } \pm 2^\circ C$). The study comprises results using the IoT TRVs and, hence, only the DR days and placebo days were investigated. The results suggest that higher DR amplitudes lead to colder average indoor air temperatures (for more information see Table 2 in Publication I).

The mean air temperature difference remained at $0.4^\circ C$ throughout, but variations in user satisfaction could be distinguished between intervention days and placebo days. According to the thermal satisfaction survey, the perceived thermal comfort decreased during DR days. As anticipated, the lowest average satisfaction rates were perceived during the DR period with a heating setpoint amplitude of $\Delta T = \pm 2^\circ C$.

DR measures are constrained either by the shifting time interval or the amplitude of the setpoint based on consumers’ individual preferences, e.g. utility and loss of comfort. By constraining the shifting time interval, the annual utilisation of the DR resource capacity decreases significantly. Therefore, the results...
suggest that restricting the amplitude of setpoint modulation in a decentralised control strategy to an amplitude of \( \Delta T = 2^\circ C \) or below can lead to better thermal comfort results. The time of the modulation is solely defined based on the price signal received from the DH operator. Therefore, the amount of DR has not been decreased in Publication II but rather constraining the magnitude of DR interventions based on each zone’s usage type and inertia.

4.1.2 Controlling each room separately based on flexibility Potential

In Publication II, a different approach was used: rooms were categorised based on their DR setpoint amplitudes in rooms of ‘high flexibility’, ‘moderate flexibility’ and ‘low flexibility’, with DR setpoint amplitudes of \( \Delta T = 2^\circ C \) (denoted as Cat I), \( 1^\circ C \) (denoted as Cat II) and \( 0.5^\circ C \) (denoted as Cat III), respectively. As in Publication I, this publication indicates as well that the building structures cannot store sufficiently the heating energy to balance the mean indoor air temperature fluctuations during DR interventions. Overall, colder room air temperatures, based on the S2 standard discussed in Section 2.6, were observed in the study period illustrated in the duration curve in Figure 4.1.

![Figure 4.1.](image)

Figure 4.1. Indoor air temperature duration curves for all sites during working hours (totalling 120h).

Figure 4.2 highlights the correlation between a higher \( \Delta T \) amplitude and strong indoor temperature variation. With the smallest \( \Delta T \) amplitude, almost no change in indoor air temperature can be observed, while for larger \( \Delta T \) amplitudes, the difference between maximum and minimum temperature, i.e. between charging events (control signal \( CS = +1 \)) and discharging (\( CS = -1 \)), is \( 0.7^\circ C \) for almost two hours. This fits within the temperature change velocity requirements defined in ISO 7730:2005.
Additionally, relative humidity was measured in the field study spaces. The recommended level of indoor relative humidity lies within the range of 30-60% in mechanically ventilated buildings. A review of the effects of low relative humidity on the perceived indoor air quality suggest that relative humidity should be above 40% in order to decrease low-humidity symptoms, such as dry eyes (Wolkoff & Kjærgaard 2007). Finnish offices are characterised by very low relative humidity levels, and the relative humidity during the study period's office hours was found to be approximately 20%-25%.

The load variation calculations on individual radiators and the valve position of each TRV demonstrate the load shift during DR, as illustrated in Figure 4.3. Due to individual TRV control, load shift can be implemented accurately in each room. As the investigated area accounted for only approximately 7% of the building's total heat demand, the load shift could not be determined at the substation level.

During the research period, the users were asked whether they were satisfied with the indoor environment. The users did not know on which days DR was performed. Results on thermal comfort in both Publication I and II indicate that DR lowered the perceived thermal comfort of the occupants. In Publication II, the lowest average satisfaction rates were perceived in rooms with the highest flexibility, i.e. highest setpoint change, whereas the highest rates were observed in rooms of lowest flexibility when there was no DR.

In both studies, employees reported lower thermal satisfaction during DR days than during placebo days (see Figure 4.4). This poor performance was not
unexpected as the users were situated next to the radiators and perceived the unequally distributed air mixture first-hand. Therefore, local thermal discomfort should be one of the major concerns in decentralised DR.

Thermal comfort is one of the most significant driving factors when defining the setpoint constrains in HVAC control settings, and, hence, it markedly impacts energy efficiency in buildings. Even though environmental sensing data has been available, occupant clothing insulation and activity levels were not monitored. These factors can vary unpredictably with respect to season and individual characteristics and can significantly affect the occupant’s thermal comfort. In addition, it is prudent to ensure that environmental sensors provide information of the actual occupant location. The air temperature sensor at the TRV and at the wall were not capturing the change in the thermal environment correctly at the occupant location.

When people with conflicting thermal preferences occupy the same zone, setting the wished temperature at the radiator has the potential drawback of making all occupants of such a zone dissatisfied. For example, in a zone with two occupants, one occupant prefers colder indoor temperatures while the other prefers warmer temperatures. The average result is relatively far from each individual’s optimal temperature. As pointed out by Seppänen et al. (2006), 1°C in shift of optimal temperature can result in work efficiency reduction up to 2%. For individuals, this could be avoided with personal heating devices (Kim et al. 2018). In order to improve thermal comfort for all occupants, research suggest implementing a thermal discomfort value that summons the different thermal profiles in each zone, as suggested by e.g. Ghahramani et al. (2014).

In a later research setup, radiant temperature and operative temperature measurements of one room in the test bed showed expected temperature differences between the measured air temperature at the radiator level, measured indoor air temperature at the wall, and black globe thermometer temperature. Literature provides four sources of local discomfort associated with radiant

Figure 4.3. Radiator performance during the selected week.
systems: radiant asymmetry, too low/high floor temperatures, stratification, temperature drift, and draft (Karmann et al. 2017). ASHRAE Standard 55 and EN ISO 7730 define limits for radiant asymmetry, which originate from Fanger et al. (1985). It is usually measured using half-globe thermometers to compare the temperatures of two opposing surfaces in a room, but such measures were not conducted during the research. Hence, the radiant temperature asymmetry is further discussed below. These measurements were taken during autumn 2018, i.e. they were not part of Publication II.

Figure 4.4. Thermal satisfaction during each placebo and DR period based on results in Publication I.

Figure 4.5. Black globe temperature measurement in one room of the test bed.

TRV setpoints were alternated by $\Delta T = 2^\circ C$. Measurement results shown
Results in Figure 4.5 indicate that operative temperature is significantly affected by short-term setpoint changes but also by other external factors (see annotations). Other loads in the building lead to a steady night-time indoor air temperature of around 20.0°C.

Figure 4.6. Black globe temperature measurement in one room of the test bed differentiated by control type.

Figure 4.5 also shows higher setpoint temperature and indoor air temperature measured at the radiator level compared to the indoor air temperature in the middle of the room. Figure 4.6 shows that the variation of temperatures during DR days is smaller than in reference days.

Looking at Table 4.1, the measured temperature change does not directly correlate with dissatisfaction. Furthermore, the standard deviation of the mean radiant temperature in the reference case was 0.2°C and during DR 0.4°C. The standard deviation of the dry-bulb temperature is 0.1°C and 0.3°C in the reference and DR cases, respectively.

4.2 Results in the District Heating Grid

In the hypothesis of Publication III, DR actions are expected to be profitable for both property owner and the DH company by providing cost savings and emission reductions in the DH production. To analyse this, the effect of DR is analysed on the building level via the whole-building simulation described in Section 3.2.2. Next, key performance measures on the DH production level are presented.

The reference case (Case 1) in Table 4.2 was simulated without DR control using a constant setpoint temperature for heating (21°C) and a typical control curve of ventilation supply air temperature. The peak DH power was not
Table 4.1. Statistical values of further measurements conducted in one room of the researched site.

<table>
<thead>
<tr>
<th>State</th>
<th>Variable</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR</td>
<td>Globe Temperature [°C]</td>
<td>20.14</td>
<td>0.33</td>
<td>19.60</td>
<td>21.10</td>
</tr>
<tr>
<td></td>
<td>Indoor Air Temperature [°C]</td>
<td>20.32</td>
<td>0.30</td>
<td>19.87</td>
<td>21.08</td>
</tr>
<tr>
<td></td>
<td>Mean Radiant Temperature [°C]</td>
<td>20.03</td>
<td>0.40</td>
<td>19.33</td>
<td>21.15</td>
</tr>
<tr>
<td></td>
<td>Operative Temperature [°C]</td>
<td>20.17</td>
<td>0.32</td>
<td>19.00</td>
<td>21.10</td>
</tr>
<tr>
<td></td>
<td>Setpoint Temperature [°C]</td>
<td>21.39</td>
<td>1.43</td>
<td>18.00</td>
<td>23.50</td>
</tr>
<tr>
<td></td>
<td>Air Temperature at Radiator [°C]</td>
<td>22.63</td>
<td>0.63</td>
<td>21.50</td>
<td>24.00</td>
</tr>
<tr>
<td>Reference</td>
<td>Globe Temperature [°C]</td>
<td>19.77</td>
<td>0.19</td>
<td>19.40</td>
<td>20.10</td>
</tr>
<tr>
<td></td>
<td>Indoor Air Temperature [°C]</td>
<td>19.92</td>
<td>0.12</td>
<td>19.70</td>
<td>20.12</td>
</tr>
<tr>
<td></td>
<td>Mean Radiant Temperature [°C]</td>
<td>19.68</td>
<td>0.24</td>
<td>19.19</td>
<td>20.12</td>
</tr>
<tr>
<td></td>
<td>Operative Temperature [°C]</td>
<td>19.80</td>
<td>0.18</td>
<td>19.46</td>
<td>20.10</td>
</tr>
<tr>
<td></td>
<td>Setpoint Temperature [°C]</td>
<td>21.24</td>
<td>0.93</td>
<td>18.00</td>
<td>21.50</td>
</tr>
<tr>
<td></td>
<td>Air Temperature at Radiator [°C]</td>
<td>22.31</td>
<td>0.26</td>
<td>21.50</td>
<td>22.50</td>
</tr>
</tbody>
</table>

limited in the reference scenario, but it was determined by using normal design temperatures for indoor (21°C) and outdoor air (Southern Finland: −26°C) based on Ministry of the Environment 1010/2017 (2017).

Table 4.2. Selected DR scenarios adapted from whole building simulations by Martin (2017).

<table>
<thead>
<tr>
<th>DR scenario</th>
<th>Space heating</th>
<th>Heating of ventilation</th>
<th>Charging</th>
<th>Discharging</th>
<th>Peak power limiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (ref.)</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Case 2</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Case 3</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Case 4</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y (-35%)</td>
</tr>
<tr>
<td>Case 5</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y (-43%)</td>
</tr>
<tr>
<td>Case 6</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y (-50%)</td>
</tr>
</tbody>
</table>

Case 2 and Case 3 represent adjustments in setpoint temperatures of space heating and supply air through rule-based DR control algorithms simulated by Martin (2017). In both cases, thermal comfort of the occupants remained at an acceptable level. In Case 2, setpoint temperatures were only lowered during DR, whereas in Case 3 the building was charged with cheaper marginal DH prices during the rising price trend in the heating season by increasing the setpoint temperatures of space heating and ventilation to the maximum values. Thereby, the flexibility factor was maximised. In the simulated building, heat loading during inexpensive price periods has not been beneficiary. This might be due to the cooling effect of the ventilation system that blows the additional heat
out. The duration curves of each case presented in Figure 4.7 show that, while heating power is used less for approximately 88% percent of the year in Case 3 than in other cases, it uses significantly more energy during the coldest winter times. Further information on the selected cases can be found in Publication III.

In cases 4-6, heating of spaces and ventilation was controlled similarly as in the reference case, but the peak DH power of the cases was cut by 35-50%. The power limiting affects space heating only, i.e. the AHU heating of supply air was not restricted. As the simulation utilises the Finnish test reference year weather data (Jylhä et al. 2012), it does not include colder ambient temperatures than approximately \(-20\)°C. Martin’s simulation results showed that a 35% power cut (Case 4) had no noticeable effect on the indoor temperature or thermal comfort as only 0.5% of the annual heating hours were affected. Limiting power by 43% (Case 5) affects 3.4% of the annual heating hours, maintaining a minimum indoor temperature of 18.4°C in the coldest room, but the temperature is below 20°C for only 0.6% of the occupied hours (about 17 hours) during the examined year. Limiting power to 50% (Case 6) affects 10.4% of the annual heating hours. That resulted in a minimum indoor temperature of 16.6°C, with 4.4% of the occupied time (about 124 hours) being below 20°C, so the effect on indoor temperature or thermal comfort can be considered as notable.

The analysis showed that only some of the DR cases reduced DH production costs and emissions (see Table 4.3). Although the whole building stock was not required in any of these cases, the gained cost savings are marginal at its best. The effects of DR measures in DH production were largest in Case 2 and slightest in Case 3. The hot water tank (HWT) supported the economic and
Results

environmental benefit of DR cases 2, 4 and 6 but had no influence on cases 3 and 4. Further analysis of the cases can be found in the result section of Publication III.

Table 4.3. Effect of DR on DH company production costs and emissions.

<table>
<thead>
<tr>
<th>DR scenario</th>
<th>Optimal share of buildings with DR [%]</th>
<th>Optimal HWT capacity [GWh]</th>
<th>Cost decrease [%]</th>
<th>Emission decrease [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without HWT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>38</td>
<td>-</td>
<td>0.7000</td>
<td>0.800</td>
</tr>
<tr>
<td>Case 3</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 4</td>
<td>13</td>
<td>-</td>
<td>0.0004</td>
<td>0.001</td>
</tr>
<tr>
<td>Case 5</td>
<td>38</td>
<td>-</td>
<td>0.0300</td>
<td>0.002</td>
</tr>
<tr>
<td>Case 6</td>
<td>42</td>
<td>-</td>
<td>0.3000</td>
<td>0.040</td>
</tr>
<tr>
<td>With HWT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>42</td>
<td>20.1</td>
<td>1.4000</td>
<td>0.800</td>
</tr>
<tr>
<td>Case 3</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 4</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 5</td>
<td>42</td>
<td>20.1</td>
<td>0.0200</td>
<td>0.002</td>
</tr>
<tr>
<td>Case 6</td>
<td>42</td>
<td>20.1</td>
<td>0.3000</td>
<td>0.040</td>
</tr>
</tbody>
</table>

As indicated by Hast et al. (2017), a heat storage had a positive economic effect on the thermal system under assumptions of increased variable renewable energy sources in the power system. Additionally, a large heat storage allows the CHP unit to produce more electricity and, thus, increase revenues. In a sensibility analysis it was found that the optimal capacity of heat storage depends on the average electricity price and on the amount of variation in the electricity price. Although the results are thought-provoking, a sensibility analysis on alternating prices for electricity of fuel prices were out of the scope of Publication III.

As concluded by previous studies (Dominković et al. 2018), the heating cut-off resulted in energy savings (Case 2). The effect of preheating control was found to affect the heat flexibility potential of buildings positively (i.e. Case 3), but the cost saving potential is dependent on, e.g., the U-value of the building and, hence, its potential should be evaluated individually for each building.

Comparing the reference cases in Table 4.4, the production capacity of the HOB is reduced to approximately one third when adding the HWT to the system. In addition, the results propose that without the HWT in the system, the operating hours of the CHP unit would remain at the same level in each DR case, and it would operate continuously. When the storage is included, the CHP unit always runs in co-generation mode. Including DR features does not change the HOB’s operating hours significantly. As the HOB plant has a high emission factor, total emissions do not decrease significantly (see Table 4.3). The results in Table 4.4 also indicate that using an HWT increases the total ramp-on and -off costs. However, it is anticipated that it only partially reduces the total cost savings.
The number of HOB start-ups decrease significantly, and the number of CHP start-ups increase when including the HWT in the cases.

**Table 4.4.** Key operation results of the DH system in different DR cases with and without a HWT in the system.

<table>
<thead>
<tr>
<th>DR scenario</th>
<th>Operation hours, CHP (of which heat-only mode)</th>
<th>Operation hours, HOB</th>
<th>Number of CHP start-ups</th>
<th>Number of HOB start-ups</th>
<th>Heat production in CHP [GWh]</th>
<th>Heat production in HOB [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without HWT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1 (ref.)</td>
<td>8760 (794)</td>
<td>1301</td>
<td>134</td>
<td>121</td>
<td>1012</td>
<td>31.80</td>
</tr>
<tr>
<td>Case 2</td>
<td>8760 (794)</td>
<td>1299</td>
<td>134</td>
<td>131</td>
<td>1003</td>
<td>32.50</td>
</tr>
<tr>
<td>Case 5</td>
<td>8760 (794)</td>
<td>1300</td>
<td>134</td>
<td>124</td>
<td>1012</td>
<td>31.80</td>
</tr>
<tr>
<td>Case 6</td>
<td>8760 (794)</td>
<td>1271</td>
<td>134</td>
<td>126</td>
<td>1012</td>
<td>31.00</td>
</tr>
<tr>
<td>With optimal HWT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1 (ref.)</td>
<td>5285</td>
<td>51</td>
<td>232</td>
<td>3</td>
<td>1033</td>
<td>9.95</td>
</tr>
<tr>
<td>Case 2</td>
<td>5244</td>
<td>49</td>
<td>236</td>
<td>3</td>
<td>1025</td>
<td>9.50</td>
</tr>
<tr>
<td>Case 5</td>
<td>5286</td>
<td>51</td>
<td>233</td>
<td>3</td>
<td>1033</td>
<td>9.90</td>
</tr>
<tr>
<td>Case 6</td>
<td>5287</td>
<td>47</td>
<td>232</td>
<td>3</td>
<td>1034</td>
<td>9.10</td>
</tr>
</tbody>
</table>

The results show that the number of operation hours, as well as heat production, with the CHP unit are lowest in Case 2. In Case 2, heat production with the HOB is slightly higher than in the reference case or in the other profitable DR cases when HWT is not included. On the other hand, heat production with the CHP unit decreases by 9 GWh. That amount compensates the usage of the HOB and the decrease in electricity revenue as seen in Figure 9 of Publication III. Revenues from electricity sales drop slightly or remain the same in DR-only cases. When adding the HWT to the system, revenues grow by 11%. Furthermore, adding an optimal DR scheme to the system increased revenues by less than 1%. Hence, the results suggest that an investment in an HWT is markedly more profitable than investing in a decentralised DR system.

During the coldest winter days in the test reference year, the load cannot be decreased for longer time periods, as high heat losses affect room-air temperature and, thus, dissatisfaction in thermal comfort increases (see Case 6 above). On the other hand, temporarily increasing the load during wintertime is challenging as the system is already operating at its limits, and energy is lost in heat transfer through the building elements (see Case 3). Case 3, in which the flexibility factor was maximised, was the least feasible option from the economic standpoint. Dominković et al. (2018) also found that while preheating buildings affect the heat flexibility potential positively, it should be evaluated individually for each building type. Consumption of biomass and oil in the profitable cases is presented in Figure 4.9.

Depending on the definition of ‘cold ambient temperatures’, one can find expressions for high and low flexibility potential. In Dominković et al. (2018), for instance, an average ambient temperature of −3°C was defined as a cold winter day in Denmark, and a study by Sweetnam et al. (2019), the impact of DR on space heating was normalised for the demand at 7°C. Helsinki's heating degree-day values during the normal period (i.e. during 1981 to 2010)
Results

is 3878 degree-days and the average temperature during heating season (i.e. October to April) is 1°C (Finnish Meteorological Institute 2018a). Therefore, ambient temperature needs to be considered when comparing demand flexibility strategies.

![Figure 4.8. Thermal store content in cases 2, 5 and 6 and the reference case.](image)

During summertime, DR has not been performed and, hence, the load curve is not affected. The hot water storage, on the other hand, was used during summertime, as illustrated in Figure 4.8. It shows how the heat store content changes in the DR cases 2, 5, and 6 compared to the reference case in the course of the year. As seen in Figure 4.8, the HWT is charged almost to its full capacity during June and mid-July and it is not discharged until early August. The seasonal variations of thermal storage do not differ between the DR cases. Only minor daily and hourly variations are observed. As summertime heat demand consists almost solely of domestic hot water, the thermal store content of each HWT case does not differ from the reference case. Similarly to the study by Dominković et al. (2018), the buildings’ thermal mass behaved as intraday storage that shaved daily peaks, while the HWT behaved more akin to seasonal storage that shifted loads for water usage.

Depending on the heat load profile of each load control strategy, the DH plants were differently operated, which results in different changes in CO₂ emissions as shown in Figure 4.9. The biomass fuel used in the simulation contains biomass (with an emission factor of 0 kgCO₂/MWh) and peat (381 kgCO₂/MWh) as a co-firing fuel. The emission factor used in the HOB is 284 kgCO₂/MWh.

As noted by Difs et al. (2010), load control reduces the electricity production in the local CHP plants and, hence, these measures benefit from a CO₂ perspective depending on the fuel type of the CHP plant. Overall, it was found that the hours of active DR are scarce. As found in a similar study on large DH systems (Kontu et al. 2018), the share of heat produced with peak plants was only 1%. Hence, cutting these hours through DSM is very challenging in large DH systems.
4.3 Implementation Strategies Towards a Smart and Resilient City

This subsection focuses on innovations that enhances resiliency in the city of Helsinki, especially focusing on the case study at Viikki Environmental house. The objective is to study the effect of direct DR signals from an energy company on room air temperature. Additionally, the study investigates how room-based heating control affects the energy consumption of an energy efficient office building. Thermal comfort control was studied via the thermal comfort model developed by VTT. During the first test period from January 2018 to April 2018, the weather-corrected heating energy consumption of the building dropped by an average of 10% compared to 2017. The reduced heat equals 5-7 MWh per month, which is solely insufficient to justify economically an investment in IoT devices. The effect of DR on total heating energy consumption was not analysed in this study, but it is expected to reduce the overall energy efficiency as the building was frequently charged immediately before a discharge event occurred (see Figure 4.10).

The air temperature measured at the radiator level remained steady during DR with an amplitude of \( \Delta T = \pm 1^\circ C \). Even smaller changes in indoor air temperature were measured by the building automation system. However, neither measurements of mean radiant temperature nor globe temperature were
performed in the rooms, which could distinguish temperature asymmetries as pointed out in Figure 4.5 and in Figure 4.6. Based on the QR questionnaires, the thermal environmental satisfaction remained unchanged during the test period.

The main outcomes of the demonstrations are verified technical solutions in the HVAC sector, amongst other areas, with emphasis on performance and cost. The results provide pathways for developing methods and tools needed in the decision making, design and performance verification of these building types in a cold climate.
5. Discussion and Conclusion

The research conducted as part of this dissertation assessed the effect of DR signals on individual thermal comfort and decentralised load shifting on radiators, the economic and environmental effect of DR to the DH system, and pathways to implement IoT devices in the existing built environment. This section presents the discussion and conclusions of the publications presented in the dissertation, as well as suggestions for future research.

5.1 Discussion

One major assumption in this dissertation is that DR measures become market-based in DH systems. Currently, DR profitability is not clear for the property owner. Since the liberalisation of the power sector in the Nordic countries, increased competition was afforded to the market. Based on the characteristics of the day-ahead and intraday electricity market, i.e. short-term marginal cost of production variation based on, e.g., on the time of day, wind energy production, and ambient weather conditions, the potential for consumer-centric DR programs is larger than in the monopolistic DH sector.

As already seen in the power sector, dynamic pricing encourages the demand-side to optimally manage their resources, which can become a viable option for DR consumers as well. First steps, namely open DH, are taken towards a signal methodology that reflect the opportunity cost of demand dispatch, and while such signals exist, as presented in Publication I and Publication II, the business model is still in development. As shown in this dissertation, economic incentives to develop this pricing scheme are not present.

DR in heating grids is prone to large thermal lags, i.e. restricting or increasing radiator water flow can be measured only moments later at the substation. This depends on the structure of the hydronic system. Mishra et al. (2019) studied the effect of centralised control on room air temperature in a similar office building as presented in Publication I and Publication II and found that variations in the circulating water temperature can be measured with a short time-lag after in the rooms. However, load shifting at the substation also should be timed in
Discussion and Conclusion

a manner that it benefits the heat supplier. Thermal comfort survey results show a decline in thermal satisfaction during DR days, which emerges partly due to the implementation of electronic TRVs that still required technological validation. However, previous research did not include continuous feedback from users, which could have captured shifts in thermal satisfaction.

As seen in Difs et al. (2010), Kontu et al. (2019) and in Publication III, the cost and CO₂ savings depend widely on the plant composition in the local energy system. Simulating a typical DH system in the Nordic countries might give some indication of the benefits and investment costs associated with control measures but scaling such findings can lead to erroneous conclusions. The results of Publication III are in line with previous research: the cost saving potential of demand-side management by utilising the thermal mass in buildings is limited in DH systems (Dominković et al. 2018, Kontu et al. 2019).

Further verification of the results found in this dissertation are the following: firstly, hot water tanks have greater capability to store short-term thermal energy and, hence, can shape the demand curve to a larger extend than load control in the DH connected buildings (Romanchenko et al. 2018). Next, cumulative heat load curves show (see Figure A2 and Figure A3 in Publication III) that the most significant effect of DR is during the intermediate season (Difs et al. 2010, Kontu et al. 2019). However, demand-reduction during the most critical hours of operation were not achieved. Finally, small economic benefits to the DH operator and long payback periods for the required technologies have been identified as significant barriers for the deployment of DR in thermal energy systems in Finland. Similar barriers for DR on the building level have been identified in the electricity sector (Annala et al. 2018).

Large-scale demand-side interventions can affect the short-term in operational strategies of thermal plants. In the long-term, it can lead to structural changes in DH systems, such as DH operator’s changes in investment decisions, energy fees, and quantity and profile of heat demand. Adding flexibility to the system can support feasibility for other heating sources which will affect the marginal CO₂ emission intensities of heat production. However, these changes are found to be negligible according to the simulations in Publication III. A substantially larger effect on the costs and CO₂ emission intensities in the system are seen by the implementation of a large thermal energy storage. However, energy system models are simplified representations of real systems, and results of the simulation should be therefore treated as one case amongst others.

One way to validate the significance of DR in building heating systems is to compare it with other technologies that increase flexibility in the DH system. Simulations on the potential of large heat pumps in existing DH systems by Kontu et al. (2018) showed that the largest potential for heat pumps is in small-sized DH where they reduce the usage of fossil fuels. However, in medium and large systems with CHP production, the potential of heat pumps is smaller. Another source for flexibility is the usage of excessive distribution networks as thermal storage, which is feasible but limited Basciotti et al. (2009).
Publication IV presents the potential of room-based heating as a method to decrease heating consumption in a granular zone and increase thermal comfort for the individual. With a sophisticated personal comfort model that is connected to the BMS, greater satisfaction in indoor conditions can be achieved. Furthermore, comfort-based heating control can lead to better results in DR, achieving a wider setpoint range and thereby enabling greater flexibility in the building.

5.2 Limitations and Further Research

In this dissertation, the research questions were answered by using whole building simulations, energy system simulations, field studies and case studies. Studies in limited spaces are commonly used in the literature for validating technologies and algorithms. Although simulating the effect of control algorithms is a well-established approach, many challenging aspects of the control strategies might not be observed in simulations. Hence, field studies with either a researcher-controlled approach or a user-controlled approach are required to give feedback for mathematical models and decrease model error.

As discussed in Section 3.1 and 3.3, the IoT devices used in the studies were on different levels of maturity. Therefore, the studies have also addressed improvements in communication and control technologies, and not all outcomes could be utilised. The studies show that development of data storage, control logic, and connectivity interference are required to further scale smart controls in building automation systems.

However, as buildings represent inexpensive or even complimentary thermal energy storage, and the access to inexpensive internet-connected devices make it an attractive form of balancing load, the dissertation found several limitations, which first need to be overcome. First, the effect of short-term alternations on target heating setpoints on local thermal discomfort limit the flexibility more than previously expected, as discussed in Publication I and Publication II. Next, in order to receive full return on investment on the IoT devices, the whole building’s thermal capacity need to be utilised (Publication II). Next, current utility structure requires DR actions only during intermediate seasons, as shown in Publication III. Lastly, deploying new technologies to existing built environment require collaboration efforts between different entities as the adopted IoT devices’ return on investment cannot solely rely on energy savings.

In Publication I and Publication II, rule-based algorithms have been deployed and evaluated in a test area with closed office spaces equipped with both a centrally controlled HVAC system and a TRV-controlled, decentralised system. Open plan offices, without partitioned spaces may require additional personalised heating control (Kim et al. 2018). Detection of occupancy patterns and integration of occupancy related information, such as metabolic rate and clothing insulation, into the feedback system are suggested as future avenues of research.

The setpoint temperature change amplitude was a constant value either for
the whole test area or for each zone. Further development of a dynamic value for flexibility with regards to thermal comfort could enhance the flexibility potential of buildings, and, hence, DR becomes more valuable. As discussed in Section 3.1, there is room for other forms of increasing flexibility in the thermal system, and further research could compare the economic and environmental potential of the methodologies.

In Publication III, the outcome from the energy model created cannot be verified against real data since it is an illustration of a typical Finnish DH system. As the publication is based on a whole-building model of just one building type, it is challenging to scale the consumption profiles to a system level as space heating loads and hot tap water demand vary significantly amongst e.g. building type, construction year and ventilation system. As noted by Kontu et al. (2019), there is not a general one-size-fits-all DR control strategy for DH companies.

Rather, the DR strategy has to be developed individually for each individual DH system. The results in this publication do not encourage a system-wide DR implementation without careful investigation of the economic feasibility in the DH system. However, by combining new types of services with DH, economic feasibility could be achieved in other ways and customers would get a new experience in how they consume energy. Additionally, future research could focus on actual case studies and actual measured data of a variety of building types, which could be combined and formulated to a system-wide optimisation model. However, this should be done for each DH system separately. The composition of the DH network and the thermal plants can affect DR operation and savings in production costs and emissions considerably.

Further development of energy services and other business models are required to scale DR in DH connected buildings. As the building in Publication IV with its minor energy index presents a niche in the existing building stock, the potential of smart control is challenging to prove from other than the technical aspect. As suggested in Publication IV, with more accurate indoor air measurement and thermal comfort feedback, DR measures can be deployed in buildings whilst maintaining occupant comfort. However, future research should focus on accurately determining parameters on local discomfort.

5.3 Conclusions

The EU commission’s pathways to meet the goals listed the Paris Agreement from the building sector’s point of view include the decarbonisation of buildings, entailing to increase energy efficiency and renewable energy in the existing buildings stock, and decarbonise the electricity and DH sectors. Using state-of-the-art IoT devices, buildings can be automated to increase occupant satisfaction and to provide flexibility in the energy systems. Thereby, they move towards a comprehensive 4GDH system.
Space heating is characterised with the ability to shift loads for a limited period in time due to the thermal capacity of existing building structures. In the literature, demand is shifted by preheating building structures and reducing load during peak hours. However, this control logic implemented in hydronic radiator operations can lead to dissatisfaction in thermal comfort. This might be due to local differences in the thermal environment, i.e. temperature drift and radiant temperature asymmetry. Furthermore, preheating can lead to not only large energy waste but also to increased peak loads in colder climates like Finland as loads aggregate during the recovery period. When scaling the control logic to the local energy system, these peaks can diminish cost and CO₂ emission savings. In buildings with exceptionally high thermal capacity, more radical demand side interventions can be included without abandoning thermal comfort. However, in highly energy-efficient buildings, the overall energy demand is too low to achieve a justifiable payback time.

In dense build environments, DH is a highly efficient method to heat buildings, but decarbonisation requires investment in new technologies on both the supply and the demand side. As the building stock generally renews by 1% per annum, solutions for the existing building stock are required. Furthermore, similarly to the heating network, investments in infrastructure can be considered instead of sunk costs as platforms for smart, sustainable energy systems. Therefore, this dissertation aims to examine the effect of radiator-based control on thermal comfort in office buildings (Q1), to identify the effect of utilising the existing building stock as a thermal energy storage for optimising the DH system (Q2), and present interventions of smart systems in the built environment for energy resilience in cities (Q3).

In the dissertation, the building's thermal energy store content is exploited through DR, which has been defined as interventions in a building's heating energy profile based on a market signal. Three different methods of evaluating cloud-based control in the existing built environment are deployed: small-scale technical demonstrations, advanced system modelling and concepts for scaling well-performing technologies in cities. The dissertation assesses, by multiple case studies, the usage of IoT in buildings for optimising the DH's supply side. To validate the research questions, multiple field studies were deployed in district-heated office spaces in Southern Finland. These methods and technologies described may also be applied to the control of electrothermal control schemes and, therefore, practical lessons are broadly applicable. The following sections summarise the findings of this dissertation.

**Research question of Publication I and Publication II (Q1): How is thermal comfort affected by decentralised demand response in office buildings?**

In Publication I, a novel method of conducting DR in DH connected buildings with electronic TRVs is described. Marginal price signals from a local DH company were processed on a cloud server to modulate room-level temperature...
setpoints. Temperature readings and thermal satisfaction surveys were completed to measure the effect of decentralised DR on room air temperature and thermal comfort. The surveys showed that occupants generally felt more dissatisfied during periods with DR measures than during placebo periods possibly due to temperature asymmetry. Similar results have not been found in literature as the decentralised method used combined with the magnitude of point-in-time surveys deployed in Publication I and Publication II have not been previously performed.

In Publication II, further features were implemented to the control algorithm: weather forecasts were used to deploy night-time setbacks, and rooms were controlled individually based on their usage type and thermal flexibility. Users could also change setpoints during the study. Additionally, the radiator-specific heat output was measured.

The room air temperature was sustained within the targeted indoor environmental constraints that are defined by Finnish indoor climate classification codes. However, similar results in decreased thermal satisfaction were obtained as in Publication I. Although satisfaction rates slightly decreased in DR days, they were generally at a satisfactory level. In the study, the TRV position and emitted heating power were measured and increased or decreased based on the desired DR intervention. The measured effect of DR on heating power modulation is short as the PID controller tends to yield good performance in both load disturbances and setpoint disturbances. Hence, best results were gained in short-term DR modulations.

The research suggests dividing rooms into flexibility zones in order to fully utilise the DR potential of the building. This can be achieved by adjusting the setpoint temperature amplitude individually. Furthermore, indoor air temperatures can be adjusted based on the occupant’s individual heat perception.

The results show that DR can be accurately deployed on a decentralised level. If thermal comfort is prioritised, the setpoint temperature amplitudes can be lowered. To conclude from Publication II, by applying a decentralised control scheme, an investment in IoT devices can both enhance accurate setpoint temperature settings and increase the building’s heating flexibility potential.

Research question of Publication III (Q2): What effect does demand-side interventions have on a typical Finnish DH system?

Publication III investigated the potential of utilising the building’s structural mass for thermal storage in DH systems. It was conducted by using previous analysis on DR control options in a whole-building simulation with simulation tool IDA-ICE and implementing the modulated demand curves in a system-wide simulation with energyPRO. Modelling of DH systems is required to analyse the actual effects of integrating flexibility measures on marginal production costs and CO₂ emissions.

The DH system consisted of a biomass-fired CHP plant and an oil-fired HOB. In addition to a reference case, the simulation included five DR cases with
and without a large thermal energy storage, denoted as HWT. The simulation included comparisons between decentralised DR control and centralised HWT control and additional projections on how these storage types work together. The DR strategies focused on commercial buildings, which account for 42% of the total building stock in the simulated system.

The results of this publication are in line with previous research: DR has only a slight positive effect on production costs and emission levels in a DH system. While the DR-only strategies result in rather modest savings, implementing a large HWT benefited not only solely the system but enhanced the DR control strategy as well. The best investigated DR control strategy was performed in space heating and ventilation when the marginal price trend for DH was declining. If the HWT storage was included, annual production costs decreased by 1.4% and emissions decreased by 0.8%. This strategy was optimal also for the property owner when considering artificial dynamic DH prices.

Not all control strategies were advantageous. Performing DR in space heating and ventilation when the price trend was either rising or declining was uneconomic for both the property owner and DH the supplier. Overall, investing in a large HWT alone can bring benefits, including DH cost reductions and increased electricity revenue. Charging all buildings with the same strategy at the initial low-cost hours can lead to the formation of new peak load hours. The cost-saving potential depends on the time of DR and the number of buildings using the same strategy.

The publication concludes that selecting the right DR strategy is crucial from the production-side perspective. With a dynamic price for DH, the property owner can perform multiple DR actions, which would be beneficial for her but not necessarily for the DH supplier. Hence, DR effectiveness can only be accomplished from a DH supplier’s viewpoint by granting clear incentives to the market. However, cost and emission savings are, even in the best cases, marginal. In addition, combining DR strategies with a large HWT enhances the CHP and HOB operations. Utilising large HWT are not necessarily overlapping with DR control, but they rather enable a larger share of the building stock to participate in DR as overproduction can be compensated.

**Research question of Publication IV (Q3): From the perspective of DR and flexible heating, what tools can a municipality implement in the built environment to promote climate resilience?**

Publication IV presents projects in the city of Helsinki to increase understanding of collaboration with innovative companies and technologies, which contribute to a smart city resilience. The actions are described from a technological, economical, and social point of view. To validate on the technology performance and investment cost, internet-connected TRVs’ were deployed in a highly energy-efficient district-heated office building in Finland. With room-based heating control, the total heating consumption in an energy efficient office building decreased by 10% compared to the previous weather-corrected
year, and thereby improving further the energy performance of the building. Thereby, accurate decentralised DR signals could be deployed. The results suggest that a thermal comfort concept can control a room’s thermal environment autonomously.

By opening APIs between the heating control operator, the thermal comfort operator, and the local energy company, perceived indoor air comfort can be sustained, or even increased, while reducing energy usage and increasing building flexibility. This can create opportunities for new business models, which follow a heating-as-a-service approach. Hence, the thermal control of buildings is not restricted to standardised design values but to actual, real-time measured data and precise heating control, which follows the requirements of the environment the building is operating in.


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Demand Response in District-heated Buildings

Sonja Salo