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Optimization of demand response control strategies in Finnish city-owned buildings

Thesis submitted as a partial fulfillment of the requirements for the degree of Master of Science in Technology.

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The entire energy business from producers to energy end-users is currently undergoing major reforms due to more and more ambitious targets for climate change mitigation measures and energy efficiency of buildings stemming from various international agreements and dwindling of conventional fossil fuel resources. Both supply and demand side measures are required to tackle the issues at hand and much work has already been done in regards to developing and increasing renewable energy generation and demand side energy efficiency. Demand response is a more novel demand side action which targets reducing energy demand during peak demand hours, which in turn can reduce the need for expensive peak production and contribute to increasing the stability of the grid when system reliability is jeopardized. In practice, demand response means that energy use is changed from its typical patterns when it is beneficial from the relevant parties' point of view.

This thesis investigates heat load reduction potential for demand response purposes in typical Finnish city-owned district heated buildings. The potential is analyzed for three different types of buildings individually (office, school and apartment building) and on a city scale for a certain city located in southern Finland by creating building energy models for example buildings in the simulation software IDA ICE and optimizing demand response control strategies in the optimization software MOBO. MOBO is used to determine an optimal combination of controls for these strategies in terms of maximum direct cost saving potential resulting from reduced energy consumption. The optimizations are conducted for a few different example days in winter and in spring, and for a single three-hour-long demand response event on these days. Furthermore, the district heat producer's point of view is regarded by using hourly marginal cost based district heat pricing as one of the minimized objectives in the optimizations. Hourly heat production costs and marginal costs before and after demand response implementation are calculated for the studied city in a previously developed MATLAB simulation model.

The results of the simulations and optimizations indicate that heat load reduction potential for demand response in individual buildings is 50-80% for a single demand response event during the day and depending on the building type. On a city-scale, the achieved heat load reduction is 59 MW or 60-70% of the original heat demand at most, which accounts for approximately 10% of the heat demand of the entire city at the time.

Keywords Demand response, district heating, demand response strategies, building energy simulation, optimization, marginal cost of district heat production

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Energiateollisuus ja energiajärjestelmät tuottajista loppukäyttäjiin ovat tällä hetkellä keskellä merkittävää uusiutumista ja suuria muutoksia johtuen yhä kunnianhimoisemmista kansainvälisistä ilmastotavoitteista ja jatkuvasti tiukkenevista kansallisista energiatehokkuusmääräyksistä. Muutokset koskevat sekä tuottajia että kuluttajia, ja paljon työtä on jo tehty liittyen uusiutuvien energiamuotojen kehittämiseen ja käytön lisäämiseen sekä kuluttajapuolenkin energiatehokkuuteen. Kysyntäjousto on eräs vähemmän yleistynyt kuluttajapuolen toimintamalli, jolla pyritään vähentämään energiankulutusta kulutuspiikkien aikana, jolloin myös kalliin huipputuotannon tarve vähenee, ja parantamaan tarvittaessa systeemin tasapainoa sen ollessa uhattuna. Käytännössä kysyntäjousto tarkoittaa energiankäytön hetkellistä muuttamista normaalitilanteesta sen ollessa kysyntäjoustoon osallistuvien osapuolten kannalta edullista.

Tässä diplomityössä tutkitaan kaukolämmön kysyntäjoustopotentiaalia lämmitystehon pienentämisen kannalta tyypillisissä Suomen kaupunkien omistamissa kiinteistöissä. Potentiaalia tutkitaan kolmessa erilaisessa rakennuksessa (toimisto, asuinkerrostalo ja koulu) yksitellen sekä koko kaupungin tasolla eräässä Etelä-Suomen kaupungissa. Esimerkkirakennuksista luodaan energiasimulointimallit IDA ICE – ohjelmalla, jonka jälkeen MOBO-optimointityökalulla määritetään erilaisista talotekniikkaohjauksista koostuva optimaalinen kysyntäjoustokombinaatio, jolla voidaan saavuttaa suurimmat energiankäytön vähenemisestä johtuvat kustannussäästöt kiinteistönomistajan sekä kaukolämpöyhtiön kannalta. Optimointitapaukset tehdään esimerkinomaisille talvi- ja kevätpäiville, joina kumpanakin toteutetaan yksi kolmen tunnin pituinen kysyntäjoustojakso aamupäivän aikana. Kaukolämmön tuottajan näkökulmaa pyritään tuomaan esille käyttämällä yhtenä optimoitavan tekijänä kaukolämmön kuluttajahintana käytettäviä lämmöntuotannon tuntikohtaisia marginaalikustannuksia. Tuntikohtaiset tuotantokustannukset ja marginaalikustannukset ilman kysyntäjoustoa ja sen kanssa määritetään MATLAB simulointimallia hyväksi käyttäen.

Simulointien ja optimointien tulosten perusteella kaikilla kolmella rakennustyypillä on selvää tehonleikkauspotentiaalia kysyntäjoustotarpeisiin. Yksittäisille rakennuksille tehon alenema yksittäisen kysyntäjouston aikana on 50-80% alkuperäisestä kaukolämpötehosta. Koko kaupungin tasolle skaalattuna tämä tarkoittaa yhteensä maksimissaan 59 MW:n kaukolämpötehon leikkausta, joka on 60-70% alkuperäisestä näiden rakennustyyppien koko kaupungin omistaman rakennusmassan tehosta ja yhteensä noin 10% koko kaupungin kyseisen hetken kaukolämmön tarpeesta.

Avainsanat Kysyntäjousto, kaukolämpö, kysyntäjoustostrategiat, rakennuksen energiasimulointi, optimointi, lämmöntuotannon marginaalikustannus

Preface

This Master's thesis was conducted at Aalto University for Fortum Oyj as part of a larger cooperation project between Fortum and the city of Espoo aiming to develop and implement carbon neutral energy solutions for the city. The objective of the thesis was to investigate mainly district heating related demand response possibilities in typical city-owned buildings and to determine which control strategies are best suited for creating load reductions during demand response events.

First and foremost, I would like to thank both Aalto University and Fortum Oyj for providing the opportunity to write a thesis on such an interesting and topical subject. Special thanks to my instructor Heikki Ihasalo at Aalto University, who provided excellent guidance and constructive feedback during the making of the thesis, and my supervising professor Sanna Syri at the Department of Mechanical Engineering at Aalto University for giving helpful advice and feedback when it was needed. I would also like to thank Niko Wirgentius at Fortum Oyj for help and advice in steering the thesis in the right direction.

I also thank my colleagues at Aalto University and Granlund Consulting Oy for all the technical help and advice during the thesis. I am extremely grateful for the continued support and flexibility at Granlund Consulting Oy, who have been immensely helpful before and during the making of the thesis even if they weren't directly involved in the project.

Lastly, I would like to thank my friends and family for their continued support and all the help and advice they have given me during the making of this thesis.

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Abbreviations

AHU	Air handling unit
aNSGA-II	Non-dominated sorting genetic algorithm II with an active archive
BAS	Building automation system
BPM	Balancing power market
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
DR	Demand response
DSO	Distribution system operator
EV	Electric vehicle
EU	European Union
FCR-D	Frequency containment reserves for disturbances
FCR-N	Frequency containment reserves for normal operation
FRR	Frequency restoration reserves
HOB	Heat-only boiler
HVAC	Heating, ventilation and air conditioning
ICT	Information and communications technology
IDA ICE	IDA indoor climate and energy software
MOBO	Multi-objective building optimization tool
NBCF	National Building Code of Finland
NSGA-II	Non-dominated sorting genetic algorithm
PMV	Predicted mean vote
PPD	Percentage of people dissatisfied
ppm	parts per million
SFP	Specific fan power
TSO	Transmission system operator

Introduction

1.1 Background

Energy conservation and climate change mitigation have been subjects of growing discussion in the past few decades, which is manifested by international agreements as well as national decrees with hard emission reduction and energy efficiency targets. To achieve these targets and effectively reduce the effects of climate change, major reforms in both the supply and the demand side of the energy systems have been required and will still be needed in the future. In the supply side this has meant improvements in production efficiency and increasing the amount of renewable energy penetration. The demand side has seen major developments as well, mainly in energy efficiency of buildings and building operations, which has already decreased buildings’ energy consumption by a considerable amount. Demand response (DR) is another concept related to improving the efficiency of energy systems which ideally yields both economic and environmental benefits for all parties involved. While energy efficiency aims to reduce the overall energy consumption of buildings, the target of demand response is to reduce energy demand during peak demand hours when the most expensive production units are generally in operation.

Although the concept of demand response is not novel, it has been a relatively uncommon practice until recently. In Finland, the electricity transmission grid operator has maintained some demand response reserves but typically these reserves have been mainly offered by large and energy-intensive industrial facilities instead of smaller energy consumers. Smaller individual consumers’ participation in demand response activities has garnered considerable interest in recent years as well, which has manifested in several studies conducted on the subject. The common denominator in these studies has been that definite untapped potential has been identified in the overwhelming majority of them regarding adjustability of demand in times when such measures are beneficial to the overall energy system.

Often the subject of DR related studies is load management of electricity consumption, however the same principles apply for demand response in district heating systems as well. District heating has been the dominant heating type in Finland for a while now and interest in demand response possibilities in district heat systems has been increasing in the past few years. Several studies have been made on the subject in recent years and a handful of pilot tests have been a carried out as well, implying that the concept is gaining traction among producers. Increasing competitiveness of alternative heating methods such as heat pumps has pushed district heat producers to develop new products and business opportunities, one of which could be demand response in the near future.

1.2 Research objective and scope of the thesis

The objective of this thesis is to investigate what kind of load reduction potential for demand response purposes do typical average Finnish city-owned buildings have, and more specifically buildings owned by a certain city in southern Finland. The focus of the study is on district heat load reduction, but electric loads are not ignored and the possibilities for demand response of electricity use are discussed as well. The empirical portion of this thesis is based on constructing building energy simulation models for three different generic city-owned buildings with building energy simulation software IDA ICE. The modeled building types are an office building, an apartment building and a school building. Each modeled building means to represent a typical building of said type in the building stock owned by the city of

Espoo. State-of-the-art literature is studied to determine the most potential methods for single buildings to practice heat and electricity load adjustment for demand response, and the most suitable strategies for each building type are picked for the simulations and otpimizations. The economic potential of load reductions is investigated with a multi-objective building optimization software MOBO, which in this thesis is used to determine the optimal combination of demand response strategies among the ones included during a hypothetical 3h demand response event on a single simulated day.

Finally, a rough estimate of the full demand response potential of the building stock of the city of Espoo in regards to the relevant building types is made, based on the optimization made for the case buildings. Another investigated issues in this thesis is the optimal combination of demand response strategies that yields the maximum benefits, and which strategies in this combination contribute to the total load reduction potential the most. Comparing the demand response strategies should shed some light on which demand response strategies would be the most beneficial to implement strictly in regards to load reduction potential and cost savings. The economic impacts of said load reductions are investigated both from the producer's and the property owner's point of view. Investigating the investment requirements for implementing said demand response strategies, which is undoubtedly an important factor in reality, is not in the scope of this study due to the nature of the modeled buildings. The research questions could be summarized as the following:

- *What is the load reduction potential of an average city-owned building for demand response purposes?*
- *What is the optimal way of achieving the load reduction in terms of demand response strategies and energy costs?*
- *What are the effects of the demand response related load reductions for the building owner and for the heat producer?*

The main focus on this study is in adjusting district heat load in a beneficial way from the heat producer's point of view, although both district heat and electricity consumption demand response markets are included in the literature review part of this thesis. The demand response in this thesis is strictly focused on load reducing rather than load shifting, which would produce slightly different results in terms of economic and demand reduction potential. District heat producer driven demand response is the object of further investigation in the empirical part of the thesis. This is conducted by determining realistic optimal hourly production costs in the district heat system of Espoo city for a single year with a mathematical programming software MATLAB, based on calculations conducted in a previously made thesis on the subject. The results of the MATLAB optimization include the hourly variable production costs of heat and the hourly marginal costs of heat production, which are in turn used in the simulations and optimizations of the study. One 3h demand response event is simulated for each example day, and the timing of the event is based on the calculated hourly variable heat production costs with the demand profiles in the simulated buildings taken into account.

Although the focus in the thesis is on district heating, demand side management of electricity consumption is also considered as it is predicted to have an increasingly important role in energy systems in the future. In addition, some of the studied demand response strategies can be used for both district heat and electricity demand response purposes, so from the consumer's point of view it would be beneficial to consider all possibilities for demand response. Furthermore, during the summer season the district heat demand is low and thus demand side management of heating during that time is not meaningful. Since the same strategies can still be applied in summer as in winter, the consumer could take advantage of electricity consumption related demand response programs instead during the summer.

1.3 Structure of the thesis

The thesis consists of a literature review of important subjects related to understanding demand response and possibilities of partaking in DR activities in Finland, and an empirical study where demand response in three different building types is investigated with simulations and optimizations. While demand response of district heating is the main focus, possibilities for demand response of electricity use are considered as well and the electricity market and related demand response markets are introduced.

Chapter 2 describes the operation and characteristics of the electricity and district heating markets in Finland and in the city of Espoo in detail in order to better understand how demand response can be carried out. Chapter 3 introduces the concept of demand response and the current possibilities to carry out demand response in Finland. Again, both electricity and district heat demand response are considered in this part. Chapter 3.5 compiles state-of-the-art demand response strategies for public buildings found in literature and Chapter 3.6 describes which strategies are deemed most suitable for the empirical part of the study.

Chapter 4 includes detailed descriptions of the building energy modeling process and the input data used in the models. The process and the tools used for optimization of demand response strategies are also described in this chapter. The optimization uses marginal costs of district heat production as the price of district heat to simulate the producer’s viewpoint in the optimizations, thus it is required to calculate the marginal costs beforehand. Chapter 4.2 includes a brief introduction to the district heat marginal cost calculation method and presents the results of this calculation. Chapter 5 of the thesis is dedicated to presenting results for the three different buildings that were modeled, to discussing the implications of the results and to reflect on the impacts of the assumptions made and limitations of the methodologies of the study.

2 Energy markets in Finland

To understand the possibilities and challenges related demand response for electricity and district heating, it is necessary to understand how the electricity and district heating systems in Finland and in Espoo operate and what kind of stakeholders are involved in these markets. Chapter 2.1 briefly describes the composition of the Finnish electricity system and introduces the different market places for electricity trade in Finland. Chapter 2.2 describes how district heating systems and markets in Finland function, focusing especially on the district heat system in the city of Espoo as the buildings investigated in the experimental part of this thesis are located there.

2.1 Electricity markets in Finland

The power system in Finland can be roughly divided into four main components: production units, the transmission grid, distribution grids and the end user. The transmission grid is a high-voltage grid connecting large production units to regional, lower-voltage distribution grids which further distribute electricity to customers. The Finnish transmission grid is also interconnected with the neighboring countries' grids through several direct or alternating current transmission connections (Fingrid Oyj 2017a). The transmission grid is maintained by Fingrid Oyj while the distribution grids are managed by local companies.

The Finnish electricity market was deregulated in 1995 leading to major restructuring of the market. The deregulation resulted in the emergence of Fingrid as a fusion of two competing transmission grid operators as well as Finland joining a shared power market with Sweden and Norway operated by Nord Pool (Pineau and Hämäläinen 2000). Nowadays the Nord Pool power market connects all Nordic and Baltic countries in a single power market.

The most important market for electricity trading is Elspot, the day-ahead hourly electricity market organized by Nord Pool, where producers sell and suppliers buy electricity for the next day based on hourly prices determined by the balance between supply and demand. In 2012 84% of all electricity trade in the Nordics was carried out in Elspot (Järventausta et al. 2015). The prices reflect the forecasted marginal cost of production during each hour, meaning that when consumption, and therefore production, is high the prices will be high as more expensive production units are needed to satisfy the demand. For each day of delivery the Elspot market closes at noon the day before, meaning that trading in the market is based on forecasts for consumption and renewable energy generation, which in turn are based on weather forecasts and historical data (Nord Pool 2017a).

In addition to the day-ahead electricity market, Nord Pool also has an intraday power market called Elbas which covers the UK and German markets in addition to those included in the Elspot market. The purpose of Elbas is to supplement the day-ahead market by offering a marketplace for trading electricity between the closing of the day-ahead market and the time of delivery the next day. Unpredictability of certain renewable generation, inevitable inaccuracies in the forecasts and unexpected faults in the system mean that the amount of electricity buyers have acquired rarely equals the actual demand. Elbas is a continuous market and closes only one hour before the time of delivery so it has a key role in securing the necessary balance of supply and demand in the power market. (Nord Pool 2017a)

While Elspot and Elbas markets cover the bulk of the electricity trade in Finland, imbalances between supply and demand still occur as the aforementioned markets can't react to changes real-time. In Finland it is the transmission system operator Fingrid whose responsibility it is to secure momentary power balance and reliability of the transmission grid, something that cannot be guaranteed with Elbas and Elspot market trading only. Fingrid does not have regulating capacity of its own to maintain the power balance so it organizes a separate market, the Balancing Power Market (BPM), for dealing with more rapid changes in the power balance. Any capacity holders who can implement a 10 MW power change in 15 minutes can submit bids in the BPM for up- or down-regulation. Up-regulation means increasing production or reducing consumption and down-regulation means reducing production or increasing consumption. The bids are submitted 45 minutes before the specific hour at latest and they are used in price order as well as possible. In comparison to the Nord Pool markets the capacity requirement for participating in bidding in this market is much higher (10 MW versus 0,1 MW in Elspot and Elbas) so access is limited to larger producers and consumers in practice. Examples of possible electricity consuming participants are large industrial consumers which have the ability to adjust their production quickly without considerable economic losses. (Fingrid Oyj 2017a)

Concurrently with the balancing power market, Fingrid maintains another types of reserve resources called frequency reserves, which can be further divided into frequency containment and frequency restoration reserves. The nominal frequency of the transmission grid in Finland is 50 Hz and it is an indicator of the momentary balance of supply and demand. Deviations in the balance between power production and consumption cause fluctuations in the frequency, which are typically small and the frequency remains between 49,95–50,05 Hz. Frequency Containment Reserves for Normal operation (FCR-N) are used to maintain the grid frequency within its normal range of [49,9 Hz; 50,1 Hz] and they are used more or less constantly. Larger deviations from the normal frequency range are possible though, for example when a major production unit unexpectedly disconnects from the grid, which activates another type of reserves called Frequency Containment Reserves for Disturbances (FCR-D) into use. FCR-D starts to activate when frequency drops below 49,9 Hz and is completely in use at 49,5 Hz, and its core purpose is to replace the production deficit caused by the disturbance. (Fingrid Oyj 2017a)

Frequency Restoration Reserves (FRR) on the other hand are used to return the frequency back to the nominal value of 50 Hz and to release any activated frequency containment reserves back to use. The FRR includes both automatically (FRR-A) and manually (FRR-M) activated reserves. The former are procured in an hourly reserve market while the latter consists of the BPM and several reserve power plants owned by Fingrid. (Fingrid Oyj 2017a)

The Nordic transmission system operators have agreed upon reserve obligations for each type of reserves for each country. The obligated reserve capacities for Finland are approximately 140 MW of FCR-N, 220-265 MW of FCR-D, 70 MW automatic FRR during morning and evening hours and 880-1100 MW manual FRR, which should cover any faults in the transmission grid in Finland. In normal operation at least 2/3 of the obligated reserves must be maintained nationally so that frequency can be maintained in island operation, in other words when connections to other countries are cut. The rest of the reserves can be purchased from other Nordic countries as well. (Fingrid Oyj 2017a) Each type of reserve has a requirement for response time ranging from seconds for FCR-D to 15 minutes for manually activated FRR. In addition, each reserve has a minimum regulating capacity requirement ranging from 0,1 MW to 10 MW that bidders must have in order to participate (Pöyry 2014).

Additionally, one more type of reserves exist in Finland called strategic power reserves, which are procured and maintained by the Finnish Energy Authority. The purpose of this peak-load capacity reserve is to secure the supply of electricity in situations when market based electricity production is unable to completely cover consumption and it is based on Finnish peak-load reserve capacity act 117/2011. The Energy Authority periodically reviews the capacity needs and procures the reserves accordingly. The current peak-load capacity reserve is 299 MW and it consists of two power plants (129 MW and 160 MW) and a 10 MW demand side flexibility facility. For each two year period, the Energy Authority chooses the most suitable facilities for the reserve among the candidates who offered to participate. The facilities that have been chosen to the peak load capacity reserve cannot participate in any other electricity markets during that time so the only compensation these facilities receive is from this reserve. (Energy Authority 2017)

As mentioned previously, price of electricity in the Elspot market reflects the marginal cost of production for every hour of the day. Marginal cost of production is the cost of producing one more kWh of energy from the most expensive source needed to satisfy the demand during that time, so that in a competitive market like Elspot, electricity is produced at the lowest possible cost at all times (Nord Pool 2017a). The Elspot market is segmented into several regions which can have different regional prices that are not the same as the system price. Finland is a single region so the price of electricity is the same everywhere in Finland but for example Sweden is divided into four different regions. However, the high interconnectivity of the markets involved means that regional price levels follow the overall system price closely. Norway has vast hydro power resources connected to the Nordic power system and as hydro power is extremely cheap, the availability of said resources highly influences electricity prices in the market. During peak load hours, which typically occur in wintertime, more expensive production units like gas turbines and oil-fueled condensing units are needed which drives the price of electricity up (Nord Pool 2017a). The price differences between the lowest and the highest prices during any given year can be significant: in 2014 the lowest market price for electricity in Elspot was 1,95 €/MWh (3.11.2014 03-04) and the highest was 200,05 €/MWh (29.12.2014 15-16). Price fluctuations within a single day are of course less severe but differences between consecutive hours can still be tens of €/MWh (Nord Pool 2017b).

The Elbas intraday prices on the other hand are completely based on bids by buyers and sellers, and the market price is basically the best deal available (Nord Pool 2017a). Price formation in the BPM works in a similar fashion: the price is based on bids submitted and they are used in order of price taking necessary constraints into account. For up-regulation, the cheapest bid available is used first and the upper balancing power price is the price of the most expensive bid used. For down-regulation, the most expensive bid is used first and the lower balancing power price is determined based on the cheapest down-regulation bid used. The upper and lower balancing power prices are constrained by Finnish regional Elspot prices: the upper balancing power price must be equal or greater than the regional Elspot price and the lower balancing power price cannot exceed the regional Elspot price. The participants whose bids were used all receive or submit payments for the energy agreed according to the upper or lower balancing price based on which type of regulation was used. (Fingrid Oyj 2017a; Fingrid Oyj 2017b)

Markets for frequency controlled reserves can be based on hourly bids or yearly or longer contracts. In hourly markets, the market price is based on submitted bids for any given hour while in yearly markets the reserve provider receives a yearly fixed capacity payment. Fast disturbance balancing power reserves and some frequency controlled disturbance reserves also include a component for activated amount of energy in the yearly payment in addition to the capacity component. (Järventausta et al. 2015)

For consumers, the cost of electricity use consists of a contract with an electricity supplier and a contract with the local distribution network operator. The local distribution system operators (DSOs) operate and maintain the entire electricity distribution system in the region, and thus hold a monopolistic status in their respective regional markets. Electricity distribution price formation is basically dependent on regional characteristics and it is supervised and regulated by the Energy Authority of Finland according to a principle of reasonable rate of return (Energy Authority 2015). The electricity supplier can be chosen freely, on the other hand. Contract type possibilities with the supplier vary, ranging from various fixed price contracts to time-of-use contracts to direct Elspot market price -based contracts with hourly varying electricity cost. The latter two contract types are the most naturally suitable ones for demand response purposes and could even encourage well-informed customers to practice load management without any external driving forces if the potential economic gains are sufficiently large versus the related inconveniencies.

2.2 District heating in Espoo

District heating is a method of providing heating for buildings. It is a well-known commodity with mature technology, and common in larger urban areas in Northern and Western Europe and in parts of Asia and North America. In Finland, in 2014 district heating had 46% market share of all heating in residential, commercial and public buildings, which makes it by far the most important heating solution in the country today (Finnish Energy 2016a). Advantages of district heating over more traditional detached single-house heating systems include better energy-efficiency, lower environmental impacts and that a wide variety of possible heat sources and fuels can be used to produce district heat. District heating has also a very high reliability of supply, it is a simple and low maintenance system for the customer and the initial investment from the customer's point of view is low. (Kontu 2014) District heat produced in Combined Heat and Power cogeneration plants (CHP-plants) has also positive impacts on emissions generated from electricity production as low-cost and efficient CHP-production replaces electricity produced in condensing power plants. (Difs and Trygg 2008) The capital investment of an entire new district heat system is high compared to other forms of heating though, and it is only suitable for sufficiently densely populated areas (Kontu 2014). Because of this, district heating is the preferred heating solution mainly in urban areas where consumers are located close to each other.

Broadly speaking, the district heating system consists of central production units, a network for heat distribution from the production unit to end-users and heat exchangers which transfer heat from the distribution grid to secondary heat networks, usually heat distribution networks of single buildings. Heat is generated in the production units, from which it is distributed to the consumers with a heat transfer medium. The heat transfer medium is usually water but technically it can be any other heat transfer fluid or even steam. Unlike in the electricity grid, in a district heating system the production must be relatively close to the customer as heat losses in the distribution network increase as the total length of the network increases. Heat losses in the distribution network are also dependent on supply water temperature, which is controlled by the producer. To minimize heat losses the temperature is kept as low as possible while keeping it high enough to satisfy the heat demand of every customer connected to the district heat network. The supply water temperature is also dependent on outdoor temperature with a maximum of 120°C during wintertime. (Kontu 2014)

Heat production units in Finnish district heat networks are cogeneration plants or either stationary or transportable heat-only boilers (HOBs). In 2015 the total district heat production in Finland was 33,3 TWh of which a little over 73% was produced with CHP-plants. A wide variety of different fuels are used to produce heat in Finland, with the most notable fuels being wood/biomass, coal, natural gas and peat. Figure 1 shows the distribution of different fuels used for heat and electricity production in CHP-plants in 2015 as an example. (Finnish Energy 2016a) Industrial waste heat can be sold to the district heat network as well, assuming that the industrial site is in close enough proximity to the heat grid and the waste heat has sufficient temperature level (Kontu 2014). Utilizing waste heat is especially common in Sweden nowadays, where industrial waste constituted nearly 8% of the country's heat production in 2015 (Energiföretagen Sverige 2017). Another possible district heat production method is using large heat pump stations to generate heat to district heat network. A notable quantity of heat produced in the district heat systems of Sweden is generated with heat pumps and there is small amounts of district heat production with heat pumps in Finland as well (Energiföretagen Sverige 2017; Finnish Energy 2016b). Waste heat from data centers is a more novel but perfectly feasible source of district heat as well. Data centers require large amounts of constant cooling and the resulting low-grade waste heat can be recovered for district heating with proper technology. (Ebrahimi et al. 2014)

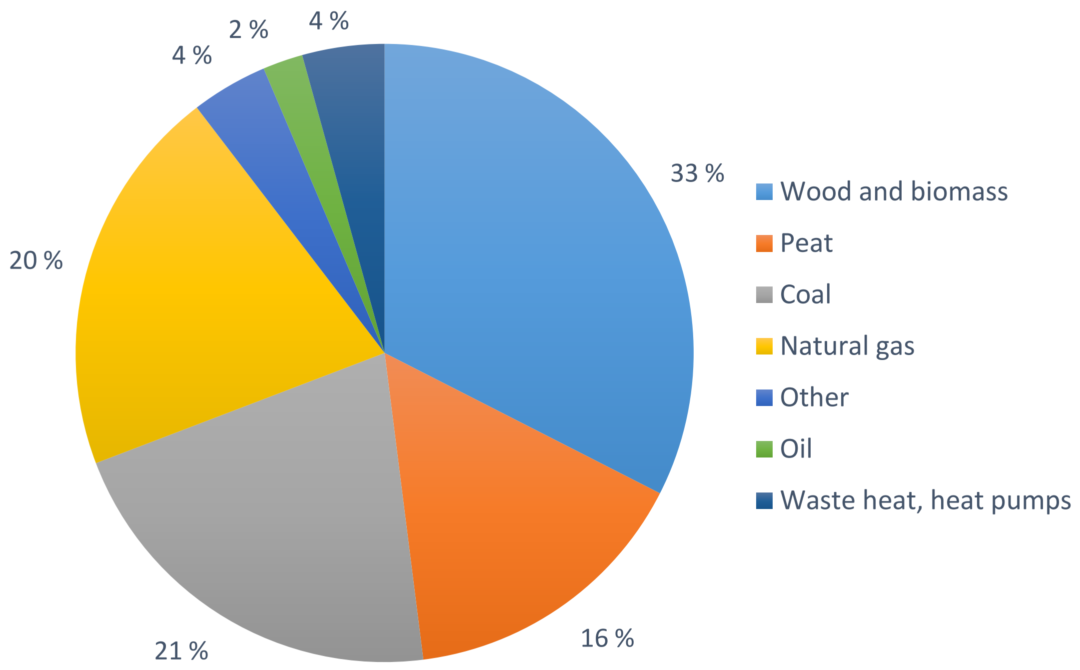

Figure 1. Distribution of fuels used in heat and electricity production in CHP-plants in Finland in 2015 (Finnish Energy 2016a).

The main advantage of combined heat and power plants is that they produce heat and electricity with a higher efficiency than what a separate heat-only boiler and a condensing plant would produce, in other words less fuel is needed to produce the same amount of heat and electricity. In a district heat system, the produced electricity lowers the marginal heat production costs as it is sold to the market and profits made are deducted from the marginal cost of heat production. The operation of a CHP-plant is subject to profitability of electricity production to an extent though, depending on how the variable costs of production are allocated between heat and electricity production. Usually CHP-plants constitute the base production in district heat networks while heat-only boilers are used more as peak production units. Because of the aforementioned dependence on hourly varying electricity prices as well as other factors such as adjustability constraints and additional start-up costs the optimal operation of a CHP-plant is more complex than that of a heat-only boiler and determining it often involves some type of optimizations. (Rong and Lahdelma 2007)

The district heat system of Finland, if such a term can be used, consists of smaller isolated district heat networks operating regionally. Due to distribution losses affiliated with district heating, individual networks typically cover only one city or other urban area. The distribution networks are owned by a single private or municipality-owned company, which typically also produces all heat into the grid with the exception of any possible waste heat sources connected to the network. The possibilities of further opening the district heat market for third parties and individual producers has been studied some in recent years. Mäkelä (2014) and further Syri et al. (2015) for example investigated the economic effects of connecting a small amount of solar heat and third party heat production to the district heat network of Espoo, and the results revealed potential for significant cost savings due to decreased operation of peak production plants. Third party access could result in difficulties in operating the system cost-efficiently, especially in networks with significant combined heat and power (CHP) generation capacity (Söderholm and Wårell 2011).

The empirical part of this thesis considers buildings located in the city of Espoo in southern Finland, so the characteristics of the district heat system in Espoo in particular are briefly introduced. District heating has been available in Espoo in some capacity already since the 1960’s which makes it one of the oldest DH networks in the country. The district heat distribution network operator in Espoo is Fortum Power and Heat Oy, which also produces all heat into the city’s DH network (excluding external waste heat sources). District heating is also the most prominent heating method of buildings in Espoo, servicing 70% of residential buildings in the city at the end of 2015. Fortum Power and Heat Oy also operates the district cooling network in the city, though the production capacity is currently very small and connection to the network is available in certain few regions of the city only. (Finnish Energy 2016b; Finnish Energy 2015)

The heat production capacity of the district heat system in Espoo consists of three combined heat and power plants, several heat-only boilers, a 12 MW external heat source and a heat pump plant. Suomenoja 1 CHP plant can be operated to produce both heat and electricity (CHP mode) or in theory it can be operated to produce heat only (HOB mode), while Suomenoja 6 and Suomenoja 2 CHP plants can be operated only in CHP mode. However, operating Suomenoja 1 in HOB mode is challenging according to Fortum sources and thus it is assumed later in this paper that the facility can be run in CHP mode only. The plants use a variety of different fuels with coal and natural gas being the two most commonly used fuel types. (Finnish Energy 2016b) The plants of the district heat system in Espoo, the plants’ nominal capacities and fuel types used for heat generation in these plants are shown in Table 1. The Suomenoja heat pump station uses water-to-water heat pumps to produce district heat from warm pre-treated wastewater. In addition to the existing heat production units shown in Table 1, a large ground source heat pump station pilot project is under construction in Otaniemi, which can potentially cover up to 10% of heat demand in Espoo. Fortum also has an 800 MWh heat storage in the Suomenoja power plant area, which can be utilized for CHP-plants’ production optimization purposes, for example. (Fortum 2015a)

Table 1. District heat production plants in the Espoo city DH network (Finnish Energy 2016b, Mäkelä 2014).

Plant	**Heat output**	**Electricity output**	**Main fuel**
Suomenoja 1 CHP	162	75	Coal
Suomenoja 2 CHP	213	234	Natural gas
Suomenoja 6 CHP	80	49	Natural gas
Suomenoja 3	70	0	Coal
Suomenoja 7	35	0	Natural gas
Kivenlahti	130	0	Heavy fuel oil
Tapiola	160	0	Natural gas
Vermo	80	0	Natural gas
Kaupunginkallio	80	0	Light fuel oil
Otaniemi	120	0	Natural gas
Auroranportti	15	0	Light fuel oil
Juvanmalmi	15	0	Natural gas
Kalajärvi	5	0	Light fuel oil
Vermo	90	0	Natural gas
Masala	5	0	Natural gas
Kirkkonummi	31	0	Natural gas
Confidential external heat	12	0	none
Suomenoja heat pumps	40	0	Electricity
Vermo	35	0	Bio-oil
Kivenlahti	40	0	Wood pellets

2.2.1 District heat pricing

In the past district heating has usually been a cost-effective heating solution in Finland for heat consumers in urban areas with existing district heat networks. However, in recent years some alternative heating methods, especially various heat pump solutions, have become a competitive option for district heating due to decreasing prices in technology and reformation of energy policies in the European Union (EU) and national levels (Kontu 2014). Likewise increasing energy efficiency requirements for buildings in recent years have steadily decreased heat consumption, which makes less investment-heavy heating options like heat pumps attractive options. These developments pose a challenge for district heat companies and encourage them evolve with the market in order to maintain a dominant position as the main heating method in the future as well.

Currently the status of district heat companies in the Finnish heating market is interesting. It is evident that the market position of a district heat company in its regional district heat market resembles a natural monopoly since currently there are no competing district heat networks servicing the same region, and constructing a competing DH grid to a region with an existing one is not economically feasible (Wissner 2014). In the context of the heating market, the DH producer's status is more complicated though, since there are several other possibilities to cover the heat demand of a building in addition to district heating, such as detached boilers, heat pumps or direct electric heating. The DH producer is once again in a dominant position in the context of the heating market as well if the customer has made the initial investment for a district heat connection to the building since it is not economically attractive to change the heating method at that point. (Asianajotoimisto Krogerus Oy 2014)

Due to the dominant market position of district heat producing companies, heat price formation is entirely up to the producer to decide. While district heat systems in Finland are not regulated by the state, the pricing must obey the regulations regarding dominant market actors defined by the Finnish competition authority, which prohibit the abuse of dominant market position which in this case would mean increasing heat prices to an unjustifiable level and not treating similar customers the same way (Competition Act 948/2011). District heat producers' compliance to the Competition Act is further supervised by the Finnish Competition Authority. The aspect of customer satisfaction is naturally a factor in price formation as well, since it is beneficial for the DH producer to maintain a good image and the ability attract new customers.

As mentioned previously, there is no strict legislation in Finland regarding how district heat companies should define heat prices for customers. The limitations defined by the Competition Act implicate that prices should be more or less based on the marginal costs of heat production in plants connected to regional heat distribution grids. The cost of producing district heat varies hourly just like the cost of producing electricity does, especially in a DH network with multiple CHP plants. In heat-only boilers the heat production cost is related to fuel prices and fuel taxes while in CHP plants the total energy production cost is also influenced by the hourly price of electricity. Fuel taxes in Finland have no hourly or daily variations and fuel prices may or may not vary depending on the market. Variations in the price of electricity on the other hand can significantly affect the hourly energy production costs in CHP plants since generation of heat and electricity go hand in hand in these plants. Heat prices in different regions can thus vary rather heavily depending on the type of production units in the DH system and other local characteristics.

Typically the price of district heat is composed of several price components which are the connection fee, a fixed charge or a power charge and an energy charge. The connection fee is a one-time price component which is usually paid when the building is connected to the district heat grid. The size of the connection fee typically depends on the maximum heating power capacity or the design district heat water flow of the connection and the fee increases as the connection size increases (Energy-An Consulting 2009).

The power charge and the energy charge are recurring price components, on the other hand, which often depend on realized consumption. The power charge is a fixed yearly price component calculated based on the power connection capacity or design district heat water flow of the building's DH connection. The energy charge is a monthly price component that is directly related to the amount of energy consumed by the customer. Some district heat providers offer heat contracts which have seasonal variation in the energy charge component loosely based on marginal production costs of heat so that the energy charge's fixed factor is lower during summer due to lower marginal production costs. (Energy-An Consulting 2009) Table 2 presents one available contract type offered by Fortum for customers located in Espoo. This particular contract type has the aforementioned seasonal variation in the energy charge –component. The heat prices in Table 2 are also the prices used later in the simulation parts of this study.

Table 2. Recurring costs of district heating for customers of Fortum Kausilämpö –district heat product (Fortum 2016).

Type of fee		**Cost**
Energy charge	Summer	22,70 €/MWh
	Spring & autumn	46,30 €/MWh
	Winter	62,50 €/MWh
Power charge	Paid yearly	29,20 € x kW

3 The concept of demand response

The following chapter is dedicated to discussing demand response in more detail. Although district heat demand response is the focus of this study, electric demand response is also discussed in this chapter in some detail since it is a far more studied subject and the number of different market places for demand response of electricity use are far greater than those for district heat. The concept of demand response and the driving forces behind it are discussed first. Additionally, possible market places for demand response in Finland are introduced as well as the market actors involved and their specific incentives for demand side activities. The challenges of implementing demand response in these markets are also discussed. Lastly, in Chapter 3.5 state-of-the-art methods for carrying out demand response are introduced for a better understanding of what types of loads can be used for demand response purposes. In Chapter 3.5 the focus will be on adjustable loads of individual public- and residential buildings, as these are the type of buildings that are further investigated in the experimental part of this paper.

3.1 The principles of demand response

The power system as well as district heat systems operate with the principle that supply and demand are in equilibrium at all times. In traditional energy markets production follows demand to ensure this energy balance, in other words production is adjusted when demand changes. Demand response in practice is load following production instead, when it is beneficial from the system's point of view. Demand response is a broad concept and can be defined as changes in energy usage by end-users from their usual consumption patterns in response to market signals such as time-variable prices or incentive payments (European Commission 2013, DOE 2006). The referenced definitions are specifically for demand response of electricity consumption but the concept is exactly the same in regards to district heating. The quintessential aim of demand response is to optimize the energy system by reducing demand during peak load hours in order to reduce peak production capacity requirements or contribute to increasing the stability of the grid when system reliability is jeopardized (Goldman 2010). Ideally, practicing demand response is a win-win situation for the parties involved: the energy consumer receives economic gain for momentarily reducing their energy use, directly from smaller energy bills or from supplementary payments by the demand response organizer. Concurrently the organizer achieves its goals for demand response, which can be for example reducing peak production capacity or increasing system stability depending on the organizer in question.

Demand response can be considered a subtype of demand side management measures which also includes energy efficiency in addition. Demand response and energy efficiency are closely related concepts but not to be mixed; energy efficiency in principle aims to produce the same level of energy services using less energy while demand response aims to reduce energy consumption during certain brief periods of time only, e.g. during peak demand hours (York and Kushler 2005). Energy efficiency involves replacing existing equipment with devices using less energy without sacrifices in performance or comfort level. Demand response, on the other hand, involves a reduced performance during the event which can manifest in lowered level of provided service, for example lowered indoor thermal comfort. Another notable difference is that the definition of demand response describes it as changes of energy-use from its usual patterns, while energy efficiency assumes no changes in actual operation. (Goldman 2010)

Energy efficiency and demand response are heavily connected though and both have some effect on one another. Logically installing more energy efficient equipment leads to decreased energy consumption and often to decreased peak demand as well. On the other hand, active demand response can lead to energy savings depending on the exercised demand response strategy. (Goldman 2010) Certain demand response strategies involve loads that are often shifted in full, like the heat demand of a domestic hot water tank which consumes the same amount of energy regardless of timing. Light dimming, which is a viable demand response strategy reducing electricity demand, on the other hand directly produces energy savings as lighting is a load that generally cannot be shifted in a meaningful way.

As mentioned in the previous paragraph, demand response can be practiced in a few different ways. Load-shifting means shifting the timing of a certain load completely, for example shifting the aforementioned heat load of a domestic hot water tank heating. Heating the water in the tank consumes the same amount of energy and only the timing of the load is changed. Whether load-shifting results in tangible effects for the consumer depends on the load in question and the timing of the demand response. Shifting space heating from morning peak hours to a few hours earlier, essentially preheating the building, results in a reduced heat load during the event, possibly no change in actual energy consumption and small changes in indoor temperature during the demand response event. Light dimming, on the other hand, is an example of load limiting. Load limiting demand response actions are such that do have a tangible effect of some sort; the load is limited during the event which is enabled by accepting a change from an otherwise preferred state, for example a slightly worsened indoor comfort level. The deviation from the normal state should be minimal though, otherwise demand response becomes less attractive from the consumers point of view.

Demand response which involves direct energy savings naturally leads to smaller energy costs and thus there is some economic incentive to practice DR. Load-shifting, however, does not automatically have any economic value for the consumer considering their total consumption does not change in the process but is merely shifted to another time. There are some incentives in current energy pricing mechanisms that encourage load-shifting, like spot price -based hourly electricity fees or fees related to peak power use like in some district heating networks. It’s also possible that the demand response organizer offers a fixed yearly payment for the consumer in exchange for readiness to provide demand response when it is necessary. The current district heat pricing mechanisms, which have no variation between consecutive hours, offer no incentive for consumers to practice DR though, which means that either another pricing system should be developed or the producer should offer some compensation for participants.

3.2 Demand response in electricity systems

Demand response in electricity markets has been a subject of much studies for a while now as it is currently seen as an important part of future electricity systems. The complexity of the current Finnish power system and the number of different actors involved in it leads to the existence of a number of different market places for demand response of electricity consumption. Figure 2 illustrates the market actors of the Finnish power system and the market places within it. The figure shows that from an electricity consumer’s point of view there are numerous possibilities to participate in demand response activities, ranging from reserve power markets to simple consumer-driven demand response which only aims to reduce electricity costs for the consumer. The stakeholders in Figure 2 have different goals for demand response and some electric loads are unsuitable for certain markets due to size or lack of adjustability of the load. Some of these markets, such as the reserve power markets, have participation requirements for minimum adjustable load and minimum activation time, which set boundaries for demand response as well.

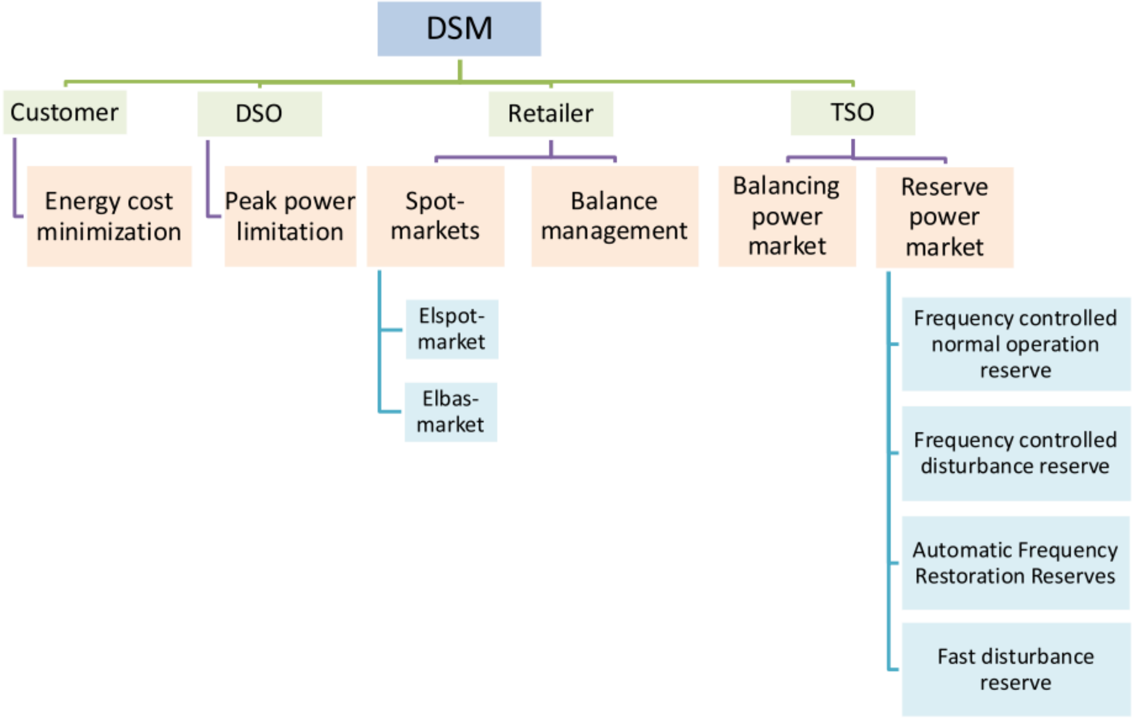

Figure 2. Market places for DR of electricity in Finland and interests of different stakeholders involved (Honkapuro et al. 2015).

The possible demand response markets operated by the transmission system operator Fingrid have especially strict requirements for both minimum load size and activation time, since these reserve and balancing power resources are integral parts of the system which ensures the security of supply at all times. Thus it is important that these reserves can be activated in times of need exactly as planned, regardless if the reserves are supply or demand side resources. The requirements vary depending on the type of reserve in question, for example frequency controlled reserves for normal operation require a minimum adjustable load of 0,1 MW with an activation time of 3 minutes at most. On the other end of the spectrum are the fast disturbance reserves, for example, for which the corresponding requirements are 10 MW in 15 minutes at most. The use of these reserves vary as well, meaning that in some of these markets demand response would be carried out much more often than in others. The aforementioned FCR-N reserves are activated almost constantly while fast disturbance reserves are activated perhaps once a year on average. (Fingrid Oyj 2017a) These requirements naturally limit the possibilities of offering certain demand response resources to these markets since such large and quick load reductions can be difficult to achieve. Markets with load requirements of several megawatts are completely unfeasible for individual small electricity consumers for example, at least without substantial aggregation of resources. Likewise an activation time of seconds or a couple of minutes can be difficult to achieve for smaller customers and aggregated loads due to delays in data transfer systems. Reliable load-specific measurements verifying controls real-time, which are required in real-time market places, are generally missing for smaller loads as well (Valtonen et al. 2015)

Compared to the transmission systems operator, the distribution system operators in Finland have more limited needs for demand response. The main points of interest for demand response from the DSO's point of view is that it can be used to flatten load profiles in the distribution grid and increase the utilization rate of various network components. The utilization rate of a grid component means the average load level of the component divided by the maximum load capacity of the component. In essence, a high utilization rate means that the network is used efficiently and near its intended design capacity while a low utilization rate implies that the network is oversized. Additional positive effects of demand response from the DSO's point of view are decreased distribution losses, which result from flatter load profiles, and increased reliability of the distribution grid during disturbances. (Rautiainen 2015)

Electricity retailers in the Nordic power system typically trade for electricity in the Nordic power markets which they then sell to consumers. Retailers with their own electricity production also sell the electricity produced to the Nordic power markets. Thus the retailers also aim for the supply and demand equilibrium, where demand is based on forecasts and the supply is bought from the Elspot and Elbas markets. Demand forecasts feature inaccuracies though, which can lead to a deviations from the energy balance and economic losses since the surplus or deficit of electricity must be evened out in other electricity market places. Adjusting the consumers' loads could be used in these situations to even out the imbalances. This way demand response could be helpful for the retailer when planning the procurement of electricity, and perhaps it could lower the general price level in the process. (Rautiainen 2015)

Demand response strictly based on hourly varying Elspot market price signals can be carried out without any external party involved since market price information is freely available to everyone for the next day. The way that the Nord Pool electricity trade functions means that there is no single entity, other than the consumer, that would directly benefit from Elspot price -based demand response so organizing such is left for building owners themselves. The overall system does benefit from price-based demand response though, since it reduces the need of expensive peak production which in turn results in environmental benefits as well. Price-based demand response can result in decrease in overall price level if implemented in large enough scale which benefits everyone purchasing energy from the market. Demand response could also be a useful tool for consumers with their own small-scale production in regards to optimizing their energy use and production (Rautiainen 2015)

Some studies have been made in recent years investigating the economic potential of demand response in the different electricity markets in Finland. Valtonen et al. (2015) studied the theoretical economic potential of electric heating and water heating load control in the balancing power market compared to potential of the same load control in the Elspot market. The electricity retailer was assumed as the market party implementing the load-control in the study, with control limited to one hour periods at a time and maximum five times in a day. They discovered that for an example group of approximately 1400 customers and using the customers' real consumption data, the theoretical maximum income potential in the balancing power market is significantly higher than the potential in the Elspot market. It was also noted that the retailer's bidding strategy has a major impact on the economic potential of DR, yet even with a simplified strategy where the retailer bids load-control capacity with a fixed price the potential far and away exceeds the Elspot market's potential if the bid price is set appropriately. Järventausta (2015) presented simulation results which indicate that for a 1 MW controllable load, both the balancing power market and the frequency controlled reserve markets offer significantly larger profit potential compared to Elspot price –based demand response of the same load.

Some types of demand response are already rather common in Finland though. According to a report by Pöyry (2014), energy-intensive industrial companies offer demand response resources to the reserve and balancing power markets in significant capacities already. These industries also react to Elspot-prices and adjust processes to minimize energy costs, since the economic benefits available can be substantial due to high electricity consumption. Electric heating load shifting based on time-of-use tariffs has been long practiced in Finland as well, especially in cases where the building is fitted with a hot water tank. The time-of-use tariff then encourages the consumer to heat the water in the tank at night when electricity prices are lower.

Major challenges still exist before large-scale demand response implementation becomes reality. According to a report by Honkapuro et al. (2015), which surveyed Finnish retailers and distribution system operators, the main obstacles mentioned in the survey results were the lack of economic benefits, the lack of motivation among customers, the lack of standards in data system interfaces and insufficient market models, among others. Another issue that the study by Honkapuro et al. (2015) highlighted is that there is no general agreement on which party should be active in developing the infrastructure required for demand response. Conflicts of interest among stakeholders is another issue often mentioned, and it is definitely a thing that should be considered when planning DR activities. Strbac (2008) also highlights the lack of proper information and communications technology (ICT) infrastructure and the lack of understanding of the benefits of DR as major reasons for the slow implementation of DR in larger scale.

As abovementioned, conflicts of interest among market actors can be problematic when practicing demand response. The optimal timing for demand response according to a producer may not coincide with what would be the optimal timing for a distribution system operator for example and in a worst-case scenario demand response has a negative effect on the business of the actor that is not directly involved in organizing the demand response. A solution to prevent any negative effects is to analyze the potential and effects of demand response on system level rather than concentrating on parts of the system only. (Järventausta et al. 2015; Rautiainen 2015) One such conflict of interest situation can occur when the consumer or retailer organizes spot price –based demand response which results in a large shift in electric load in some part of the distribution grid, which can cause adverse effects on grid voltage levels for the harm of the DSO.

3.3 Demand response in district heat systems

As mentioned previously, demand response in district heat systems is a lesser-known subject compared to electricity related demand side management likely due to the simple fact that district heating in itself is not relevant in many parts of the world. It is a mainstay heating method in Northern Europe though, and thus the concept of demand response in district heating systems has garnered much interest as well in recent years. Due to the nature of the district heating systems in Finland and the current pricing mechanisms for district heating, which were explained in Chapter 2.2, the only real possible driving force for demand response at the moment is the district heat producer.

District heat demand response has various positive effects from the heat producer's point of view. Reducing peak loads decreases the utilization rate of expensive peak production units and helps to minimize the overall production costs of heat generation. As the overall heat demand curve becomes more flat, less start-ups and shutdowns occur for said peak production units, which further lowers the costs of operation. Load-shifting in particular works the other way around as well, since moving demand from peaks to off-peaks flattens the valleys of the demand curve as well, which in turn increases the utilization rate of base production units such as CHP-plants. Postponement or elimination of network capacity enlargement needs and additional production capacity needs are another positive effect of demand response. (Valor Partners Oy 2015; Kärkkäinen et al. 2004) Increased CHP-plant utilization and decreased peak HOB-plant utilization can have positive environmental effects as well, depending on fuels used by the plants.

A typical district heat consumer is not interested in the effectiveness of the overall operation of the district heat system, however. From the consumer's point of view, the important aspects are comfortable indoor climate conditions at all times and the availability of hot water when needed, as well as the cost of acquiring these commodities. Indeed, from the consumer's point of view demand response essentially means balancing sacrifices in comfort and cost savings to an acceptable equilibrium. By carrying out demand response the consumer can gain some direct cost savings if the practiced load management results in reduced heat consumption. In regards to load-shifting, where consumption does not necessarily decrease but is merely shifted, no direct cost savings are materialized without developing alternative district heat pricing mechanisms that have deviation in prices between peak and off-peak hours. Another option to incentivize customer participation is to compensate the consumers for demand response activities with separate payments based on load reductions. (Valor Partners Oy 2015; Kärkkäinen et al. 2004)

Valor Partners Oy (2015) also lists some adverse effects that demand response could potentially results in. Load-shifting from peak to off-peak could lead to an even larger demand peak in a worst case scenario if the DR process is not properly implemented. Considering that demand response event timing is based on forecasts for demand, the uncertainties in these forecasts could lead to negative effects at system level if forecasted and realized demand differ significantly. Investment requirements for demand response implementation have to be carefully reviewed to avoid too lengthy payback periods. Compensation paid to consumers for demand response activities in advance could lead to economic losses for the producer if the expected cost savings do not materialize. There is also a possibility that a load reduction leads to unacceptable indoor climate conditions for the consumer, which leads to general customer dissatisfaction.

Various studies attempting to estimate district heat demand response potential in different types of buildings have been made in recent years. Salo (2016) developed a predictive demand response control which optimized the heat consumption of a building by shifting loads according to marginal costs of heat production. 11% savings in heat costs and 22% peak load reduction were discovered for a single winter day case in Salo's study. Kontu (2014) compiled the results of a 2013 study by Jokinen (2013), which investigated the DR potential of a handful of Finnish apartment buildings with IDA ICE –based simulation models by evoking a one hour DR event every weekday morning and allowing the indoor temperature to drop by a maximum of 1°C during the event. The results of the study scaled to a city level revealed an approximately 80% momentary heating power reduction potential.

There have also been several pilot projects in recent years experimenting with district heat demand response, mostly conducted in Finland or in Sweden. In 2015 Fortum Oyj organized a district heat demand response pilot in apartment buildings in southern Finland where the participating buildings were equipped with temperature sensors and intelligent control systems with the aim of shifting heat demand automatically from production cost –based peak hours to off-peak hours (Fortum 2015b). In a similar pilot project in 2015 by Fortum Oyj, an automated demand response system was tested in an educational building. In this pilot project, the space heating equipment's supply water temperature was lowered in times when heat production costs were high. The changes in indoor temperature and occupant satisfaction were simultaneously followed and according to the measurements, 2-4 hour demand response events resulted in only small changes in indoor temperature. (Fortum 2015c). Pilot tests by Kärkkäinen et al. (2004) on one office building and one senior day care center, both located in Finland, revealed heat load reductions of up to 20-25% during 2-3 hour DR events while experiencing less than 2°C temperature drops in indoor spaces simultaneously. Kärkkäinen et al. (2004) carried out a similar pilot test on a German office building, which resulted in only a 4,1% peak heat demand reduction and a 14% increase in total heat consumption due to deployed preheating.

Wernstedt et al. (2007) carried out pilot tests for a residential area in Sweden, where an agent-based model was implemented to optimize the heating of the entire residential area. These pilot tests revealed fluctuating 2-6% heat load reduction potential on average over the course of a single day. (Wernstedt et al. 2007; Wernstedt and Johansson 2008) Johansson et al. (2010) later deployed the same agent-based model in a proof-of-concept pilot study in three separate district heat systems in Sweden (Stockholm, Västerås and Linköping). The pilot study resulted in 7,5% savings in total energy consumption over the course of one week and peak load reductions of approximately 20%. Kensby et al. (2015) performed pilot tests in Gothenburg, Sweden in 2010 and 2011 for five residential buildings with the objective to evaluating the buildings' thermal storage potential while keeping indoor temperature changes to a minimum, and the results of the tests revealed significant storage potential with minimal indoor temperature -related consequences.

3.4 Infrastructure for demand response

A major prerequisite for larger-scale implementation of demand response activities is developing and constructing the necessary infrastructure to practice it efficiently. In essence, DR infrastructure means the ICT systems needed to control the loads at the building level and to verify the load reductions real-time (Rautiainen 2015). Several pilot projects related to both electricity and district heat demand response prove that the necessary technology already exists, however it is extremely likely that the average building today is not equipped with the necessary equipment to carry out DR properly without some kind of initial investments. Typically these investment needs would be related to adding load-specific metering, additions to the building automation system or additions to load control equipment (Kärkkäinen et al. 2004).

An essential part of demand response is the signal that evokes the DR events and informs the consumer to reduce demand. This signal is completely dependent on the type of demand response practiced and in what market it is practiced, and it can be based on some specific need, like in the reserve power markets for example, or it can be based on just energy prices. On a building or building cluster level, the signal can be dealt with in a few different ways which lead to slightly different ways of carrying out demand response during the events.

Essentially the question of how the signal is received effects how loads are controlled in the building; whether the control is manual or automated, and whether the responsibility of load control is given to the consumer or is consumer input separated from the equation during events (Kärkkäinen et al. 2004).

One way of carrying out demand response is to distribute the DR signal to consumers which manually adjust whatever loads it deems acceptable to be adjusted for the duration of the DR event. This type of demand response naturally includes uncertainties on whether the wished load reductions will materialize since the decisions for load adjustments are made by the consumer only. In this case, the supplier or market actor organizing the demand response can attempt to influence the consumer in some way to encourage him to make the decision to practice DR. Such influencing methods could be varying price levels for the commodity, such as time-of-use tariffs or dynamic pricing, some kind of penalty payment mechanisms for excessive energy use during DR events or directly limiting the available amount of commodity. (Kärkkäinen et al. 2004) Implementing this type of manual demand response does not ensure that load reductions materialize, but it does mean that the consumer has the freedom to decide which loads to adjust, which should diminish the possibility of too significant adverse effects resulting from DR for the consumer. More responsibility requires more effort from the consumer though, which could be unattractive in the long run especially if DR events occur frequently.

Another way of carrying out DR is to take advantage of a central building automation system to coordinate demand response in buildings automatically. During a DR event, the automation system would receive a DR signal and adjust loads accordingly based on some predetermined load adjustment configuration or based on some optimization algorithm which determines the loads to be adjusted real-time. Predetermined load adjustments are of course much easier to implement since it merely requires adding some kind of special case scenario to the automation system, which causes a deviation from the typical operation of building systems, e.g. the automation system uses a lower heating set point temperature in spaces during the DR event. (Kärkkäinen et al. 2004) The ideal situation would be that the automation system could calculate the optimal way to carry out demand response in the building real-time and then adjust loads accordingly. Manually overriding DR controls via the automation system would typically be possible as well, and although ideally it would not be needed, even the possibility of manually overriding any DR control could enhance the attractiveness of this type of DR implementation. Automating the DR process at the building level also relieves the consumer from actively participating in the load control process after the initial control configurations have been made.

Direct load control by the energy supplier, DR organizer or some third party is yet another way to carry out demand response. In this situation the DR signal is sent directly to the load control equipment which adjust the individual loads accordingly, e.g. a frequency converter of an air handling unit (AHU) receives a DR signal and reduces air flows during the DR event accordingly. A load-specific smart meter could be the source for demand response control to an extent as well. Currently most electricity customers in Finland are required to have dynamic electricity consumption meters according to Finnish legislation (66/2009), which are not load-specific but could potentially be used to control some loads (Rautiainen 2015). Direct load control could be a potential DR implementation strategy in buildings with no advanced building automation systems, such as most detached houses in Finland nowadays or even older apartment buildings. Direct load control measures should be properly planned to ensure that the load control's effect on occupants' comfort level is minimized (Kärkkäinen et al. 2004).

Aside from offering load control potential, load-specific smart meters have a significant role in verifying that the intended load reduction is realized accordingly during demand response. Verifying load reductions real-time is important in market places where demand response is offered as specific amount of load reduction, such as the balancing power market or the reserve power markets, to ensure that the contractual obligations are fulfilled. Likewise distributing compensatory payments for customers in e.g. district heat demand response programs with stationary energy prices would require verification of load reductions, since it would be reasonable from the DH producer's point of view to remunerate consumers individually based on the amount of load reduction achieved (Valor Partners Oy 2015).

As mentioned previously, the consumer is mostly interested in quality of service, which means that the effects of demand response controls on the occupants' comfort level should be minimal. To ensure that no unacceptable effects occur, ideally all relevant spaces should be equipped with "comfort sensors" such as indoor air temperature sensors and carbon dioxide –content (CO_2-content) sensors. These sensors could be used to verify that no unacceptable conditions occur and to possibly make adjustments to the load controls in case conditions become too poor. Such sensors could also contribute to load control in some cases, for example the CO_2-sensors would reduce the ventilation air flow until the maximum allowable limit in CO_2-content in the space is reached.

Carrying out demand response in a single building is hardly lucrative from the DR organizers point of view since the benefits from a single building's load reduction measures are extremely small. Establishing demand response programs for large building owners with large quantities of building mass, such as cities for example, would be a more beneficial approach, as implementation of necessary systems is easier and the aggregated load reductions are potentially large enough to incentivize the process for both the producer and the consumer. Another option would be to create an aggregator or a DR operator, which acts as a middleman in the DR process, distributing DR signals to the building level and offering aggregated demand response resources to various market places. An aggregator would make small individual customer's participation in demand response activities more feasible as well. (Rautiainen 2015)

3.5 Demand response strategies

In theory, any adjustable load can be used as a demand response resource on a building level since the party organizing the demand response, which in this study is the district heat producer, it does not matter how load reduction is achieved but rather just that demand decreases when needed. From the building owner's point of view, the "how" of demand response is obviously very important on the other hand, as many factors affect which loads can be viable candidates for demand response purposes. Such factors are economic ones like investment needs for required control equipment, realistic adjustable load potential, load predictability and possible effects of the load adjusting on building occupants, for instance. The goal of demand response is to decrease heat load during certain periods of time while sacrificing occupant satisfaction as little as possible in the process. Essentially this means that when heating related demand response is carried out, the change in indoor temperature is limited to e.g. one or two degrees at most (for example Kontu (2014) and Kärkkäinen et al. (2004)).

In district heated buildings heat is distributed to spaces with space heating equipment, ventilation or both. To produce heat load reduction for demand response purposes, the momentary heating power in these systems must be limited in one way or another. Electric load reduction for electricity related demand response purposes involves more load-shedding possibilities ranging from HVAC-equipment to small home appliances such as dishwashers or the like. The means to achieve the necessary load reduction during a demand response event, called demand response strategies henceforth, are typically such that are easy to implement and control, and such that produce the wanted load reduction quickly. The magnitude of the adverse effects the demand response strategy causes must be taken into account as well of course. Demand response strategies concerning heat load reduction naturally often lower the indoor temperature, however a strategy such as ventilation air flow reduction has additional effects on indoor climate conditions as well. In the end it is often these adverse effects that set a limit to the load reduction potential in any given building unless it happens to be possible to stop heating during demand response completely.

Often in current public buildings, such as offices and schools, the HVAC-systems of the building are controlled with a central building automation system (BAS). A modern BAS is used to follow and operate all HVAC-systems of the building real-time, and typically it is possible to make adjustments to the systems' operation in real-time as well either manually or with predetermined automated schedules. The building automation system has an extremely important role in enabling demand response in public buildings as well, especially if the amount of loads that are controlled during a demand response event is high. There are a few options on how the loads in a building can receive the signal to switch to an alternate state of operation during the demand response event, one of which is to have the BAS receive the signal for demand response which in turn "distributes" it to all necessary connected loads. Another possibility is to control each load directly: in other words the load receives the adjustment signal directly so that in essence the control of the load is at the hands of the signal's sender for the duration of the demand response event. (Kärkkäinen et al. 2004) The advantage of utilizing the BAS to administer the load reducing actions is that the consumer still has full control of the HVAC-systems of the building during demand response events and is able to override any action that has unacceptable adverse effects. Using the automation system adds to the complexity of the process though, which typically increases the probability of faults.

District heating involves a limited number of possibilities to practice demand response as heat demand of a district heated building typically consist of space heating and domestic hot water (DHW) heating. It is also possible to use district heat for snow melting or to prevent sloped driveways or outdoor walkways from freezing over in winter, but these applications use electric heating more typically and whether the building has such heating needs in the first place is entirely dependent on the property in question. Space heating needs in public buildings are satisfied with heated ventilation supply air, with space heating equipment such as radiators or with the combination of these two. Ventilation based heating can be based on supply air with constant temperature or the temperature can change dynamically to keep the air temperature in spaces at the set point. The remaining heating needs can be satisfied with space heating equipment such as radiators, heating panels or floor heating.

Nowadays nearly all buildings in Finland are equipped with some kind of mechanical ventilation. In buildings with mechanical supply and exhaust air ventilation featuring supply air heating, there are a few possible ventilation related demand response strategies that can be implemented to produce load reduction during a DR event. For one, the temperature of the heated supply air can be lowered during a demand response event to reduce heat load. Kärkkäinen et al. (2004), for example, used ventilation supply air temperature decrease as one demand response strategy in an office building and in a senior citizen care center. Decreasing the supply air temperature should be combined with adjusting the heating capacity of other space heating equipment in some way in buildings that feature such, as otherwise the lowered ventilation heating will be compensated by increase in the space heating equipment's heat consumption. Supply air temperature adjustment is something that can be generally done directly via the building automation system, which makes it a rather easy to implement demand response strategy and it is unlikely that large investments are needed for implementation of this strategy. The exact same method applies to cooling load reduction in cooling season with buildings and ventilation machines equipped with cooling, except that instead of lowering the supply air temperature it is allowed to increase by a certain amount (Motegi et al. 2006). Ventilation supply air temperature set point change is a strategy that affects all spaces served by the AHU in question, which can be problematic if these spaces are very different in terms of internal heat gains, occupancy and such.

Another ventilation-related possibility to produce load reduction for demand response purposes is to reduce the ventilation supply and/or exhaust air flows during the DR event. The nominal air flows in a mechanical ventilation system are designed to maintain good indoor air quality at all times. Decreasing air flows by adjusting the ventilation fans' power affects both electricity and heat consumption of the air handling unit, since a lower air flow rate lowers the fans' electricity consumption and reduces the amount of heat consumed by the heating coil of the AHU. Air flow reduction naturally affects indoor temperature but it also has an effect on other indoor air quality parameters, one of which is the carbon dioxide (CO_2) content in the space. The National Building Code of Finland (NBCF) as well as the Indoor climate guidelines include maximum allowable CO_2-content limits and in normal operation the content is typically well below these limits (NBCF D2/2012; LVI 05-10440 en 2010). When air flow is reduced though, the CO_2-content will begin to increase and with a large enough reduction for a long enough time, the accumulated CO_2-content begins to cause occupant discomfort. Air flow reduction in summer can be used to reduce the building's cooling load as well. Ventilation air flow reduction is likewise a global demand response strategy affecting all spaces served by the AHU.

As mentioned, ventilation air flow reduction can be easily implemented by adjusting the power of the supply and exhaust air fans with a frequency converter for example, or in extreme cases by simply shutting down the fan completely. The initial investment needs for new frequency converters can make this demand response strategy less enticing depending on the situation though. Ventilation air flow reduction is an often studied demand response strategy, although usually studies have aimed to reduce the cooling load in a building and the DR events take place in summer season. Demand response studies including ventilation air flow reduction include Motegi et al. (2006), Christantoni et al. (2016) and Aduda et al. (2016) for example, all investigating its effects and potential in cooling season.

Aside from ventilation, space heating and cooling equipment can be naturally used for demand response purposes as well. A simple method of lowering the heat or cold demand of a building is changing the zone heating set point during the DR event. The zone heating set point is the minimum air temperature of the space that the space heating equipment aims to maintain, thus lowering this set point for the duration of the demand response event in a heating season directly lowers the heating power demand of said equipment. Cooling power of space cooling equipment can be adjusted in a similar manner by increasing the zone cooling set point during a summertime demand response event. This demand response strategy is one that could be possibly carried out via the building automation system or directly controlling space-wise thermostats. Global temperature set point adjustment was another demand response strategy studied by Motegi et al. (2006) and also by Christantoni et al. (2016), both who investigated increasing the cooling set point temperature during a summer demand response event.

There are also a few other possibilities to limit the heat distributed to spaces from the heat distribution center of the building. One such way is to limit the heat distribution capacity of the entire heat distribution plant during a DR event. Heat demand of the heat distribution center is related to the mass flow and temperature increase of the water in the heat exchanger connecting the district heat distribution network and the building's heat distribution network. Limiting the mass flow of hot water through the heat exchanger while maintaining the same outlet temperature lowers the heat demand, as does lowering the outlet temperature while keeping the mass flow same. During a summer season DR event, the same strategies can be applied for the building's chiller or district cooling heat exchanger to limit the cooling consumption. Motegi et al. (2006) for example had chiller water flow limiting as one of the demand response strategies they investigated, and Christantoni et al. (2016) raised the chilled water temperature during a DR event as one of the demand response strategies they investigated. Kärkkäinen et al. (2004) on the other hand used lower supply water temperature in radiator heating network to produce district heat load reduction for demand response purposes. Lowering the supply water temperature at the heat distribution network has naturally the same effect in all space heating appliances connected to the heat distribution circuit.

Outside space heating and ventilation heating, the third major heat load in buildings is domestic hot water heating. Possibilities to utilize the domestic hot water system of a district heated building for demand response purposes are very limited though, due to restrictions specified in the national building code and due to the variable nature of the heat load. The regulations regarding water supply and sewerage equipment of properties state that the hot water distribution network in a building should be designed in such a way that the domestic hot water temperature in the network does not drop below 55°C in order to minimize the possibility of Legionella contamination (NBCF D1/2007; CEN/TR 16355:2012). Commonly hot water temperature in the DHW network is slightly above this minimum limit, thus leaving little room for load reduction.

Buildings with hot water storage possibilities, whether for water used in space heating circuits or domestic hot water, would be ideal for demand response since storage enables easy shifting of heat load. Hot water tanks are more common in small residential buildings with electric heating though, rather than in the type of buildings investigated in this study. Buildings featuring hot water tanks have been identified as having major demand response potential though (Järventausta et al. 2015; Evens et al. 2010) and should such system exist in district heated buildings, they would definitely create additional DR potential. Heat storage in building mass is also something that has been investigated recently, and it is a demand response strategy well suitable for district heated buildings as well. In essence, using the building mass as thermal storage means heating or cooling the building prior to the demand response event, allowing a load reduction during the event. Salo (2016) for example studied thermal storage potential of buildings for demand response by shifting the district heat load from peak hours to more preferable times from the system's point of view. An interesting study by Qureshi et al. (2011) investigated thermal storage potential of buildings using advanced building materials for peak heating reduction purposes in New Zealand.

Lighting power reduction during demand response events is another demand response strategy appearing in some studies. It has a direct effect only on the electricity demand of the building though, so this strategy is not something a heat producer would be interested in. Lighting also generates heat in spaces, so lighting power reduction does actually have an indirect effect on either heat or cold demand depending on season. When lighting power is reduced, the internal heat gain decreases and heat demand during heating season actually increases by a small amount which depends on the magnitude of lighting power reduction. In the cooling season, lighting power reduction naturally decreases the cooling demand on the other hand, as less heat needs to be removed from spaces. Motegi et al. (2006), for example, introduced several different lighting related demand response strategies such as light dimming or partial shut-off of light fixtures.

Using lighting as a demand response resource can be a bit problematic though, since the load reduction potential in reality is very dependent on the type of spaces and the type of lighting systems in the building. Time schedules of lighting in office and school buildings are fairly predictable and have little variation between weekdays but on the other hand sufficient level of lighting is required in office and school work which limits the load reduction potential. Lighting in residential buildings can be divided between lighting in apartments and lighting in general spaces such as hallways, and both have an unpredictability factor that diminishes the potential of this strategy. Certain energy efficiency measures greatly lessen the load reduction potential as well, such as lighting controlled by motion sensors, timed on/off switches or daylight sensors, all of which are common features even in older buildings these days.

There are many more electric appliances in residential buildings which could potentially be utilized as demand response resources, however most are appliances owned and operated by residents rather than the building owner. Dishwashers, washing machines and saunas are electric loads which can be potentially shifted from peak price hours to a more favorable time, as identified by Evens et al. (2010) and Järventausta et al. (2015), for example. A Belgian pilot study also discovered notable electric load reduction potential when shifting the time of use of residential wet appliances (D'hulst et al. 2015). The aforementioned home appliances are less prominently featured in public buildings though, and as such they are not considered in this study.

Various outdoor heating applications to prevent sloped driveways and drainpipes from freezing over in winter or to prevent snow accumulation in pedestrian walkways in the property are not uncommon features in public building these days. More typically the necessary heat in these applications is created with electricity, but it is also possible to use district heat in some cases, in which case these additional heat consumers would be potential sources of district heat load reduction during wintertime demand response events. The operation of freeze prevention heating equipment is typically easy to predict too, since usually they are automatically turned on when outdoor air temperature is in certain temperature range, for example between -3°C and +3°C. Järventausta et al. (2015), for instance, identified that electric drainpipe and roof drain heating have small load reduction potential in offices, school buildings and commercial buildings in Finland.

Car preheating in winter is also extremely common in Finland and has considerable electric load reduction potential as a result according to Järventausta et al. (2015). The typical use of car preheating in the morning also corresponds rather well with the peak electric consumption hours in the winter, and switching off or shifting car preheating to an earlier time merely affects the comfort level in the car for the most part. Outdoor lighting in properties could also be used as a demand response resource, as it is another load with distinct time schedules. The amount of outdoor lighting in a single property is dependent on the size and type of the property though, and it can be very low if the property features little outdoor spaces. City-owned general outdoor lighting such as street lights could enable much more significant electric load reductions though, compared to outdoor lighting of individual buildings (Järventausta et al. 2015).

Electric vehicles (EVs) are becoming more common in urban environments and their number is only expected to grow in the future. An electric vehicle can act as a mobile electricity storage which can ideally be charged according to electricity price signals, and perhaps even discharged to replace some electricity purchase from the grid during a demand response event. The lack of uniform charging infrastructure for larger electric vehicle penetration is already a challenge though, not to mention that using EVs as electric storage during demand response events likely requires additional installations to typical charging systems. It has also been a concern that constant charging and discharging of electric vehicles would shorten the lifespan of the batteries significantly. The lifetime of an EV battery can be estimated as 25 years while the lifetime of the vehicle in itself is significantly less than that, so the degradation of the battery resulting from its use as demand response resource has very minor consequences if any. (Rautiainen 2015)

3.6 Demand response strategies used in the empirical study

The demand response strategies chosen for further investigation in this study are briefly presented in this chapter. The main focus is district heating demand response, thus the majority of the strategies are heating related. The chosen strategies are then modeled into the building energy simulation models, or rather the controls that enable the load reduction of these strategies, and finally the controls of these strategies are inserted as variables into the optimization problem. As investment needs are not considered in this study, it is required that the strategies in the optimization have something else in common so that the optimization would work as intended. The common denominator for the strategies in this case is that they all have some effect on indoor climate conditions. Allowing only a limited change in indoor climate conditions during a demand response event means that strategies with less effect on indoor conditions and more economic or load reduction potential will be presumably preferred.

The first building type to be investigated is an office building fitted with mechanical supply and exhaust air ventilation, space heating and space cooling. Ventilation related strategies chosen for this building type are supply air temperature adjustment and ventilation air flow reduction. Indoor air temperature set point can be also adjusted during a demand response event as one demand response strategy. Two strategies related to the heat distribution center are also included: reducing the power of the entire plant or lowering the heating supply water temperature in the space heating and ventilation heating circuits. The office building is a special case in this thesis in that it is the only building featuring cooling and considering that the same or very similar strategies can be applied for both heating and cooling load reduction, a summer demand response event case is also investigated although no heat load reduction during this event is expected. Thus both space temperature set point and ventilation supply air set point can be adjusted either downwards (relevant in heating season) or upwards (relevant in cooling season). Additionally in the summer day demand response case it is possible to limit the chiller's power similarly as it is possible to limit the plant's power in heating season cases. A small lighting power reduction is also considered as a demand response strategy in the office building although no heat load reductions due to this strategy are expected. The reason to include this strategy, even though it does not result in any heat load reductions, is to briefly investigate its potential as lighting is a feature in all buildings and thus a potentially suitable strategy for any building type

Another type of building to be investigated is a typical apartment building. The demand response strategies chosen to be investigated in the apartment building's DR cases are similar to those for the office building, but due to less complex HVAC-systems slightly fewer possibilities exist. The strategies chosen for the apartment building are ventilation air flow reduction, space heating temperature set point adjustment, plant power reduction and heating supply water temperature set point adjustment. It is assumed that the ventilation system in the apartment building does not feature supply air side at all and thus no heating of supply air either. Lighting power reduction is assumed unfeasible in an apartment building due to lighting in apartments being the residents' responsibility.

Last building type to be studied is a typical Finnish school building with a variety of different types of spaces. The exact same demand response strategies are investigated for the school building as are for the office building, with the exception of cooling related strategies since it is assumed that the school building is not fitted with comfort cooling As aforementioned, the school building features more variety than the office building though, which means that the controls of these demand response strategies are divided somewhat so that for example classrooms' ventilation and general spaces' ventilation can be controlled individually. Essentially this means that each space type has its own variable to be optimized for certain demand response strategies.

4 Empirical study

The empirical part of this study concentrates on investigating demand response and its effects in more detail in a few different types of buildings. The methodology of this part consists of first constructing building energy simulation models for three separate building types in the simulation software IDA ICE. The models include proper control mechanisms for a variety of different methods to produce a desirable effect for demand response purposes. All buildings use hourly Elspot market prices for all their electricity consumption, including cooling, and either seasonal pricing of district heat or alternative hourly prices directly based on marginal costs of heat production. The alternative pricing mechanism of district heating is discussed in more detail in Chapter 4.3. Lastly, an optimization software MOBO is used to determine an optimal combination of different demand response methods for each building type for a few different kind of example days in winter, spring and summer. The focus will be on minimizing district heat consumption and heating costs during the demand response events in winter and spring example days. In summertime district heat consumption is marginal and mainly used for domestic hot water heating only, so in the summer example day electricity consumption is minimized instead. The main focus of the optimizations is in district heat load reductions, however as same demand response methods can affect both district heat and electricity consumption, the reductions in electric power are not ignored either. Although the district heat production company has no interest in the electric power reductions that occur, it is interesting from the consumer's point of view as reducing consumption directly creates additional savings.

4.1 Building energy modeling of case buildings

The first task was to construct the building energy simulation models for typical buildings owned by the city of Espoo. Building types chosen for the study were an office building, a school building and an apartment building. These three types are chosen to investigate whether optimal demand response methods differ in different types of buildings, and also because the city of Espoo owns a considerable building stock of each type. A permission to access a property register database for the purposes of this study was given by Espoo officials and according to the database, the city owns approximately 540 000 m^2 school buildings and 150 000 m^2 office buildings. Apartment buildings are not included in the database but the 2015 annual report by Espoon Asunnot Oy, the organization owned by Espoo city and which manages the residential building stock of Espoo, states that there are approximately 886 000 m^2 city-owned rental apartments in Espoo (Espoon Asunnot Oy 2016).

Each building is more or less a unique entity and many small details affect the energy use of the building. The building simulation models were constructed to depict a simplified average building of each type, and for the sake of simplicity the models use standardized values based on Finnish national building regulations and guidelines for most energy use -affecting parameters, like time schedules, heat loads and heat transfer coefficients (U-values) of building structures. There are some exceptions to this rule due to more accurate information being available or based on empirical evidence on typical Finnish building stock, and these exception are explained later in this chapter in detail. Brief discussion of relevant parameters used in simulations is included in this chapter, while Appendix I contains detailed information regarding values used for the relevant parameters for each building type in tabular form.

The building energy simulation models are constructed in a software called IDA ICE, which is a commercial indoor climate and energy simulation tool capable of dynamic multi-zone simulations. The tool permits very detailed building and system control modeling, the latter being especially necessary to investigate realistic demand response potential and its effects on indoor climate conditions. The buildings are not actually modeled in their entirety, for the larger the model is and the more zones it has, the longer the optimization in the next step of the study would take. For office and apartment buildings, the simulation model consists of a single 1000 m^2 floor mid-building, i.e. both the roof and the floor are assumed to be connected to other floors with similar indoor temperatures and thus no heat losses through the floor or through the ceiling occur. The school building model has the same floor area as the office and apartment buildings but it is considered a single-floor building, which means that heat losses through the floor and through the roof are taken into account.

The reason for opting to use such simple simulation models merely constituting of a single floor is that a more complex model with several floors, and many more individual spaces as a result, would multiply the required optimization time for a single case. Time and resource constraints taken into account it was decided that simpler models would be sufficient and as the models are heavily based on standardized values and generalizations, it would not really offer any additional insight on the demand response potential of these buildings even if more complex models were used. The decision to model a floor in the middle of a building for the office and apartment buildings is based on the observation that offices and apartment buildings in Espoo are mostly multi-storied buildings and thus heat losses through the ceiling and through the floor are more often than not negligible. Statistics extracted from Aluesarjat database, which is an open databank for building stock information for the Helsinki region, support this assumption in regards to apartment buildings, as the statistics can be divided based on the number of building floors and they show that buildings with four or more floors constitute more than half of the total apartment building floor area in Espoo. As for schools, buildings with only a few floors are much more common so the modeled school building includes both a floor connected to ground and a roof connected to ambient air.

The aforementioned property register database includes the year of construction for most buildings, and from this a weighted average year of construction for the building stock was calculated for each building type separately. The weighting was based on floor area only and the weighted average was calculated as follows:

$$T_{wa} = \frac{A_1 * T_1 + A_2 * T_2 + \cdots + A_n * T_n}{A_1 + A_2 + \cdots + A_n} \tag{1}$$

In formula (1), T_{wa} is the weighted average year of construction, $A_1 \ldots A_n$ are the floor areas of each building and $T_1 \ldots T_n$ are the corresponding buildings' construction years. The resulting weighted average for office buildings is 1983 and for school buildings it is 1981. For the city-owned apartment buildings, a similar weighted average could not be calculated, for information about each building's year of construction was not available. However, from the statistics database Aluesarjat it can be calculated that the average apartment building in Espoo was constructed between 1980 and 1989. Figure 3 depicts the share of apartment building floor area for certain ranges of years, according to information extracted from the Aluesarjat database, and the weighted average construction year is calculated with Equation 1 according to these shares. This database includes all apartment buildings in Espoo though, not just the ones owned by the city itself, but for lack of a better estimate, this range for the average year of construction was used for strictly city-owned apartment buildings as well.

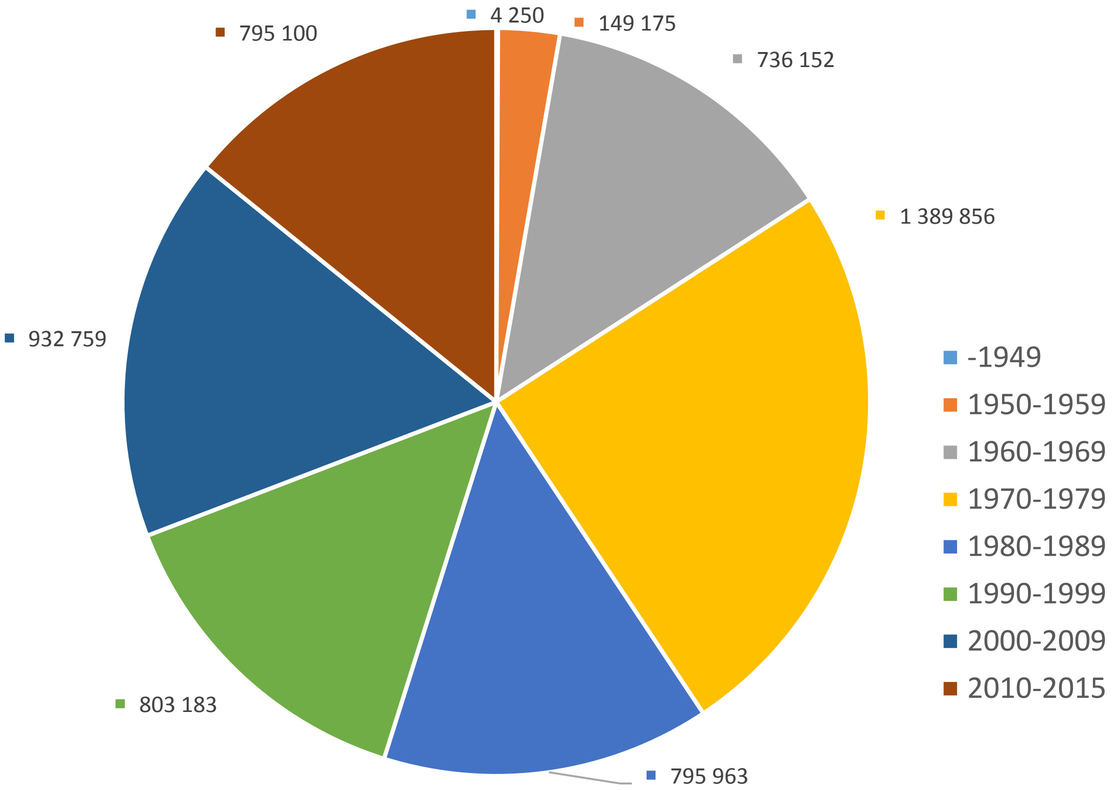

Figure 3. Building construction year ranges for all apartment buildings in Espoo based on built floor area in m^2.

It is important to note that any possible past renovations to these buildings are ignored when calculating the weighted average age of the building types. The property register does contain building specific information about the renovation year if such has been carried out, however no information of the extent of the renovation is included; i.e. it is not known whether the entire building body and its subsystems were renovated or if the renovation included a part of the building only. Hence it can be considered safer to ignore any possible renovations and consider all building structures original. In general, the average life expectancy of a ventilation machine is 25-30 years which means that in average the ventilation equipment in the simulated buildings would have been already renewed at least once in all building types and furthermore, the controllability of old ventilation systems for demand response purposes is questionable. Not to mention that installing DR-related control equipment to a ventilation system that is near the end of its lifetime is economically unreasonable. Thus, it is assumed that the ventilation systems included in the simulation models are according to energy efficiency standards of the early 2000's, i.e. the air handling units feature standard level heat recovery and reasonable fan efficiencies.

The year of construction affects certain parameters that are chosen for the simulation models, namely the heat transfer coefficients (U-values) for different structures of the building envelope, the rate of air leakage through the building envelope and the characteristics of the ventilation system. The U-value [W/m^2K] of a building structure, like an external wall or roof, represents the magnitude of heat transfer through one square meter of the structure over a one Kelvin temperature difference. Heat transfer coefficients are highly dependent on thickness of the insulation layer of the structure, and the maximum allowed U-values in new construction by the Finnish national building code have decreased over the years, as indicated by i.e. 176/2013 Liite 1 (2013).

While heat transmission through the building envelope constitutes a large part of the building's heat losses during heating season, additional heat losses also result from air leakage through the building envelope, thermal bridges, ventilation exhaust air and waste water (Vihola et al. 2015). In modern ventilation systems, heat losses are minimized with efficient heat recovery from exhaust air and the recovered heat is used to heat supply air. Requirements for heat recovery from exhaust air were introduced in the Finnish national building code not until 2003 though, so heat recovery installations are somewhat rarer in older buildings. Heat recovery from waste water is still an emerging technology and currently no requirements for any waste water heat recovery exist. Air leakage factor or air tightness represents the amount of uncontrolled air flow through the building envelope caused by pressure differences between the building interior spaces and the ambient air outside. Requirements for minimum level of air tightness in buildings were introduced in the Finnish building code in the 70's, and the required level has been lowered slightly first in 2003 and again in 2012, when the requirement metric changed from n50-value to q50-value. The main difference between the two metrics is that the former is derived from building volume while the latter derives from building envelope area. Development of the Finnish building regulations regarding U-values of different building structures, air tightness and ventilation system are shown in Table 3. For each building type modeled in this study, U-values and air tightness were chosen from Table 3 corresponding the calculated average construction year of the building type. Hence, the building regulations from 1978 were used for offices and schools while regulations from 1985 were used for apartment buildings.

Table 3. Development of the Finnish national building regulations (NBCF 176/2013).

Parameter	**National building code year of passage**								
	-1962	1969-	1976-	1978-	1985-	10/2003-	2008-	2010-	2012-
Wall U (W/m^{2}K)	0,81	0,81	0,7	0,35	0,28	0,25	0,24	0,17	0,17
Roof U (W/m^{2}K)	0,47	0,47	0,35	0,29	0,22	0,16	0,15	0,09	0,09
Floor against ground U (W/m^{2}K)	0,47	0,47	0,4	0,4	0,36	0,25	0,24	0,16	0,16
Window U (W/m^{2}K)	2,8	2,8	2,1	2,1	2,1	1,4	1,4	1.0	1.0
Door U (W/m^{2}K)	2,2	2,2	1,4	1,4	1,4	1,4	1,4	1.0	1.0
Air tightness n50	-	-	6.0	6.0	6.0	4.0	4.0	4.0	4.0
Ventilation heat recovery efficiency	0 %	0 %	0 %	0 %	0 %	30 %	30 %	45 %	45 %
SFP-number	-	-	-	-	-	2,5	2,5	2,5	2.0

Thermal bridges are "weak spots" in the insulation of the building envelope: junctions between exterior walls and exterior roofs or floors, junctions between windows or doors and walls, and corners in exterior walls. The national building code features guidelines for thermal conductance coefficients for thermal bridges, which can be used if design values are not available, and which are used as input data in the simulations in this study. Heat losses via thermal bridges are relatively small compared to the other heat loss factors at any rate so no inaccuracies of significance will occur by not using more accurate values.

District heating is assumed as the sole heat source for all buildings, satisfying all heating needs the buildings have, including both domestic hot water heating and space heating. Each building has a heat distribution center with realistic maximum heating power capacity, which is connected to district heat supply with a heat exchanger. Heated water is circulated from the heat distribution center with pumps to the ventilation machine and to space heating equipment. Additionally, the office building is assumed to feature a chiller which provides ventilation and space cooling for the building. The apartment building and the school building do not have any cooling equipment installed, on the other hand. All space heating equipment as well as the maximum capacity of the heat distribution center are designed to endure a temperature of -26°C, which is the applied design temperature in southern Finland according to the Finnish building code (NBCF D3/2012). The maximum capacity of the space cooling equipment in the office building is determined in a similar vein corresponding to the cooling need of the building on a very warm summer day.

Heat distribution system losses are likewise based on standard values from the nation building regulations. It is assumed that domestic hot water circuits in all buildings have a modest level of insulation in accordance with the related regulations, and that 50% of the heat losses from the circuit contribute to heating spaces in the buildings; i.e. only 50% of the circuit's heat losses are actual heat losses at building level. Space heating losses are assumed as 10% of heat delivered by the heat distribution plant in the building, and likewise 10% of cold delivered by chillers is lost if the building is equipped with space cooling. Pumps in heat and cold distribution systems and in the domestic hot water system are modeled as additional constant electricity consumption in accordance with the national building code.

One deviation from the standard values is the profile of domestic hot water (DHW) use in the buildings. The national building code defines the standard amount of domestic hot water use for several different types of buildings, including the ones chose in this study, but profiles for DHW use are not specified at all. Instead of using a flat profile for the DHW consumption, profiles based on measured hourly DHW consumption data from Norwegian offices, educational buildings and apartment buildings are used (Ulseth et al. 2014). The profiles for the three building types are shown in Figure 4. Norway is culturally and geographically close to Finland so using these profiles without adjustments should be reasonable. Although the power demand of DHW heating is generally much smaller than that of space heating, these more detailed profiles do contribute to creating realistic power demand profiles for the buildings' total district heating consumption.

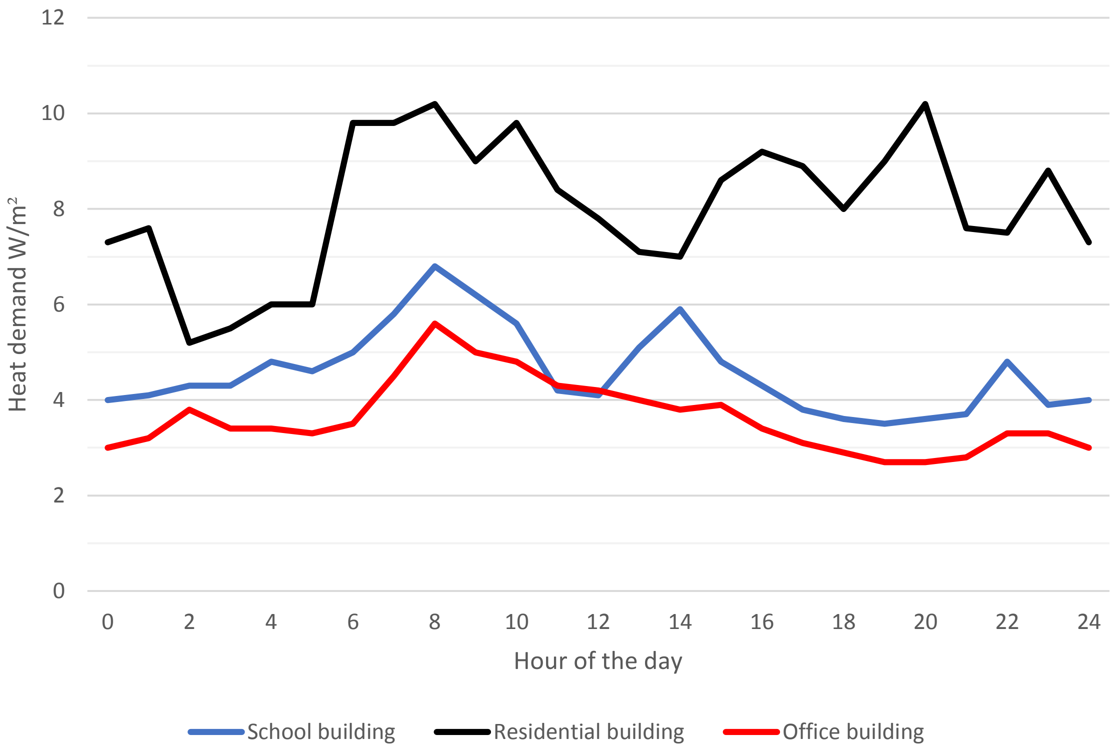

Figure 4. Domestic hot water heat demand on weekdays for schools, offices and residential buildings (Ulseth et al. 2014).

Weather data used in all simulations is actual historical weather data for Helsinki from the year 2014. As Helsinki is a neighboring city of Espoo, using Helsinki's weather data is sufficiently accurate. Similarly, electricity prices used for all building and user equipment electricity consumption are realized 2014 Elspot market prices for Finland. It is not known what type of electricity contracts the city has in reality, and it is possible that they have contracts based on more fixed price levels instead of contracts directly based on Elspot market prices. Contracts with dynamic prices are freely available in Finland for any type of customer though, and such contracts can enable larger possible savings when practicing demand response, especially if the signal for demand response is based on these market prices (Katz et al. 2016).

4.1.1 Office building simulation model characteristics

As mentioned previously, the simulation model for the office building is a single 1000 m^2 floor in the middle of a hypothetical building. The modeled floor contains a number of smaller office rooms and a few larger and more open office areas. Other than size, there are no other significant differences between the smaller and larger office areas. Figure 5 shows a view from outside the building and the layout of the floor can be seen in figure 5 as well, based on the dark lines on the ceiling. All spaces on the modeled floor are served by the same air handling unit. This AHU provides a standard constant supply and exhaust air rates when operating in its normal state. The AHU is equipped with a heat recovery from exhaust air and hydronic heating and cooling coils. The supply air temperature after the heating and cooling coils is a constant 17°C, after which it increases one more degree in the supply air fan so that supply air to spaces is actually at 18°C in normal operation. The heat recovery of the AHU is assumed to operate at 45% yearly efficiency and the specific fan power of the

AHU is assumed as 2,5 kW/(m^3/s). Specific fan power of an AHU represents the efficiency of the supply and exhaust air fans; essentially it is the sum of the electric power of the supply and exhaust air fans divided by larger of the supply or exhaust air flows in cubic meters per second. Heat recovery efficiency of the AHU as well as the specific fan power are typical values for slightly older ventilation equipment.

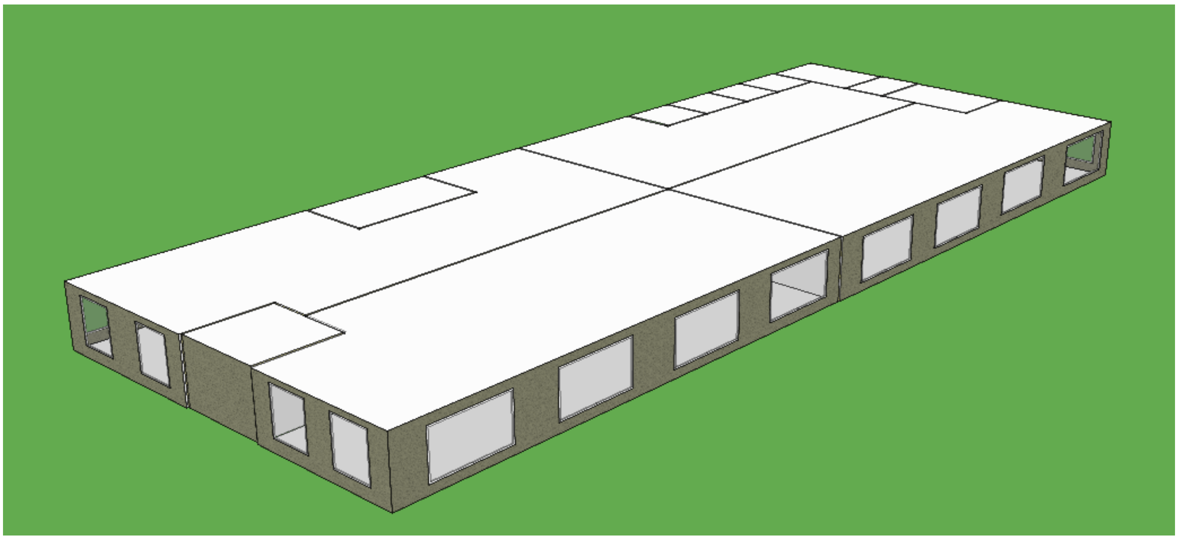

Figure 5. View from outside the modeled office building floor.

Space temperature set points in the building are 21°C for heating and 25°C for cooling under normal operation, which are also the standard temperature set points according to the Finnish national building regulations. Space heating and cooling are provided with ceiling panels in each space with realistic design heating and cooling capacities. Windows in the office building are assumed to be triple pane windows with a U-value of 1.4 W/m^2K and a g-value of 0.55. The g-value, or the solar heat gain coefficient, of a window represents the fraction of solar radiation that passes through the window. The g-value is an important factor as heat gains from solar radiation have a significant effect on the maximum cooling power needs in summertime, especially in spaces with southward-facing windows. All windows in the office building are assumed to be equipped with venetian blinds between the outer two window panes which are controlled according to the sun's movements (a default control method in IDA ICE), which in turn also reduces cooling demand in summer. The blinds are set to be drawn when solar radiation level on the inside surface of the window is above 100 W/m^2.

The office building model, as do the other two models as well, includes several custom controls constructed to adjust heat and electric loads during the simulated demand response events. These custom demand response controls were made from scratch by the author of the thesis, with the help of a fellow thesis worker Waltteri Salmi, utilizing the versatile customization tools that the simulation software provides. Plant power reduction during DR events is accomplished by limiting the amount of heat that can be supplied to zones with a control that can limit the building's heat distribution center's pumping power. Additionally, the space heating equipment's supply water temperature can be changed with another custom control, which is able to adjust the standard set point during demand response. The modeled AHU includes control mechanisms which can change the standard supply air temperature set point after the heating and cooling coils of the AHU. Ventilation air flow reduction control mechanism simply lowers the supply and exhaust air rates during a DR event to some percentage of the nominal air flow rates. Zone heating and cooling set point changes are performed in the space heating and cooling equipment controls which affect the entire building at the same time. More detailed information regarding the input data of the building energy model can be found in Appendix I.

4.1.2 Apartment building simulation model characteristics

The building energy simulation model for the apartment building is a single 1000 m^2 floor in the middle of a hypothetical apartment building, similarly to the model of the office building. The modeled floor consists of several apartments of different size and a hallway/stairwell connecting the apartments. The sizes of the apartments vary between 35 m^2 and 90 m^2, and they are modeled as single zones, i.e. the apartments themselves consist of a single room instead of several smaller spaces. The hallway/stairwell area connecting the apartments is approximately 100 m^2. View from outside the modeled building floor as well as the layout of the floor can be seen in Figure 6. Each apartment has two or more triple pane windows with sun-controlled venetian blinds between the outer two window panes, exactly as in the office building. The large window in the hallway, which can be seen in Figure 6 as well, does not have a venetian blind but is otherwise similar to windows in the apartments.

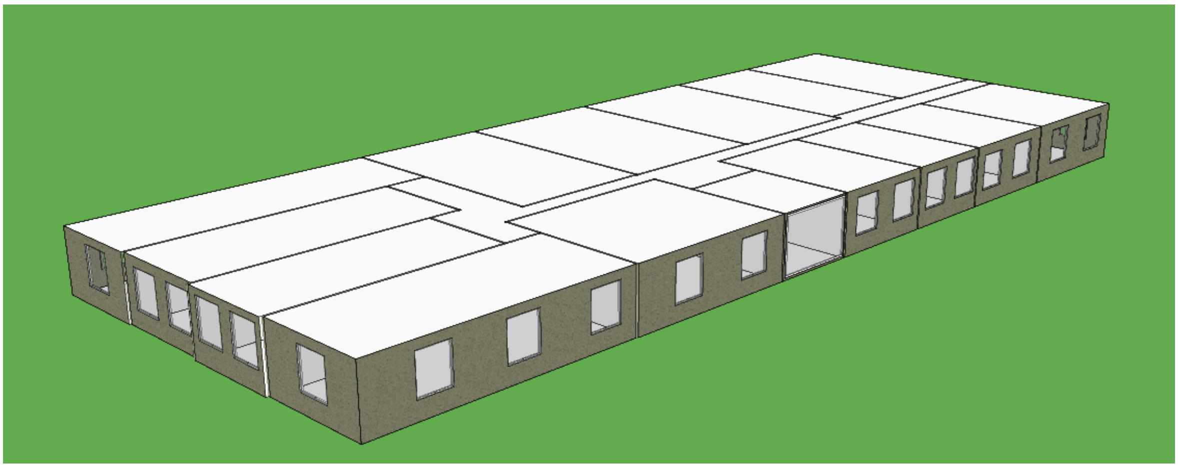

Figure 6. View from outside the modeled apartment building floor.

It is assumed that each apartment is equipped with a small exhaust air unit providing a steady 0,5 (l/s)/m^2 exhaust air flow 24 hours a day, in accordance with the national building code (NBCF D2/2012). Although in reality exhaust air units in an apartment building, if such are installed in the first place, are often separate for each apartment, they are modeled here as a single ventilation machine to simplify the optimization process of demand response methods related to ventilation in the building. This simplification limits the maximum potential of any demand response method related to ventilation somewhat, as the absolute optimal parameter values may not be exactly the same for every apartment. Generally the corner spaces of a building and spaces with several windows are critical in that operative temperatures are lowest in these spaces under normal operation conditions, and thus such spaces act are limiting in regards to global demand response related controls (Kontu 2014). Modeling and optimizing the parameters for each apartment individually would burden the optimization process significantly and the results would likely be similar in any case, as the optimal parameters would not differ much between apartments. Another exhaust air unit extracts air from the stairwell area an exhaust air flow rate in accordance with NBCF D2/2012, which states that the design air flow in a stairwell area of an apartment building should equal to air change rate of 0,5 1/h. This exhaust air unit serving the general spaces of the building can be controlled separately from the apartments' unit. Both AHU's have a SFP-value of 1,0 kW/(m^3/s).

Temperature set point for heating in apartment spaces is 21°C and for heating in the stairwell it is 17°C, both of which are in accordance with NBCF D2/2012. It is assumed that the building is not equipped with space cooling and thus no maximum temperature set point exists. Heat is delivered to all spaces with thermostat-controlled radiators with hot water circulation, which keep the air temperature in spaces above the minimum set point. Once again, the control of these thermostats is simplified so that same controls during demand response events apply to all spaces simultaneously, i.e. the adjustment is global while the absolute optimal would likely include some small differences between apartments. The model does not take into account uncontrolled air transfer via opened doors or windows, which are certainly not uncommon in residential buildings. Such natural ventilation is unpredictable and dependent on the occupants only, and while it directly affects indoor temperature and air quality, it is ignored because of said unpredictability.

Heat loads in the building and their time schedules are set according to the national building code, with the exception of heat load from occupants in the stairwell area, which is set to zero as realistically the stairwell area in an apartment building is not a space that is constantly occupied. Lighting in the stairwell area is constant and in accordance with the national building code, although in reality lighting in general spaces of residential buildings these days is often either fully automated or has an automatic shut-off.

The apartment building model has similar custom control mechanisms as the office building for adjusting loads during demand response events. Plant power reduction and heating supply water temperature set point adjustment controls are identical to those in the office building. Exhaust air flow rates can be adjusted for the two exhaust air units separately and space heating temperature set point adjustment control concerns apartments only. Examples of these controls as well as more detailed information regarding input data used in modeling of the building can be found in Appendix I.

Generally speaking, modeling and optimizing an apartment building as realistically as possible is magnitudes more difficult than modeling an office building since in a residential building many things can be controlled by the occupant, and thus the conditions in spaces are likely to differ somewhat from the standard conditions which are assumed in this study. Some of the occupant's actions, such as adjusting the room temperature in the apartment with a thermostat or opening a window, can directly affect the demand response potential in these spaces, but such actions and controls cannot be reliably modeled in any capacity.

4.1.3 School building simulation model characteristics

The simulation model for the school building is also very similar to the models of the office and apartment buildings. The total floor area of the school building is 1000 m^2 and the building is divided into several different types of zones, all of which can be typically found in an ordinary Finnish school building. Unlike in the office building and apartment building models, there is distinct variation between some zones when it comes to internal gains, occupancy schedules and such. The building features several different-sized classrooms, a large general hallway area, a dining hall connected to the hallway area, a kitchen and some bathroom spaces, all of which are modeled in accordance with the regulations for a school building. These spaces constitute approximately 75% of the total area of the building. In addition to these, there is a small office area for the school staff, which is modeled in accordance with the regulations for an office building. There is also an approximately 100 m^2 sports hall type area which is, in turn, modeled according to regulations for a sports hall. The gym area and the dining hall are modeled with a room height of 6 meters, while all other spaces have room height of 3 meters. All windows in the model are triple-pane windows and the ones in classrooms and office spaces have venetian blinds between the outer two window panes. A view from outside the building is presented in Figure 7.

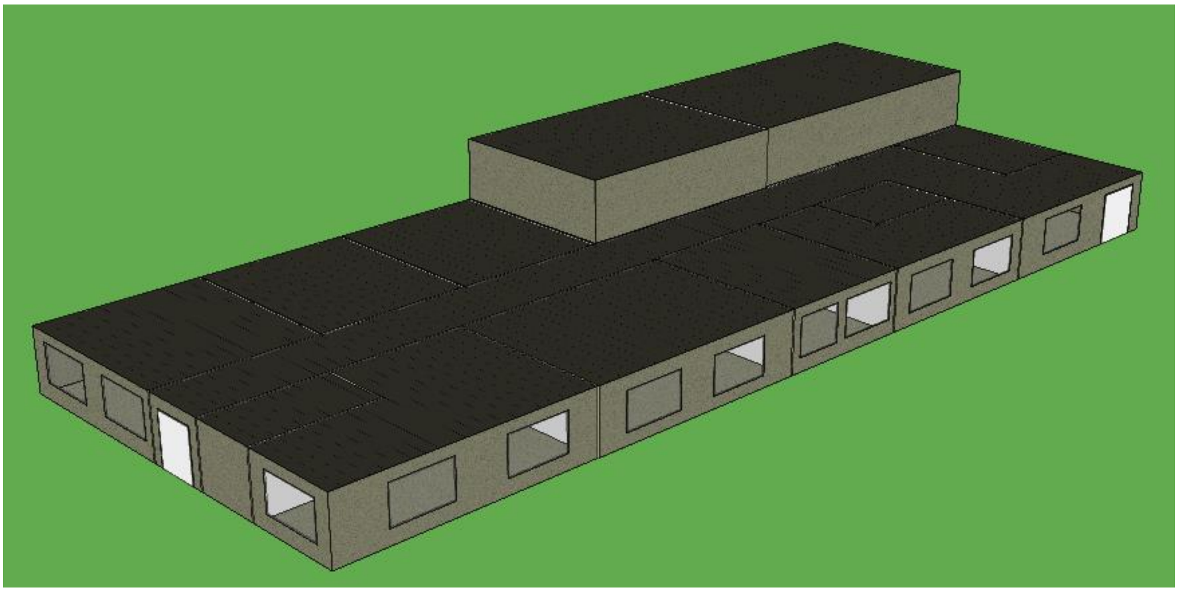

Figure 7. View from outside the modeled school building.

Since there are several different types of spaces in the building with space type -specific characteristics, it is appropriate to divide ventilation into several separate ventilation units as well. Three separate AHUs are included in the model in total; one for the classrooms and the office, one for the sports hall area and one that serves the rest of the building, including the general hallway, the dining area and the bathrooms. The bathrooms are kept separate from other general spaces in regards to ventilation air flow controls though, so that air flows in the bathrooms cannot be reduced for demand response purposes. The basis of modeling the different types of spaces in the school building is that each type is modeled according to national building regulations related to said type, i.e. the office area uses heat loads and time schedules of an office building, the gym uses values of a sports hall building and the rest of the school uses values of a school building. This principle is extended to the AHU serving the gym area, which uses the standard ventilation time schedule of a sports hall building. A single AHU provides ventilation for the classrooms and the office area, so the ventilation schedule is that of a school building. The office area is so small that a separate AHU would be unrealistic and needlessly complicate the model further. All three AHUs are equipped with supply air heating, and the supply air temperature is assumed to be minimum 18°C constantly in school and office spaces. The supply air temperature is minimum 17°C in the gym area since heating set point in the gym is also slightly lower according to the national building code. During heating season, the heating coils in the AHU's ensure that supply air is at this temperature but since the building has no cooling, supply air temperature exceeds 18°C when outside air temperature is higher than 17°C (a 1°C temperature increase is assumed in the supply air fan). All three AHUs can be controlled independently for demand response purposes.

Heat is delivered to zones with thermostat-controlled radiators with hot water circulation in the same manner as in the apartment building. Heating set point in the school and office spaces is 21°C, while heating set point in the gym area is 18°C. The building is not equipped with cooling and thus the maximum room temperature set point is not relevant. Every space in the school building model has a floor connected to ground and roof connected to outside air, which means that the relative heat loss rate of the building is larger than in the office and apartment buildings where ceilings and floors are assumed to be connected to other building floors.

The modeled school building also features similar demand response enabling control systems as the two previously introduced buildings. The building's heat distribution center has a control to reduce supply water flow in the heat distribution circuit during demand response, and another control to decrease the heating supply water temperature. All three AHUs in the building are equipped with a custom control which is able to reduce the temperature of the supply air flow, and supply air flow reduction controls can be made for the classrooms' AHU and the general spaces' AHU. Space heating equipment's heating set point can be lowered in classrooms, in the gym and in general spaces of the building except for in the kitchen and in the bathrooms. Further information regarding the building model and demand response controls included can be found in Appendix I.

4.2 Marginal costs of district heat production

As discussed in Chapter 2.3, the increasing competitiveness of alternate means of heating for buildings in urban areas, and the perceived decline in specific heat consumption of buildings among other factors encourage district heat producers to develop their operations and market strategies. Demand response of district heat consumption provides many benefits for the producer, which makes it an interesting concept from their point of view and one that has been gaining more traction in recent years. The current district heat pricing mechanisms for customers are rather inflexible though, and as such provide little incentive for load management as prices do not reflect changes in production costs near real-time, like for example the Elspot market price of electricity does. To increase the appeal of demand response, producers could, for example, opt to share some of the profits made from lowered production costs during demand response with the customer or develop a pricing mechanism that directly reflects hourly district heat production costs in such a way that it encourages customers to participate in load management when the production costs are high.

One such pricing mechanism could be hourly variable pricing based on marginal costs of district heat production, similarly to how the Elspot market price for electricity is determined for example. The marginal cost of production is defined as the cost of producing one additional unit of energy, and it varies based on demand and on variations in any variable production cost factors such as fuel prices or fuel taxes. The objective of hourly marginal cost based pricing is an efficient allocation of resources, where the marginal cost is always based on the production cost of the most expensive production unit in operation (Schramm 1991). Fuel types and fuel costs, plant efficiencies and other differences between plants determine the marginal cost of production for each plant, and further determines the running order of the plants. Ideally, plants in a district heat system are ran in order from lowest marginal costs of production to highest at all times, however there are some real-life constraints that limit constant shutdowns and start-ups of certain plants.

Besides pricing district heat based on marginal costs of production, a variety of other pricing mechanisms for district heating have been developed over the years which aim to address some of the issues in currently available pricing mechanisms. Such pricing mechanisms are, for example, the incremental cost method and the shadow price method. The incremental cost method is based on the marginal costs of production but it takes costs of future changes, such as replacement or expansion costs, into account in addition. The incremental cost method minimizes the potential for unjustified losses or surpluses for the district heat producer, and the method is inherently self-sustaining as it ensures that required funds for maintaining or expanding the system are always available. The shadow price method is the same as the marginal cost based pricing method with the exception that the shadow price method takes into account investment costs for potential new plants. (Li et al. 2015)

Implementing an hourly varying marginal cost based district heat pricing mechanism would be a way to automatically incentivize participation in demand response programs, considering that the benefits of load adjusting would be immediate for the consumers as well. Hourly varying heat prices would perhaps add transparency to the demand response process from the customer's point of view as well, since it directly links the producer's costs to the costs for the customer. Price-conscious customers could be encouraged to practice load management outside demand response events also, if the economic benefits that could be gained are high enough. Separate consumer-driven demand response could be a two-edged sword though, since in extreme cases it could create peak heat demand situations in low-price hours should a large enough percentage of customers carry out demand response simultaneously.

4.2.1 Calculation of marginal costs

As mentioned earlier, a district heating pricing mechanism based on marginal costs of production is used in the simulations of this study. Mäkelä (2014) and Syri et al. (2015) investigated the concept of an open district heating market for Espoo city with a district heat pricing concept based on marginal costs of production. The marginal costs of production in those studies were determined with a MATLAB optimization model with hourly resolution, which calculated the cost optimal dispatch order of plants for every hour of the year according to variable production costs. This exact same optimization model is used in this study, with some small modifications to the model's input data.

The input data for the marginal cost optimization model consists of hourly heat demand in the city's district heat network, realistic fuel prices and taxes, the plants' heat production capacity and electricity prices. In Finland, heat produced in HOB's is taxed in full while only 90% of heat produced in cogeneration plants is taxed. Electricity sold to the Nordic electricity market is not taxed according to Finnish legislation. (1996/1260) The optimization is conducted with a commercial mathematical simulation software MATLAB, with an objective function minimizing the hourly sum of production costs of every plant. Relevant output of the optimization for the purposes of this study includes hourly plant specific production costs and the total marginal costs of production for a one year period. (Mäkelä 2014) As mentioned, some modifications were made to the input data when calculating the marginal costs for this study compared to the data Mäkelä used in his thesis. For one, the electricity prices were changed to correspond 2014 Elspot market prices. Additionally, in Mäkelä's thesis one of the CHP-plants was modeled in such a way that it could operate in either cogeneration mode or in heat-only production mode. However, in the marginal cost calculation carried out in this study the model was modified so that all three CHP-plants can operate in cogeneration mode only. Other input data for the optimization model is the same as in Mäkelä's study.

Changing the input electricity price data also affects possible operational hours of the CHP-plants since the optimization model functions with the assumption that CHP-plants produce electricity if and only if marginal production costs of electricity production can be covered with profits from selling the electricity in the Nordpool Elspot trade market (Mäkelä 2014). If the market price for electricity is not sufficiently high, the CHP-plants will be turned off completely as it is assumed that they cannot operate in heat-only mode. Electricity production is not taxed in Finland, thus the only factors influencing the variable electricity production cost in this model are the price of fuel and the plant efficiency. Production costs in the optimization model are allocated in such a way that the marginal production costs of electricity consist of variable costs, i.e. fuel costs in this case, divided by the production efficiency of the CHP-plant. The marginal costs of heat production in a CHP-plant are calculated as total production costs of producing heat and power simultaneously, from which the profits made from electricity sales are subtracted. While electricity production costs of a CHP-plant determine whether the plant can be in operation during any given hour, the marginal costs of heat production and the running order of the plants along with heat demand will still determine whether the CHP-plant will actually be in operation or not.

It should be noted that the CHP-plants' production planning method used in this study is a simplification and does not fully reflect reality. Determining the operational state of a CHP-plant solely based on market prices of electricity is a simple planning method which does not really lead to a cost-optimal way of operating a district heat production system consisting of cogeneration plants and heat-only plants. This method can lead to situations where the market price for electricity is marginally too low to cover production costs allocated to electricity production in CHP-plants, which results in the plants to be unavailable for heat production, yet simultaneously the cost-optimal running order of heat production units would include CHP-based production as well. In other words, up to a certain minimum market price for electricity it is sometimes cost-efficient from the producer's point of view to run the CHP-plants even if the variable costs allocated to electricity production in this manner are not covered entirely. Furthermore, the model assumes that all electricity is always sold to the Elspot market, but in reality there are several other markets for electricity in Finland that the producer could potentially take advantage of in case selling electricity to the Elspot market is not cost-efficient.

The inclusion of an electricity consuming heat pump plant in the heat production system is also interesting to note. The model assumes that the heat pump plant purchases all electricity it needs directly from the market, but considering that the plant is in the vicinity of the producer's CHP-plants, it is possible that there is an option to divert some of the producer's electricity production directly to the heat pumps. Electricity and heat storages would naturally complicate the marginal cost calculation further, however any such possibilities are ignored here. Fortum does have a district heat storage with 800 MWh capacity, which is located at the Suomenoja CHP-plant area, so storing heat is already a viable option (Fortum 2015b). Adding a dynamic heat storage to the optimization model would require extensive modifications though, and considering that the marginal cost optimization and utilization is but a small part of this study, such additional work was defined out of scope for the thesis. The opposite of storing energy would be to direct heat produced in CHP-plants to the sea or to other heat sinks. This can be a beneficial alternative for the producer in situations where electricity prices are very high and heat demand is low, so that CHP-based heat production is not needed. In a situation like this it may be cost-efficient to run the CHP-plants and generate electricity sales profits while directing the produced redundant heat to heat sinks (or to the heat storage in reality). Any production capacity up- and down-regulation constraints as well as possible additional costs related to start-ups of plants are ignored in this paper, which in reality are contributing factors in production planning. In practice, the planning horizon for a CHP-plant's operation is several days ahead, and plants are not started and shut down on an hourly basis like it assumed in this paper. In conclusion, the operation of a district heat system with CHP-production capacity is very complex and dependent on several factors which are not considered in the marginal cost optimization of this study. A separate optimization could be used to determine optimal short- and long-term operation of a CHP-plant in a district heat system, but such an optimization is out of scope of this study (Rong and Lahdelma 2007). A simplified marginal cost optimization is perfectly suitable for the purposes of this study though, as the focus of the thesis is on determining the demand response potential of city-owned buildings rather than developing a realistic district heat marginal cost simulation method.

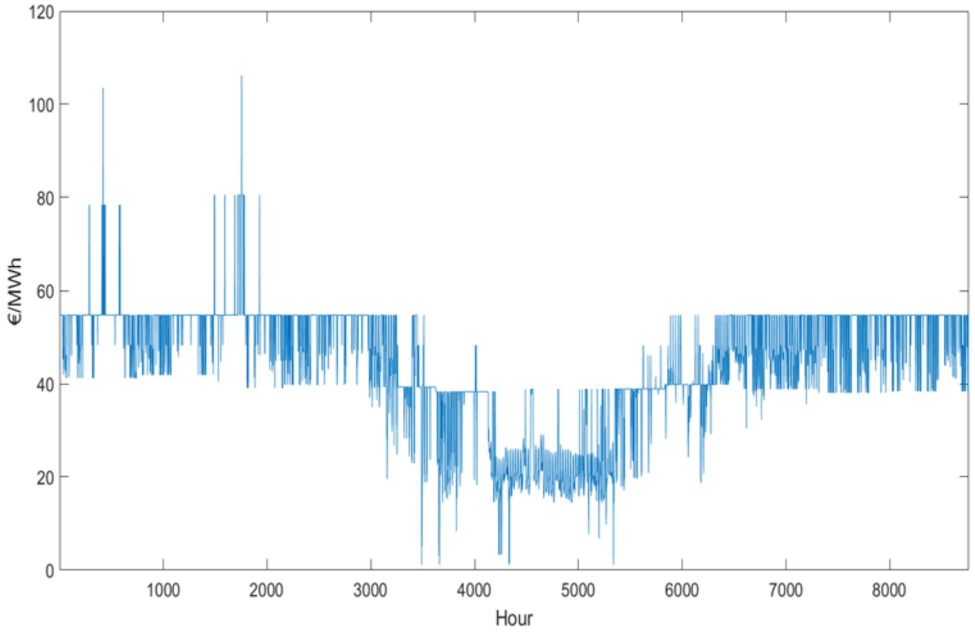

Figure 8. MATLAB-optimized hourly marginal cost of district heat production in €/MWh.

The calculated marginal costs of district heat production according to the MATLAB optimization are shown in Figure 8. As expected, the general cost level is noticeably lower during summertime while the cost level during heating season is approximately 55 €/MWh for most of the time. Peak marginal production costs occur in January and March, when the costs increase to over 100 €/MWh during the highest peaks. The original marginal cost calculations (Mäkelä (2014) and Syri et al. (2015)) do not feature these very high peak costs of 100 €/MWh which can be seen in Figure 8. The culprits of this notable difference are the modifications to the electricity cost data and the CHP-plant operations, which lead to activation of some of the light- and heavy fuel oil plants in some instances, which did not occur in the original simulations by Mäkelä (2014). The mostly unchangeable daily maximum value in heating season is a result of multiple heat-only plants having the same marginal cost of production due to no discrepancies between variable production costs in different plants that use the same fuel type.

4.2.2 Timing of demand response events

As discussed in Chapter 3, the timing of demand response events is always based on some signal relevant to the parties involved. In the case of district heat producer driven demand response that is studied here, variations in heat production costs are a typical signal to evoke demand response events and they are chosen as such in this study as well. While the calculated marginal production costs feature moderate variation only, as shown in Figure 8, the absolute or average production costs have considerably more fluctuations as the variations in electricity prices are much more visible. Figure 9 shows the variable production costs in €/MWh on three studied example days in winter, spring and in summer, while Figure 10 shows the corresponding marginal costs of production on these same days. The cost curves in Figure 9 are calculated for each hour as total production cost in € divided by the total production in MWh, so essentially they represent an average cost to produce one MWh of heat during the hour. Using the marginal cost as a signal for demand response would be the better and correct approach, however the marginal costs calculated in this study feature so little variation, especially during the winter season, that suitable candidates for winter day demand response based on changes in marginal costs could simply not be found. The few higher peaks that can be seen in Figure 8 occur either at night or during weekends, which are outside the typical office and school building's hours of operation and thus the buildings' heat demand during those times is very low in the first place. Night-time demand response could absolutely be feasible in apartment buildings though, which have relatively steady heat demand around the clock.

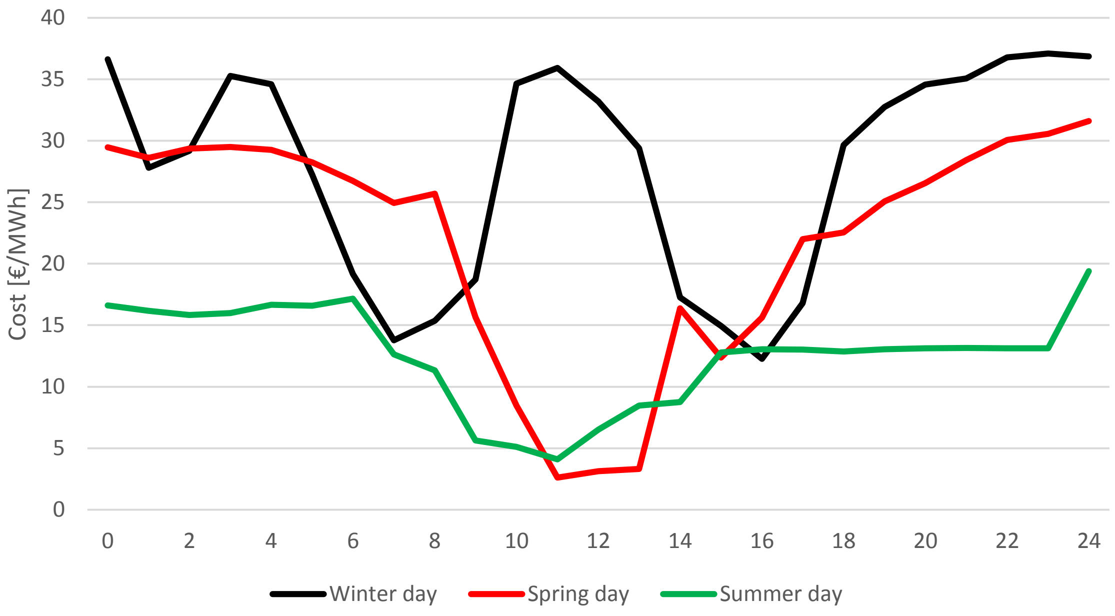

Figure 9. Marginal costs of heat production on the studied example days.

For simplicity, three different example days were chosen and demand response potential of the buildings was determined for these three days only. These three days were chosen based on production costs of heat and the outdoor temperature during the day, and the aim was to choose days that are representative of different seasons. Figure 11 shows the outdoor temperature on the chosen example days. In this case, the winter day represents a cold day on which outdoor temperature is around -10°C or a little lower throughout the day, and the spring day represents both early spring and late autumn when outdoor temperature is between 10°C and 0°C. Outdoor temperature on the example summer day is over 20°C almost throughout the day so space heating should not be needed at all. Outdoor temperature is an important factor when determining demand response potential of a building since it directly affects heat demand and thus the demand response potential of district heating as well. It should be noted that the simulated winter day is a rather cold one, and in recent years the average temperature in the winter months in southern Finland has been above -5°C (Finnish Meteorological Institute 2017).

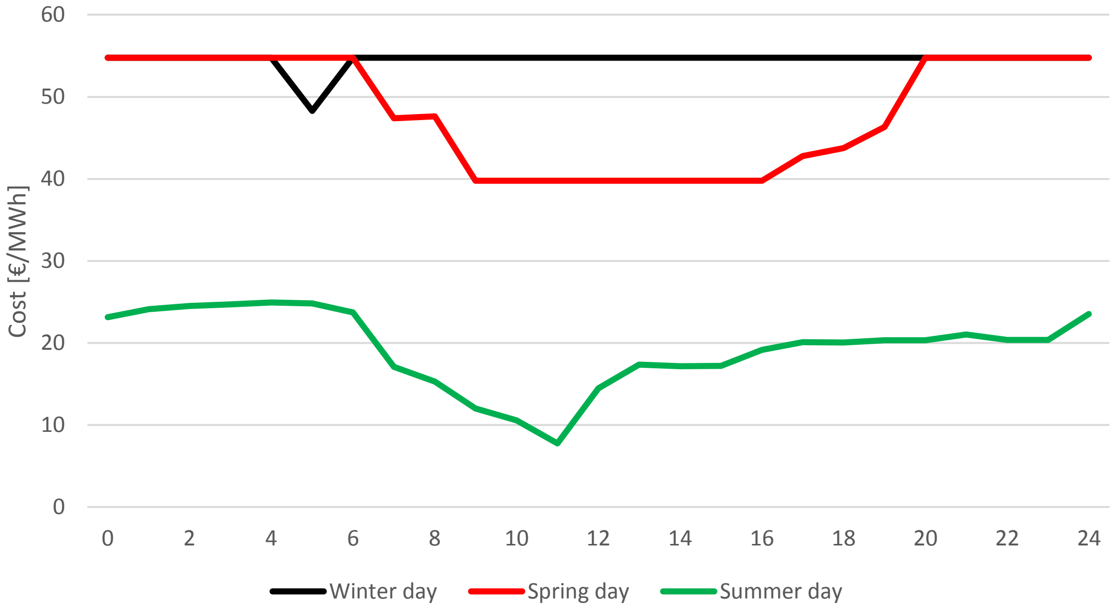

Figure 10. Marginal costs of heat production on the studied example days.

As aforementioned, Figure 10 shows the marginal costs of heat production during the simulated example days in winter, spring and summer. As it can be seen, the marginal cost is almost constant throughout the winter day, while in spring and in summer there is some more variation due to CHP being the marginal production type. The curves in Figure 10 are fairly typical production cost profiles for the season they represent, according to the output data of the marginal cost optimization, and the marginal cost profile for the winter day illustrates why choosing changes in marginal costs as the signal to evoke demand response was not perfectly feasible in this study. However, it should be noted that the results of the MATLAB optimization show that two of the three CHP-plants in the district heat system are atypically sparsely in operation due to the applied variable cost allocation method and the electricity production profitability requirement constraints used in this thesis. As discussed earlier, the optimal, and likely more realistic, operation of these CHP-plants would lead to an increased utilization rate and more variability in marginal costs, and thus also to the possibility of using changes in marginal costs as a demand response signal.

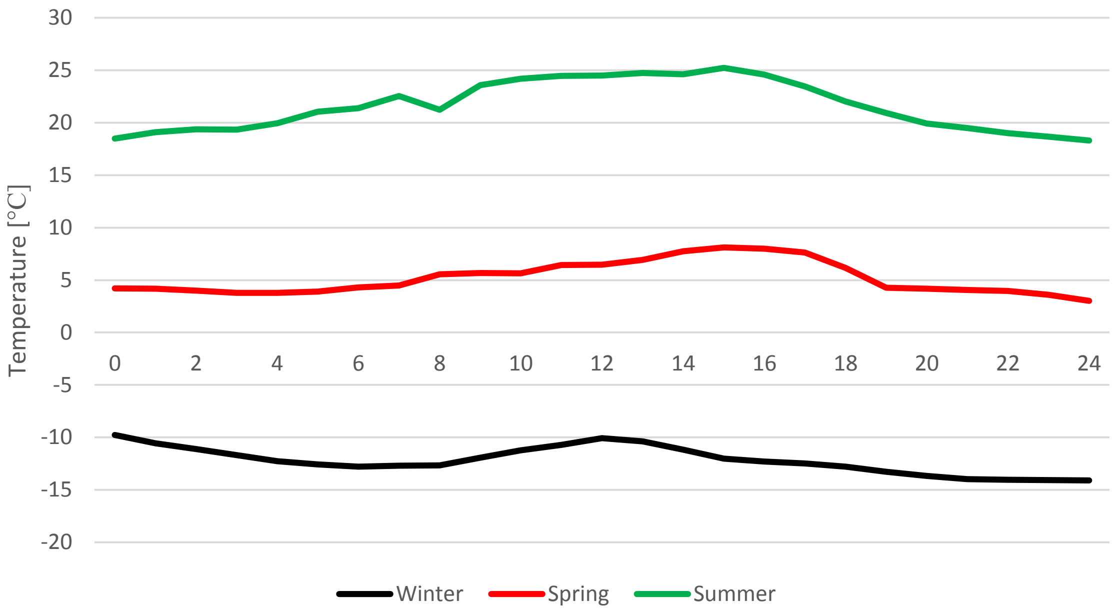

Figure 11. Outdoor temperatures on the studied example days.

Comparing Figures 9 and 10 it can be clearly seen that there is much more fluctuation in the average production costs compared to the marginal production costs. The average production costs are affected by costs of all different production units, rather than just the costs of the marginal production unit, which leads to the kind of fluctuation illustrated in Figure 9 in DH systems that have large amounts of CHP production. As for the studied example days, the wintertime production cost profile features the most fluctuation and has noticeable moments of low costs during the morning and early evening hours. In spring and in summer, the production costs in Figure 9 are lower during the day in general and neither curve features any significant peaks. The influence of electricity prices on district heat production cost curves is substantial, as mentioned previously. Figure 12 shows the Elspot market prices for electricity on the same example days for comparison, and the correlation between these prices and the DH production costs is evident as the production cost profile is practically the Elspot price profile inverted. There is naturally some correlation between variations in average production costs and variations in marginal production costs as well, especially when cogeneration is the marginal production methods. This is especially evident when comparing the spring and summer day cost profiles in Figures 9 and 10, which show very similar behavior during the day

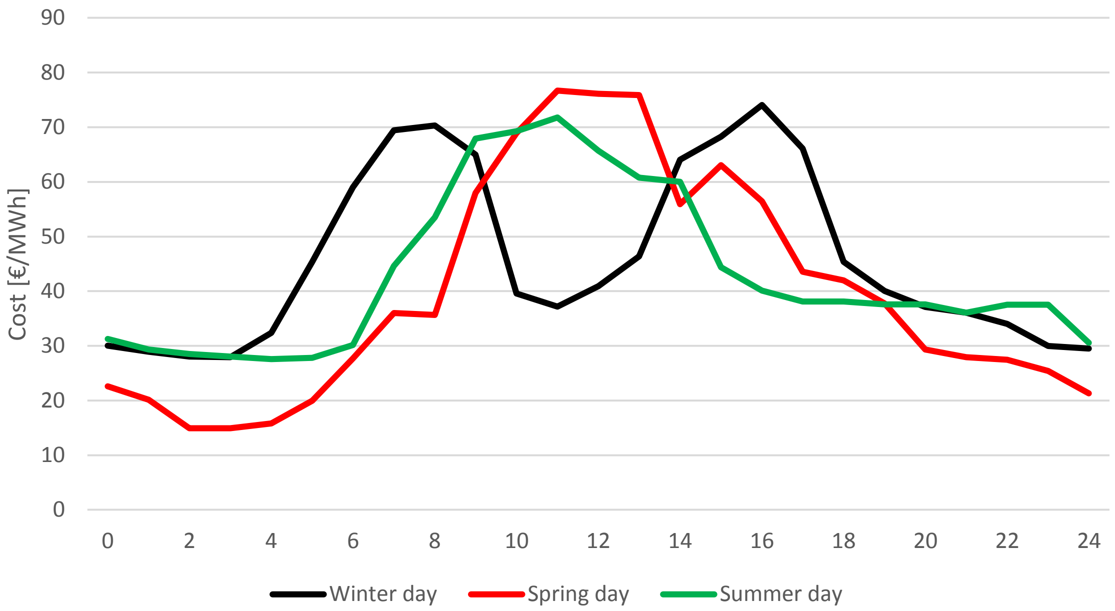

Figure 12. Elspot electricity market prices on the studied example days (Nord Pool 2017a).

The timing of the demand response events is decided based on the cost profiles in Figure 9. Occupancy schedules and heat load profiles in the modeled buildings are also taken into account in that they determine the earliest and the latest hours of the day for carrying out meaningful demand response. Weekend days are also ruled out as it is assumed that the office and school buildings are unoccupied on weekends. The daily occupancy profiles and ventilation time schedules suggest that the office and school buildings have minimal heat demand between 20:00 – 06:00, while the residential building has a relatively steady heat demand around the clock since it is occupied 24 hours a day. It is assumed in this case that the demand response activation signal is same for every building type, i.e. the timing of the event is the same for all buildings instead of event timing tailored for each building type separately. This can lead to non-optimal timing of event in regards to heat demand in some cases, but it is an easy to implement strategy since it requires no additional estimates of the buildings' hourly heat demand. This also means that an approximation of total demand response potential can be made later for the total city-owned building stock in regards to the three investigated building types.

For the simulated winter day, Figure 11 clearly shows that the best possible timing for the three hour long demand response event is in the middle of the day between 10:00 and 12:00, and this is the timing of the event that is also chosen for the optimizations. All three modeled buildings have notable heat demand in the middle of a typical weekday so it is expected that all buildings have notable demand response potential during the predetermined event. Choosing a suitable time for the demand response event in the spring day is slightly more difficult since the production cost curve produces a valley during the day, rather than a peak like the curve for the winter day does. The early morning hours from 06:00 to 09:00 do still have noticeably higher production costs compared to following hours, and since these hours also overlap with the hours of operation of the office and school buildings, albeit only partly in regards to the school building, they are chosen as the hours when demand response is carried out on the spring example day. Another option for the timing of an event on the spring day are the early evening hours when the costs again start to increase towards the higher night-time cost level. Peak demand in the office and school buildings occurs in the morning though, when ventilation turns on, so choosing the morning hours for the demand response event's timing should be more beneficial and should yield larger load reductions.

The heat production costs and marginal costs during the summer are rather low throughout the day compared to other seasons, as is visible in Figures 9 and 10. Additionally, heat demand on the example summer day in the modeled buildings is entirely for domestic hot water heating, and since demand response strategies related to DHW are not included in this thesis, there is no potential at all for heat load management in these buildings on the summer day. The office building is equipped with space cooling though, and on a hot summer day there is significant cooling demand too, which could be used to carry out electricity use related demand side management. Figure 12 shows that the Elspot market price for electricity peaks between 09:00 and 11:00 on this example summer day, and for this reason the three hours between 08:00 and 11:00 are chosen for further investigation. This summer event is simulated and optimized for the office building only as it is the only one that is equipped with space cooling. Schools are typically used little if at all in summer and the demand response strategies investigated in this thesis do not provide any substantial electricity load management potential in a residential building during the summer. The summer day demand response event has no benefits for the heat producer though, so they would not be the party that sets such an event in motion. Similar demand response strategies can be applied for summer and winter though, so it may be in the interest of the building owner to practice demand response during summer days as well and take full advantage of the demand response enabling control systems. The results of the summer day case are presented in Chapter 5, but not much attention is paid to it when analyzing the results as the focus in this thesis is on district heat demand response potential of the modeled buildings.

In reality, determining the optimal timing of demand response events can be somewhat problematic, especially if there is a limit for the maximum amount of events that can be evoked during a certain time frame. Without a limit for the number of events, the scheduling is relatively simple as it only requires short-term forecasts for energy demand and energy prices, and the events are then evoked when some relevant parameter exceeds a predetermined limit value. An example case would be always triggering a demand response event when district heat production costs exceed a certain maximum limit or the differences in production costs between consecutive hours exceeds some predetermined limit value. Depending on the way these stationary limit values are chosen, demand response can be triggered several times a day or in rare occasions only, for example merely during very high peak demand hours. Looking at the cost curves in Figure 9 it is likely that on the example spring day another demand response event would be triggered at 14:00, if event scheduling based on stationary limits was used.

As aforementioned, the task of determining optimal demand response event scheduling becomes a more complex problem when a limit is set for the number of events that can be triggered during a certain time frame. If the demand response organizer aims to trigger as many events as the limits allows, it will need some kind of longer term forecasts to predict whether it is optimal to invoke demand response during the short-term forecasts' time frames. Long-term forecasts for energy prices and demand include uncertainties, which in turn inevitably leads to non-optimal scheduling of demand response events. One way to tackle this scheduling problem are probability-based methods, which take into account the remaining number of available demand response opportunities and adjust the threshold of triggering a demand response event accordingly. Practically it means that if there are several demand response events still available but little time to use them, the threshold of triggering an event will be lowered in order to exhaust all available opportunities in the shorter time frame. Chen et al. (2013), for example, studied such probability-based demand response event scheduling methods for electric utilities, which yielded modest improvements over the utilities' current scheduling methods and lead to scheduling closer to true ex-post optimum scheduling of events. (Chen et al. 2013; Tyagi et al. 2011).

From a district heat producer's point of view, the important factors related to demand response event scheduling are heat demand, fuel prices and the price of electricity. Heat demand can be forecasted based on weather forecasts and observed demand patterns, while the Elspot market prices for electricity are always known accurately for the next day. Long-term forecasts for both of these have significant uncertainties though, so some type of probabilistic demand response event scheduling methods would likely be the best approach for district heat producers as well. In this study, the events are scheduled based on the best possible times for each example day, and whether they represent optimal timing in the bigger picture is not considered since it would require determining the number and timing of events for a longer period of time.

The length of a single demand response event is similarly an interesting and important factor to consider. From the organizers point of view, the length of an event would optimally be as long as necessary and dependent on the length of the peak price period. Carrying out demand response typically has some negative effects on the indoor climate conditions though, which affects the occupants' comfort level and essentially sets limits for the demand response event length. This study focuses on demand response strategies that change the typical operation of HVAC-equipment in the building, which has an immediate effect on indoor climate conditions. Some of the effects accumulate over time, which means that conditions worsen the longer the event lasts which either limits the length of the event or the maximum load adjustment that can be applied. An example of such an accumulating negative effect is CO_2-content in a space, which is relevant when reducing ventilation air flow: if air flows are reduced, the CO_2-content in spaces starts to increase as the smaller ventilation rates are unable to remove CO_2 generated by the occupants at an adequate rate. The CO_2-content in the space continues to rise until a new equilibrium is reached or the demand response event ends.

Typically in previous studies regarding demand response potential in buildings, the length of a single demand response event ranges from one hour to four hours or so. For example, a study made by Christantoni et al. (2016) involving analysis of demand response potential of a multi-purpose commercial building using building energy simulations uses DR event lengths of 1, 2 and 4 hours. In the work by Kontu (2014) heat load is cut in an apartment block for 1 hour in the morning and in Kärkkäinen et al. (2004) the length of a single demand response event is 2-3 hours. The production cost curves also limit the length of the events in that the winter day production cost peak lasts for about three hours and the operational hours of the modeled buildings limit the reasonable length of the spring day event to 2-4 hours. Three hours was chosen as the length of the demand response events on each studied day as a compromise and taking into account the aforementioned factors.

4.3 Optimization of demand response control strategies

The cost-optimal combination of HVAC control strategies to produce load reduction for demand response purposes is determined in this study with the optimization software MOBO. More specifically, MOBO is used to find the optimal control parameters for all the different demand response strategy possibilities that are implemented into the models. In other words, the optimal combination determined by MOBO actually includes optimal control parameters for all included demand response strategies, although some of these “optimal” parameters in reality have little effect on energy demand of the building. After the optimization, the parameters are then input back in the simulation models where the parameters’ usefulness, among other things, is investigated with further simulations.

The optimization software MOBO is a generic optimization tool developed in 2013 by VTT Technical Research Centre of Finland and Aalto University. MOBO, or Multi-Objective Building Optimization tool, was developed specifically for building performance optimizations, and it can be coupled with several different simulation programs, including IDA-ICE which is the simulation tool used in this study. MOBO features multiple optimization algorithms, some of which can also handle multi-objective optimizations with discrete or continuous variables. The software has an easy-to-use graphical user interface in which the user can set input values for variables and constraint functions for the optimization. Optimization results are presented in spreadsheet form, which also includes the simulated values of the variables being tracked for constraints or other purposes. (Palonen et al. 2013).

The optimizations in this study were made with one of the genetic algorithms of MOBO, the Pareto Archive NSGA-II –algorithm (aNSGA-II), using multiple-objective optimizations and discrete input variables. The NSGA-II is a well-known elitist non-dominated genetic sorting algorithm, which can be used to solve multi-objective optimization problems with Pareto-optimal solutions (Deb et al. 2002). The aNSGA-II is an algorithm developed further from NSGA-II, which uses an active archive that enables the use of smaller population sizes in optimizations and it should increase the rate of convergence. The aNSGA-II has been demonstrated with tests as effective in multi-objective building optimization problems and it has shown to be capable of producing quality solutions close to optimal. (Hamdy et al. 2012). Using discrete variables decreases optimization time and promotes realism, as in reality there is only so much accuracy one can use in actual building controls such as in temperature set point controls. Furthermore, the inaccuracies in the results due to using discrete variables instead of continuous ones are marginal as the steps of the discrete variables are small, e.g. for temperature adjustments the step is 0,2°C and for power and air flow adjustments the step is 5% from the nominal value. The discrete variables’ maximum and minimum values are set based on initial simulations and logical constraints. All variables and possible values for the variables used in the optimizations are presented in more detail in Appendix II.

The optimization process in MOBO is based on communication between the optimization software and the energy simulation software, in this case IDA ICE. MOBO first assigns some values to all variables to be optimized, after which the simulation program is launched via scripts that also input the variable values chosen by MOBO to the program. The simulation software then runs a predetermined energy simulation, using the input values chosen by MOBO in various control mechanisms during the demand response event, and produces an output file which includes the essential information for MOBO to continue the optimization, e.g. in the optimization problems of this thesis MOBO reads the heating and total energy costs on the simulated day from the output file. After this, the evaluation loop is restarted and new values for variables are assigned, and this continues as long as desired. Using one of the genetic optimization algorithms ensures that simulation results start to converge towards the requested optimum with enough simulation loops. The amount of simulations to be made in the optimizations has to be predetermined and in the optimization problems in this study, a population size of 16 with 64 generations were used, which accounts for 1024 simulations in total. It was assumed that this number of simulations would be enough to produce the optimal solution or a solution close to the optimal at least, and the results of the optimizations indicate that this assumption was justified.

Operative temperatures and the CO_2-contents in spaces were chosen as constraining factors in the optimizations as they are tracked in IDA ICE by default and affect occupants' satisfaction on the indoor climate. Classification of Indoor Environment 2008 –guide by Finnish Society of Indoor Air Quality and Climate is used to an extent to determine suitable limits for the chosen constraints. The Indoor Environment guide defines three classes of indoor climate quality, ranging from satisfactory to very good, and these classes were used as basis in determining suitable values for the constraints in the optimizations in this study. The guide defines maximum allowable CO_2-content in spaces as well as the allowable operative temperature ranges, which are outdoor temperature –dependent to a degree. (LVI 05-10440 en 2010)

While the indoor climate guidelines define target values for several indoor climate –related parameters to aid in building design, it is not actually necessary to follow any of these as they are merely guidelines and not to be confused with actual regulations. There are some regulations in the Finnish national building code regarding indoor temperatures and CO_2-content as well: the maximum allowable CO_2-content in a building, defined in the ventilation related regulations D2, is 1200 ppm (parts per million), and the energy efficiency related regulations define that the indoor temperature can exceed a certain maximum, building type –specific temperature by 150 degree hours at most during summer season (NBCF D2/2012; NBCF D3/2012).

For the optimizations in this study, a maximum CO_2-content of 900 ppm is used, which corresponds to the maximum allowable CO_2-content in the Good-class of the Classification of Indoor Environment –guidelines (LVI 05-10440 en 2010). Using standard ventilation rates the CO_2-content in the modeled buildings is well below this maximum throughout the day, which enables adequate potential for ventilation air flow reduction during demand response events. The maximum allowable CO_2-content in spaces in the lowest indoor climate class of the aforementioned guidelines is 1200 ppm, which if used instead would naturally enable even more adjustability. However, in reality there are a lot of factors which influence the CO_2-content in a space which could not be taken into account reliably in the models, and thus a middle-ground limit was chosen to avoid overestimation of the air flow reduction potential.

The minimum allowable operative temperature in the optimizations is set at 19°C and the maximum is set at 27°C, which are also used as the upper and lower bounds for the actual indoor temperature set points in relevant demand response controls. Picking suitable temperature limits was less straightforward than picking the CO_2-content limit as regulations concern measured temperatures only, while the indoor climate guidelines are related to operative temperatures. Operative temperature and measured air temperature are connected but not the same, and the problem lies in that the latter is used to control space heating and cooling equipment while the former is a factor in occupant satisfaction that is typically not measured real-time as it takes into account temperatures of the surfaces in the space in addition to the air temperature.

Going by the Indoor Classification of Indoor Environment –guidelines again, the absolute minimum allowable operative temperature according to the Good-class is 20°C, but in initial simulations it was discovered that operative temperatures during the winter example day are around 20°C in most spaces in the model even with no demand response activated. Thus a lower temperature minimum had to be chosen to enable any meaningful demand response. 19°C was chosen as an arbitrary lower limit for the optimizations, which could be lowered even more for different results. For example the lowest operative temperature level in the indoor climate guidelines' lowest indoor climate class is 18°C, and a lower minimum temperature naturally leads to larger demand response potential during heating season. Keeping the minimum temperature during demand response close to the design temperature lessens occupant dissatisfaction though, and increases the acceptability of practicing demand response from the occupants' point of view as a smaller change goes unnoticed more easily. (LVI 05-10440 en 2010)

CO_2-content and operative temperature are parameters measured or calculated for single spaces separately, therefore constraint functions had to be set for each space separately as well. All constraint functions across all optimization cases are identical in regards to both operative temperatures and CO_2-contents, with the exception of the lower bound of the operative temperature in the gym space of the school building. Design indoor air temperature in the gym according to the national building code is 18°C so an operative temperature minimum of 19°C obviously could not be used (NBCF D2/2012). As the indoor climate guidelines do not take into consideration the possibility of lower design temperatures, it was decided that the air temperature could be lowered by two degrees maximum during the demand response event, which is also the maximum decrease in every other space, and that the lower bound of the operative temperature in the space would be 16°C as well. These lower bounds are not based on any regulation or guideline since such do not exist, so the actual lower bounds in these types of situations should be decided based on whatever is deemed as an acceptable temperature limit in reality.

The changes in indoor climate conditions and occupant comfort level in the buildings were considered as well, since IDA-ICE has built-in tracking for operative temperature, CO_2-content and thermal discomfort indicators such as Percentage of People Dissatisfied (PPD) and Predicted Mean Vote (PMV). The PPD and PMV indices were developed by P.O. Fanger to quantify the degree of discomfort in indoor spaces. PMV is defined as the predicted mean vote of a large group of people according to the scale in Table 4. PPD is directly related to PMV and is at a minimum of 5% when PMV is 0, while a PMV value of -1,0 or +1,0 corresponds to a PPD of approximately 25%. (Fanger 1973)

Table 4. Fanger's Predicted Mean Vote (PMV) scale for indoor thermal discomfort (Fanger 1973).

cold	cool	slightly cool	neutral	slightly warm	warm	hot
-3	-2	-1	0	+1	+2	+3

Minimizing total energy costs and heating costs in the buildings were chosen as the objective of the winter and spring day optimizations of this study. Initial simulations revealed that space heating is redundant during the chosen summer day, thus cooling costs and total energy costs were chosen as the minimized objectives in the summer optimization case. In a way optimizing both total energy costs and heating costs aims to create the best possible scenario for both the district heat producer and the customer, as consumer's point of view is considered in the total cost minimization and the DH producer's production costs are effectively considered when heating costs are minimized. The heat producer's view and the building owner's view are further connected by applying the hourly marginal costs of heat production, which were presented in Chapter 4.3.1, as the price of heat to calculate heating costs for the optimizations. These marginal cost –based heat prices are shown in Figure 13 along with current standard seasonal district heat prices, which are used in simulations later. Using the marginal costs of production directly as the heat price means that demand response related heat savings reflect production cost savings, assuming that the marginal production method does not change as a result of the decreased demand.

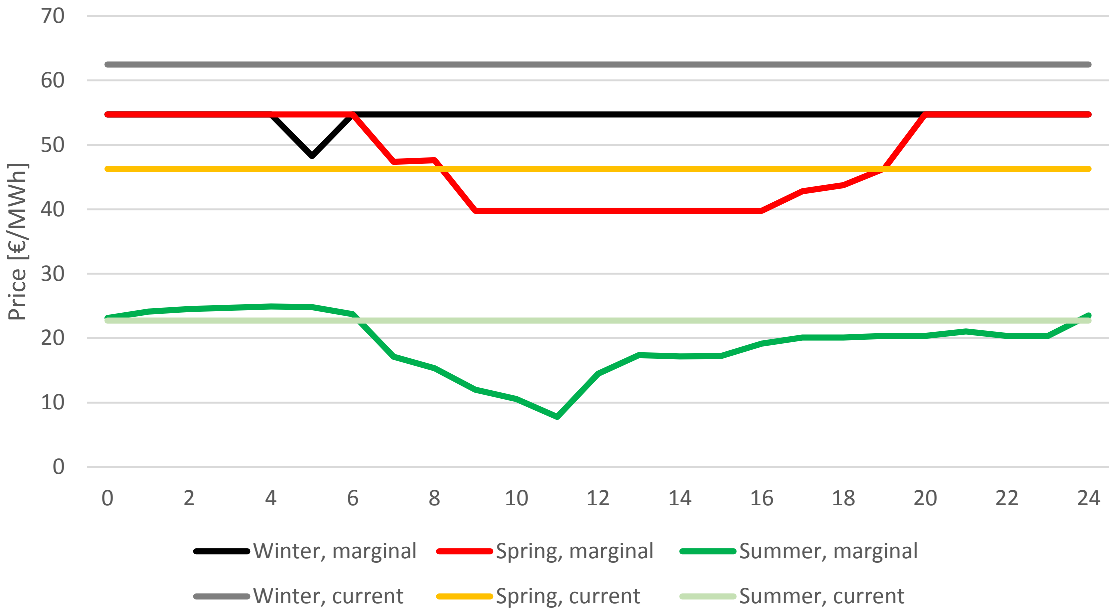

Figure 13. District heat prices used in the optimizations and simulations.

5 Results and analysis

The results of the optimizations and additional simulations are presented in this chapter. All results are based on optimal parameters determined by MOBO, which were then inserted into the simulation models again as input data. Differences in the buildings' total energy costs and power demand curves on the specified example days were calculated using the optimal control parameters and either marginal cost based district heat prices or currently available seasonal heat prices for comparison. Calculated cost savings are a result of decrease in energy consumption during the DR event, and pre-conditioning of the buildings to offset the adverse effects of load reductions somewhat during the events is not considered here. Individual demand response control strategies' impact on total load reductions achieved by demand response were also investigated.

5.1 Office building results and analysis

The optimal parameters for the investigated demand response strategies' controls for the office building are presented in Table 5. In cases where the original value is 1 in Table 5, the optimal value can be interpreted as a percentage of the original value, i.e. the optimal ventilation air flow during demand response is 20% of the nominal ventilation air flow. Plant supply water temperature adjustment denotes reduction from the original supply water temperature, which is dependent on outdoor temperature and determined for each hour separately based on a curve (see Appendix II for details). The optimal value for that strategy indicates that supply water temperature during the demand response event is the value from the curve adjusted by -14°C. Lighting power reduction was not part of the optimized strategies, but rather the "optimal" value was predetermined. Lighting reduction has no notable effect on the constraining indoor climate parameters and a very small effect on heating and cooling demand, thus if included in the optimizations the optimal result would very likely always be the lowest lighting power allowable since direct electricity cost savings are larger than the possible small increase in heating costs. The parameters in the second column of Table 5 are introduced so that the strategies' can be referenced more easily later in this chapter.

In addition to the strategies presented in Table 5, adjusting supply air temperature after heat recovery was initially investigated as well. The original set point for supply air temperature after the heat recovery is of course 17°C, so that ideally no supply air heating or cooling is needed. Since temperature set points after the heat recovery and after the heating and cooling coils are so obviously connected, it is important to adjust the set point after heat recovery too when the set point after heating and cooling coils is changed, so that no unnecessary heating or cooling occurs. It was discovered that on the simulated winter day with heat recovery operating in full capacity, the supply air temperature after heat recovery is below 4°C at all times. Even on the spring day, supply air temperature after the heat recovery does not exceed 15°C. Since the supply air temperature set point adjustment's minimum limit was set at 15°C and the air temperature after heat recovery never reaches that, there will always be some supply air heating required and optimizing the temperature set point value after heat recovery is redundant. On the studied summer day, the heat recovery is turned off due to high outside air temperatures and thus optimization of the set point is not required. Both a4 and a9 in Table 5 are strategies that change the ventilation supply air temperature; the difference is that a4 is essentially the supply air set point for the AHUs heating coil while a9 is the set point for the cooling coil. Both possibilities are left open for optimization on the spring day, in case both are needed at some point.

Table 5. Optimal parameters for demand response strategies' controls in the office building.

Demand response strategy		**Original parameter value**	**Optimal parameter value, winter**	**Optimal parameter value, spring**	**Optimal parameter value, summer**
Zone heating temperature set point adjustment	a1	21°C	19,8°C	19°C	▨
Heat distribution plant power reduction	a2	1	0,5	0,75	▨
Ventilation air flow reduction	a3	1	0,2	0,15	0,2
Ventilation supply air temperature heating set point adjustment	a4	17°C	15°C	15,2°C	▨
Lighting power reduction	a5	1	0,8	0,8	0,8
Plant supply water temperature adjustment	a6	curve	-14°C	-6°C	▨
Zone cooling temperature set point adjustment	a7	25°C	▨	25°C	25,6°C
Chiller power reduction	a8	1	▨	0,05	0,7
Ventilation supply air temperature cooling set point adjustment	a9	17°C	▨	17,6°C	19°C

The optimal parameters presented in Table 5 were then used as input in further simulations, which were made to verify the parameters' validity, to compare the effectiveness of each demand response strategy and to determine demand response's effect on hourly power demand of the building. It was discovered in some initial optimization cases that sometimes the optimal results according to MOBO were visibly non-optimal, which is likely due to the relatively small number of simulations included in an optimization case and any restrictions related to the optimization algorithm. The majority of the optimal results according to MOBO, however, were verified in further simulations as optimal and within the applied constraints. A total of four different simulation cases were done for each building type and for each example day: two simulations with current district heat prices and two with the assumption that the consumer pays for consumed heat directly according to the marginal costs of heat production. The different district heat prices from the customer's point of view are presented in Figure 13 for all three studied example days. Both of these different district heat pricing cases include a simulation with demand response activated as well as a base case without demand response.

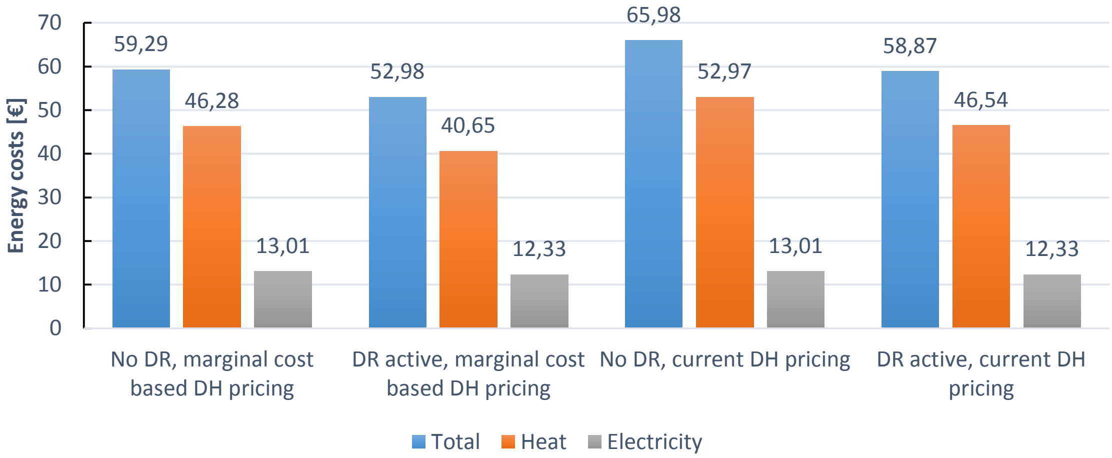

Figure 14. Total energy costs for the office building on the simulated winter day.

Total energy costs for the office building on the simulated winter day for all four aforementioned cases are presented in Figure 14. The costs presented in Figure 14 represent the energy costs from the consumer's point of view, and are a direct result of decrease in energy consumption. The decrease in heating costs between the marginal cost based pricing cases can be interpreted as a decrease in production costs from the producer's point of view as well, since the pricing method reflects the production costs of the marginal production mode. The previous holds true only if the marginal production method does not change as a result of the decrease of production though. If the marginal production unit changes due to reduced load, it is possible that the cost savings would be smaller as the marginal production cost savings for a part of the decreased amount of heat might be lower. The assumption that the marginal production type remains the same before and after the production decrease can be considered reasonable in this case, since the reduction in heat demand for a single building is small, only some tens of kilowatts, in relation to total heat production at the time which is hundreds of megawatts. The assumption is more in question when savings are aggregated and the potential of the entire city-owned building stock is approximated.

According to the simulation results presented in Figure 14, total energy cost savings for the consumer on a cold winter day are 10-11% when demand response is applied. The majority of the savings result from decreased heating costs, as expected, but small decrease in electricity costs occurs as well due to e.g. reduced ventilation fan power. As mentioned previously, decreased heating cost represent both tangible cost savings for the consumer and in the first two cases in Figure 14 also decrease in heat production costs from the producer's point of view. The decrease in heat costs is approximately 12% from the costs in the base cases, and the decrease in electricity costs is a little over 5% according to the simulation results. While the presented results regard the whole day, differences in costs can be attributed to the three hours when demand response is practiced (cost decrease) and to a few hours after the event if any rebound heating occurs (small cost increase).

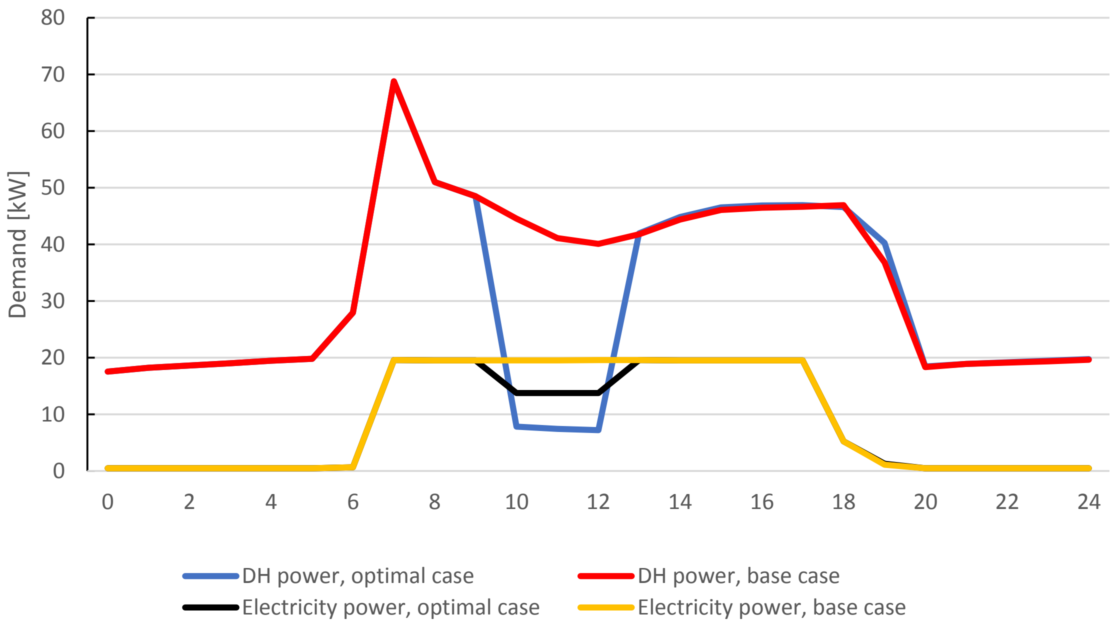

Figure 15. District heat and electricity power demand profiles of the office building on the simulated winter day.

Figure 15 shows district heat and electricity power demand curves of the office building for the simulated winter day. The simulation software's post-processing uses 15 minute sliding averages to produce output data, and the curves in Figure 15, and in other similar figures later, use hourly resolution for data which results in "smooth" changes in demand in the figures. All control related to demand response are almost instantaneous though, so the demand decrease at the start of the event depicted in Figure 15 is actually immediate, instead of smooth as the figure would indicate. The effect of demand response on the curves can be clearly seen between 09:00 and 12:00, especially on the heat demand curve which shows nearly a 37 kW decrease on average during the first hour of the demand response event. Proportionally, the maximum decrease is a little over 80% of the original heat demand. The decrease in electricity power demand remains the same, at about 5,8 kW, throughout the demand response event due to otherwise flat demand curve. In reality the electricity demand curve would hardly be flat throughout the day, but lack of custom time schedules for electric loads means that there is no hourly variation in demand during the building's hours of operation. The noticeable one hour peak in heat demand in the morning results from the time schedules used in the model: the building is occupied from 07:00 onwards on weekdays while ventilation in the building is fully turned on from 06:00 onwards. The lack of internal heat loads result in more heating need during the hours when ventilation is in full operation but the building is not occupied, which manifests in a small demand peak in the morning.

One of the objectives of this study was to investigate which demand response strategies show most potential based on the optimizations. The optimization results in a combination which includes optimal parameters for all the investigated strategies, which means that the total calculated demand response potential is the result of this combination of strategies as well. A straightforward comparison between the strategies is somewhat difficult in this case, as the parameters obtained from the optimization may not be optimal if the same demand response strategy controls are applied individually. Hence, a better comparison method was attempted where all demand response strategies are first active according to the optimal parameters, and then each strategy's effect on the total load reduction is separately investigated by reverting the optimal parameter value to its original one and performing a simulation to see how maximum heat and electric load reductions during the demand response event are affected. The results of these simulations for the winter day are presented in Figure 16. The results for individual strategies use the case titled "All DR active" as a base case, so essentially a smaller bar in Figure 16 compared to the "All DR active" –case indicates that load reduction without implementing the strategy in question is smaller. The parameters a1-a6 represent the corresponding demand response strategies from Table 5. The figure shows that out of the investigated demand response strategies, ventilation air flow reduction (a3 in the figure) has by far the biggest impact on both heat and electric load reduction; for example implementing all DR control strategies of the optimal combination other than ventilation air flow reduction would decrease the heat load reduction achieved during a winter DR event by about 25 kW. Zone heating set point adjustment (a1) from the original 21°C to 19,8°C provides a small contribution to the total heat load reduction, and lighting power reduction (a5) is the second biggest contributor to electric load reduction potential although still a rather small one. Smaller lighting power means less internal heat gains though, which means that heating demand is actually very slightly increased as a result from decreased lighting power.

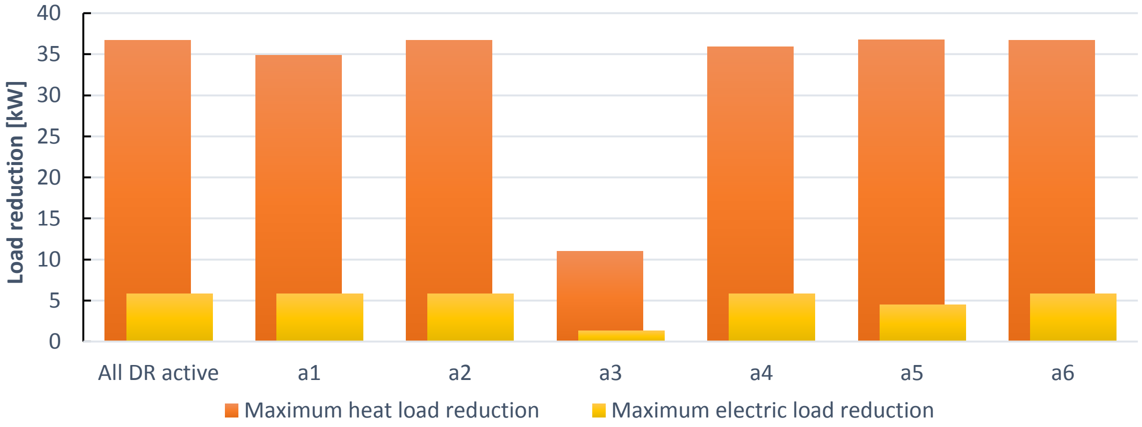

Figure 16. Relative effectiveness of investigated DR strategies for the office building on a winter day.

The exact same simulations and comparisons were made for the chosen example spring day as well, using the optimal parameters presented in Table 5 for the spring day case. The simulated day can be seen to represent typical weekdays in either early spring or late autumn, based on the outside air temperatures during the day. Figure 17 shows the calculated total energy costs and heating costs for the office building on this studied spring day. Cost savings on this day are smaller, as expected, as heat demand is considerably smaller due to higher outdoor temperatures. Figure 17 shows that heating costs are lowered by approximately 16% as a result of the demand response, while electricity costs show similar decrease of 5,5% as was the case with the winter day event. It can be noted from Figure 17 that on a spring day electricity costs account for a larger share of total costs than in winter, which means that even as percentage-wise the heating costs lower slightly more, total cost savings are still about 10,5% compared to the base case. On this particular day, using the current standard seasonal heating prices actually yields slightly lower overall heating costs than using the marginal production costs directly as a basis for heat prices.

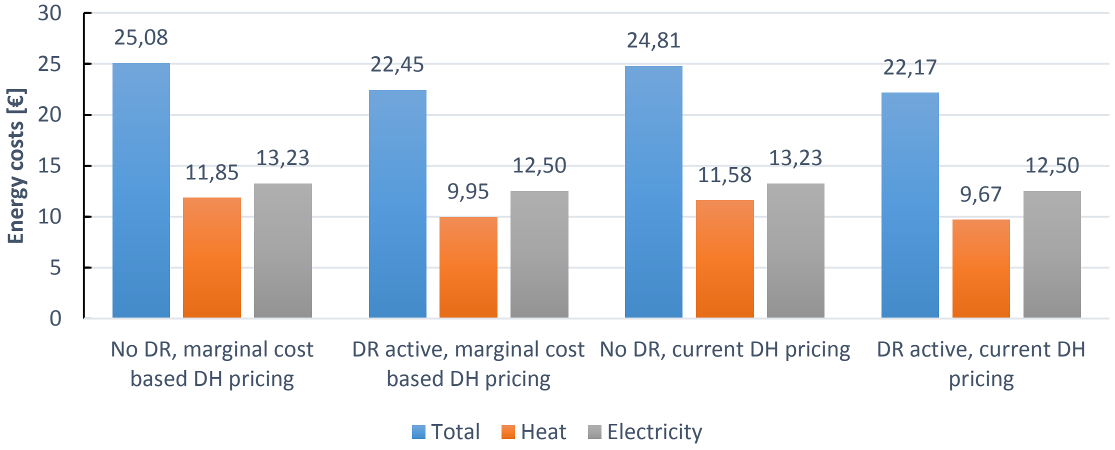

Figure 17. Total energy costs for the office building on the simulated spring day.

Figure 18 shows heat and electricity demand curves for the office building on the simulated spring day, both with and without demand response activated. Now the demand response event coincides with the peak demand hour of the building, which is again the early morning hour between 06:00 and 07:00. This accounts for a bigger percentage-wise decrease in heat demand compared to the studied winter day, which on this spring day is almost 90% from the heat demand in the base case. Reduction in electricity demand is approximately 6 kW and 30% compared to the base case, both of which are largely similar as the corresponding reductions on the examined winter day.

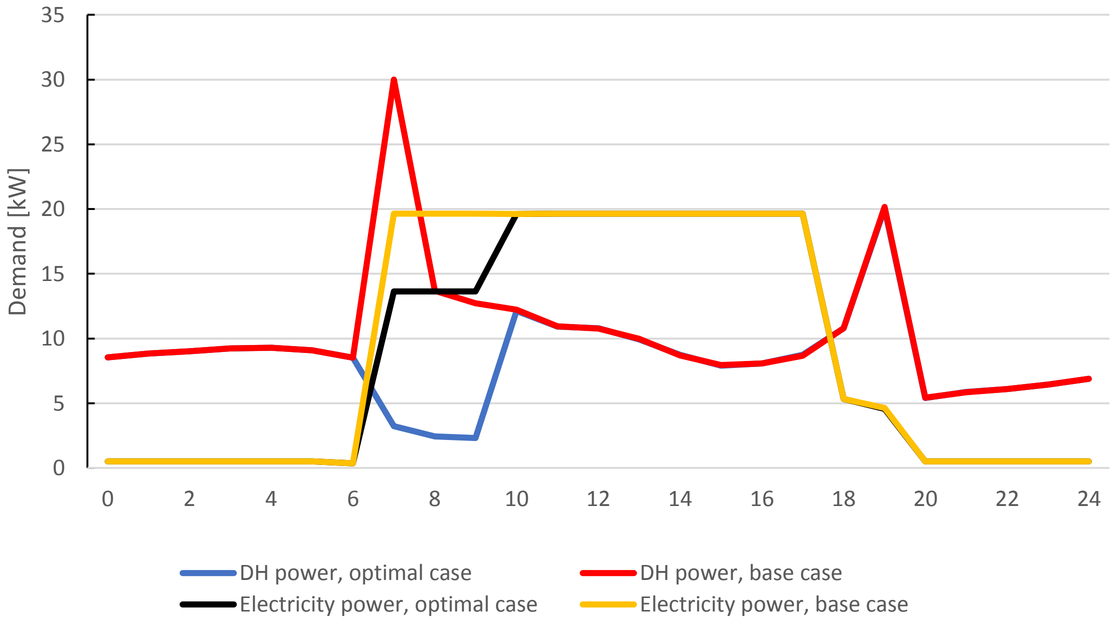

Figure 18. District heat and electricity power demand profiles of the office building on the simulated spring day.

Finally, the effectiveness of the different strategies in relation to each other was investigated in a similar manner as in the winter day case. The results of this effectiveness analysis for the spring day are presented in Figure 19. Again, parameters a1-a9 indicate the corresponding demand response strategies introduced in Table 5. Ventilation air flow reduction (a3 in the figure) again has the most effect on both heat and electric load reduction of the building. Adjusting the heating temperature set point in spaces (a1) also has a notable effect on total heat load reduction during the DR event, and Figure 19 also shows that supply air temperature adjustment (a4) has a small impact on the achieved load reduction. Electric load reduction potential of lighting power reduction (25) is similar in spring as in winter. All other demand response strategies seemingly have no effect on the achieved load reductions regarding either heat or electricity demand.

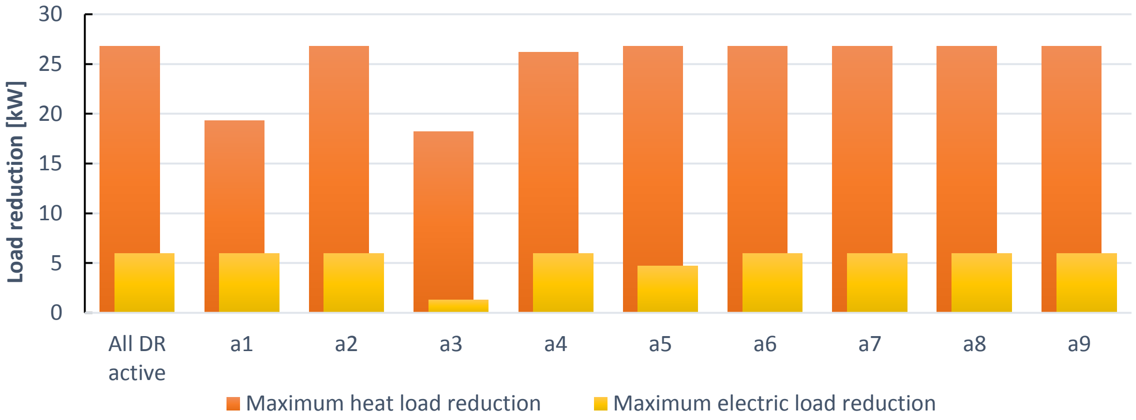

Figure 19. Relative effectiveness of investigated DR strategies for the office building on a spring day.

The demand response potential of the office building was also investigated on a hot summer day since the building is equipped with comfort cooling, which can act as a demand response resource in a similar way as heating does. The optimization itself for the summer day differed from the other two cases in that the building has no heat demand apart from domestic hot water heating, which in this paper is assumed as non-adjustable. Thus, no heating-based demand response potential exists and optimizing heating costs would be redundant, so electricity costs were chosen as the other minimized objective in the optimizations instead. Cooling for the building is produced with a typical chiller with a constant Coefficient of Performance (COP) of 3, which means that the chiller is able to produce three units of cooling while consuming one unit of electricity in the process.

Figure 20 presents total energy costs and cooling costs for the office building on a summer day. The cooling costs in Figure 20 are actually the electricity costs related to cold production, and they are also included in the overall electricity costs presented in the figure. Carrying out demand response on the studied summer day yields some 11% cost savings in total costs, which is a similar percentage-wise cost reduction than in both winter and spring cases as well. Cost savings on the summer day consist entirely of decrease in electricity costs as heating costs remain the same regardless if demand response is applied or not. Demand response reduces electricity costs related to space and ventilation cooling by about 12,5%, but the actual monetary savings are quite small since cooling related costs are rather small even on a hot summer day.

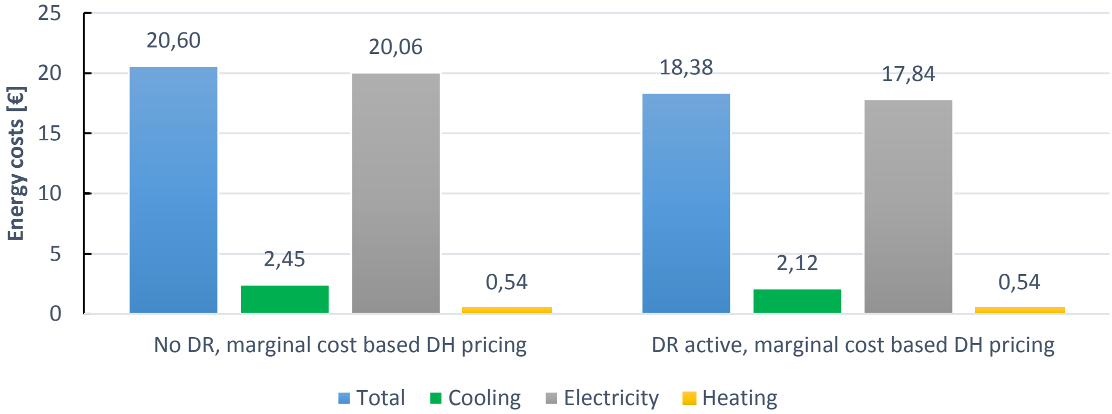

Figure 20. Total energy costs for the office building on the simulated summer day.

The building's cooling and electricity demand during the studied summer day are presented in Figure 21. Heat demand curve is not included in the figure since it follows the domestic hot water consumption schedule directly. Maximum decrease in cooling power demand during the demand response event is 6,7 kW, or approximately 56% from the demand in the corresponding hour in the base case. Electricity power reduction on the summer day is predictably the largest among the three studied days, about 40% from the original demand. Figure 21 also shows that according to the simulation results, there is a distinct cooling power rebound effect right after the demand response event, which actually results in a slightly higher daily peak when demand response is carried out compared to what the highest daily peak demand is without it. The increase in cooling demand during this momentary rebound compared to the base case is 2,3 kW on average during the first 15 minutes after the event, which is still a relatively small increase.

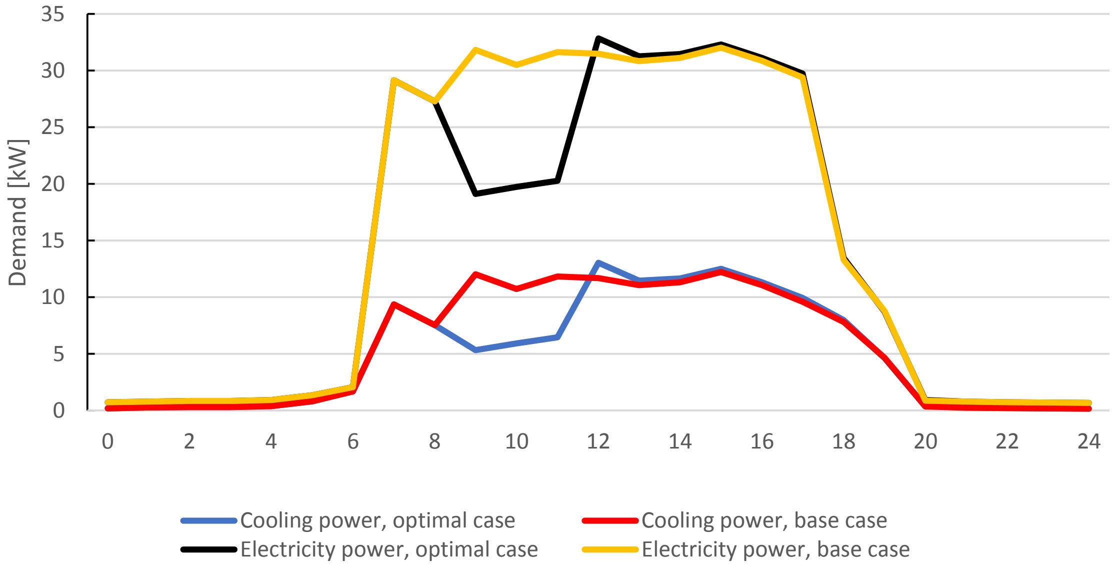

Figure 21. Cooling and electricity power demand profiles of the office building on the simulated summer day.

The relevant demand response strategies' effectiveness compared to each other was analyzed for the summer day as well in a similar manner as in the previous two cases, with the exception that cooling was investigated instead of heating. The results of this analysis are presented in Figure 22. Predictably, ventilation air flow reduction (a3 in the figure) once again yields largest load reductions according to the results. Zone cooling temperature set point adjustment (a7) is the other notable contributor in cooling load reduction, and lighting power reduction has an increased effect on electricity demand since the lowered internal heat gain decreases cooling demand slightly as well.

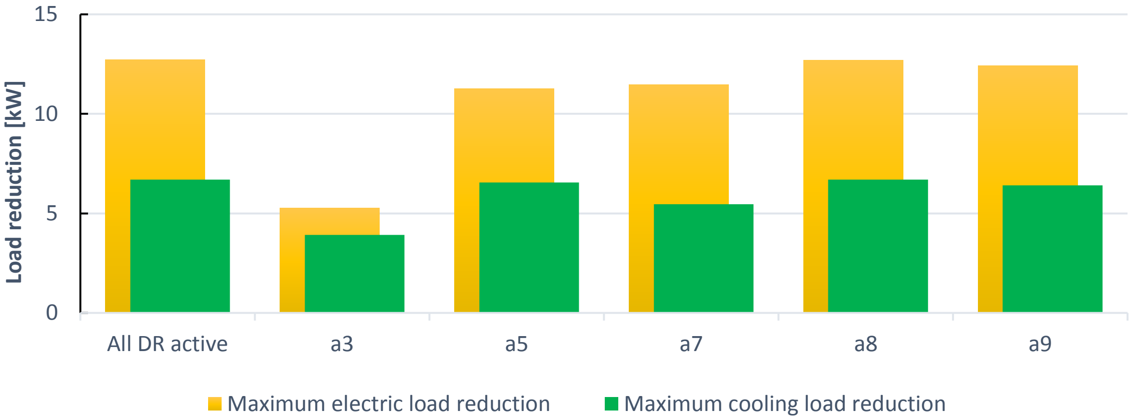

Figure 22. Relative effectiveness of investigated DR strategies for the office building on a summer day.

Due to the nature of the demand response investigated in this paper, direct effects resulting from demand response can be observed in the building's indoor climate. The effects of demand response on operative temperature and CO_2-content in one of the spaces, a 19 m^2 office room in the southwest corner of the building, during the investigated winter day can be seen in Figure 23. Figure 24 shows the results of corresponding comparisons made for the studied summer day. This particular office room was chosen for these further temperature and CO_2-content analyses because it has the highest percentage of dissatisfied occupants when DR is carried out. The horizontal green line in the figure implies both the minimum or maximum operative temperature limit and maximum CO_2-content limit allowed during the demand response event. As figure 23 shows, operative temperature in the example space during the studied winter day decreases by approximately 1°C during the demand response event and simultaneously CO_2-content increases by a maximum of about 300 ppm due to reduced ventilation. However, both the operative temperature and CO_2-content are still well within the acceptable range. Figure 23 also shows well how differently temperature and CO_2-content behave under abnormal conditions: operative temperature decreases to a lower level during the first hour and remains relatively stable throughout the rest of the event, while the CO_2-content accumulates almost linearly over time reaching its peak at the very end of the event. Clearly the conclusion that can be drawn from this is that the optimal ventilation air flow reduction is highly dependent on the length of the demand response event.

The reason why an operative temperature minimum lower than the indoor climate guideline S2-level's minimum allowed operative temperature (LVI 05-10440 en 2010) was chosen can be clearly seen in Figure 23 as well. The minimum level in the guidelines is 20°C, but operative temperature in the example space, and in most other spaces in the modeled building as well, is already below this minimum level most of the day even in the base case, and thus additional room for adjustments is needed for meaningful heating-related demand response to be possible with the DR strategies that were investigated in this study.

For the investigated spring day, the operative temperature and CO_2-content curves are very similar to the ones shown for the winter day in Figure 23. The chosen spring day is still considered heating season and the operative temperature minimum is a limiting factor along with the the maximum allowable CO_2-content. The operative temperature curves act differently on the summer day though, as can be seen in Figure 24. Notably, the limiting factor regarding operative temperature is now the allowable maximum instead of minimum. The PMV index values show small differences of -0,2…+0.2 at most between base cases and demand response cases, indicating that thermal discomfort in spaces does not increase much when carrying out demand response. Maximum PPD value of 17,85%, taking all simulation cases into account, occurs in one of the smaller office rooms during the summer day demand response event, although even then the increase from the base case is only about 3 percentage points.

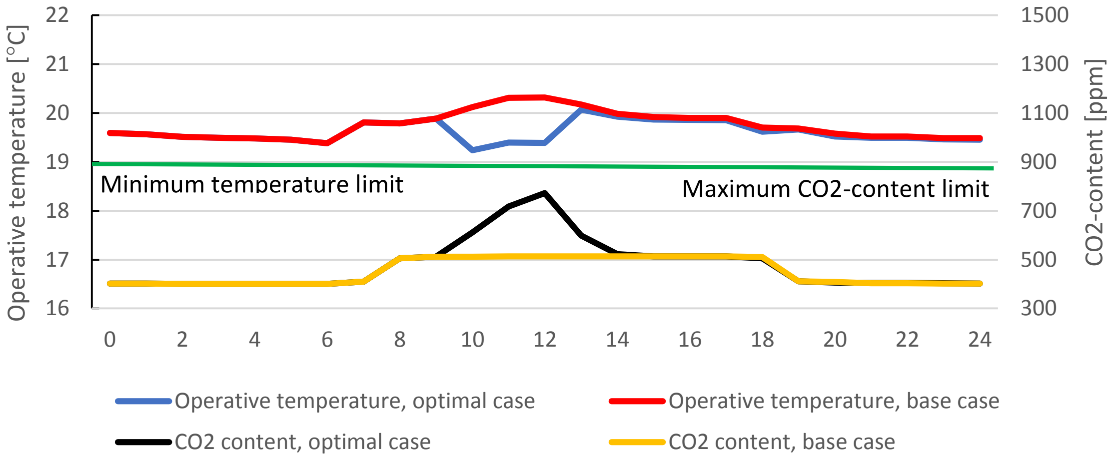

Figure 23. Effects of demand response in an office room on a winter day.

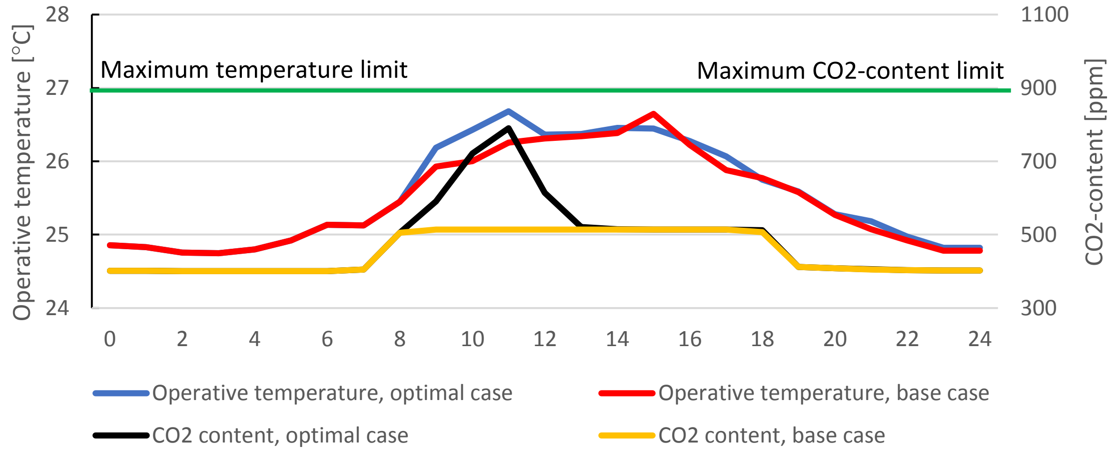

Figure 24. Effects of demand response in an office room on a summer day.

5.2 Apartment building results and analysis

Optimization and simulation results for the apartment building are presented in this chapter. Table 6 displays the optimal parameters determined by MOBO for demand response strategies' controls for the apartment building. Notably fewer strategies were investigated for the apartment building due to less complex HVAC-systems which offer less opportunities for load adjustments. The labels in the second column are again there to ease referencing these strategies later in the chapter. The results presented in this chapter are achieved with simulations that were identical to the simulations done for the office building. Summer day case was not studied for the apartment building because the building is not equipped with cooling and high indoor temperatures occur on hot summer days regardless if demand response is practiced or not.

It should be noted that in these following simulation results, it has been assumed that user equipment and lighting electricity consumption in the apartments produce costs for the residents rather than for the building owner, and as such they are not included in the cost and power demand analyses. Furthermore, all electricity related demand response affects the building owner's electricity use and the resulting costs. Ignoring residents' electricity leaves HVAC-equipment as well as standard lighting and equipment in general spaces as relevant electricity consumers from the building owner's point of view. HVAC-equipment includes the apartments exhaust air ventilation units' consumption and pumps for heat distribution. Heating costs, on the other hand, are assumed to be the building owner's responsibility for the entire building, including the apartments. This type of distribution of heating costs within an apartment building corresponds to a situation where heating is included in the rent as a fixed portion, for example.

Table 6. Optimal parameters for demand response strategies' controls in the apartment building.

Demand response strategy		**Original parameter value**	**Optimal parameter value, winter**	**Optimal parameter value, spring**
Zone heating temperature set point adjustment in apartments	b1	21°C	19°C	20,2°C
Heat distribution plant power reduction	b2	1	0,85	0,2
Ventilation air flow reduction in apartments	b3	1	0,45	0,45
Ventilation air flow reduction in general spaces	b4	1	0	0,05
Plant supply water temperature adjustment	b5	curve	-3°C	-35°C

Energy costs for the apartment building on a winter day according to the simulations are presented in Figure 25. It can be noted that heating costs dominate the energy cost structure in the apartment building, consisting of almost 97% of the total energy costs on the simulated winter day. From the consumer's (i.e. the building owner's) point of view, savings in heating costs constitute nearly all of the total achieved cost savings which are generated by carrying out demand response. Percentage-wise, heat cost reduction is approximately 6,8% of the heat costs in the base case. The small costs and cost savings related to electricity use are not surprising since there are significantly less electric loads in the modeled apartment building compared to the office building, for example. From the district heat producer's point of view, demand response potential on a winter day in the modeled apartment building is noticeably smaller than the potential in a similar-sized office building (Figure 14).

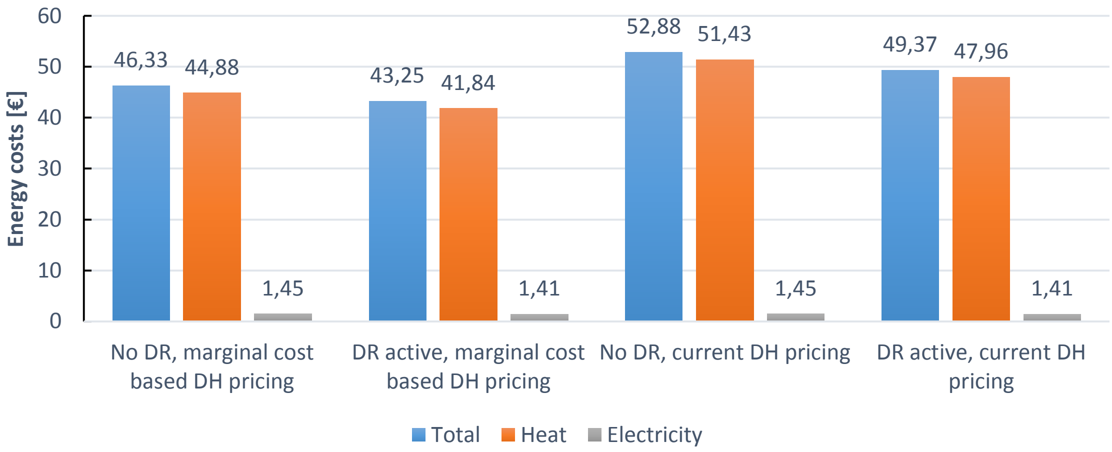

Figure 25. Total energy costs for the apartment building on the studied winter day.

The effects of demand response on heat and electricity demand profiles was investigated for the apartment building as well, and the load profiles with and without demand response on a winter day are presented in Figure 26. A secondary y-axis is used for electricity demand for clarity since it is so much smaller than the district heat demand of the building. As the figure shows, heat demand of the apartment building displays much less time-of-day –based variation than the office building, due to the fact that the building is occupied 24/7 to some extent. While the office building model's heat demand was influenced by HVAC and heat load schedules, the only true variables that affect the demand in the apartment building model are outdoor temperature and the domestic hot water consumption profile. For lack of better information available, occupancy and internal heat load profiles in the apartment building are flat throughout the day. Likewise electricity load profile of the apartment building is completely flat due to flat load profiles and no variable elements defined. These flat load profiles are of course somewhat unrealistic, as typically electric loads such as lighting and some general building equipment are used less during the night.

The hourly averaged district heat load reduction during the winter day demand response event in the apartment building is 24,5 kW at most, or approximately 75% of the heating power demand in the base case, so the apartment building certainly shows considerable load reduction potential as well, based on these simulations. Electric load reduction potential with these demand response strategies is only 0,4 kW, on the other hand. The timing of this demand response event actually fits to the heat demand profile rather poorly, occurring when daytime heat load of the building is at its lowest. A notable rebound effect in heat demand after the demand response event can also be seen in Figure 26. The rebound effect increases heat demand 3,3 kW on average in the first hour after the event compared to the base case, and decreasing the time-step of the output data in IDA-ICE to 15 minutes reveals that heating demand increases by 5,75 kW on average during the first 15 minutes of the rebound period. For whatever reason heating power demand never returns to the "normal" state after the demand response event, hovering at around 1 kW above the power demand curve of the base case. This could be due to numerical issues with the simulation software since there seems to be no valid reason why heat demand would remain higher hours after the demand response event.

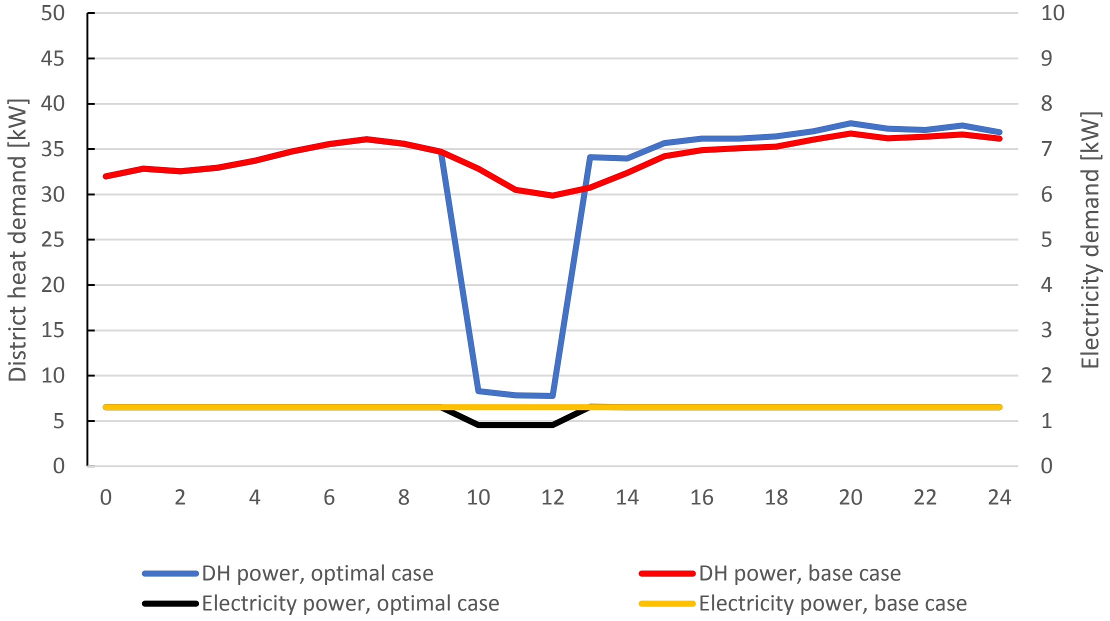

Figure 26. Heating and electricity power demand profiles of the apartment building on the simulated winter day.

The effectiveness of the different implemented demand response strategies compared to each other was also analyzed with the same methods that were used in the corresponding analyses for the office building. Results of said effectiveness analysis for the winter day case for the apartment building are presented in Figure 27. According to the figure, lowering zone heating temperature set point (b1 in the figure) and reducing exhaust air ventilation in apartments (b3), and to an extent in general spaces (b4), all have a noticeable contribution to the total heat load reduction. Changes in electricity demand and in the achievable load reduction are negligible across the board, as Figures 26 and 27 both suggest. It can be noted that zone heating set point adjustment in apartments is the most important strategy in regards to achieving the load reduction in the apartment building, which makes sense since ventilation air flows in an apartment building are small and radiators are the main heating mechanism for the building, unlike in the office building where ventilation contributed to space heating as well. In reality, it is possible that there is actually no mechanical ventilation air flow at all in an apartment building as natural ventilation is not uncommon especially in older buildings. From Table 6 it can be seen that the optimal parameter value for ventilation air flow reduction on the winter day is 0,45 or in other words an exhaust air rate of 0,225 (l/s)/m^2 during the demand response event. The simulation model does not take into account that the occupant likely has the opportunity to open windows in the apartment to provide a sort of additional natural ventilation, which would enable reducing the mechanical ventilation even further.

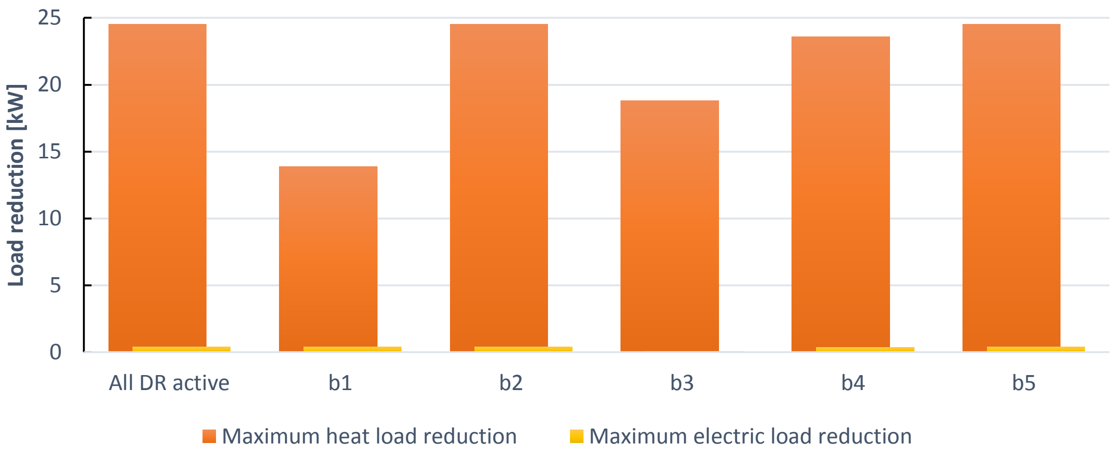

Figure 27. Relative effectiveness of investigated DR strategies for the apartment building on the studied winter day.

Results of the spring day case simulations for the apartment building are presented in Figure 28. Actual cost saving potential on the spring say is small, although percentage-wise it is comparable to the winter day case. Reduction in heating costs is 7,3%, which is proportionally actually slightly more than on the winter day. Electricity cost reduction potential is approximately 4,1% according to the results, although actual costs savings are extremely small.

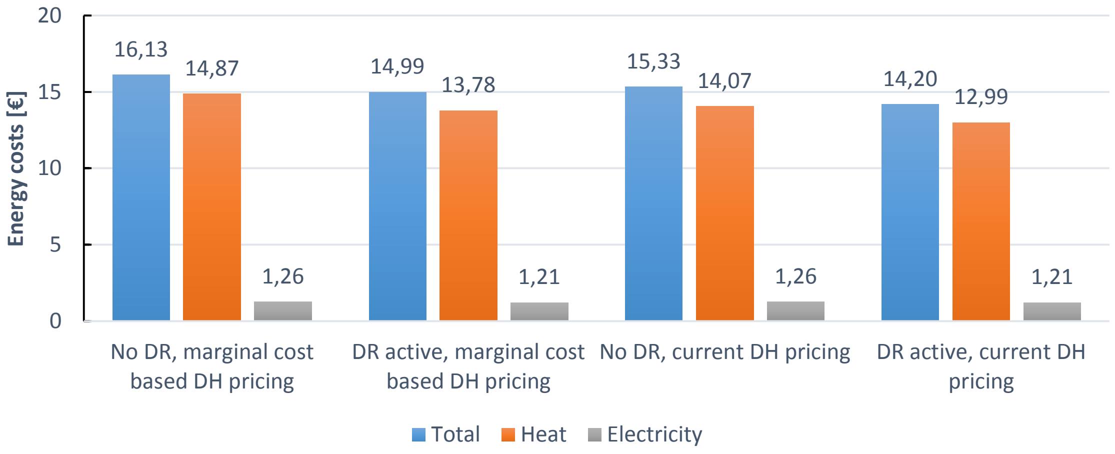

Figure 28. Total energy costs for the apartment building on the simulated spring day.

Heating and electricity power demand profiles for the apartment building on the investigated spring day are shown in Figure 29. As it can be seen from the figure, the timing of the demand response event fits the district head demand profile much better compared to the winter day case, now occurring at least partly when heat demand of the building is also highest. The reduction in heating power demand is approximately 24,5 kW, or ~75% of the original heat demand, on average during the first hour of the DR event. The load reduction of electricity use is the same as in the winter day simulation. Some rebound effect in heating power can be seen on the spring day as well, although it is much smaller than on the winter day. The heating power increase during the rebound period is approximately 1 kW on average during the first hour and 1,3 kW during the first 15 minutes after the demand response event.

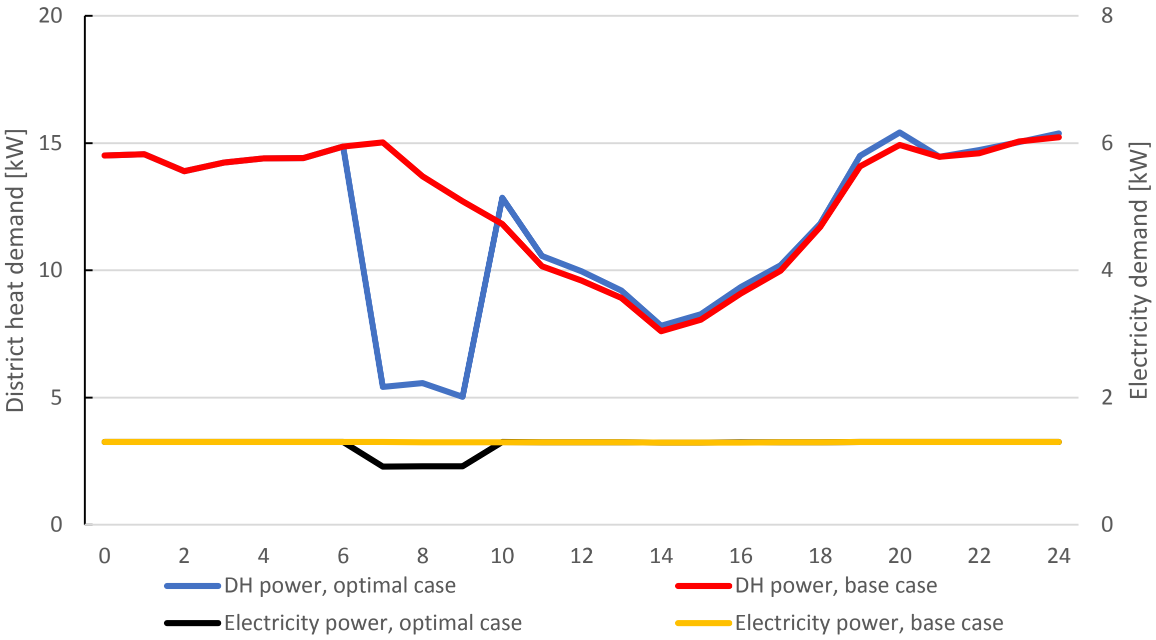

Figure 29. Heating and electricity power demand profiles of the apartment building on the simulated spring day.

Finally, results of the demand response strategy comparison for the spring day are presented in Figure 30. The figure seems to indicate that none of the strategies have any effect on the total heat load reduction achieved by implementing the optimal demand response control strategies though. This obviously cannot be true since load reduction is achieved and it has to be a result of something. Further investigation on the spring day results revealed that space heating demand is reduced to practically zero during the DR event, which can be achieved with a few different methods. For this particular case, the optimal demand response control strategies were investigated individually as well, i.e. having a case with no demand response as a base case and studying the effects implementing each DR strategy individually. Figure 31 shows the results of these simulations, and it reveals why Figure 30 fails to show any meaningful changes in heat load reduction between different demand response strategies. As it can be seen from Figure 31, both heat distribution plant's power reduction (b2 in the figures) and lowering supply water temperature in the radiator circuit (b5) by 35°C during the demand response event are both able to produce the load reduction of the optimal combination even when implemented individually. In other words, in this case simply cutting off space heating for the duration of the DR event by whatever means is needed to produce the achievable heat load reduction.

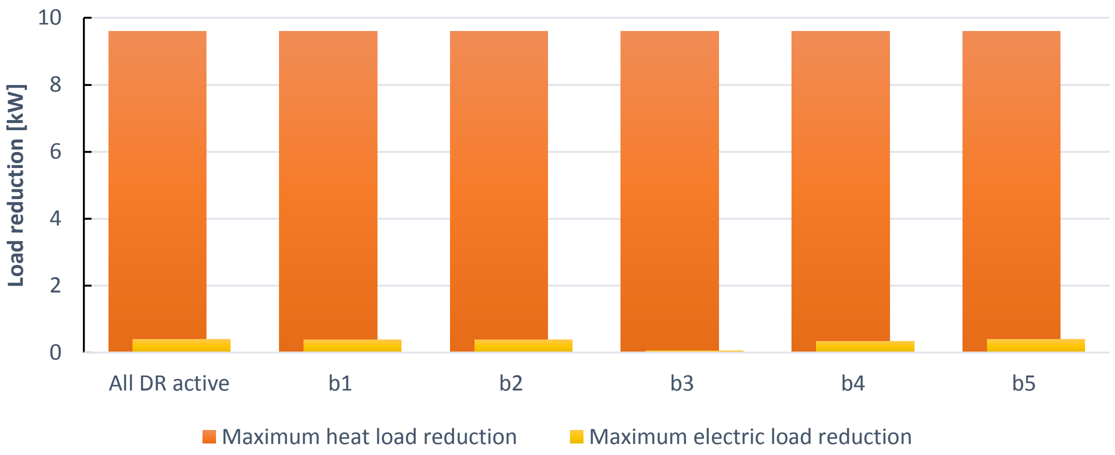

Figure 30. Relative effectiveness of investigated DR strategies for the apartment building on the studied spring day.

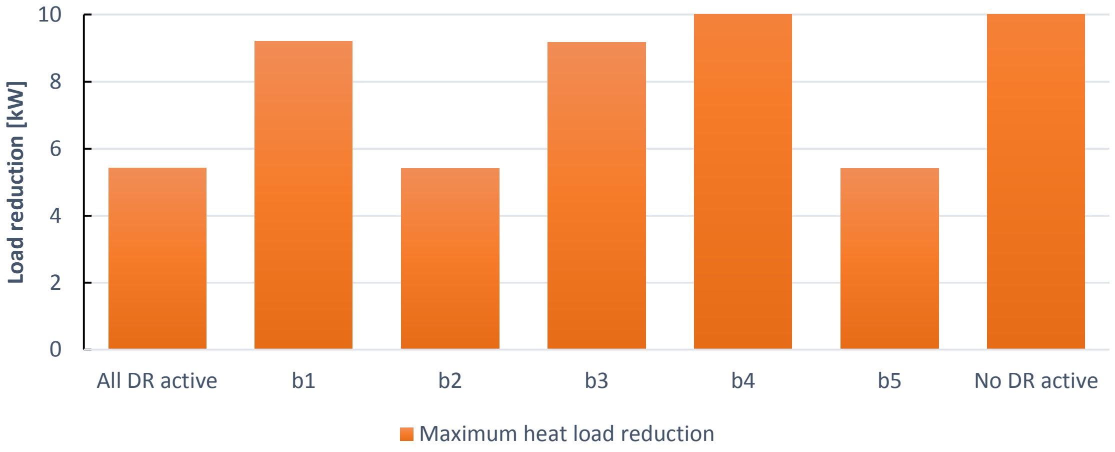

Figure 31. Load reductions achieved by implementing the investigated DR strategies individually on the studied spring day.

The effects of demand response in the building was tracked similarly as in the office building's cases. Figures 32 and 33 show the effects of demand response in two different apartments on the simulated winter day. The first figure shows CO_2-content and operative temperature profiles during the day for Apartment 4, which is a 62 m^2 apartment in the west side of the building. Figure 33 shows the same variables for Apartment 5, a 70 m^2 apartment in the northwest corner of the building. The biggest difference between these two apartments is that 50% of the walls in Apartment 5 are external walls while only 15-20% of the walls are external in Apartment 4. More external walls and windows lead to more heat losses, which also affects the operative temperature in the space. The reason for choosing these two spaces for further investigation is that applying the same demand response results in markedly different effects on the indoor climate in these two spaces. The effects of heat losses can be seen quite clearly when comparing Figures 32 and 33, as in Apartment 5 the minimum operative temperature is a limiting factor while in Apartment 4 the operative temperature during demand response stays well above the allowable minimum. Regarding CO_2-content the situation is reversed: maximum CO_2-content level is clearly a limiting factor in Apartment 4 whereas in Apartment 5 it is a non-factor.

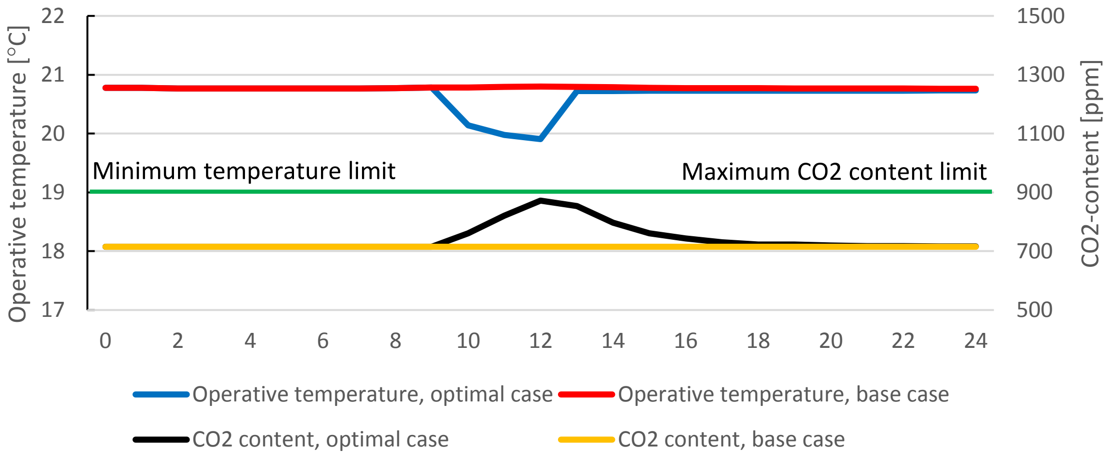

Figure 32. Effects of demand response in Apartment 4 on a winter day.

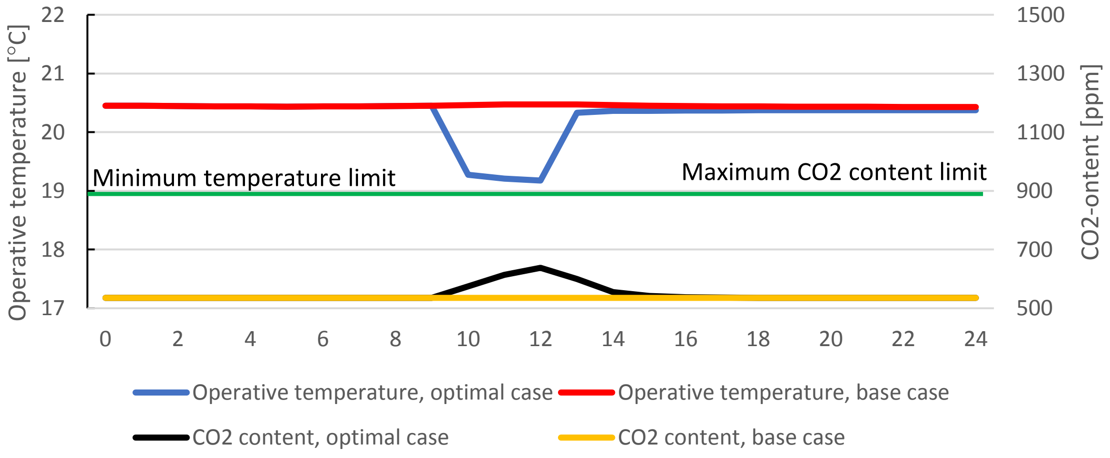

Figure 33. Effects of demand response in Apartment 5 on a winter day.

The effects of demand response in spaces on the studied spring day are largely similar to the presented winter day results. The exception is that operative temperature does not lower close to the minimum allowable value in any space during the demand response event, so the maximum allowed CO_2-content is the only limiting factor on the spring day. Even in a space such as Apartment 5, operative temperature only lowers by 0,5°C to 1,0°C during the spring day demand response event. As for occupants' thermal comfort, carrying out demand response results in only small changes in the PMV index values. In the space where the percentage of people dissatisfied is highest in all simulations, PMV only drops by 0,15…0,2 (from -0,4 to -0,6) during the winter day demand response. The maximum PPD value in any space of the apartment building during the winter or spring day demand response events is just slightly over 13%, which indicates good thermal comfort according to Fanger's classifications.

5.3 School building results and analysis

The school building was the last building type to be investigated in this thesis, and the results of the optimizations for winter and spring days are presented in Table 7. The investigated strategies are similar as with the other two building types, but the total amount of separate "strategies" that were optimized is larger due to more variety between different spaces. The same heat distribution plant still serves all spaces in the building so plant-related strategies affect the whole building in the same way. Optimal controls for ventilation and zone heating related strategies were determined separately for classrooms, the gym and general spaces, on the other hand. Separate AHUs serve each space type, which enables separate control during demand response, and the consumption and occupancy profiles for these space types differ somewhat as well. Lighting power reduction was included in the simulations in a similar manner as in the office building, although it concerns some of the general spaces of the building only, in other words the hallways and the dining hall. There are two 20 m^2 bathroom areas and a 36 m^2 kitchen in the building, which are assumed to have no demand response potential, i.e. none of the optimized strategies affect indoor environment conditions in these spaces.

Table 7. Optimal parameters for demand response strategies' controls in the school building.

Demand response strategy		**Original parameter value**	**Optimal parameter value, winter**	**Optimal parameter value, spring**
Zone heating temperature set point adjustment in classrooms	c1	21°C	20°C	19,6°C
Zone heating temperature set point adjustment in gym area	c2	18°C	17°C	16,6°C
Zone heating temperature set point adjustment in general spaces	c3	21°C	20,6°C	19°C
Heat distribution plant power reduction	c4	1	0,65	1
Plant supply water temperature adjustment	c5	curve	-2°C	-5°C
Ventilation air flow reduction in classrooms	c6	1	0,4	0,3
Ventilation supply air temperature set point adjustment in classrooms	c7	17°C	16,8°C	16,8°C
Ventilation air flow reduction in general spaces	c8	1	0,15	0
Ventilation supply air temperature set point adjustment in general spaces	c9	17°C	15,6°C	16,2°C
Ventilation supply air temperature set point adjustment in gym area	c10	16°C	16°C	14°C
Lighting power reduction in general spaces	c11	1	0,8	0,8

Energy costs for the school building with and without demand response activated on the studied winter day are presented in Figure 34. Heating costs dominate the cost structure for the school building as well, constituting approximately 90% of total energy costs on the winter day. Total costs and heating costs are also significantly higher for the school building compared to the similarly sized office and apartment buildings which were discussed in the previous two chapters. The main reason is likely the larger ventilation design air flows in the school building, which directly increases heat demand of the ventilation system. Figure 34 also shows moderate economic potential for demand response in the modeled school building. Savings in production costs for the DH producer are approximately 8€, or 8% of the costs in the base case. Heating cost savings are similar from the consumer's point of view, and since electricity cost savings are once again very small, total cost savings are also about 8%.

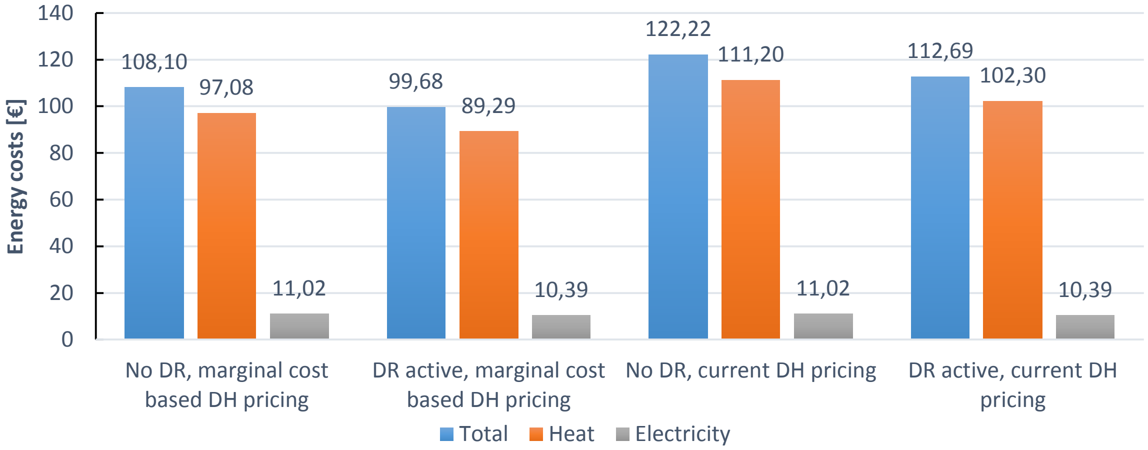

Figure 34. Total energy costs for the school building on the simulated winter day.

The school building's district heat and electricity power demand curves on the winter day case are presented in Figure 35. As the heating costs in Figure 34 indicate, heating power demand of the school building is largest of the three investigated buildings, exceeding 120 kW in the morning peak hours. As was the case with the other two building types, the demand response event does not quite occur concurrently with the peak heating demand hour of the school building on the studied winter day. Nonetheless, heating power reduction is significant according to the simulations, as the maximum hourly average load reduction is nearly 59 kW. The percentage-wise reduction is approximately 56%, which is a notably smaller relative reduction compared to the other two investigated buildings though. A clearly visible rebound effect of heating power can be seen in the power demand curve in Figure 35 too. The average heating power increase during the first hour after the demand response event is 7,6 kW, and during the first 15 minutes it is ~8,4 kW. Electric power demand, and the demand response potential as well, are remarkably similar to the office building's demand and potential on the winter day. Decrease in electricity power demand is a little over 5 kW during the demand response event, which is about 25% of the original electric power demand in the base case.

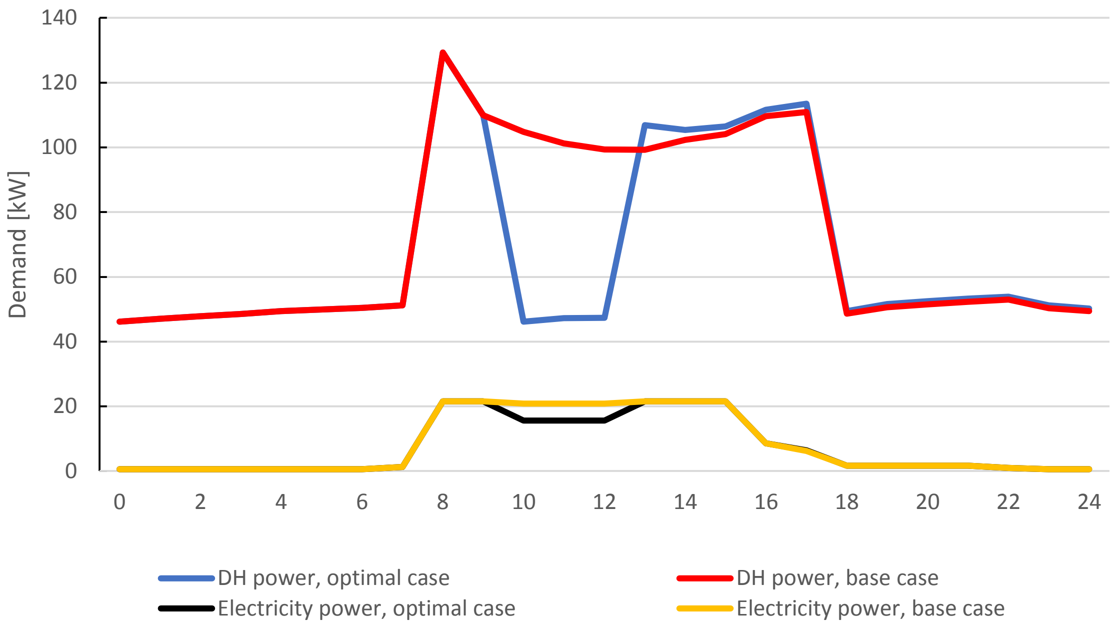

Figure 35. Heating and electricity power demand profiles of the school building on the simulated winter day.

Comparisons between the effectiveness of the investigated demand response strategies were made for the school building as well, and the results of these comparisons for the winter day case are presented in Figure 36. Ventilation air flow reduction related strategies (c6 and c8 in the figure) clearly contribute to demand response the most according to Figure 36. Changing the zone heating temperature set points (c1, c2 and c3) also contribute to load reduction, however all other strategies have very little contribution to the total load reductions, if any.

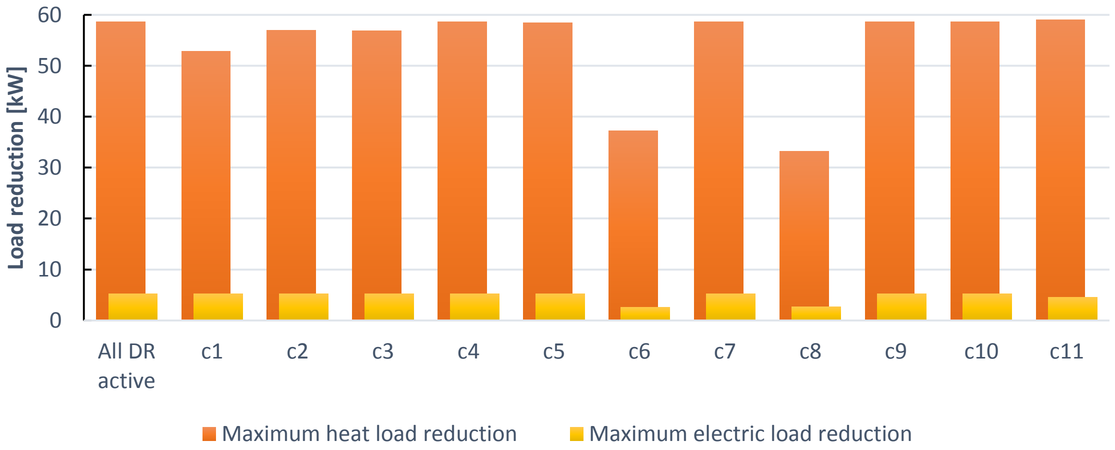

Figure 36. Relative effectiveness of investigated DR strategies for the school building on a winter day.

Results of the energy cost comparisons for the school building's spring day case are shown in Figure 37. Heat costs still account for about 75% of the total energy costs on the studied spring day and the cost saving potential of demand response for the heat producer according to the simulations is approximately 9% of the original heat production costs of the building.

Total cost saving potential relative to the original costs from the consumer's point of view is slightly larger compared to the winter day case, about 9,8%. Electricity consumption related cost savings are more or less the same for the spring day case as they are for the winter day case.

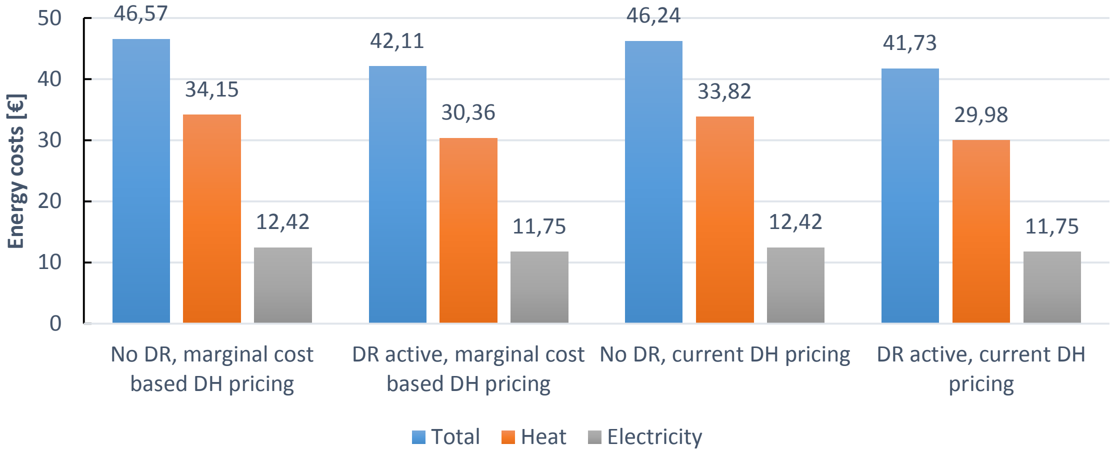

Figure 37. Total energy costs for the school building on the simulated spring day.

Power demand profiles for the school building on the studied spring day are presented in Figure 38. As the figure shows, the school building's peak heat demand on the spring day occurs at 08:00 in the morning, and timing of the demand response event corresponds well with the timing of the peak heating demand. As a result, the load reduction potential during the event is fairly significant: maximum heating power reduction according to the simulations is a little over 39 kW, which is almost 84% less than the heating demand during the same hour in the base case without demand response. A noticeable rebound effect in heat demand can be seen in Figure 38 for the spring day as well, with a peak heating power increase of 5,5 kW on average in the first hour after the demand response event and 6,3 kW on average in the first 15 minutes after the event. The increased heating power demand after the demand response event compared to the base case seems to linger somewhat for the duration of the operational hours of the building according to the simulations. A similar phenomenon can be seen in the power demand curves on the winter day as well in Figure 35, but it is a little more prominent on the spring day demand curves in Figure 38.

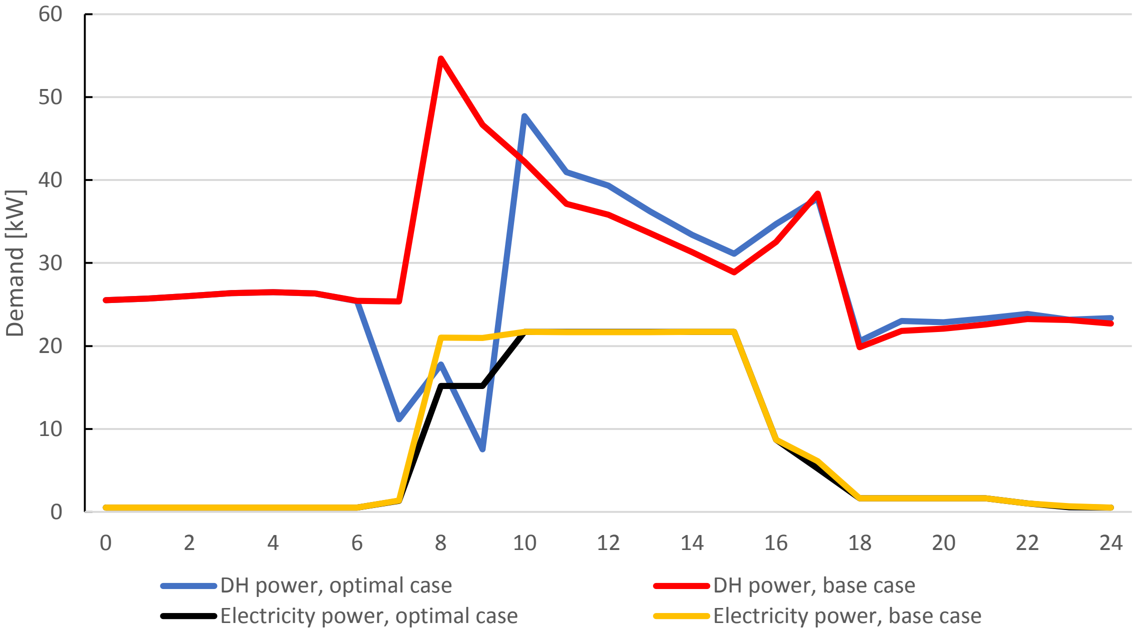

Figure 38. Heating and electricity power demand profiles of the school building on the simulated spring day.

The results of the analysis of relative effectiveness of different demand response strategies on the studied spring day are presented in Figure 39. Ventilation air flow reduction in classrooms (c6 in the figure) and in the general spaces (c8) are again the biggest contributors to both heat and electric load reduction, as the figure shows. Space heating set point adjustment in classrooms (c1) and in the general spaces of the building (c3) are other notable DR strategies according to Figure 39.

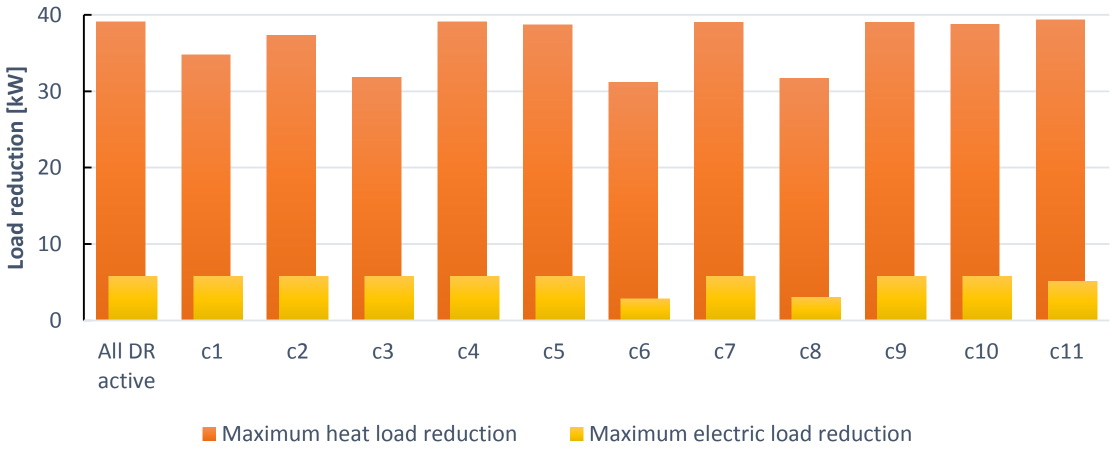

Figure 39. Relative effectiveness of investigated DR strategies for the school building on the studied winter day.

The effects of demand response in one of the classrooms on the studied winter and spring days are presented in Figures 40 and 41 respectively. The example classroom is an approximately 70 m^2 space in the northwest corner of the building with 50% exterior walls and three large windows. The location of the space and the large percentage of structures connected to outdoor air result in high heat demand in proportion to the floor area of the space, which makes this space susceptible to low operative temperatures when heating power is reduced during demand response in the heating season. Indeed, Figures 40 and 41 show that operative temperature in the space drops close to the minimum allowable value on both days when demand response is being carried out, while maximum CO_2-content in the space peaks relatively close to its maximum allowable value as well at the same time. Indoor thermal comfort level in the spaces is good in general, according to the simulations, regardless if demand response is carried out. For example, the PMV index values in the aforementioned classroom range between -0,49 and -0,54 during the winter day and between -0,27 and -0,4 during the spring day without demand response activities. Carrying out demand response has only a small effect in the comfort indices too: the maximum decrease in PMV is 0,12 on the winter day and 0,15 during the spring day DR event. The maximum PPD value in this classroom is a little under 13% on the winter day when demand response is practiced.

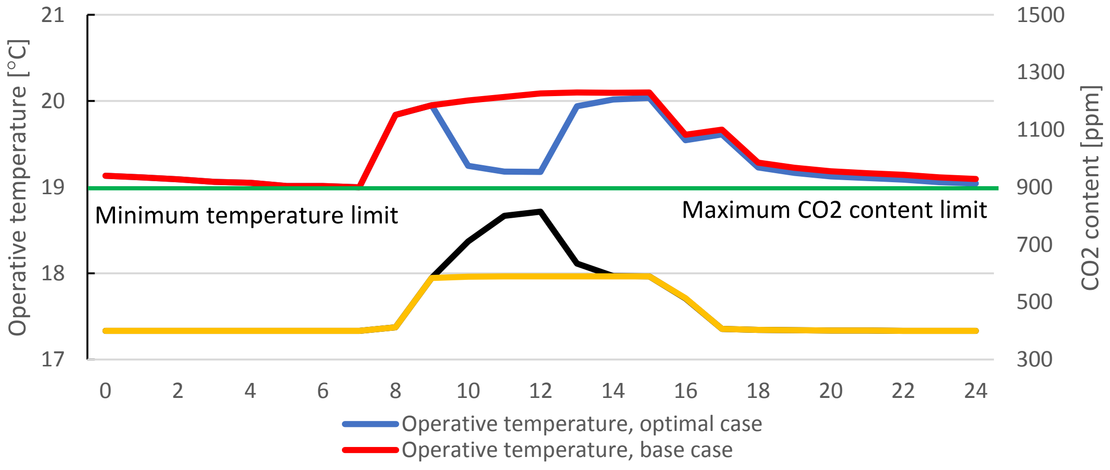

Figure 40. Effects of demand response in a classroom on a winter day.

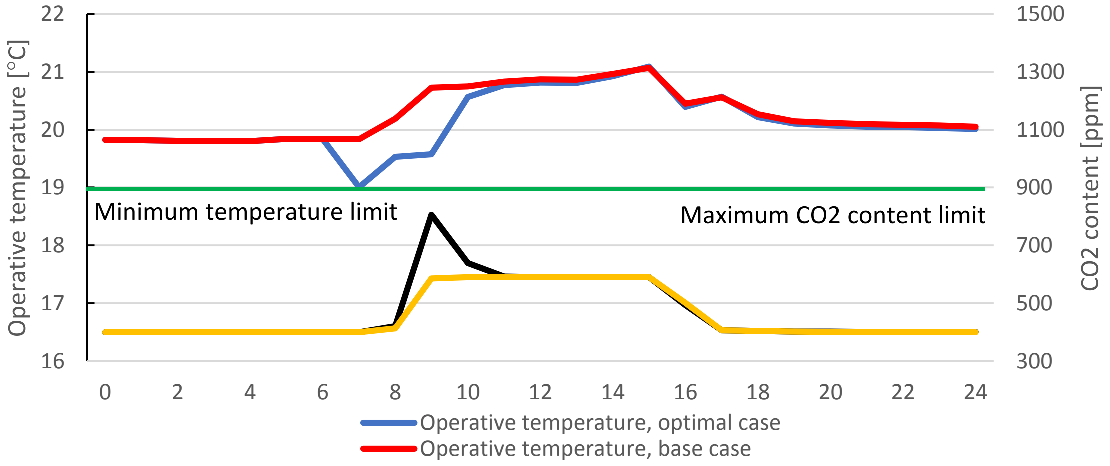

Figure 41. Effects of demand response in a classroom on a spring day.

5.4 Results and analysis on city scale

Considering that the optimizations and simulations were performed for buildings which are meant to represent an average city-owned building of each type, naturally it is reasonable to see what kind of demand response potential the entire city-owned building stock could potentially have. The amount of city-owned building mass for each of the three building types was introduced in Chapter 4.1, and the information is again summarized in Table 8. Table 8 also summarizes the cost savings resulting from demand response activities, which were presented in various figures earlier in Chapter 5. These are the cost savings that occur from the consumer's, in this case the city of Espoo's, point of view that are directly related to reductions in energy consumption when carrying out the three-hour-long demand response in the investigated buildings on the studied winter, spring and summer days. Heating costs and cost savings in Table 8 are calculated using the current pricing mechanism for district heating, which only has some seasonal variety. Figure 42 summarizes the maximum district heating power reduction potential in W/m^2 for each building type separately. As Figure 42 shows, heat load reduction potential of the modeled school building is largest of the three on both winter and spring days: nearly 60 W/m^2 on the winter day and 40 W/m^2 on the spring day. The office building shows load reduction potential of 37 W/m^2 and 27 W/m^2 on the winter and spring days respectively, while the corresponding potentials for the apartment building are 24,5 W/m^2 and 9,5 W/m^2 for the studied winter and spring days respectively.

Table 8. Summary of demand response –related cost savings from the building owner's point of view.

Building type and total gross floor area	**Heating cost savings from demand response [€ per 1000m^2]**		**Electricity cost savings from demand response [€ per 1000m^2]**		
	Winter day	**Spring day**	**Winter day**	**Spring day**	**Summer day**
Office buildings: 149 652 m^2	6,43	1,915	0,68	0,73	2,22
Apartment buildings: 885 673 m^2	3,47	1,08	0,043	0,052	
School buildings: 540 065 m^2	8,9	3,84	0,63	0,67	

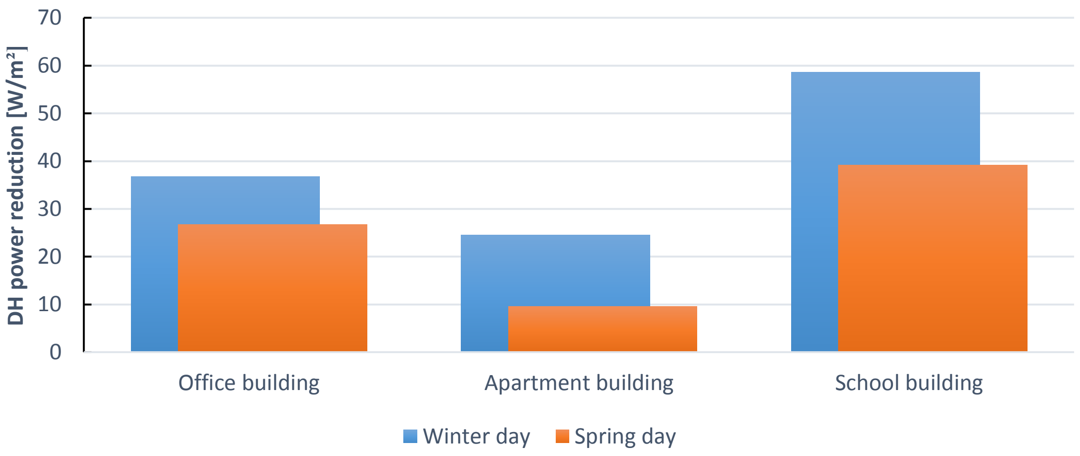

Figure 42. Maximum heating power reduction potential of the studied building types.

An estimate for the cost-saving potential of the entire building stock of Espoo city in regards to the three investigated building types can be made based on the figures in Table 8 and the total city-owned gross floor area for each type of building. Figure 43 presents these aggregated cost savings for each studied example day separately. As the figure shows, cost savings resulting from a single three-hour-long demand response event are by far highest on the studied winter day as expected. Total economic savings for the consumer resulting from load reductions during a single demand response event on a cold winter day are approximately 9300 € according to the aggregated totals, from which heating-related savings account for almost 95% of. The corresponding savings on the spring day are approximately 3800 €, from which over 86% is related to heating cost savings. No heating cost savings occurred during the studied summer day event, and the only building type for which the summer day is relevant is the office building so cost savings remain very low, only about 330 € for a single event on a hot summer day.

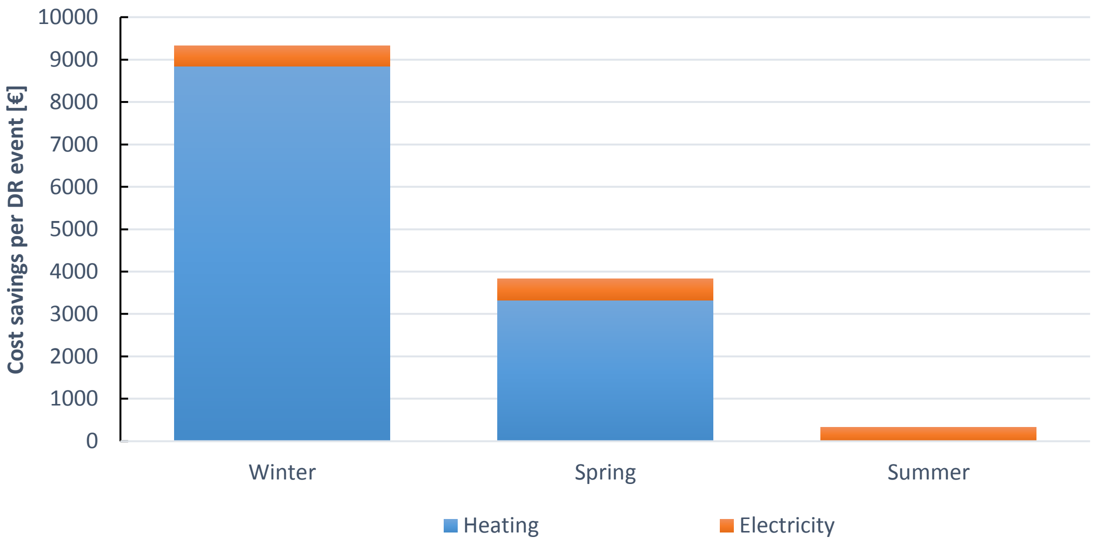

Figure 43. Aggregated cost savings on the investigated example days from the building owner's point of view.

It should be noted that the aggregated figures in Figure 43 are based on the assumption that the demand response potential of the average building, which is determined by the optimizations and simulations, represents an average of the demand response potential as well. Whether the average demand response potential determined in this study truly represents the average is impossible to tell in the scope of this study, and hence the figures in Figure 43 should be viewed as mere estimates of the magnitude of demand response potential the city's building stock has regarding offices, apartment buildings and schools. Furthermore, the studied winter day is a relatively cold one, considering the average outdoor temperatures of the winter months in recent years, so the demand response potential of a perhaps more typical winter day, when the outdoor temperature ranges between 0°C and -5°C, is somewhere between the winter and spring day potentials presented in Figure 43.

Naturally the district heat producer expects some savings from demand response as well, which result from decreased production and thus decreased production costs. Another estimate is made to depict the decrease in heat demand which would occur if demand response is carried out in every single building included in Table 8 in a similar manner as in the optimal cases for the average buildings. The aggregated district heat demand curves for the entire building mass investigated are presented in Figure 44. Again, the curves in Figure 44 were calculated under the assumption that the demand curves for the 1000 m^2 modeled buildings can be directly applied for the entire building mass of each type. Total district heat load reduction potential calculated this way is 58,9 MW, 54,3 MW and 52,6 MW on average for each hour of the winter day demand response event respectively. The rebound effect results in an approximately 7,1 MW increase in heating power demand in the first hour after the winter day DR event. For the studied spring day, the corresponding load reduction potential is 20,2 MW, 28,8 MW and 29,5 MW for each hour of the demand response event respectively. Rebound effect on the spring day results in a small 3,9 MW increase in heating demand on average during the first hour after the event.

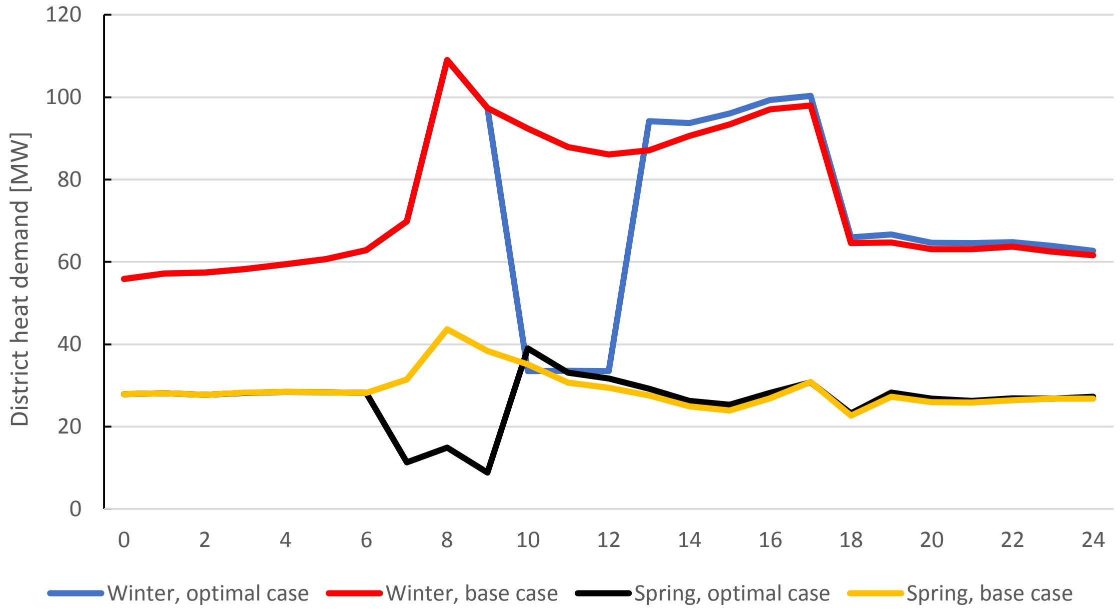

Figure 44. Aggregated district heat demand of the entire investigated building mass on the studied example days.

Calculating the economic effects of the heat load reductions during the demand response events is slightly more complex than simply scaling up the marginal cost –based savings calculated for each 1000 m^2 building in Chapters 5.1-5.3 for the entire building mass. The large aggregated reductions in heat demand may actually change the marginal method of production, in which case calculating the economic effect of load reduction based on the original marginal cost would yield incorrect results. Hence, the economic effects of the aggregated load reductions are estimated by re-calculating the production costs in MATLAB with a lower heat demand which occurs when demand response is implemented in full extent. Figure 45 shows the re-calculated total district heat production costs for the studied winter and spring days along with the original production costs for comparison. The aggregated heat load reduction from demand response decreases district heat production costs by 6370 € on the winter day and 2550€ on the spring day according to the re-calculated production costs. The production cost change takes into account both the decrease in demand during the demand response event and the slight increase in demand right after the event due to rebound effect, which is not really visible in the production cost curves in Figure 45 as the overall cost increase is rather small. Obviously the economic potential of a single demand response event is dependent on the marginal cost of production during that time, so if the event occurs when marginal costs are higher than in the cases investigated here, the production cost savings would be higher as well. The absolute peak marginal cost of heat production is over 100 €/MWh according to the simulation done in this thesis, so an appropriately timed demand response event could yield significantly larger production costs savings in the best case scenario.

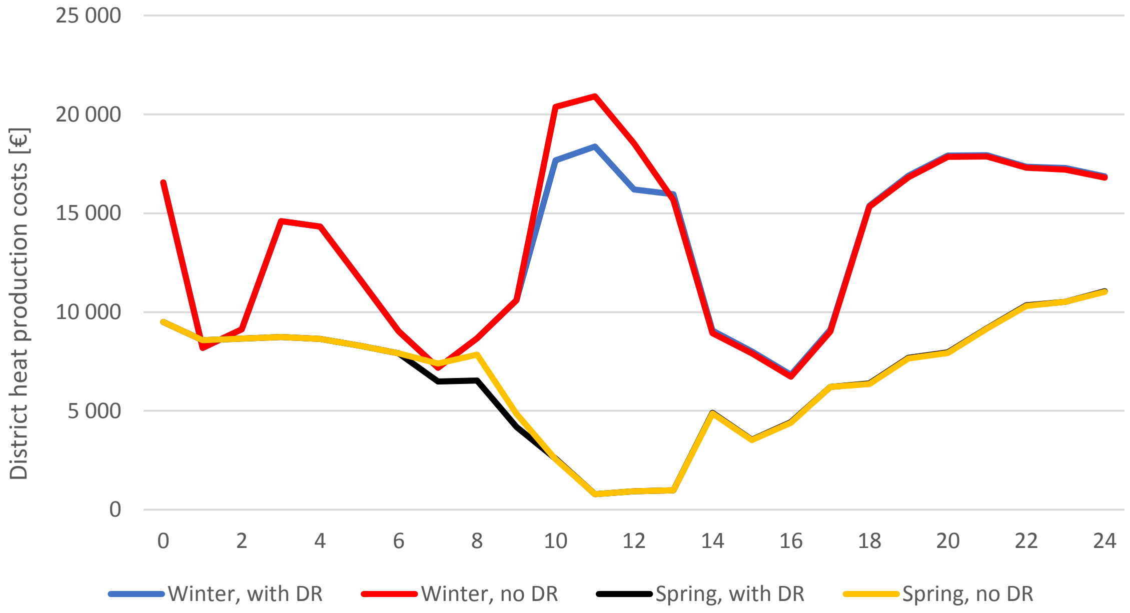

Figure 45. District heat production costs with and without demand response.

5.5 Implications and discussion

As for which demand response strategies show most promise in the modeled buildings, ventilation air flow reduction was found to have a most substantial effect on demand response related savings in every simulated case regardless of building type. In the office and school buildings, the result is not surprising since reducing air flow decreases both supply air heating demand and the AHU’s electricity demand. The apartment building has no supply air ventilation though, and thus no supply air heating is needed, yet merely reducing exhaust air ventilation surprisingly contributes to heating cost savings rather significantly. The reduced exhaust air flow is not able to effectively remove heat generated into the spaces by internal heat gains and solar radiation through windows, effectively lowering the heating need in the process. Zone temperature adjustments were another common contributor to demand response related savings in the simulated cases, although the effect on cost savings was found to be rather small in most cases. Rest of the strategies showed potential in few cases only, and the contribution of these strategies was marginal at best according to the simulations.

Lighting reduction is a strategy which offers some demand response potential in terms of electricity use but has an adverse effect on heat reductions and as such it is not a preferred strategy from the heat provider's point of view. Implementation of such partial lighting power reduction could be problematic and not very cost-effective either, since it requires dimming or partially shutting off certain light fixtures without affecting the light conditions in the spaces too much. Furthermore, modern lighting systems commonly feature motion and daylight sensors these days, which can drastically decreases the lighting system's electricity consumption and make lighting related demand response even more unfeasible. Combined with the low or nonexistent potential, lighting power reduction appears a poor demand response strategy in the modeled buildings.

Plant or chiller power reduction were not among the contributing demand response strategies in the majority of the cases, which was hardly surprising in the end. These actions affect every space in the building globally and while the adjustment step is only 5% of the nominal power, the adjustment is still so much "less precise" than for example space temperature set point adjustments that the optimizations preferred to limit heating power at the heating equipment rather than at the distribution center. If more accurate adjustments, say 1% of the nominal power at a time, were possible then perhaps this strategy would show more promise. Plant or chiller power reduction basically limits the pumping power, which should yield some small savings in electricity consumption as well though, but such savings are so insignificant that they did not improve the potential of these two strategies.

It should be noted that the effectiveness analyses of different demand response strategies, which were conducted for every individual case, use the case where all demand response actions have been activated according to the optimal parameters as a base case against which the individual strategies' effectiveness is compared. Some of the investigated strategies are notably related to each other though, which means that if implemented individually and using a case with no demand response implemented as a comparable, the results of the effectiveness analyses could be different. For example, ventilation supply air temperature set point and space temperature set point are connected so that if supply air temperature is lowered without any adjustments to the room temperature set points, the lower AHU heating power will be compensated by increase in heating power of space heating equipment. However, as the optimizations determine optimal parameter values specifically for the optimal combination of strategies rather than for strategies implemented individually, the same values may be non-optimal if strategies are implemented and analyzed individually against a base case with no demand response activated at all.

An important factor regarding different demand response strategies' potential in reality are any possible investment needs that would undoubtedly emerge when implementing HVAC-controls that enable load adjusting. The investment requirements can differ significantly between different strategies, which could make low-cost strategies with lower demand response potential more attractive than ones with high costs and higher savings. Ventilation air flow reduction, for example, may require investing in frequency converters to adjust the fan power, which likely requires a larger initial investment than e.g. space temperature adjustment that might be possible to do directly via an existing building automation system with merely a software update requirement. A full economic evaluation of the strategies should be conducted to determine the realistic potential of each strategy, taking into account the investment and operational costs of implementing the strategies in addition to the cost saving potential that was determined in this study. Investment needs especially can be very building-specific since they are dependent on the actual current state and age of HVAC and automation systems in the building, and in reality there are many more variables affecting an investment decision other than just the cost of the equipment itself.

Another thing to note when viewing the results is that the results of the optimizations and further simulations showcase the demand response potential relative to base cases with no deviations from standard use of equipment. The base cases do not take into account the possibility of custom operation of different HVAC-systems that are made possible by the installation of demand response enabling equipment such as frequency converters in AHUs. Frequency converters in ventilation machines enable air flow control and it would be reasonable to expect that the building owner would in reality take advantage of the installed equipment in full capacity outside demand response events as well, which means that the actual air flow in the base cases could be less than the standard design air flow, for example in winter it could be half the design air flow. An example simulation was made for a winter day for the office building, where the ventilation air flow in the base case is half the design air flow, i.e. half of 2,0 (l/s)/m^2. This simulation was first done without any demand response to produce the base case, and then with the same demand response applied as in the original winter day simulation in Chapter 5.1. Heat demand curves obtained from these two simulations are presented in Figure 46 along with the results of the corresponding original simulation results. With this scenario, load reduction potential of the office building on the winter day decreases about 60% compared to the original potential presented in Chapter 5.1, and the change can be clearly seen in the figure as well. The decrease in potential is a direct result of decrease in overall heat demand, which leaves less load to be adjusted during the demand response event. A constant air flow of 1,0 (l/s)/m^2 is enough to keep the CO_2-content and temperature in spaces within the normal acceptable limits, so this hypothetical scenario is certainly within the realm of possibility and furthermore could be considered energy efficient use of the equipment.

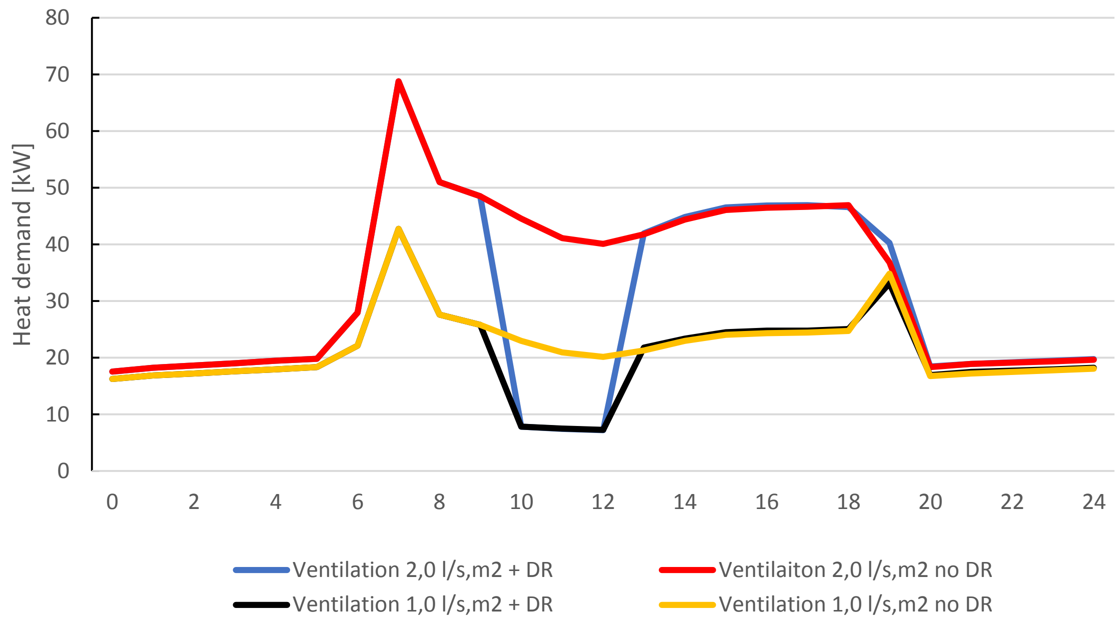

Figure 46. Effect of general air flow reduction on demand response potential.

The same effectiveness analysis of different demand response strategies as in Chapters 5.1, 5.2 and 5.3 was made for the aforementioned case with lowered ventilation air flows throughout the day. The office building and the studied winter day were chosen for this analysis as well, and the results are presented in Figure 47. Figure 47 shows that while total load reduction is significantly lower when frequency converters are used outside the DR event, ventilation air flow reduction (a3 in the figure) is still the strategy that has the most impact on total load reduction during the event.

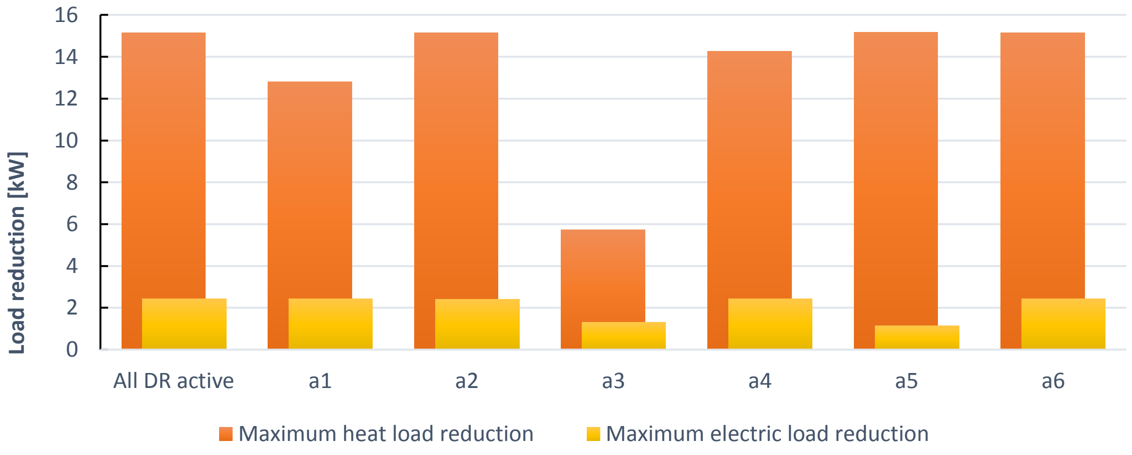

Figure 47. Relative effectiveness of investigated DR strategies with lowered ventilation air flows throughout the day.

Another issue related to the investigated strategies is that they are modeled as global or space type specific instead of space-wise, which can be a simplification and understates the potential somewhat. This is especially evident regarding space temperature adjustments, which should be perfectly doable for each space individually in reality rather than setting the space heating equipment's set point globally for the entire 1000 m^2 floor. Global adjustments mean that the optimal parameters are limited by the indoor climate constraints in one space, while the parameter values could be adjusted further in other spaces still if space-wise controls were applied. For example, when operative temperature reaches the minimum limit value during winter day demand response in one space, the global room temperature cannot be adjusted any further even though operative temperature in every other space in the building is still above the minimum limit, which would enable more adjustments in theory. Space-wise controls would therefore likely increase the potential of demand response in the buildings. The simulations showed that global temperature adjustments produce operative temperatures relatively close to the minimum value in most spaces though, so the difference between the current results and results with space-wise controls may not be large in any case. Furthermore, space type –wise controls were applied in cases were the building included markedly different types of spaces, so the adjustments were not entirely global in e.g. the school building.

Load-shifting, which is the type of demand response where energy consumption is shifted and the net total of the day does not change as a result of demand response, was not the type of demand response investigated much in this study. Technically, the rebound effect seen in some of the presented results could be considered as load-shifting of sorts, however it is not controlled per se and only a small part of the load is shifted. Salo (2016), for example, studied predictive district heat load-shifting from peak demand hours to off-peak hours with promising results. The incentive for load-shifting could be the marginal cost based district heat pricing that was used in this study to determine the savings potential from the district heat producer's point of view, for example. Since all demand response in this study reduces consumption rather than shifts it, a marginal cost based pricing mechanism does not really bring any additional benefits to the customer. Combining the demand response strategies of this study with load-shifting and the marginal cost based heat pricing mechanism, and determining the optimal again, could be an interesting subject for further studies.

An interesting simulation result is that decreasing the heating supply water temperature seems to have very little contribution on load reductions and cost savings, which is surprising considering that it is a strategy that has been successfully used in a few pilot projects (e.g. Kärkkäinen et al. (2004) and Fortum (2015d)). It seems possible that the models are perhaps too simple for this strategy to work efficiently as further examinations revealed that to produce any significant load reduction with this strategy, a large temperature set point decrease is required, for example in the office building temperature set point decreases over 30°C only begin to show reductions in heat demand. A large temperature decrease causes issues in certain spaces which are most vulnerable to indoor temperature changes when heating power is limited though, which in turn limits the amount that the temperature set point can be changed during a DR event. The full load reduction potential of this particular strategy is far from reached in the modeled buildings, in other words.

It should also be noted that in the optimizations in this study both heating costs and total energy costs were minimized simultaneously with the aim to provide best results for both parties involved. Optimizing heating costs only, effectively ignoring the consumer's viewpoint, would perhaps yield slightly different optimal results in some cases. An example winter day optimization was made for the office building to test this theory. The results of this test optimization were identical to the original optimization results with heating costs and total costs minimized simultaneously though, indicating that changing the objective solely to heating costs changes the optimal parameter values very little if at all. Furthermore, savings in heating costs are much more significant compared to savings in electricity costs in all investigated cases, as Table 8 shows, therefore the optimal including a total cost minimization should be close to the heating cost minimized optimal anyway. Additionally, the only major contributor to electricity cost savings among the investigated demand response strategies is ventilation air flow reduction, which was found to be a major factor in heating cost savings as well and as such the optimal control of this particular strategy during a demand response event is not going to change regardless if electricity costs are taken into account in the optimization problem.

The optimization itself and the constraint functions included can also produce some inaccuracies in results. The possibility of non-optimal solutions is always present in optimizations with limited population and generation sizes, even though the optimization algorithm should be capable of producing results near the true Pareto-optimal front with even smaller amounts of simulations. The constraint functions do not produce inaccuracies but it is clear that the limiting operative temperatures and CO_2-contents have a major influence on the buildings' demand response potential, and applying different limits would produce different results. The minimum operative temperature limit could be lowered even further, for example, which would enable even larger load reductions during the studied winter days. Further investigating the correlation between the constraining limits and the load reduction type demand response potential of a building could perhaps be a subject of a future study.

It cannot be stressed enough that the actual load reduction potential is very much building specific and there is likely no one "optimal" solution that can be implemented in larger scale without any additional insight into the building's energy use. Planning and implementation of demand response enabling systems in buildings should always include energy simulations that use actual building HVAC-systems' information and actual load profiles for all relevant loads as accurately as possible. The methodology used in this study is still valid however, so that when the accurate building model has been constructed, the optimization of several different strategies can be done in the same manner as in this study.

While heat demand of the modeled buildings likely resembles the heat demand of actual buildings as well, true electricity demand in real buildings is very likely notably higher than the demand in these modeled buildings. The models used in this study are bare bones type and do not include any non-standard energy consumption, likely resulting in an underestimation of electricity use especially. Heat demand is mostly dependent on outdoor temperature and heat conductivity of building structures, hence the simplified model buildings represent real buildings with sufficient accuracy. The model buildings' electricity use, on the other hand, consist of HVAC equipment related electricity consumption and standard levels of lighting and user equipment. Electricity consuming equipment such as elevators, outdoor lighting, saunas, kitchen appliances etc. are all ignored yet they are in reality not uncommon features in the types of buildings investigated. These additional energy uses do not contribute to demand response though, at least in regards to the strategies studied in this thesis, so not including them does not skew the results of the €/m^2 –based demand response potential analyses. The percentage-wise demand response potentials for electricity, presented earlier in Chapter 5, are affected by this lack of realistic electricity using equipment in the models, however.

The lack of more realistic occupancy and internal load profiles can be considered another limitation of this study. Occupancy profiles as well as lighting and user equipment electric load profiles are completely flat, with a few exceptions only, which is obviously a simplification and flattens the total electric load profiles of the building, which can be seen in all the demand curves presented earlier in this chapter. In reality, there is of course some variation in electricity loads which would be taken into account when modeling actual buildings and which would result in a more complex load curve. Using arbitrary made-up profiles would have been certainly possible but as standard values were used for almost everything else, it was perhaps more justified to use standard profiles as well. The only exception to this are general spaces in the apartment building and in the school building, both of which have custom occupancy profiles since there is very little to no constant occupancy in these types of spaces in reality and thus the occupancy in these spaces in real buildings can be estimated with a rather high accuracy. An example of a measured occupancy profile in a Finnish office building can be seen in the study by Ahmed et al. (2015), for example, and the occupancy rate during the day is certainly not constant.

One major source of possible inaccuracies in the results of this thesis are the simulation models themselves, and especially the custom control mechanisms which had to be constructed to enable load reductions during the demand response events. The controls had to be built mostly from scratch using the mathematical and logical tools the simulation software provides. In addition to the custom control mechanisms, a separate macro had to be constructed to incorporate hourly energy prices into the model since by default IDA ICE does not support such variability in prices. All these custom controls and macros were thoroughly tested before any optimizations though and they all seemingly work as intended, however there is naturally some uncertainty in such custom-made control systems and it is entirely possible that they produce some inaccuracies in results.

The limitations of the marginal cost calculation, explained in detail in Chapter 4.3.1, resulted in a situation where demand response signals based on average production costs rather than marginal costs had to be used. Realistically, marginal costs of heat production feature more fluctuation as the CHP-plants utilization rate is likely higher, making them the marginal production method more often. The “correct” way of determining the timing of demand response events is to base it on the marginal costs of production since the aim is to reduce peak production, i.e. the marginal production during peak demand hours. For the purposes of this study though, it does not really matter what is the signal for demand response since no significant load-shifting occurs as a result of the event and this study considers single example days only rather than calculating any kind of savings for a longer period of time. The more interesting aspect of the results from the heat producer’s point of view are the possible load reductions in megawatts since the economic gains of a single demand response event in reality would depend on the actual marginal cost level before, during and after the demand response event anyway, which is very much case dependent. Peak marginal production in a very cold winter day may have marginal costs more than 100 €/MWh, while a similar marginal cost peak on a spring day could be just half of that. An automated demand response event timing process, which evokes DR events based on differences in marginal costs between subsequent hours, would signal an event in both abovementioned cases if the cost difference requirement is fulfilled. Realistically, the number of events in a year the producer is planning to evoke and the consumer is willing to accept more or less determines the correct marginal production cost level that evokes a demand response event when using such an automated process.

6 Conclusions and summary

6.1 Conclusions

Demand response in terms of load reduction potential was investigated for typical Espoo city-owned buildings in this study. The goal was to determine the load reduction potential for demand response purposes in three different typical city-owned buildings (an office building, a school building and an apartment building) and to investigate which demand response strategies would be most beneficial in regards to achieving this load reduction. The load reduction potential in buildings was analyzed by creating building energy simulation models in a simulation software IDA ICE and implementing various possible demand response control possibilities related to different types of DR strategies. Optimization tool MOBO was then used to maximize savings in heat production costs during a predetermined DR event, and simultaneously maximizing the cost savings from the building owner's point of view by taking into account both heat and electricity costs. The optimization determined parameters for the implemented controls of different DR strategies which in turn produce the maximal economic savings during DR events. Economic potential of the load reductions for the district heat producer was estimated further by calculating the marginal and total production costs for the same day with and without implementation of demand response large-scale in all city-owned buildings of the investigated types for the city of Espoo in southern Finland. The marginal cost calculations were performed with a mathematical programming software MATLAB, using realistic input data for demand, fuel prices et cetera. The cost savings achieved by carrying out demand response are directly related to reduced energy consumption during the DR events rather than shifting heat or electric loads to another point in time,

The aim of the optimizations in this study was to maximize the load reduction without sacrificing thermal comfort of the occupants' too much: indoor air temperature was allowed to decrease by 2°C at most, and the CO_2-content in the spaces was not allowed to exceed the standard limit of 900 ppm. Allowing these small changes in indoor climate conditions provides adequate room for load adjustments, yet it does not cause unacceptable thermal discomfort or dissatisfaction for the occupants. The changes in occupant dissatisfaction are also tracked in the simulation software to ensure that good comfort level remains despite heat and electric load adjustments.

The performed analyses indicate that there is significant load reduction potential for demand response purposes in the building stock of the city of Espoo. An estimated maximum of 59 MW heat load reduction, or 60-70% of the original peak heat demand of this cluster of buildings, was possible according to the simulations on the studied example winter day, which accounts for approximately 10% of the district heat demand of the entire city at the time. According to further MATLAB simulations, the single three-hour demand response event would reduce district heat production costs by 6370 € on the winter day. Corresponding load reduction potential for the district heat producer on the studied spring day is 29,5 MW, which is also 60-70% smaller than the original load similarly to the winter day case. Similarly calculated difference in heat production costs on the spring day is 2550 €. Assuming that demand response is carried out in every single office, school and apartment building owned by the city of Espoo, the city would gain cost savings of 9300 € on the winter day and 3800 € on the spring day, due to a single three-hour long demand response event during these two days. The cost savings from the property owner's (i.e. the city's) point of view are a combination of heat and electricity cost savings resulting from reduced energy consumption during the demand response events.

Comparing the results of this thesis with previous studies on the subject is possible but not straightforward, as the number of district heat demand response related works with similar objectives is rather small and often such studies have been conducted with slightly differing study methodologies. Furthermore, the results in these studies are dependent on factors that are inevitably different in different studies, such as weather conditions during the time frame, the applied constraints and differences related to the investigated buildings, the last one being an especially important factor in pilot tests involving real buildings. Timing of the DR events on a given day also affects the load reduction potential of the buildings, which can be clearly seen from the spring day simulation results for the office building presented in this thesis, for example. The timing of the event in that case coincided with the morning peak heat demand, which resulted in a very large heat load reduction during that hour. Nonetheless, some comparisons can be drawn between this thesis and previous works in regards to the magnitude of the heat load reduction potential. Salo (2016) simulated 22-26% peak heat load savings by shifting heating to more opportune times and using the thermal mass of buildings as heat storage. However, a major difference between that study and this thesis is that in Salo's study heat loads are shifted in such a way that total consumption remains unchanged, whereas here heat storing possibilities are not investigated at all and total heat consumption heavily decreases.

Kontu (2014) and Jokinen (2013) investigated the DR potential in district heated residential buildings in Helsinki in a study with IDA ICE simulations and allowing a one degree indoor temperature decrease during a one hour DR event in the morning. The reported maximum relative heat load reduction in Kontu (2014) and Jokinen (2013) was approximately 80% of the momentary heat load in the DH network of the city. That particular study is perhaps the best comparable to the empirical study of this thesis, as both involve building energy modeling in IDA ICE and buildings located in southern Finland, even though otherwise the study methodologies used differ slightly. Studies based on pilot tests by Johansson et al. (2010) and Kärkkäinen et al. (2004) reported 20-25% heat load reductions during demand response events, which are considerably smaller compared to the results of this thesis. The former study reports no impact on indoor temperatures during DR events though, while in this thesis a two degree drop is allowed and often experienced. The study by Kärkkäinen et al. (2004) could be a better comparable in terms of realistic load reduction potential, since two of the three buildings they investigated are located in Finland and the study involved 2-3 hour DR events and small decreases in indoor temperatures were also reported.

The results presented in Chapter 5 should not be interpreted as accurate calculations of district heat load reduction potential in Finnish city-owned buildings though, but rather as estimates of said potential without taking into account detailed characteristics of individual buildings. Certainly more complex building energy modeling is recommended when planning practical implementation of demand response, but the estimates presented here can serve as a starting point which quantifies the benefits of DR for both the building owner and the district heat producer. The value of the presented city scale results is perhaps more substantial for the district heat producer, considering that the producer is not interested in the load reduction potential of individual buildings but rather in the cumulative potential of a large group of buildings. A large building stock includes a wide variety of different kinds of buildings with different load reduction potentials so that determining the total potential based on an estimate of the average potential is reasonable.

6.2 Limitations

There are certain limitations in the research methodology of this thesis, which should be taken into account when interpreting the simulation and optimization results presented in the previous chapters. This chapter briefly discusses the most important limitations of this study and what is the presumed impact of these limitations on the results. The next chapter further discusses possibilities for future work on the subject to mitigate the effects of the aforementioned limitations and to produce results that could be utilized more directly when it comes to practical implementation of demand response.

The building energy simulation models that were constructed in the empirical part of this thesis are not based on any actual buildings, but instead it is assumed that the buildings are constructed in accordance with the contemporary National Building Code of Finland; in other words the input data is completely based on assumptions. While input values based on the NBCF certainly reflect the state of building construction at the time, at least to an extent, using real buildings for case studies would have been more preferable in hindsight. Using models based so heavily on assumptions naturally features more uncertainties, especially in regards to older buildings such as the ones modeled here, since the NBCF's at the time were much less strict and the actual building stock is bound to be more diverse in terms of building structures and HVAC-systems. As an indirect result, the models are also extremely simple and lack the small details of actual buildings. The effect of these simplifications on the simulation and optimization results is rather unclear and difficult to quantify since it is likely that simplifying some things lead to an overestimation of DR potential while other things lead to an underestimation, which means that the overall effect of more complex building modeling hard to predict. Based on previous studies on the subject though, it is likely that a more complex and realistic model would result in smaller load reduction potential.

The simplified models may also undermine the potential of some of the studied demand response strategies since it is possible that the benefits and drawbacks of each strategy are not fully taken into account. Using extremely detailed building models could very well produce different optimal results, however it is again difficult to say whether the results would be notably different or not, when compared to the findings presented in this thesis. True cost-optimality cannot be realistically determined based on just the results presented here in any case, since investment cost needs for implementing the required controls mechanisms to the buildings are not analyzed. An analysis of investment costs combined with the cost-saving analyses would be more helpful for practical decision making purposes as well, and it would likely produce somewhat different cost-optimal DR strategy combinations in the buildings. Determining investment cost requirements without using real case buildings is rather difficult though and involves a lot of uncertainties that heavily effect the results, which is why that analysis was left out of this thesis in the end.

Cost-savings from the district heat producer's point of view were estimated by calculating the hourly production costs with and without demand response using a MATLAB simulation model developed in a past thesis by Mäkelä (2014). This simulation model is rather simple, and while it does yield a good estimate of the average and marginal production costs for district heat production in Espoo, it might underestimate the variability in marginal production costs due to reasons explained in Chapter 4.2.1. A higher marginal cost level during the demand response event would result in larger cost-savings from reduced heat production, for example an approximately 9% higher marginal cost level (5 €/MWh during the investigated winter day, for example) during a demand response event would yield similarly larger cost savings in heat production. Furthermore, a marginal cost curve with more fluctuation would make it possible to determine the timing of the DR events directly based on marginal costs of heat production.

The case studies in this thesis are made for individual days only which means that the variability of certain factors that heavily affect the results is not really taken into account. The impact of these factors, such as the outdoor temperature, electricity prices and general characteristics of the HVAC system in the building, can be clearly seen when comparing the winter and spring day results of any of the three buildings, or comparing results between different types of buildings. Some type of sensitivity analyses related to these variable factors would be required to produce a more reliable representation of the average demand response potential in the modeled buildings. Investigating a longer time frame, such as one month for example, and carrying out DR daily would be a simple way to produce a natural "sensitivity analysis" for outdoor temperature and electricity price dependence since it is a long enough period of time to contain different types of conditions in terms of both these factors. This would require developing the building models further though, as currently the optimizations are capable of producing optimal parameter values that are optimal only if the conditions are similar as in the investigated example days. In other words, using a longer time frame with multiple DR events and notable fluctuation in e.g. outdoor temperature would lead to some kind of average "optimal" parameters with the current optimization and simulation models and DR strategy control setup, which in reality would be non-optimal during most events. Investigating the results' dependence on HVAC system characteristics and various time schedules, on the other hand, would require further optimizations using different input data, which were not possible here due to time and resource constraints.

6.3 Future work

The premise of this thesis was to provide insight on the demand response potential of city-owned buildings and to perhaps aid in planning of potential demand response business models from the district heat producer's point of view. Furthermore, the thesis experiments with using the relatively novel building optimization tool MOBO for determining optimal parameter values for demand response control strategies, which could be expanded further to include more direct load-shifting possibilities in the future. Adding control strategies to IDA ICE which shift heat loads rather than limit them outright, and further optimizing the demand response controls with these additions would indeed be an interesting subject for future studies. Presumably load-shifting would be a preferable strategy as it can mitigate the effects of district heat demand response on indoor temperature conditions to an extent. Investigating load-shifting as a DR strategy also sheds more light on potential benefits of incorporating marginal cost based district heat pricing mechanisms.

Performing case studies using real buildings is another recommended next step, as it would act as validation of the optimization process and provide insight on the accuracy of the results presented here. Such a case study could also include an analysis for investment needs that arise from implementing demand response related control strategies, which in turn enables more thorough analyses on the cost-effectiveness of individual DR strategies. Taking into account all related cost factors in addition to realistic cost-saving potential is of course required for practical implementation of demand response as without sufficient realistic cost-saving potential there is little incentive for any party to actually carry out demand response in any capacity. Simulating a longer time frame, perhaps even a full year, instead of concentrating on single days would also be an interesting subject for future studies. As mentioned in the previous chapter, such an analysis would require some modifications to the building energy models but it would also give insight on the DR potential's dependence on factors such as outdoor temperature an electricity prices. Developing some kind of an active optimization algorithm for DR event timing would be preferred when studying longer time frames, but determining ex-post optimal event timing with e.g. MATLAB could be an option as well.

The only tangible benefit of demand response from the district heat producer's point of view in this study are savings in heat production costs. The differences in production costs with and without demand response are calculated with a simple MATLAB model, which means that the MATLAB model's complexity, or lack of it thereof, and the model's input data also affect the results of the production cost comparisons. Developing the current MATLAB model further to produce as realistic representation of the hourly heat production costs as possible would be recommended in case the same model is used in future studies. A more accurate model would in turn perhaps lead to more accurate estimates of demand response related cost-savings for the heat producer. Demand response can also have additional benefits from the heat producer's point of view, which are not investigated in this study but are still major factors in decision making in reality. Hence a more complete analysis of the benefits of demand response from the heat producer's point of view, taking into account the economic value of deferring investment for new production units for example, would be an interesting subject for future work as well.

References

Aduda, K. O. & Labeodan, T. & Zeiler, W. & Boxem, G. & Zhao, Y. 2016. Demand side flexibility: Potentials and building performance implications. Sustainable Cities and Society. Vol. 22. pp. 146-163. ISSN 2210-6707. doi: 10.1016/j.scs.2016.02.011.

Ahmed, K. & Kurnitski, J. & Sormunen, P. 2015. Demand controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams. Energy and Buildings. Vol. 109. pp. 115-126. ISSN 0378-7788. doi: 10.1016/j.enbuild.2015.09.052.

Aluesarjat. Helsinki region property statistics database. Available: http://www.aluesarjat.fi/ (in Finnish) [Referred 17.1.2017].

Asianajotoimisto Krogerus Oy. 2014. Määräävän markkina-aseman väärinkäyttövalvonnan kaukolämpöliiketoiminnan kehittämiselle asettamat reunaehdot. Energiateollisuus ry. 47 p. [WWW document]. Available: http://energia.fi/files/997/MMA_selvitys_kaukolampo_v4_0_2014.pdf (in Finnish) [Referred 18.4.2017].

CEN/TR 16355:2012. 2012. Recommendations for prevention of legionella growth in installations inside buildings conveying water for human consumption. Brussels: European Committee for Standardization. 23 p.

Chen, W. & Wang, X. & Petersen, J. & Tyagi, R. & Black, J. 2013. Optimal scheduling of demand response events for electric utilities. IEEE Transactions on Smart Grid. Vol. 4:4. pp. 2309-2319. ISSN 1949-3053. doi: 10.1109/TSG.2013.2269540.

Christantoni, D. & Oxizidis, S. & Flynn, D. & Finn, D. P. 2016. Implementation of demand response strategies in a multi-purpose commercial building using a whole-building simulation model approach. Energy and Buildings. Vol. 131. pp. 76-86. ISSN 0378-7788. doi: 10.1016/j.enbuild.2016.09.017.

Competition Act 948/2011. 2011. Helsinki: Finnish Competition Authority / Ministry of Employment and the Economy. [WWW document]. Available: http://www.finlex.fi/en/laki/kaannokset/2011/en20110948.pdf [Referred 18.4.2017].

D'hulst, R. & Labeeuw, W. & Beusen, B. & Claessens, S. & Deconinck, G. & Vanthournout, K. 2015. Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium. Applied Energy. Vol. 155. pp. 79-90. ISSN 0306-2619. doi: 10.1016/j.apenergy.2015.05.101.

Deb, K. & Pratap, A. & Agarwal, S. & Meyarivan, T. 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation. Vol. 6:2. pp. 182-197. ISSN 1089-778X. doi: 10.1109/4235.996017.

Difs, K. & Trygg, L. 2009. Pricing district heating by marginal cost. Energy Policy. Vol. 37:2. pp. 606-616. ISSN 0301-4215. doi: 10.1016/j.enpol.2008.10.003.

DOE 2006. Benefits of demand response in electricity markets and recommendations for achieving them. Washington, D.C., USA: Department of Energy. 122 p.

Ebrahimi, K. & Jones, G. F. & Fleischer, A. S. 2014. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renewable and Sustainable Energy Reviews. Vol. 31. pp. 622-638. ISSN 1364-0321. doi: 10.1016/j.rser.2013.12.007.

Energiföretagen Sverige. 2017. Fjärrvärmestatistik. [WWW document]. Available: https://www.energiforetagen.se/statistik/fjarrvarmestatistik/ (in Swedish) [Referred 18.4.2017].

Energy Authority. 2017. Strategic reserves. [WWW document]. Available: https://www.energiavirasto.fi/en/web/energy-authority/strategic-reserve [Referred 18.4.2017].

Energy Authority. 2015. Regulation methods 2016-2023. Helsinki, Finland: Energiavirasto. 131 p. [WWW document]. Available: http://www.energiavirasto.fi/documents/10191/0/Appendix_2_Regulation_methods_DSOs_2016-2023.pdf/b298b19e-04dc-4779-ab73-a709444bdace [Referred 18.4.2017].

Energy-An Consulting. 2009. Kaukolämmön hinnoittelumallit. Finnish Energy ry. 44 p. [WWW document]. Available: http://188.117.57.25/sites/default/files/kaukolammon_hinnoittelumallit_2009.pdf (in Finnish) [Referred 18.4.2017].

Espoo property register database. [Referred 17.1.2017].

Espoon Asunnot Oy. 2016. Annual report 2015. Espoon Asunnot Oy. 40 p. [WWW document]. Available: http://www.e-julkaisu.fi/espoon_asunnot/vuosikertomus_2015/mobile.html#pid=1 (in Finnish) [Referred 12.2.2017].

European Commission. 2013. Incorporing demand side flexibility, in particular demand response, in electricity markets. European Commission. 15 p. [WWW document]. Available: http://ec.europa.eu/energy/sites/ener/files/documents/com_2013_public_intervention_swd07_en_0.pdf [Referred 28.12.2016].

Evens, C. & Kärkkäinen, S. & Similä, L. & Pihala, H. & Seppälä, J. & Koponen, P. & Ahola, A. & Zenebu, M. & Lehtonen, M. & Degefa, M. & Räsänen, T. & Niska, H. & Kolehmainen, M. & Honkapuro, S. & Partanen, J. & Tuunanen, J. & Valtonen, P. 2010. Energiatehokkuuden kehittäminen energiayhtiöiden toimin. 90 p. [WWW document]. Available: http://www.ece.hut.fi/enete/ENETE_Loppuraportti.pdf (in Finnish) [Referred 18.4.2017].

Fanger, P.O. 1973. Assessment of man's thermal comfort in practice. Occupational and Environmental Medicine. Vol. 30. pp. 313-324. ISSN 0003-6870. doi: 10.1136/oem.30.4.313.

Fingrid Oyj. 2017a. Balancing power price. [WWW document]. Available: http://www.fingrid.fi/en/electricity-market/balancing-power/balancing-power-price/Pages/default.aspx [Referred 18.4.2017].

Fingrid Oyj. 2017b. Reserves. [WWW document]. Available: http://www.fingrid.fi/en/electricity-market/reserves/Pages/default.aspx [Referred 18.4.2017].

Finnish Energy. 2016a. District heating in Finland 2015. Finnish Energy ry. 78 p. [WWW document]. Available: http://energia.fi/files/1229/District_heating_in_Finland_2015.pdf [Referred 29.12.2016]

Finnish Energy. 2016b. Energiavuosi 2015. Finnish Energy ry. 34 p. [WWW document]. Available: http://188.117.57.25/kalvosarjat/energiavuosi-2015-kaukolampo (in Finnish) [Referred 29.12.2016]

Finnish Energy. 2015. Kaukojäähdytys v. 2015. Finnish Energy ry. [WWW document]. Available: http://188.117.57.25/tilastot-ja-julkaisut/kaukolampotilastot/kaukojaahdytys (in Finnish) [Referred 29.12.2016].

Finnish Meteorological Institute. 2017. Heating degree days. [WWW document]. Available: http://en.ilmatieteenlaitos.fi/heating-degree-days [Referred 21.3.2017].

Fortum. 2016. Fortum kausilämpö district heat prices. [WWW document]. Available: https://www.fortum.com/countries/fi/lampo/Tuotteet-ja-palvelut/hinnat-taloyhtioille-ja-yrityksille/Pages/default.aspx (in Finnish) [Referred 18.4.2017].

Fortum. 2015a. Fortum ja Leanheat yhteistyöhön TA-yhtymän ja Järvenpään mestariasuntojen kanssa - kysyntäjoustolla älykkäämpää kaukolämpöä asuinkerrostaloihin. [WWW document]. Available: http://www.fortum.com/fi/media/pages/fortum-ja-leanheat-yhteistyohon-ta-yhtyman-ja-jarvenpaan-mestariasuntojen-kanssa-kysyntajoustolla-alykkaampaa.aspx (in Finnish) [Referred 18.4.2017].

Fortum. 2015b. Fortum rakentaa kaukolämpöakun Espoon Suomenojalle. [WWW document]. Available: http://www.fortum.com/fi/media/pages/fortum-rakentaa-kaukolampoakun-espoon-suomenojalle.aspx (in Finnish) [Referred 18.4.2017].

Fortum. 2015c. Fortumin ja Aalto-yliopistokiinteistöjen kaukolämmön kysyntäjoustokokeilusta rohkaisevia tuloksia energiatehokkuuden parantamiseen. [WWW document]. Available: http://www.fortum.com/fi/media/pages/fortumin-ja-aalto-yliopistokiinteistojen-kaukolammon-kysyntajoustokokeilusta-rohkaisevia-tuloksia.aspx (in Finnish) [Referred 18.4.2017].

Goldman, C. 2010. Coordination of energy efficiency and demand response. California, US: Lawrence Berkeley National Laboratory. 75 p. Available: http://escholarship.org/uc/item/1z43c7bt

Hamdy, M. & Palonen, M. & Hasan, A. 2012. Implementation of pareto-archive NSGA-II algorithms to a nearly-zero-energy building optimisation problem. First Building Simulation and Optimization Conference. Longborough, UK. 2012. pp. 181-188.

Honkapuro, S. & Tuunanen, J. & Valtonen, P. & Partanen, J. & Järventausta, P. & Heljo, J. & Harsia, P. 2015. Practical implementation of demand response in Finland. CIRED: 23rd International Conference on Electricity Distribution. Lyon, France. 2015. 5 p.

Järventausta, P. 2015. Demand response – Practical applications and network impacts in Finland. Future flexible distribution system –seminar. Tampere, Finland. [Seminar presentation, WWW document]. Available: https://webhotel2.tut.fi/units/set/ide4l/Tampere04122015/DR-in-Finland_IDE4L-seminar_4-12-2015_v3.pdf [Referred 18.4.2017].

Järventausta, P. & Repo, S. & Trygg, P. & Rautiainen, A. & Mutanen, A. & Lummi, K. & Supponen, A. & Heljo, J. & Sorri, J. & Harsia, P. 2015. Kysynnän jousto – Suomeen soveltuvat käytännön ratkaisut ja vaikutukset verkkoyhtiöille (DR pooli): Loppuraportti. Tampere: Tampere University of technology. 360 p.

Johansson, C. & Wernstedt, F. & Davidsson, P. 2010. Deployment of agent based load control in district heating systems. First International Workshop on Agent Technologies for Energy Systems. Toronto, Canada. 2010. pp. 75-82.

Jokinen, E. 2013. Kysyntäjousto kaukolämmitetyissä kiinteistöissä. Master's thesis. Aalto University, Department of energy technology. Espoo. 78 p.

Kärkkäinen, S. & Sipilä, K. & Pirvola, L. & Esterinen, J. & Eriksson, E. & Soikkeli, S. & Nuutinen, M. & Aarnio, H. & Schmitt, F. & Eisgruber, C. 2004. Demand side management of the district heating systems. VTT Research Notes. Vol. 2247. pp. 104.

Katz, J. & Andersen, F.M. & Morthorst, P.E. 2016. Load-shift incentives for household demand response: Evaluation of hourly dynamic pricing and rebate schemes in a wind-based electricity system. Energy. Vol. 115: Part 3. pp. 1602-1616. ISSN 0360-5442. doi: 10.1016/j.energy.2016.07.084.

Kensby, J. & Trüschel, A. & Dalenbäck, J. 2015. Potential of residential buildings as thermal energy storage in district heating systems – results from a pilot test. Applied Energy. Vol. 137. pp. 773-781. ISSN 0306-2619. doi: 10.1016/j.apenergy.2014.07.026.

Kontu, K. 2014. District heating and cooling as part of smart energy systems. Licentiate thesis. Aalto University, Department of energy technology. Helsinki. 111 p.

Laki sähkön ja eräiden polttoaineiden valmisteverosta 30.12.1996/1260. 1997. Helsinki: Ministry of Finance. [WWW document]. Available: http://www.finlex.fi/fi/laki/smur/1996/19961260 (in Finnish) [Referred 15.1.2017].

Li, H. & Sun, Q. & Zhang, Q. & Wallin, F. 2015. A review of the pricing mechanisms for district heating systems. Renewable and Sustainable Energy Reviews. Vol. 42. pp. 56-65. ISSN 1364-0321. doi: 10.1016/j.rser.2014.10.003.

LVI 05-10440 en. 2010. Classification of Indoor Environment 2008. Target Values, Design Guidance, and Product Requirements. Espoo: Finnish Society of Indoor Air Quality and Climate. 24 p.

Mäkelä, H. 2014. Open district heating and marginal cost based heat pricing. Master's thesis. Aalto University, Department of energy technology. Espoo, Finland. 60 p.

Motegi, N. & Piette, M.A. & Watson, D.S. & Kiliccote, S. & Xu, P. 2006. Introduction to commercial building control strategies and techniques for demand response, LBNL 59975. California Energy Commission, PIER. 107 p.

National Building Code of Finland, D1/2007. 2007. Water supply and sewerage equipment of properties, regulations and guidelines. Ministry of the Environment. [WWW document]. Available: http://www.finlex.fi/data/normit/28208/D1_2007.pdf (in Finnish) [Referred 10.2.2017].

National Building Code of Finland, D2/2012. 2011. Indoor climate and ventilation of buildings, regulations and guidelines. Ministry of the Environment. [WWW document]. Available: http://www.finlex.fi/data/normit/37187/D2-2012_Suomi.pdf (in Finnish) [Referred 10.2.2017].

National Building Code of Finland, D3/2012. 2011. Energy efficiency of buildings, regulations and guidelines. Ministry of the Environment. [WWW document]. Available: http://www.finlex.fi/data/normit/37188/D3-2012_Suomi.pdf (in Finnish) [Referred 10.2.2017].

National Building Code of Finland, D5/2012. 2013. Calculation of power and energy needs for heating of buildings, guidelines. Ministry of the Environment. [WWW document]. Available: http://www.ym.fi/download/noname/%7B8C5C3B41-E127-4889-95B0-285E9223DEE6%7D/40468 (in Finnish) [Referred 10.2.2017].

Nord Pool. 2017a. Elspot market data. [WWW document]. Available: http://www.nordpoolspot.com/Market-data1/#/nordic/table [Referred 18.4.2017].

Nord Pool. 2017b. The power market. [WWW document]. Available: http://www.nordpoolspot.com/How-does-it-work/ [Referred 18.4.2017].

Palonen, M. & Hamdy, M. & Hasan, A. 2013. MOBO a new software for multi-objective building performance optimization. Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association. Chambéry, France. 2013. pp. 2567-2574.

Pineau, P. & Hämäläinen, R.P. 2000. A perspective on the restructuring of the Finnish electricity market. Energy Policy. Vol. 28:3. pp. 181-192. ISSN 0301-4215. doi: 10.1016/S0301-4215(99)00087-7.

Pöyry. 2014. Sähkön kysyntäjoustopotentiaalin kartoitus Suomessa. Fingrid Oyj. 21 p. [WWW document]. Available: http://www.fingrid.fi/fi/sahkomarkkinat/markkinaliitteet/Kysynt%C3%A4jousto/Fingrid_Julkinen_raportti_kysynt%C3%A4jousto_16062014.pdf (in Finnish) [Referred 28.12.2016].

Qureshi, W.A. & Nair, N.C. & Farid, M.M. 2011. Impact of energy storage in buildings on electricity demand side management. Energy Conversion and Management. Vol. 52:5. pp. 2110-2120. ISSN 0196-8904. doi: 10.1016/j.enconman.2010.12.008.

Rautiainen, A. 2015. Aspects of electric vehicles and demand response in electricity grids. Doctoral thesis. Tampere University of technology. Tampere, Finland. 168 p.

Rong, A. & Lahdelma, R. 2007. Efficient algorithms for combined heat and power production planning under the deregulated electricity market. European Journal of Operational Research. Vol. 176:2. pp. 1219-1245. ISSN 0377-2217. doi: 10.1016/j.ejor.2005.09.009.

Salo, S. 2016. Predictive demand-side management in district heating and cooling connected buildings. Master's thesis. Aalto University, Department of energy technology. Espoo. 103 p.

Schramm, G. 1991. Marginal cost pricing revisited. Energy Economics. Vol. 13:4. pp. 245-249. ISSN 0140-9883. doi: 10.1016/0140-9883(91)90003-I.

Söderholm, P. & Wårell, L. 2011. Market opening and third party access in district heating networks. Energy Policy. Vol. 39:2. pp. 742-752. ISSN 0301-4215. doi: 10.1016/j.enpol.2010.10.048.

Strbac, G. 2008. Demand side management: Benefits and challenges. Energy Policy. Vol. 36:12. pp. 4419-4426. ISSN 0301-4215. doi: 10.1016/j.enpol.2008.09.030.

Syri, S. & Mäkelä, H. & Rinne, S. & Wirgentius, N. 2015. Open district heating for Espoo city with marginal cost based pricing. 2015 12th International Conference on the European Energy Market (EEM). 2015. 5 p. ISSN 2165-4077. doi: 10.1109/EEM.2015.7216654

Tyagi, R. & Black, J.W. & Petersen, J. 2011.Optimal scheduling of demand response events using options valuation methods. 2011 IEEE Power and Energy Society General Meeting. 2011. 5 p. ISSN 1932-5517. doi: 10.1109/PES.2011.6039344

Ulseth, R. & Alonso, M.J. & Pedersen Haugerud, L. 2014. Measured load profiles for domestic hot water in buildings with heat supply from district heating. The 14th International Symposium on District Heating and Cooling. Stockholm, Sweden. 2014. 5 p.

Valor Partners Oy. 2015. Kaukolämmön kysyntäjousto. Finnish Energy ry. 32 p. [WWW document]. Available: http://energia.fi/files/439/Kaukolammon_kysyntajousto_loppuraportti_VALOR.pdf (in Finnish) [Referred 18.4.2017].

Valtioneuvoston asetus sähköntoimitusten selvityksestä ja mittauksesta 5.2.2009/66. 2009. Helsinki: Ministry of Employment and the Economy. [WWW document]. Available: http://www.finlex.fi/fi/laki/ajantasa/2009/20090066 (in Finnish) [Referred 18.4.2017].

Valtonen, P. & Honkapuro, S. & Partanen, J. 2015. Economic potential of load control in balancing power market. CIRED 23rd International Conference on Electricity Distribution, Paper 1003. Lyon, France. 2015. 5 p.

Vihola, J. & Sorri, J. & Heljo, J. & Kero, P. 2015. Heat loss rate of the Finnish building stock. Procedia Economics and Finance. Vol. 21. pp. 601-608. ISSN 2212-5671. doi: 10.1016/S2212-5671(15)00218-X.

Wernstedt, F. & Davidsson, P. & Johansson, C. 2007. Demand side management in district heating systems. Proceedings of the 6th international joint conference on Autonomous agents and multiagent systems. Honolulu, Hawaii, US. ACM. 2007. pp. 1378-1384.

Wernstedt, F. & Johansson, C., Intelligent distributed load control. Proceedings of the 11th International Symposium on District Heating and Cooling. Reykjavik, Iceland. 2008. 6 p.

Wissner, M. 2014. Regulation of district-heating systems. Utilities Policy. Vol. 31. pp. 63-73. ISSN 0957-1787. doi: 10.1016/j.jup.2014.09.001.

Ympäristöministeriön asetus rakennuksen energiatodistuksesta 176/2013 Liite 1. 2013. Helsinki: Ministry of the Environment. [WWW document]. Available: http://www.finlex.fi/data/sdliite/liite/6186.pdf (in Finnish) [Referred 10.2.2017].

York, D. & Kushler, M. 2005. Exploring the relationship between demand response and energy efficiency: A review of experience and discussion of key issues. Washington, D.C., US: American Council for an Energy-Efficient Economy. 88 p.

List of appendices

Appendix 1. Detailed input data for building energy simulation models

This appendix includes detailed information of the input data used in the building energy simulation models.

Basic information regarding the modeled buildings is presented in Table 1. The model envelope includes exterior walls, floors connected to ground and roofs.

Table 1. General information of the building energy models.

	Office building	**Apartment building**	**School building**
Model floor area	1000,0 m^2	1000,4 m^2	1001,6 m^2
Model envelope area	415,7 m^2	415,2 m^2	2596 m^2
Window area as % of building envelope	46,7 %	29,3 %	5 %

U-values used for different building structures in the models are presented in Table 2 below. “None” implies that the model does not include these building structures, e.g. the office and apartment buildings have spaces with similar room temperatures above and below the modeled building floor and thus the model’s do not have roofs or floors connected to ground.

Table 2. Building structures and U-values used in the energy simulation models.

	Office building	**Apartment building**	**School building**
Building structure	*U-value of building structure [W/m^{2}K]*		
Exterior wall	0,35	0,28	0,35
Roof	none	none	0,29
Floor to ground	none	none	0,40
Window	2,1 (g-value 0,55)	2,1 (g-value 0,55)	2,1 (g-value 0,55)
Exterior door	none	1,4	1,4
Infiltration, n50 [1/h]	6,0	6,0	6,0
Thermal bridges	NBCF D5/2012: concrete	NBCF D5/2012: concrete	NBCF D5/2012: concrete

Ventilation in the buildings is produced with IDA ICE's default air handling units with heating and cooling coils installed in the supply air side and heat recovery equipment which recovers heat from exhaust air and uses it to heat supply air before the heating coil. Table 3 presents technical information regarding the ventilation in the office building. Table 4 presents corresponding information regarding the AHUs in the apartment building, and Table 5 shows the same information for the school building.

Table 3. Technical information regarding ventilation in the modeled office building.

	Single AHU serving the entire building
Air flow rate (supply/exhaust) [dm^3/s,m^2]	2,0 / 2,0
SFP [kW/m^{3}s]	2,5
Operation schedule	weekdays 06:00 – 19:00, otherwise 0.15 dm^3/s,m^2
Supply air temperature	constant 17°C + 1°C increase in supply air fan
Heating/cooling coil effectiveness	1,0
Heat recovery efficiency	45 %
Heat recovery operation	always on

Table 4. Technical information regarding ventilation in the modeled apartment building.

	AHU for apartments	**AHU for general spaces**
Air flow rate (supply/exhaust) [dm^3/s,m^2]	0,0 / 0,5	0,0 / 0,417
SFP [kW/m^{3}s]	1,0	1,0
Operation schedule	24/7	24/7
Supply air temperature	no supply air	no supply air
Heating/cooling coil effectiveness	no heating or cooling	no heating or cooling
Heat recovery efficiency	no heat recovery	no heat recovery

Table 5. Technical information regarding ventilation in the modeled school building.

	AHU for classrooms	**AHU for general spaces**	**AHU for the gym**
Air flow rate (supply/exhaust) [dm^3/s,m^2]	classrooms 3,0 / 3,0; office 2,0 / 2,0	3,0 / 3,0 except bathrooms 0,5 / 0,5	2,0 / 2,0
SFP [kW/m^{3}s]	2,5	2,5	2,5
Operation schedule	weekdays 07:00 – 17:00, 0,15 dm^3/s otherwise	weekdays 07:00 – 17:00, 0,15 dm^3/s otherwise	every day 07:00 – 23:00, 0,15 dm^3/s otherwise
Supply air temperature	constant 17°C + 1°C	constant 17°C + 1°C	constant 16°C + 1°C
Heating/cooling coil effectiveness	1,0; no cooling	1,0; no cooling	1,0; no cooling
Heat recovery efficiency	45%	45%	45%
Heat recovery operation	always on	always on	always on

Indoor air temperature set points for all buildings, which are in accordance with the national building code, are presented in Table 6.

Table 6. Indoor air temperature set points in the modeled buildings.

	Heating set point	**Cooling set point**
Office building	+21°C	+25°C
Apartment building, apartments	+21°C	
Apartment building, general spaces	+17°C	
School building, gym	+18°C	
School building, rest of the building	+21°C	

Attributes of the heat distribution plants and the heating systems in the modeled buildings are presented in Table 7. Heating systems in each building are almost identical with the exception that space heating in the offices is done with ceiling panels and in the apartment and school buildings it is done with radiators. Maximum plant capacities are also determined for each building based on calculated design capacities. Domestic hot water use in the buildings is based on standard DHW use according to the Finnish national building code.

Table 7. Technical information regarding the heating system in the modeled buildings.

Attribute	**Office building**	**Apartment building**	**School building**
Plant capacity (excluding DHW)	103 kW	50 kW	180 kW
Plant efficiency	0,97	0,97	0,97
Heat distribution network losses	10% of heat delivered by plant	10% of heat delivered by plant	10% of heat delivered by plant
Domestic hot water temperature	55°C	55°C	55°C
Domestic hot water use	103 l/m^2 per year	600 l/m^2 per year	188 l/m^2 per year
Domestic hot water circuit losses (50% to zones)	0,2 W/m^2 floor area	0,43 W/m^2 floor area	0,2 W/m^2 floor area
Heat production extra energy use (electricity)	0,008 kW	0,008 kW	0,008 kW
Heat distribution extra energy use (electricity)	0,228 kW	0,228 kW	0,228 kW
Domestic hot water distribution pumps	0,01 kW	0,01 kW	0,001 kW
Chiller capacity	50 kW		
Chiller COP	3		
Cold distribution network losses	10% of cold delivered by chiller (50% to zones)		
Cold distribution extra energy use (electricity)	0,2 kW		

The temperature of the heating supply water which is delivered by the plant to air handling units and to space heating equipment is dependent on outdoor temperature in accordance with the profile of the curve presented in Figure 1. The outdoor temperature dependence is identical in every building.

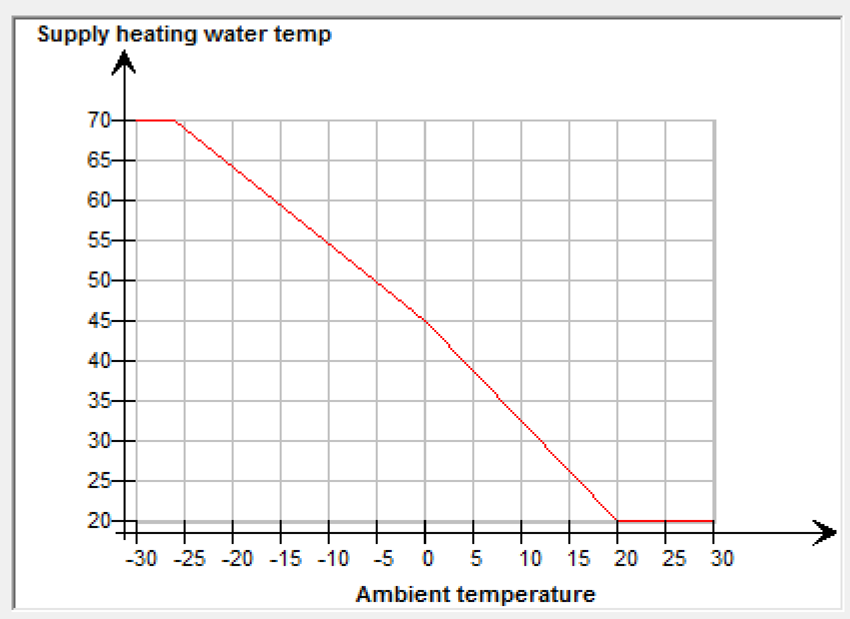

Figure 1. Heating supply water temperature as function of outdoor air temperature.

Internal heat gains and schedules for each building type are based on standard use defined by the national building code, and they are presented in Tables 8, 9 and 10.

Table 8. Internal heat gains and time schedules in the modeled office building.

Office building	**Heat gain**	**Time schedule**
Occupants, all spaces	0,067 persons per m^2	0,65; 07:00-18:00
Lighting, all spaces	10 W/m^2	0,65; 07:00-18:00
User equipment, all spaces	12 W/m^2	0,65; 07:00-18:00

Table 9. Internal heat gains and time schedules in the modeled apartment building.

Apartment building	**Heat gain**	**Time schedule**
Occupants, apartments	0,04 persons per m^2	0,6: 24/7
Occupants, general spaces	0 persons per m^2	0,6: 24/7
Lighting, all spaces	11 W/m^2	0,1: 24/7
User equipment, all spaces	4 W/m^2	0,6: 24/7

Table 10. Internal heat gains and time schedules in the modeled school building.

School building	**Heat gain**	**Time schedule**
Occupants, classrooms	0,01867 persons per m^2	0,6; 08:00-16:00
Occupants, office	0,00667 persons per m^2	0,65; 07:00-18:00
Occupants, gym	0,00667 persons per m^2	0,5; 08:00-22:00
Occupants, general spaces	0 persons per m^2 in bathrooms; 0,1867 persons per m^2 in rest	Dining hall: 0,05; 08:00-10:00 and 13:00-16:00 + 0.8; 10:00-13:00 rest: 0,05: 08:00-16:00
Lighting, classrooms	18 W/m^2	0,6; 08:00-16:00
Lighting, office	12 W/m^2	0,65; 07:00-18:00
Lighting, gym	12 W/m^2	0,5; 08:00-22:00
Lighting, general spaces	18 W/m^2	0,6; 08:00-16:00
User equipment, classrooms	8 W/m^2	0,6; 08:00-16:00
User equipment, office	12 W/m^2	0,65; 07:00-18:00
User equipment, gym	0 W/m^2	0,5; 08:00-22:00
User equipment, general spaces	bathrooms: 0 W/m^2 rest: 8 W/m^2	0,6; 08:00-16:00

Appendix 2. Input data regarding variables in the optimizations

The discrete variables used in the office building optimizations and the possible values for these variables are presented in Table 1. Plant supply water temperature change is a positive value in the optimizations due to software limitations, and in IDA ICE this value is essentially subtracted from the original plant supply water temperature value which in turn is dependent on outdoor temperature according to a linear curve (Figure 1 in Appendix I). The optimal parameter value determined by the optimization software is subtracted from whatever the original value is during each moment of the demand response event. In other words, if the optimal value is larger than zero, the curve in figure is shifted down by the optimal value's amount of degrees.

Table 1. Optimized variables for the office building optimization cases.

Discrete variable	**Possible values**	**Used in optimization problem**		
		Winter day	**Spring day**	**Summer day**
Zone heating temperature set point	19; 19,2; 19,4;…; 20,6; 20,8; 21	Yes	Yes	No
Heat distribution plant pump operation	0; 0,05; 0,10;…; 0,90; 0,95; 1	Yes	Yes	No
Ventilation air flow	0; 0,05; 0,10;…; 0,90; 0,95; 1	Yes	Yes	Yes
Ventilation supply air heating temperature set point	15; 15,2; 15,4;…; 16,6; 16,8; 17	Yes	No	No
Plant heating supply water temperature change	0; 1; 2;…; 8; 9; 10; 15; 20; 25; 30; 35; 40	Yes	Yes	No
Zone cooling temperature set point	25; 25,2; 25,4;…; 26,6; 26,8; 27	No	Yes	Yes
Chiller pump operation	0; 0,05; 0,10;…; 0,90; 0,95; 1	No	Yes	Yes
Ventilation supply air cooling set point	17; 17,2; 17,4;…; 18,6; 18,8; 19	No	Yes	Yes

The discrete variables used in apartment building optimization cases are presented in Table 2. The air handling units in the apartment building provide exhaust air only, thus no ventilation heating –related variables are needed.

Table 2. Optimized variables for the apartment building optimization cases.

Discrete variable	**Possible values**	**Used in optimization problem**	
		Winter day	**Spring day**
Zone heating temperature set point	19; 19,2; 19,4;…; 20,6; 20,8; 21	Yes	Yes
Heat distribution plant pump operation	0; 0,05; 0,10;…; 0,90; 0,95; 1	Yes	Yes
Ventilation air flow in apartments	0; 0,05; 0,10;…; 0,90; 0,95; 1	Yes	Yes
Ventilation air flow in general spaces	15; 15,2; 15,4;…; 16,6; 16,8; 17	Yes	Yes
Plant heating supply water temperature change	0; 1; 2;…; 8; 9; 10; 15; 20; 25; 30; 35; 40	Yes	Yes

The discrete variables and possible variable values used in school building optimizations are presented in Table 3.

Table 3. Optimized variables for the school building optimization cases.

Discrete variable	**Possible values**	**Used in optimization problem**	
		Winter day	**Spring day**
Zone heating temperature set point in classrooms	19; 19,2; 19,4;…; 20,6; 20,8; 21	Yes	Yes
Zone heating temperature set point in general spaces	19; 19,2; 19,4;…; 20,6; 20,8; 21	Yes	Yes
Zone heating temperature set point in gym	16; 16,2; 16,4;…; 17,6; 17,8; 18	Yes	Yes
Heat distribution plant pump operation	0; 0,05; 0,10;…; 0,90; 0,95; 1	Yes	Yes
Plant heating supply water temperature change	0; 1; 2;…; 8; 9; 10; 15; 20; 25; 30; 35; 40	Yes	Yes
Ventilation air flow in classrooms	0; 0,05; 0,10;…; 0,90; 0,95; 1	Yes	Yes
Ventilation air flow in general spaces	15; 15,2; 15,4;…; 16,6; 16,8; 17	Yes	Yes
Ventilation supply air heating temperature set point for classrooms	15; 15,2; 15,4;…; 16,6; 16,8; 17	Yes	Yes
Ventilation supply air heating temperature set point for general spaces	15; 15,2; 15,4;…; 16,6; 16,8; 17	Yes	Yes
Ventilation supply air heating temperature set point for gym	14; 14,2; 14,4;…; 14,6; 14,8; 16	Yes	Yes