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Energy Flexibility Characterization of Norwegian Residential Buildings Heated by Direct Electricity

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MASTER THESIS

for

Thea Johnsen and Katrine Taksdal

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Energy flexibility characterization of Norwegian residential buildings heated by direct electricity

Karakterisering av energifleksibilitet til Norske boligbygg med direkte elektrisk oppvarming

Background and objective

The energy flexibility of a building is the ability to manage its energy demand and generation according to local climate conditions, user needs and grid requirements. Building energy flexibility based on heating loads may be obtained by making use of thermal energy storages, typically water storage tanks, or the building thermal mass.

The objective of this Master Thesis is to evaluate (or characterize) the energy flexibility that Norwegian residential buildings can provide to the grid using simple rule-based controls (RBC). The focus is on buildings heated by direct electricity for both, space-heating and domestic hot water (DHW) which is a common heating system in Norway. Regarding thermal mass activation, the influence of the building construction type and thermal properties on energy flexibility will be evaluated. In addition, the internal thermal zoning in the context of energy flexibility, a topic not frequently addressed in academic literature, will be investigated. The impact of internal gains, which can have a significant influence on the space-heating load, will be analyzed in detail using stochastic profiles. Furthermore, the influence of electric radiator control will be discussed (i.e. on-off vs. P-control). Regarding DHW, draw-off profiles are critical so that stochastic profiles will be investigated. Finally, the overall grid interaction of the building (import-export to the grid), which requires the knowledge of realistic electric loads for appliances and artificial lighting will be analyzed.

The following tasks are to be considered:

1. Literature review with a main focus on energy flexibility, (stochastic) load profiles, internal thermal zoning and control of electric heating systems in Scandinavia.
2. Implementation of stochastic load profiles based on Norwegian statistics into IDA ICE
3. Implementation of RBC strategies for demand side management (based on spot price, schedules and/or CO_2 intensity of electricity generation in the power grid)
4. Evaluation of key performance indicators (KPI) translating the energy flexibility potential (energy use, costs, peak load reduction)
5. Writing a final report and a draft for a scientific paper with the main results from the thesis
6. Making a proposal for further work

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidates should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

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☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2018

Laurent Georges, Associate Professor
Academic Supervisor

Research Advisor:
John Clauß, PhD student
Sebastian Stinner, invited researcher

Preface

This master thesis has been carried out at the Norwegian University of Science and Technology (NTNU) in Trondheim, at the Department of Energy and Process Engineering. The thesis is a continuation of a specialization project on the same topic that was carried out in the fall of 2017.

We would like to thank our supervisor Laurent Georges for guidance and useful inputs during the work of this thesis. Furthermore, a special thanks go to our research advisor John Caluß for valuable feedback and help along the way. In addition, we want to thank Sebastian Stinner for help with MATLAB and Igor Sartori for help with understanding the models for generating stochastic internal heat gain profiles.

Lastly, we would like to thank each other, and our computers for running simulations non-stop during this entire semester.

Trondheim, 18th of June 2018

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Abstract

The objective of this thesis is to evaluate the energy flexibility that Norwegian residential buildings can provide to the electricity grid, by applying rule-based control (RBC) strategies. Aspects that are assumed to influence the energy flexibility, such as the impact of internal heat gains and occupants' preferences concerning thermal zoning of bedrooms are to be evaluated. The literature study showed that the energy flexibility is an ongoing area of investigation and there is currently no standard metrics to identify a buildings potential to offer flexibility. However, many studies have investigated the topic by applying RBC strategies, and some general properties to describe the buildings ability to offer flexibility exist. Besides, as the building stock gradually moves towards a more energy efficient standard, the impact of internal heat gains (IHG) is becoming increasingly important. However, realistic IHG profiles are difficult to model and several modelling approaches exist. In addition, the relevant literature demonstrates that there is a high level of dissatisfaction with too high bedroom temperatures in passive houses and that it is difficult to achieve this, due to a desire for higher temperatures in the rest of the building.

Two different RBC strategies have been applied to evaluate the flexibility potential using the detailed dynamic simulation tool IDA ICE. Both control strategies adjust the set-point temperature (SPT) on the direct electric space heating system. One control strategy is based on a schedule for pre-defined peak hours (OPCS) and the other is based on the spot price (SPCS). Four different building types with different levels of insulation and construction modes are investigated. Overall, both RBC strategies showed potential for shifting the power and consumption use to off-peak hours for all the evaluated building types. The potential for shifting the power and energy consumption is higher for the highly insulated buildings, but the magnitude is much more significant for the less insulated buildings.

Different IHG profiles have been evaluated in the context of energy flexibility. The results show that the timing of IHGs is important, especially for the highly insulated buildings. The results with a stochastic IHG profile distributed in both time and space achieved the largest potential for energy and power shifting, and this indicates that the flexibility potential might be under-estimated when modelling the IHGs according to the current practice. This is also supported by the aggregated result of 20 buildings with different stochastic IHG profiles. The type of radiator control is found to have an impact on the flexibility potential at a building level. However, when investigating several buildings together, the results indicate that the more predictable behaviour with proportional control can be used to describe the behaviour of several buildings with thermostatic control.

The increase of bedroom temperatures due to the implemented RBC strategies and IHGs is most significant for the highly insulated buildings. The influence of the RBC strategies on the bedroom temperatures is found to be largest in the colder months, as the impact of the IHGs becomes more dominant with lower heat loss from the building envelope. By decoupling the bedrooms from the RBC strategies, the temperatures are improved, but the improvement is dependent on the internal constructions of the building. Moreover, the flexibility potential is reduced by decoupling the bedrooms.

Sammendrag

Formålet med denne masteroppgaven er å vurdere energifleksibiliteten norske boliger kan tilby elektrisitetsnettet ved å anvende regelbaserte kontrollstrategier. Aspekter som kan være kritiske med hensyn til energifleksibilitet som innflytelse av internlaster og beboeres preferanser når det gjelder termisk soning av soverom skal vurderes. Litteraturstudiet viste at energifleksibilitet i boligbygg er et kontinuerlig undersøkelsesområde, og at det for tiden ikke finnes standardverdier for å identifisere bygningers potensiale for å tilby fleksibilitet. Imidlertid har mange studier undersøkt emnet ved å benytte regelbaserte kontrollstrategier, og noen generelle egenskaper for å beskrive en bygnings evne til å tilby fleksibilitet eksisterer. Dessuten, ettersom bygningsmassen gradvis beveger seg mot en mer energieffektiv standard, blir innflytelsen av internlaster stadig viktigere. Det er vanskelig å modellere realistiske internlastprofiler og det eksisterer flere metoder for å gjøre dette. I tillegg viser litteraturen at det er en høy grad av misnøye med for høye soveromtemperaturer i passivhus, og at det er vanskelig å oppnå dette på grunn av ønske om høyere temperaturer i resten av bygningen.

To forskjellige regelbaserte kontrollstrategier har blitt anvendt for å evaluere fleksibilitetspotensialet med bruk av det detaljerte dynamiske simuleringsverktøyet IDA ICE. Begge kontrollstrategiene justerer settpunkttemperaturen på et direkte elektrisk romoppvarmingssystem. En kontrollstrategi er benytter en forhåndsdefinert tidsplan basert på gjennomsnittlige topplasttimer (OPCS) og den andre er basert på spotpris (SPCS). Fire forskjellige bygningstyper med forskjellige isolasjonsnivåer og konstruksjonstyper er undersøkt. Samlet sett viste begge kontrollstrategiene potensiale for å flytte effekt- og energiforbruk til timer utenfor topplasttimer for alle de evaluerte bygningstypene. Potensialet for å skifte effekt- og energiforbruk er høyere for de høyisolerte bygningene, men magnituden er mye større for de mindre isolerte bygningene.

Ulike internlastprofiler har blitt evaluert i sammenheng med energifleksibilitet. Resultatene viser at timingen av internlaster er viktig, spesielt for de høyisolerte bygningene. Resultatene med en stokastisk internlastprofil fordelt i både tid og rom oppnådde det største potensialet for effekt- og energiforskyvning, og dette indikerer at fleksibilitetspotensialet kan bli underestimert når modellering av internlaster blir gjort i henhold til gjeldende praksis. Dette støttes også av det aggregerte resultatet av 20 bygninger med forskjellige stokastiske internlastprofiler. På bygningsnivå har type radiatorkontroll en innvirkning på fleksibilitetspotensialet, men ved undersøkelser av flere bygninger sammen indikerer resultatene at den mer forutsigbare oppførelsen med proporsjonalkontroll kan brukes til å beskrive flere bygninger med termostatkontroll.

Økningen av soveromstemperaturene som et resultat av de implementerte kontrollstrategiene og internlastene er mest signifikant i de høyisolerte bygningene. Effekten av kontrollstrategiene på soveromstemperaturene er størst i de kaldere månedene, da virkningen av internlastene blir mer dominerende med lavere varmetap fra bygningskroppen. Ved å ekskludere soverommene fra de regelbaserte kontrollstrategiene blir temperaturen forbedret, men forbedringen er avhengig av bygningens indre konstruksjoner. I tillegg reduseres fleksibilitetspotensialet ved å ekskludere soverommene fra de regelbaserte kontrollstrategiene.

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Nomenclature

C_p	Specific heat capacity [kJ/kg]
H	Heat transfer coefficient [W/K]
n_{50}	Air tightness at 50 Pa [h^{-1}]
P	Power [W]
Q	Energy [kWh]
t	Time [s]
η	Efficiency [-]
τ	The time constant of a building
T_i	Indoor temperature [K]
T_e	Exterior temperature [K]
Φ	Total power contribution [W]
S	Heat storage capacity [Ws/K]
Ψ''	Normalized thermal bridge factor [W/m^2K]
θ_{ym}	Yearly mean outdoor temperature [°C]

Abbreviations

CS	Control Strategy
DB	Deadband
DHW	Domestic hot water
DSM	Demand side management
IDA ICE	IDA Indoor Climate and Energy
IHG	Internal heat gain
KPI	Key Performance Indicator
MPC	Model predictive control
NS	Norwegian Standard NS 3031
OPCS	Off-peak control strategy
$OPCS_{bdc21}$	Off-peak control strategy: decoupled bedrooms with a constant SPT of 21 °C
$OPCS_{bdc16}$	Off-peak control strategy: decoupled bedrooms with a constant SPT of 16 °C
$OPCS_{db2}$	Off-peak control strategy: deadband of 2 °C
$OPCS_{ph0.5}$	Off-peak control strategy: preheating of 0.5 hours
$OPCS_{ph2}$	Off-peak control strategy: preheating of 2 hours
PHH	Building with specifications according to the passive house standard (PH), heavy construction mode (HCM)
PHL	Building with specifications according to the passive house standard (PH), light construction mode (LCM)
RBC	Rule-based control
SFH	Single family house
SM_t	Time distributed internal heat gain profile from stochastic model
SM_{ts}	Time and space distributed internal heat gain profile from stochastic model
SPCS	Spot price control strategy with overruling from 23:00-06:00
$SPCS_{bdc21}$	Spot price control strategy: decoupled bedrooms with a constant SPT of 21 °C
$SPCS_{bdc16}$	Spot price control strategy: decoupled bedrooms with a constant SPT of 16 °C
$SPCS_{nor}$	Spot price control strategy: no overruling of control strategy from 23:00-06:00

SPCS$_{20\text{-}80}$	Spot price control strategy: low-price and high-price thresholds of 20 % and 80 %
SPCS$_{30\text{-}70}$	Spot price control strategy: low-price and high-price thresholds of 30 % and 70 %
SPT	Set-point temperature
TABULA (TB)	Typology Approach for Building Stock Energy Assessment
TBH	Building with specifications according to the 1980s TABULA example building (TB), heavy construction mode (HCM)
TBL	Building with specifications according to the 1980s TABULA example building (TB), light construction mode (LCM)
TEK	Technical building works regulations
TES	Thermal Energy Storage
TMY	Typical mean year
TUS	Time-use survey
TS	Technical specification 3031
ZEB	Zero energy building

Key Performance Indicators

q_{tot}	The change in yearly energy consumption relative to the reference case with constant SPT, with the same building type and internal heat gain profile
q_{ph}	The change in yearly energy consumption in the pre-defined peak hours relative to the reference case with constant SPT, with the same building type and internal heat gain profile
p	The change in maximum power consumption relative to the reference case with constant SPT, with the same building type and internal heat gain profile
p_{ph}	The change in maximum power consumption in the pre-defined peak hours relative to the reference case with constant SPT, with the same building type and internal heat gain profile
c	The change in yearly energy cost relative to the reference case with constant SPT, with the same building type and internal heat gain profile

1 Introduction

To make the transition to a sustainable energy system, more of the energy production must be derived from intermittent, renewable energy sources. However, increased production from these energy sources, such as solar and wind, may have serious effects on the stability of the electricity grid. Furthermore, the use of power demanding appliances is increasing, meaning that consumers are demanding more power from the grid than they have before [1]. Therefore, it will become increasingly important to shift from a system based on generation-on-demand to a system where the use of energy is controlled according to the intermittent energy production. This means that the energy consumption will have to become more flexible in order to achieve a large-scale production from renewable energy sources. In addition to facilitate a larger share of renewable energy production, a flexible energy consumption can reduce the need for upgrading the electricity grid due to capacity issues [2]. [3]

The energy flexibility of buildings can be explained as the buildings ability to control the energy demand, and potentially on-site production, in accordance with different external forcing factors, such as local climate, occupant needs and the surrounding grid without compromising the occupant comfort [3]. Even though energy flexibility is not a new concept, there is limited knowledge of how much energy flexibility different building types have to offer the grid. There has however been an increasing focus on this, and the IEA (International Energy Agency) EBC (Energy in Buildings and Communities Program) program "Annex 67: Energy Flexible Buildings" was started in 2015. The aims of this project are to gain knowledge, identify critical aspects and demonstrate possible solutions regarding the energy flexibility that buildings can provide for the energy grids. [4]

Demand side management (DSM) is a wide definition that includes measures to utilize the energy flexibility in buildings, which is often concerning load control with the purpose of shifting the energy demand in time [5]. Especially the thermal demand, such as heating, cooling and domestic hot water have a high load shifting potential [3]. In Norway, the energy use in residential buildings represented approximately 20 % of the total energy use in the mainland in 2015 [6]. Moreover, most of the residential buildings in Norway use direct electric heating for space heating [7]. Thus, the implementation of strategies in residential buildings to shift the energy and power use for heating in time may have a significant potential for reducing the level of stress on the electricity grid. In addition, the limited understanding of energy-related occupant behavior results in a discrepancy of expected energy performance, especially for highly insulated buildings [8]. This may therefore have an influence on the actual energy flexibility potential of buildings as well.

1.1 Objective and Limitations

The main objective of this thesis is to evaluate and characterize the energy flexibility that can be provided to the grid by Norwegian residential buildings by means of simple rule-based control strategies. This will be evaluated for buildings with a direct electrical space heating system. The effects of different levels of insulation and building construction type in the context of activating

the thermal mass are to be investigated. Parameters that are believed to have an influence on the available flexibility potential, regarding both the electric heating system and the implemented control strategies, will be evaluated. As internal heat gains (IHG) can have a significant influence on the heating demand, the influence of different internal heat gain profiles is to be investigated in the context of energy flexibility. In addition, the topic of internal thermal zoning and the impact this may have on the flexibility shall be evaluated.

A limitation of the thesis is that the heating of domestic hot water and the buildings overall interaction with the grid are not included. This has been decided in agreement with the supervisors in order to focus on more advanced questions regarding the space heating.

1.2 Thesis Overview

This section provides an overview of the structure of this thesis. The second chapter consists of the theoretical framework related to the objectives of this thesis. In addition, literature from relevant research areas is presented, to provide an overview of the work that is already done. This includes demand side management and control strategies to utilize buildings thermal mass, modelling of occupant behavior and electricity load profiles, and measures to achieve occupant satisfaction of bedroom temperatures in highly insulated buildings.

After this, the modelling approach for the investigations of this thesis is presented in chapter 3. Here, the simulation tool and building models are presented. Furthermore, the methodology for modelling the internal heat gains from occupants, appliances and lighting is described. This is followed by a presentation of the selected rule-based control (RBC) strategies and the approach for evaluation of bedroom temperatures. Finally, this chapter contains an explanation of the performance indicators used to evaluate the results before a summary of the methodology is given. The results from the dynamic simulations are presented in chapter 4, followed by a discussion to further analyze the results. Finally, a conclusion of the work is made followed by suggestions for further work.

The referring to literature is organized in a manner so that if a reference is placed after a sentence, but before the period, this reference only applies to that sentence. If a reference is placed at the end of a paragraph, the reference is used to retrieve information for the whole paragraph.

As the work of this thesis is based on previous work done in a specialization project of fall 2017, some sections in the theoretical framework and the modelling approach are partially based on this work. This applies to the following sections:

- Chapter 2 with sections: 2.1, 2.2, 2.3, 2.4, and 2.5
- Chapter 3 with sections: 3.1, 3.2 and 3.6.

2 Theoretical Framework

In this chapter, relevant literature and theoretical framework for this thesis are presented. First, there is a short presentation of the Norwegian residential building stock, electricity consumption, electricity price and electric radiator control. Theory about heat storage in thermal mass is also included. Furthermore, there is included a literature review of the potential for utilizing the energy flexibility of residential buildings and relevant measures for demand side management.

Since an objective of this thesis is to investigate how the IHGs influence the flexibility potential, theory of IHG profiles from Norwegian standards and literature on stochastic modelling of dynamic IHGs are presented. As the desire for thermal zoning of bedrooms also will be evaluated in the context of energy flexibility, the final section presents literature on this topic.

2.1 The Norwegian Residential Building Stock

A typology for the Norwegian residential building stock has been developed as a part of the IEE (Intelligent Energy Europe) project EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks). The methodology is based on the previous project TABULA (Typology Approach for Building Stock Energy Assessment). This project divides the building stock typology into three building types; single-family houses (SFH), terraced houses (TH) and apartment blocks (AB). These building types are divided into seven age categories, resulting in a total of 21 segments. In the TABULA project, each of these segments is represented by an example building. This example building represents a typical average building for the specific segment, with respect to building body, energy supply system and energy performance. [9]

The Norwegian building stock is dominated by SFH, and in addition, a large share of residential buildings is built before 1955. This share amounts to around 28 % of the residential building stock, while 38 % is built after 1981, in a period with increasing stringency in the building regulations regarding energy demand. However, over 39 % of the buildings built before 1980 have had energy-related refurbishments, and the share is significantly higher for the buildings built before 1970. For buildings built after 1981, this share is only 17 %. The composition of the inhabited building stock, divided into building type and age category, per 31st of January 2013 is shown in Figure 2.1. [7, 10]
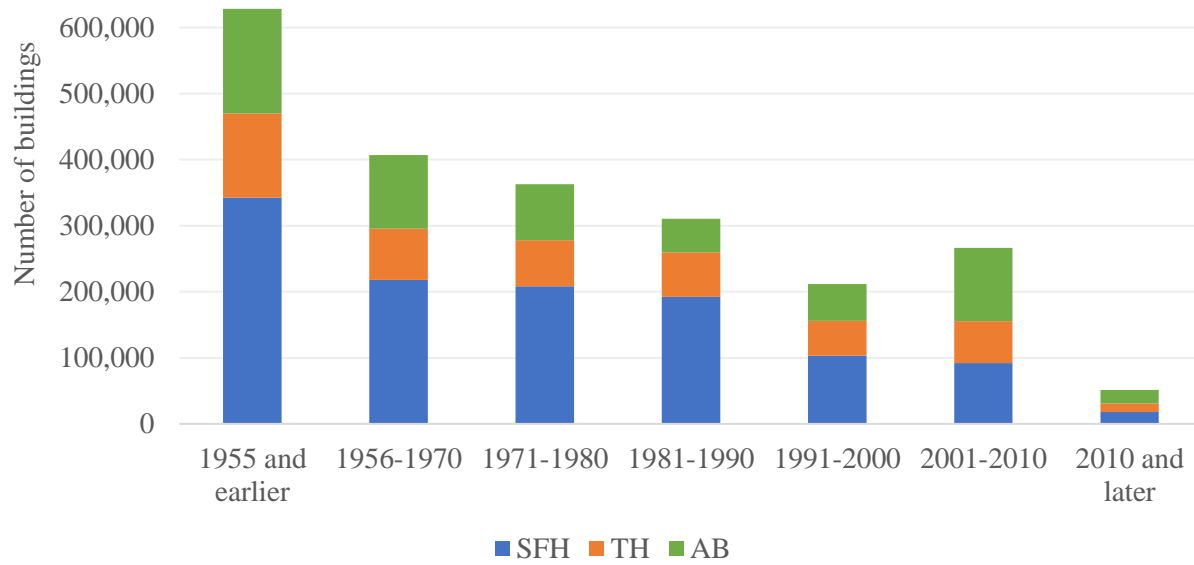
Figure 2.1 Composition of the inhabited residential building stock per 31st of December 2013, divided into single-family houses (SFH), terraced houses (TH) and apartment blocks (AB). Made with data from the TABULA project [9].

The interest in high-performance energy buildings in Norway is rapidly increasing, with several stakeholders being involved in the development of this market. Commonly, these aim for a better energy performance than what is required in the technical building regulations. Examples of this are low energy houses, passive houses and Zero Energy Buildings (ZEB). However, in 2013, when studying the entire residential building stock, only 2 % of SFHs and 4 % of ABs had achieved an energy labelling corresponding to the passive house standard or better. Nevertheless, the Norwegian government has set high ambitions for energy efficient buildings, where the aim is technical building regulations with near ZEB standard from 2020 [11]. This indicates that there will be an increasing share of high-performance buildings in the future. [12]

2.2 Energy Supply and Radiator Control

As opposed to most other European countries, electricity is the main energy source for space heating, heating of ventilation air and domestic hot water in Norway. Numbers from Statistics Norway show that the average energy consumption for all Norwegian residential buildings was 185 kWh/m^2 per year in 2012. Of this energy consumption, an average of 79.3 % was supplied by electricity, and 94 % of the households had equipment for electric space heating. Even though the number of heat pump installations in Norway is increasing, electric radiators are still the most space heating system. [7, 13]

According to electric radiator manufacturers, the most common method to control the heater output for electric radiators is an electric thermostatic controller [14, 15]. The heating output is either 100 % or 0 % and is therefore also called an on/off controller. The output of the radiator will switch

when the measured temperature crosses the set-point temperature (SPT), but to avoid repeatedly on and off switches at a very high frequency the controller has a deadband (DB) around the SPT, where the output state is unchanged. [16]

As opposed to a thermostatic controller, a proportional controller (P-control) changes the output in proportion to the measured error. This control is only active when the measured temperature enters the P-band which is an interval around the desired SPT. Below the P-band the output will be 100% and over the P-band the output will be 0 %. With a P-controller, there will always be an offset error from the set-point as the controller requires an error to produce a proportional output. The working principle of a thermostatic controller and P-controller is illustrated in Figure 2.2. [16]
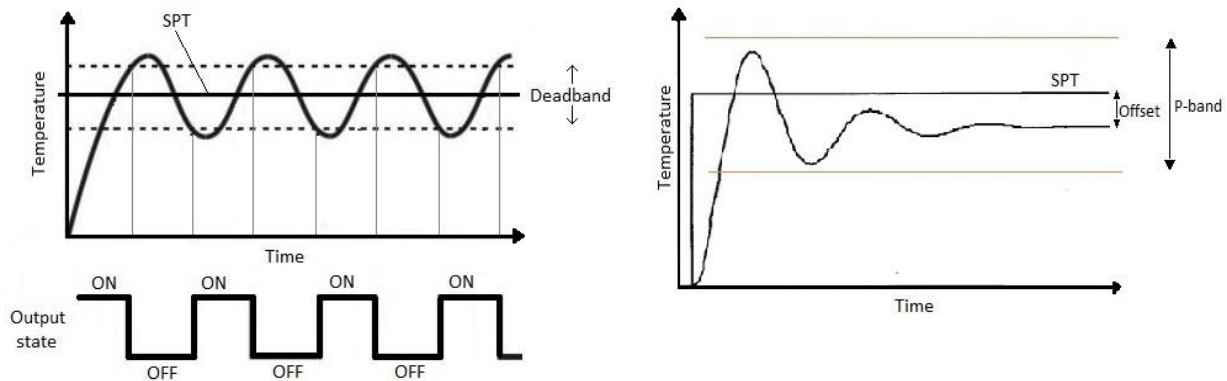
Figure 2.2 Principal illustration of a thermostatic controller and a P-controller. Made with information from [16, 17].

2.3 Electricity Demand and Spot Price

The power grid is dimensioned to accommodate the highest possible load that can occur, but since the consumption of electricity varies significantly over hours, days and years, the grid will only experience this dimensioning load for short periods [1]. The electricity consumption in residential buildings and non-residential buildings in Norway peaks between 08:00 and 10:00 on an average weekday, as illustrated in Figure 2.3. The main reason for this is that the heating of domestic hot water (DHW) in residential buildings is designed so that the heating of the water starts as soon as hot water is used, and the startup of technical installations in non-residential buildings. If only looking at residential buildings, the electricity consumption is highest from 07:00-10:00 and 16:00-21:00. The electricity consumption is less during the middle of the day as people are at work or school. [18]
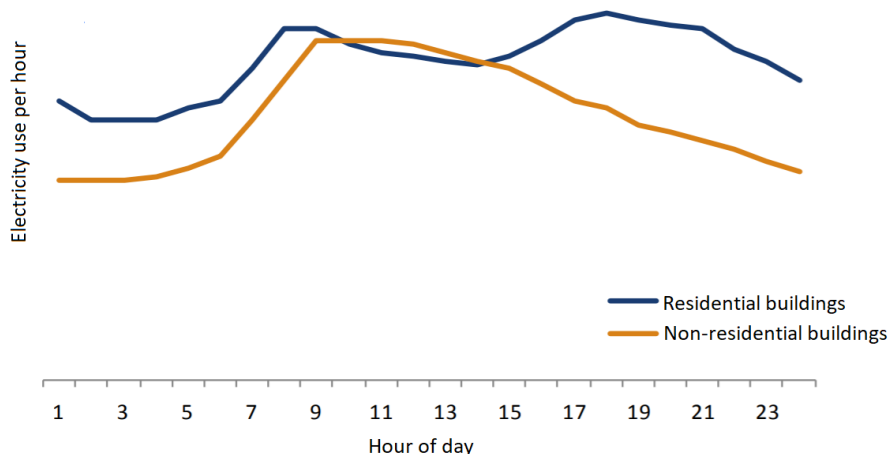
Figure 2.3 Illustration of the average electricity consumption in residential and non-residential buildings on a weekday. Modified from [18].

The electricity price is dependent on the supply and demand of electricity. Nord Pool Spot is the common Nordic stock exchange market, which facilitates the market price for electricity. Through the Nord Pool day-ahead trading system, suppliers of electricity send information about the amount of electricity they will be able to deliver and at which price for the next day, hour-by-hour. Buyers of electricity, which is typically utilities, assess how much electricity they require to meet the demand for the following day, also on an hourly basis. Based on this information, the spot price for each hour of the following day is determined. The highest electricity demand is during winter because of the higher heating demand, which is also reflected in the spot price. Figure 2.4 shows the daily average day-ahead spot price for 2016 and shows that the price in average is at its highest in the 9th hour of the day, i.e. between 08:00 and 09:00. After 09:00 the price is decreasing before another peak occurs in the evening around 18:00. [19]
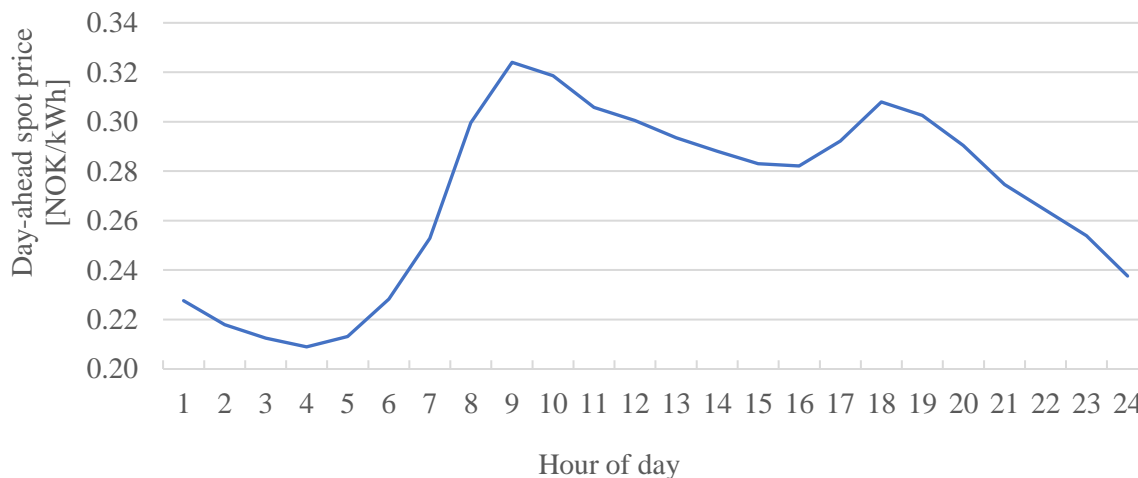
Figure 2.4 The average day-ahead spot price for a day in 2016. Made with data from Nord Pool [20].

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2.4 Thermal Energy Storage in Buildings

Thermal energy storage (TES) in residential buildings can be beneficial for numerous reasons. This can be due to reduced energy prices at night, limitations of electrical power that can be delivered by the local power grid, large variations in heat production from alternative heat sources such as solar thermal, and to ensure smoother operation of energy sources with intermittent operation, such as heat pumps Adjustment of buildings heating power by storing thermal energy can also be done to offer flexibility to the grid. A TES in a building accumulates more energy than is required in periods with low energy use, which can be used in periods when the consumption is high. [21]

TES systems are classified into three categories; sensible, latent and thermochemical storage. In a sensible storage, the heat is stored by changing the temperature of the storage material, which will be the focus of this thesis. The amount of energy stored is proportional to the specific heat capacity, density, volume and temperature variation of the material used for storage. Another important characteristic of TES is the rate at which the heat can be extracted. [22]

Water storage tanks are a common way to store heat in buildings. The structure of the building itself, e.g. the thermal mass of the walls, can also offer a potential for heat storage. The potential for controlling and storing heat in the thermal mass is dependent on several factors, such as the level of insulation and type of heat emitters. In addition, the potential is dependent on the outdoor temperature. [23]

If the air temperature changes in a room due to changes in the heat gain or heat loss, this will result in changes in the temperature and heat content in the building structures and furnishing. The thermal properties of the different materials, the dimensions of the surfaces and the rate of the temperature change in the room will determine the amount of heat accumulated or emitted. The amount of thermal capacity that is activated will also depend on the duration of the temperature load, i.e. the duration will affect how deep the temperature change penetrates the material. Concrete is a beneficial TES material because it has a high specific heat, good mechanical properties and resistance to thermal loading [24]. [22]

The "heat storage capacity of a room", S, is an expression of the thermal connection between the thermal capacity of the structures in the room and the indoor air. This is given as the total heating power that can be stored or released from the building structures with a changing rate of the room temperature at 1 K per time unit. Generally, the dynamic thermal balance of the room (or a whole building) can be expressed as in Equation (1). Here, the heat transfer coefficient, H, is the sum of power losses per K difference between the exterior (T_e) and interior temperature (T_i), due to transmission, infiltration and ventilation. Φ is the total power supplied to the room. [22]

$$\Phi = H \cdot (T_i - T_e) + S \frac{dT_i}{dt} \qquad (1)$$

A simplified method for calculating the area-related thermal capacity of sections of a building can be estimated according to NS-EN ISO 13786. This can be used to assess the thermal inertia of the building. The time constant of a building, τ, characterizes the thermal inertia and is expressed as the relationship between the heat storage capacity and the heat transfer coefficient, as shown in Equation (2). The time constant expresses the time it takes for a temperature change in room or a building to reach 63.2 % of its final value. It is highly dependent on the building structure, and the values can range from 15 to 20 hours for buildings with light construction to 50 to 200 hours for buildings with heavy construction. The time constant must be considered when evaluating the possibilities of changing the SPT in a building, determining the time intervals of set-back and start-up temperature and selecting the control system of the building. [22]

$$\tau = \frac{S}{H} \tag{2}$$

Rearranging Equation (1) to yield the interior temperature-changing rate and including Equation (2), the dynamic thermal balance can be expressed according to Equation (3).

$$\frac{dT_i}{dt} = -\frac{1}{\tau}(T_i - T_e) + \frac{\Phi}{S} \tag{3}$$

This differential equation gives the indoor temperature as a function of time, with varying exterior temperature and power contribution. With a certain step change between two constant power contributions from the heat supply system, the temperature will change to a new stable temperature in a way that can be approximated by an exponential curve. I.e. in the beginning, the temperature change is significant, and as the heat losses out to the structures increase, the temperature changes more slowly. The time before the temperature settles is dependent on the power of the heating system and the time constant of the building. [22, 25]

2.5 Demand Side Management

Operational flexibility in power grid systems is an important property, and can be described as the ability to balance electricity supply and demand, and at the same time achieving acceptable service quality to connected loads [26]. Energy flexibility can be divided into two categories; supply side flexibility and demand side flexibility. Supply side flexibility is related to having the capacity to make up for the mismatch between generation and consumption on the supply side. However, the costs of operating and maintaining such flexibility sources on the supply side are high. Therefore, there has been an increasing focus on demand side flexibility in later years. [27]

Energy flexibility on the demand side is related to the ability of demand side installations to control or regulate the consumption in accordance with needs of the surrounding electricity grid [27].

8

Demand side management (DSM) is a broad term that encompasses all means to change the pattern or magnitude of the end use of electricity with the aim of e.g. offering flexibility to the grid. Other objectives for DSM measures can, for example, be energy conservation or reduction of greenhouse gas emissions. [2]

Two classic forms of load management that can be applied for DSM are load shifting and peak reduction and these are illustrated in Figure 2.5. Peak reduction can be explained as a reduction of the consumption in periods with high use of power. The principle of load shifting is to shift load from periods with a high use of power to periods with lower consumption. For buildings, this can be achieved in several ways, for example by utilization of storage water heating, heat storage in the thermal mass, adjustability of HVAC-system use and shifting of plug loads [4]. The benefit with load shifting, compared to other DSM measures, is that it can allow for demand side flexibility without compromising the quality of the offered service [2]. [5]
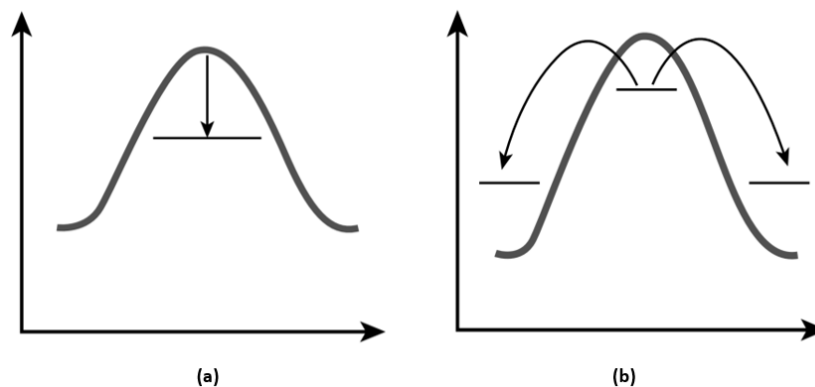
Figure 2.5 Peak reduction (a) and load shifting (b). Modified from [5].

Methods for DSM implementation can be separated into indirect load control, autonomous load control and direct load control. Indirect load control means that users manually adjust their consumption according to incentives, whereas with autonomous load control devices receive information about the power system and automatically adjust their consumption accordingly. Direct load control means that the utility operator is controlling the devices centrally. [28]

Residential buildings represent a source for demand side flexibility, and the possibilities for utilizing buildings as a source of flexibility in power systems is a relatively new idea. Utilization of this flexibility in buildings is done by shifting the energy use in time or by applying on-site energy storage capability, whilst at the same time maintaining the required indoor climate. Generally, DSM is undertaken with the implementation of four types of components [24]:

- Energy efficient end-use devices.
- Standard control systems to turn end-use devices on and off as required.
- Additional equipment, systems and control allowing for load shaping.
- Communication systems between an end-user and an external party.

The energy flexibility of buildings is a complex topic, and the potential for offering flexibility is strongly related to the building design, the installed energy supply and energy distribution system and the control of the energy demand in the building. Also, user behaviour and local climate may influence the actually attainable energy flexibility. Several studies have defined characteristics for the demand side flexibility potential of buildings and methods applied to assess the flexibility potential are diverse. However, in the work with the ongoing IEA EBC Annex 67 three general properties that are usually communicated when describing the energy flexibility have been summarized. The first is the capacity, which can be described as the amount of energy that can be shifted per time unit. The second is related to time aspects, such as starting time and duration. Thirdly the potential for cost saving and changes in energy use as a result of activating the energy flexibility. [4, 29]

2.5.1 Activation of Thermal Mass

Building energy flexibility often concerns the electricity consumption for heating and cooling, and to utilize the full flexibility potential a thermal storage is necessary [30]. The end use of energy for space heating in residential buildings has a relatively predictable load pattern, and if the objective is to change this pattern to meet the demands of the surrounding grid the desired change in consumption can be decided accordingly. The storage applied is usually thermal energy storage, such as the thermal mass of the building or water storage tanks [27]. Storage in the building structure itself, i.e. the thermal mass, has been identified by several studies as a promising and cost-effective way for buildings to offer flexibility [23]. The available storage capacity in the building structure is not only dependent on the material properties but also on the geometry of the building, the distribution of thermal mass and the interaction with the heating system. In addition, the performance of a structural thermal storage will vary with time, as the climatic boundary conditions and occupant behaviour will affect the available storage capacity. [31, 32]

Moreover, the thermal resistance on the surfaces in the building will have a large impact on the possibilities for utilizing the available thermal mass. This is because the thermal resistance on the surfaces, e.g. floor linoleum, will reduce the thermal connection between the air and the structure. Therefore, interior thermal insulation on for example a concrete structure will break the thermal connection between the concrete and indoor air. [22]

Utilization of the thermal mass of the building can offer flexibility by decoupling the interaction between the energy supply system and the heating demand of the building. This means that the building can be heated or cooled by electricity during off-peak hours, and thus the load profile can be flattened during peak hours. I.e. the utilization of a TES is appropriate for load shifting, and heat pumps in combination with a TES system are one of the most promising technologies for DSM in buildings. For buildings with on-site photovoltaic generation, a TES may also offer flexibility in terms of increasing the self-consumption of electricity [12]. [24]

There are several approaches for activating the thermal mass, and the most relevant for this thesis are surface activation and direct activation of material with electric heating cables. Surface activation refers to actively heating or cooling the buildings thermal mass by controlling the indoor air temperature. This means that the thermal mass is indirectly activated because the changes imposed on the indoor air will affect the thermal mass. This approach requires no additional mechanical equipment, as it only relies on the HVAC-system. A limitation to this method is that the changes in indoor SPT must be done with consideration to the thermal comfort of occupants in the building. Thus, the variation should not be of more than a few degrees. [33]

To utilize the thermal mass, the SPT can be increased to "charge" the thermal mass, and consequently reduced to "discharge" the heat stored in the structure. However, by storing heat in the building structure, the transmission and ventilation losses will increase. This means that it is expected that storage in the thermal mass will have a higher efficiency in well insulated buildings. If the SPT of the heating system is reduced over a time period and then increased again, this will cause the heating system to supply as much power as possible to reach the new SPT. This may result in a "rebound peak" in a time period after the SPT is increased. It is desirable to reduce or avoid this rebound effect as much as possible when changing the SPT. [25, 31]

As a result of the increased temperature, and consequently increased heat losses, only a part of the heat that is stored in the building structure may be used later when the heating power is decreased. The storage efficiency can thus be described as the fraction of the stored heat that it is possible to use effectively to reduce the heating power later. A report by Reynders et. al. from 2015 show that the storage capacity and storage efficiency of the building structure is highly dependent on the thermal properties of the building and that the heat loss and available thermal mass is the most important factors. In addition, the storage capacity and storage efficiency are not constant but vary with time and the climatic boundary conditions. In terms of power shifting capability, the study applied a definition that also considered time. This means that the power shifting capability was not only showed as the amount of power that can be shifted by activating the thermal mass but also for how long the shift can be maintained. [31]

Another study carried out by Reynders et. al. from 2013 investigated the possibilities for heat storage in the thermal mass of a nearly-ZEB dwelling in Belgium, with a PV-system, heat pump and hydronic heat distribution. The storage potential was tested for a light and heavy building construction with different thermal capacity, and three different levels of insulation. The study showed great potential for peak shifting over hours or days, by DSM using the structural storage capacity in building and the electricity use for the heat pump was significantly reduced during peak hours. The highest peak load reductions varied between 75 % and 94 % for a radiator heating system and a floor heating system, respectively. This show that the potential for peak shaving is larger for floor heating. This is because the floor heating activates the thermal mass directly, while the radiators mostly tend to heat the indoor air, which gives faster temperature fluctuations. In addition, the heavy building showed a higher potential for DSM in comparison with the lightweight

building. Overall, the total energy use of the building was increased by activating the thermal mass. [32]

A study by Le Dréau and Heiselberg from 2016 investigated the potential for exploiting the energy flexibility of residential buildings with different thermal properties by using short-term storage in the thermal mass. The SPT was increased to store heat and decreased for heat conservation. This study showed that both investigated buildings, i.e. a poorly insulated building and a building with passive house standard located in Denmark, had possibilities to provide energy flexibility to the power grid. However, the best results were achieved with different strategies for the two building types due to the different characteristics, where the time constant had the most significant influence. The most successful strategies showed that both buildings managed to shift a considerable share of the energy use in time and that the potential for energy shifting was larger for the passive house. The study also showed that the poorly insulated building had a high capacity for both storing and heat conservation for short periods of time, i.e. between two to five hours. Longer activation periods should be avoided for this building to maintain comfortable conditions in the building. The passive house building was able to modulate less heat, but on the other hand, the activation periods could be long. Since well-insulated buildings are sensitive to over-heating, the study recommends that extra caution should be taken regarding heat storage strategies. [23]

2.5.2 Rule-Based Control Strategies

To activate a TES or the thermal mass of a building to utilize the flexibility potential, a control strategy (CS) for the heating system must be implemented. The standard NS-EN 15251 gives the common approach for calculating the energy needs of a building, where fixed set-point temperatures for the heating system is applied [34]. This ensures that constant indoor temperatures and DHW temperatures are achieved. Physical variables outside the building, such as price variations of electricity or the level of stress of the surrounding grid are not considered for the control of the building. Neither is the flexibility of occupants with regards to variations in the indoor temperature and the possible storage capacity of the heating system. Thus, if a suitable control strategy taking other constraints into consideration is applied, the building performance may be greatly improved. [35]

However, with the increasing focus on offering flexibility to the grid, there are several factors contributing to changing the way heating systems are controlled. Some of the developments contributing to a changing focus in the control strategies are easily available forecasts and cheap computation capacity on a controller level. [36]

There are different control strategies that can be applied, two examples are rule-based control (RBC) and model predictive control (MPC). RBC strategies make changes in a system based on pre-defined decision rules. This means that the SPT in the heating system is pre-defined, based on for example set-points for indoor temperatures or levels of CO_2-intensity of the electricity, to operate the system in a more efficient manner. MPC makes decisions by predicting the future state

of the system, by making a simplified model of the building. The MPC makes use of an objective function, which optimizes the schedule of the heating system for a chosen parameter, this can for example be to achieve minimum costs of operation. [35]

Thus, the main difference between these control strategies is that MPC predicts the future system state for an optimized operation, while RBC is non-predictive. Therefore, MPC strategies represent a more complex control strategy with more information necessary to optimize the control [36]. However, RBCs are restricted to mainly fulfilling one certain control objective. To achieve optimization of the overall system, with regard to low energy consumption, reduced energy costs and a high load shifting potential, more complex strategies such as MPCs should be applied. [30]

There will always be some unknown disturbances that affect the controlled heating system. Two of the most considerable sources of disturbances are the outside weather conditions and the internal heat gains from occupants, equipment and lighting. In general, RBC strategies will take into account very few of the disturbances, whereas MPC needs to forecast some of them to predict the future state of the system. The most common disturbance to be taken into account is the climatic weather conditions. [37]

A study from 2017 by Fischer et. al. compared different predictive and non-predictive control strategies for a variable speed heat pump in a residential building. The study investigated possible trade-offs between performance and complexity of different controllers when considering the variable electricity prices and on-site PV-generation. Among the investigated CS were different RBCs, rule-based predictive controls and MPC. In terms of annual operational costs, efficiency and comfort, the MPC gave the best results. However, the RBC approaches were found to be less computationally demanding and easier to design. The study also emphasizes that the fine-tuning of the RBC approaches is demanding and that the controllers should be continually adjusted according to the varying boundary conditions. The study also provides some recommendations of factors to be aware of and considerations that should be taken with regards to choosing control strategy. These include being aware of the trade-offs when offering flexibility, the needed level of complexity for the respective case, the robustness of the control strategy with changing boundary conditions and the influence of the choice of temperature settings. [36]

Due to its simplicity, RBC strategies are a common control approach for energy systems in buildings [30]. However, in addition to optimizing energy use, RBC strategies can be used to improve the energy flexibility of HVAC systems, which is the objective of this thesis. This strategy uses pre-defined decision rules to adjust e.g. the indoor SPT. This can contribute to peak-shifting/shaving by coupling the control strategy to pre-defined peak hours based on power grid data or the electricity spot price. [35]

In 2017 Clauß et. al. investigated time-scheduled control strategies amongst other RBC strategies in a passive house, where the SPT for space heating and heating of DHW was adjusted according to pre-defined peak hours. The CSs was implemented in a ZEB with a lightweight construction and a hydronic heating system with a heat pump as the energy source. Before the pre-defined peak-hours, the DHW tank is heated and the thermal mass activated by increasing the SPT. This

was done both for the thermal mass and DHW tank separately, and a combination of the two. For the activation of thermal mass, only the common rooms were included in the RBC. The peak hours were in this study defined to be between 07:00-10:00 for the space heating, and the pre-heating started at 04:00 and ended at 06:30. The results with the pre-defined schedules succeeded in loading the DHW tank, but not the thermal mass of the building. Instead of activating the thermal mass during pre-heating, the energy was transferred from the storage tank to the floor heating system. Thus, the need for a better control approach is needed in the future to activate the thermal mass. Another aspect of this type of control strategy is that the actual peak-load hours have to occur according to the pre-defined schedule. [35]

Another approach is to couple the RBC to the electricity prices by introducing a threshold for low and high electricity prices, as the hourly tariff price for electricity can be assumed to represent the level of stress on the grid [38]. By doing this, the SPT for the heating system can be increased if the price is below the threshold and decreased if the price is above the threshold. The thresholds can for example be set by comparing the current hourly price with the minimum and maximum spot price of the following day, which can be found at Nord Pool's homepage. When the changes in the electricity price are known, as facilitated through an implementation of smart power meters, the heating system can be controlled to maximize the operation during low-price hours. This can also lead to reduced electricity expenses for the customer. All Norwegian customers will have their old power meters replaced with a smart power meter by January 1st 2019 [39]. In addition, there is currently an ongoing debate about how the power demand tariff should be handled. The Norwegian Water Resources and Energy Directorates (NVE) have proposed a power subscription which has met a lot of resistance, and a power demand tariff based on peak hours have been suggested [40]. [35]

This RBC approach is investigated in a study by Dar et. al. in 2014 [38], and the aforementioned study by Clauß et. al. also investigated this RBC strategy. For the latter, the threshold was set based on the day-ahead spot price (SP) with a lower and higher threshold set to 25 % and 75 % of the difference between the maximum and minimum day-ahead SP. Below the lower threshold, the SPT for space heating is increased with 3 K and over the higher threshold the SPT is decreased by 2 K. The results showed that this strategy led to both a higher energy consumption (+ 9 %) and higher energy costs (+ 5 %) compared to a constant SPT of 21 °C. This was mainly because the SPT during nighttime increased because of the low SP. Even though the SP is lower during nighttime, it did not compensate for the extra energy use. [35]

2.5.3 Key Performance Indicators

Performance metrics are necessary to measure the effect of strategies implemented to achieve a certain performance goal, which can be to provide service to the power grid by utilizing the built-in flexibility. A key performance indicator (KPI) is a parameter or value that provides simplified information about complex systems and points to the general state or trends. KPIs can thus be used to evaluate the performance of a system with respect to a certain desired result. In building simulation, the conventional KPIs used to evaluate the results does not focus on the interaction of the building with the grid and the building energy flexibility. Indicators that are used correctly may improve the building performance regarding flexibility. The most common indicators that quantify the energy flexibility are price-based load shifting, self-generation and self-consumption. [30, 41]

KPIs for energy efficiency at a building level is common, and some examples of conventional performance measures are final energy use, energy demand, cost of energy, primary energy use and CO_2-emissions. If a KPI is effective, it gives an accurate measure of overall system status, and by doing so, it also provides a basis for decision making. KPIs for buildings must also be applicable during the systems operational lifespan, all seasons and different levels of occupancy. KPIs that evaluate the energy flexibility a building can offer to the surrounding grid is becoming more important, and there exist several indicators that quantify different aspects of demand side flexibility. [30, 41]

Indicators of building flexibility can describe for example physical features, such as storage capacity, or the magnitude of the building's response to external signals, e.g. the electricity price. Indicators that provide information about the flexibility potential or characteristics regarding flexibility can be load-matching and grid interaction indicators or energy flexibility indicators. Load-matching and grid interaction indicators identify the peak power consumption periods and can provide information about the share of the buildings energy load vs. the on-site electricity production. Energy flexibility indicators are often based on price, and the aim is to show whether the energy is consumed during periods of high or low prices. [30]

2.6 Occupancy and Electricity Load Profiles

The behavior of occupants and the timing of their energy use may have an impact on the peak-shifting potential, and thus flexibility potential of residential buildings. Especially for highly insulated buildings, where the significance of the internal heat gains from occupants, lighting and appliances is high [42]. When investigating demand side strategies with the ambition of shifting the consumption in time it can be beneficial to consider the residents' behavior in terms of when it is likely that they will use household appliances, lighting and heating [43].

2.6.1 Internal Heat Gain Profiles from the Norwegian Standards

The IHG profiles used by the industry today are given in the Norwegian Standards and Technical specifications. NS 3031:2014 "Calculation of energy performance of buildings – Method and data" contains load profiles for lighting, electrical appliances and occupants and will hereafter be referred to as "NS". These profiles are used for validation according to the technical requirements and defined as uniform in space and time. SN/TS 3031:2016 "Energy performance of buildings – Calculation of energy need and energy supply" is a supplement to NS 3031 and will hereafter be referred to as "TS". This is a technical specification that provides a more comprehensive method for energy calculations. It considers the interaction between the building body and the technical equipment used for heating, cooling and energy production for calculation of the energy need and energy supply. One important difference from NS is that the electrical load profiles are dynamic in time, which represent a more realistic user profile. The sum of the internal heat gain profiles for occupancy, lighting and appliances provided in NS and TS is illustrated in Figure 2.6. [44, 45]
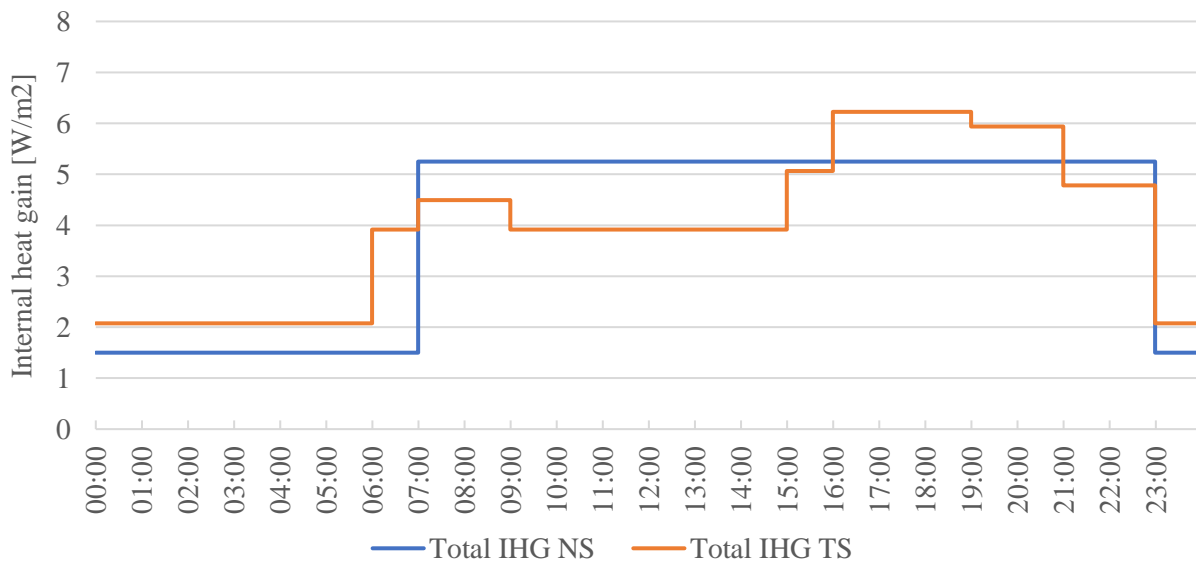
Figure 2.6 Total internal heat gain profiles from the standard NS 3031 and TS 3031. Made with information from [44] and [45].

2.6.2 Modelling Stochastic Occupancy and Electricity Demand Profiles

Simplifications with regards to occupant behavior, such as the NS and TS IHG profiles with fixed schedules, is one reason for the gap between the predicted energy use of a building and the actual energy use [46]. The behavior of occupants, and the generated heat gains from their activities will in reality be stochastic and variable in space, time and scale. In recent years the behavior of the occupants and their impact on the energy performance of the building has been increasingly investigated. For example, the IEA EBC program "Annex 66: Definition and Simulation of Occupant Behavior in Buildings" was started in 2013 with the objective to evaluate the impact occupant behavior has on the building performance [8]. In general, the energy-related behavior of

occupants depends on several factors. One is the energy-related household variables, such as the number of appliances and daily usage. The individual and personal characteristics of occupants, such as energy-related attitude, family size and profession, also have an influence. Furthermore, the building characteristics, e.g. the level of insulation, and the perceived human comfort have been found to be influencing the energy-related behavior of occupants. In this section, a methodology for modelling electricity demand based on occupant behavior is presented, which can be used to retrieve IHG profiles. [47]

There are mainly two approaches for modelling the domestic electricity demand, these are statistical top-down models and bottom-up models. The top-down model uses measured load data and aims to describe and reproduce the characteristics of the input data. This model can be helpful to understand the influencing factors such as season, temperature or the size of the household, but often lacks examination of the effects of user behavior. It cannot separate the electricity demand into different household activity purposes. The bottom-up models can overcome this disadvantage by first modelling the occupant behavior and then relate this to the energy consumption. This method is time-consuming and requires a lot of detailed input data, but can provide important information on e.g. flexible demands that can be controlled and random demands. A stochastic process is often used to generate load profiles with a bottom-up model. [48]

In 2008, Richardson et. al. made a detailed method for generating realistic occupancy data for the United Kingdom, based upon time-use survey (TUS) data. The proposed method generates statistical occupancy data with a resolution of ten minutes, based on a first-order Markov-Chain technique. This means that each state that is determined for every time step is dependent on the previous state and the probabilities for the changes of the state. Seven different occupancy states are used, i.e. between zero and six active occupants. In addition to the current state, the probabilities of the change of state in the next time step are dependent on the household size and time of the day. It also separates between weekdays and weekends. The energy use in residential buildings will depend on the number of people living in the building, and if they are home and "active". An "active occupant" is defined as a person who is in the building and not asleep. [43, 49]

Furthermore, Richardson et. al. developed a comprehensive high-resolution electricity demand model particularly for the study of local electricity grids, with the aim to represent the stochastic nature of the electricity demand. The model is called the CREST (Center of Renewable Energy Systems Technology) Domestic Electricity Demand Model which uses a bottom-up modelling approach. The stochastic occupancy model described earlier is implemented in this model to generate active occupancy schedules. To accurately model the electricity demand, the sharing of energy use between occupants for lighting and appliances is taken in to account, so that when there is more than one active occupant in the dwelling an "effective occupancy" value is used. This means that a doubling of active occupants in the building do not necessarily result in a doubling of the energy use. The models for lighting and electrical appliances is described further in the following paragraphs. [50]

The electricity use for lighting depends mainly on the incoming level of natural lighting and the activity of the occupants. With these factors as basic inputs, a high-resolution electricity demand

model for domestic lighting was created by Richardson et. al. in 2009 as a part of the CREST Domestic Electricity Demand Model. The occupancy schedule in combination with an irradiance profile for each month gives the lighting demand profile. The installed lighting unit count, type and power ratings in the dwelling are randomly chosen based on examples made from statistics. To ensure that the overall energy use for lighting is in accordance with statistics, a calibration scalar is implemented to the model to give an overall mean energy use over numerous simulation runs. The fact that some lighting units are more frequently used than others is considered by adding a weighting factor to each unit. A stochastic model is used to determine if a switch-on event occurs, and a probability distribution is used to determine the on-duration length. The model is validated based on an indirect comparison with a lighting demand model built upon measured electricity data from 100 dwellings in the UK. [51]

The use of electrical appliances was added to the model by Richardson et. al. in 2010 to get the full domestic electricity demand model. The generation of active occupancy schedules is also implemented here, as the use of appliances is highly related to active occupancy. The TUS data is used to create daily activity profiles which represent the probability of performing different activities at different times. The different activities are linked to suitable electrical appliances with power use characteristics. The model selects appliances for the dwelling based on statistics, and each appliance is assigned with an annual energy demand. In each time step in the simulation, the switch-on event for an appliance is determined by four steps. First, the activity profile is chosen based on the appliance activity (e.g. cooking), the number of active occupants and whether it is a weekend or not. Then the probability that any of the active occupants are involved in the appliance activity at this time is found from the activity profile. This probability is then multiplied with a calibration scalar which represents the average number of how many times the appliance is used during a year. Finally, this probability is compared to a random number between 0-1, and the switch-on event occurs if the probability is higher than the random number. [50]

The synthetic data generated from the domestic electricity demand model is compared to measured data which show a very good representation of the demand diversity between multiple dwellings. However, at night time with no active occupants, the model assumes that the lights and appliances are off, and the synthetic data therefore under-represent the demand compared to the measured. Nevertheless, for the study of local electricity grids, the demand diversity is critical, and the model is therefore considered to be representative for this purpose. [50]

The architecture of Richardson's electricity demand model for appliances and domestic lighting is illustrated in Figure 2.7. Here, the inputs and output for the two models are illustrated together. The square in the middle is representing the dwellings, and each separate dwelling is given a data series of active occupancy and a number of appliances and lighting units. The appliances are linked to the daily activity profiles, which represent the likelihood of the occupants performing the specified activities at given times of the day. The lighting units are linked to irradiance data. In addition, each dwelling has a household irradiance threshold, which is the natural light level that the occupants will consider using artificial lighting. Furthermore, a calibration scalar is applied for both models to ensure that the mean value of several simulations is in compliance with statistics. When an appliance or light unit is switched on, the electricity demand is determined based on a

given set of characteristics. The sum of the power demand of all appliances and lighting units gives the demand of the dwelling, while the overall power demand is given by summing the power demand in all dwellings. [50, 51]
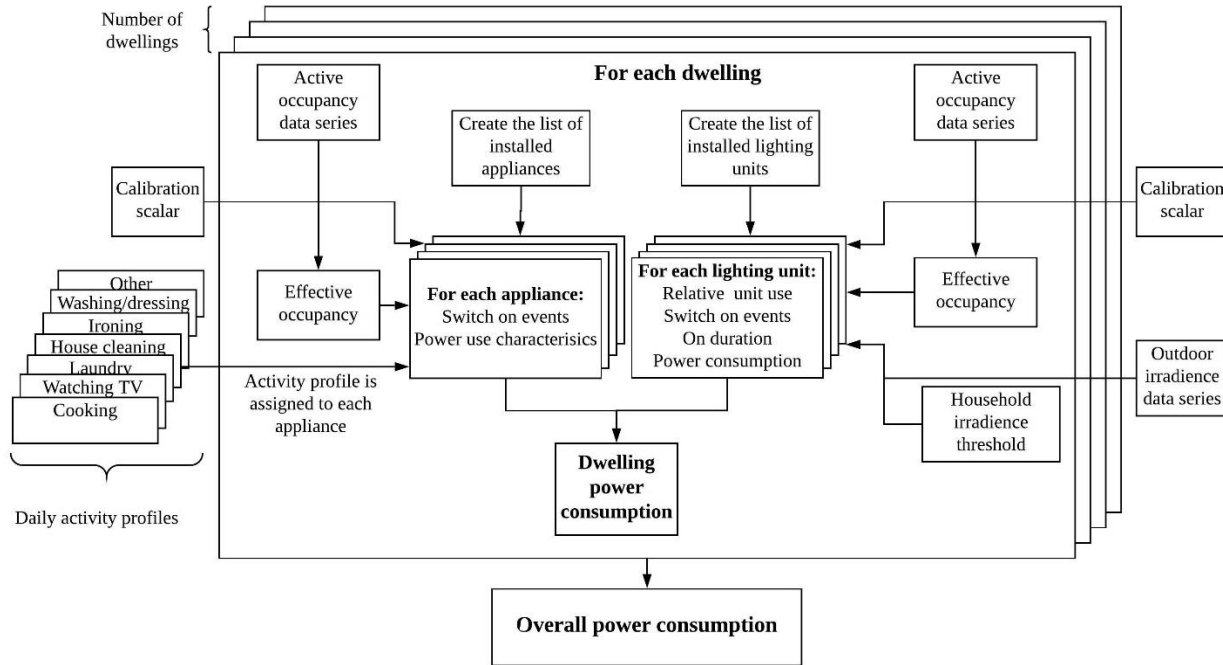
Figure 2.7 Architecture of the electricity demand model made by Richardson et.al. The figure is made with information from [50, 51]

For the models developed by Richardson et al. to be applied in Norwegian residential buildings, the data should be adapted to the behavior of Norwegian residents. This was done by Eline Rangøy in an NTNU master thesis in 2013 [49]. Here, the methodology developed by Richardson is adapted to the TUS data from the Norwegian survey "Tidsbruksundersøkelsen", executed by Statistics Norway. In addition, the output is calibrated to other research projects and surveys, i.e. the REMODECE project, Eldek project, data from The Norwegian Water Resources and Energy Directorate, and the Swedish Energy Agency. The main issue with this adaptation is that the Norwegian TUS data is used person selection, as opposed to household selection for the UK TUS. [49]

The validation of the models based on the Norwegian data is somewhat limited, mainly due to limited access to measured Norwegian data. If the generated demand profiles for lighting and appliances are calibrated separately for each household size, comparison to measured data shows that these demand profiles can be used in building simulation software. The occupancy profiles, however, have a realistic shape of the daily profile, but the average for one day is low. Therefore, according to Rangøy, the occupancy profile based on the Norwegian TUS data should not be directly used in building simulation software. Even though the occupancy profile is a basis in the models for appliances and lighting, it only affects the "switch-on" event, as the "duration on" time

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is based on its own probability distribution which is calibrated to Norwegian data. In addition, the energy use and occupancy of the models is a bit low for the first hours of the day. This is assumed to be because the output is simulated for 24 hours at the time, which is not connected in any way so that appliances and lights that are turned on at the end of a day is turned off at the beginning of the new day. [49]

A study from 2015 by Dar et. al. investigated the effects of realistic occupant behavior on the heating demand and energy system performance for well-insulated residential buildings in a cold climate. The study applied the methodology developed by Richardson and calibrated to Norwegian data by Rangøy for occupancy, lighting and appliances. Stochastic DHW draw-off events were also included. The study identified household size and occupancy patterns, i.e. the work schedule of the residents, to be parameters that considerably affect the gap between the predicted and actual energy use of the buildings. Furthermore, the variation that can occur in household size was described as an important parameter for understanding why the energy use of similar building types has large variations in actual energy use. [47]

Due to the stochastic nature of occupants, the buildings composing a neighborhood will seldom have the peak load occurring at the same time. The coincidence factor describes this phenomenon, and this is always lower than one. For residential users, the coincidence factor is often around 0.6. This might even be lower for highly insulated buildings, where the energy consumption is more dependent on the user appliances than the need for heating. A study by Sartori et. al. from 2014 investigated the aggregated load of 200 all-electric residential passive houses with a heat pump. The study was based on stochastic user profile inputs for occupancy, appliances and lighting. The results showed how the high variability in peak load for a single household is considerably reduced as the demand of more households is included. [42]

2.7 Occupant Preferences Regarding Internal Thermal Zoning

One key characteristic for DSM is user acceptability. Studies have defined the user acceptability to be the share of compromise of load service that the users are willing to accept in order to provide flexibility. Regarding this, the occupants desire for internal thermal zoning in the context of energy flexibility is a topic not frequently addressed in literature. Therefore, this section provides a short presentation of some key aspects regarding thermal comfort and an overview of literature regarding the desire for thermal zoning in passive house buildings in a cold climate. [27]

HVAC systems main task is to provide a good indoor climate for the occupants, which include thermal comfort. The definition of thermal comfort can be expressed as "a state of mind in which a person expresses full satisfaction with their thermal surroundings" [22]. There are several factors that affect the thermal comfort of a person, such as the dry-bulb temperature, thermal radiation, air velocity and level of clothing. To describe the thermal surroundings, the most common parameter used is air temperature. However, if there are major heat radiating sources in the room, the operative temperature is more suitable as a measurement. The operative temperature is the weighted value of dry-bulb air temperature and the mean radiant heat temperature, which results in the same heat exchange through convection and radiation as the actual surroundings. [22]

With the development from leaky and poorly insulated buildings to high-performance buildings, e.g. passive houses, there have been considerable improvements regarding thermal comfort. As opposed to the original passive house definition by the Passive House Institute in Germany, the Norwegian Passive House Standard does not require that the thermal comfort is provided solely by air heating. User evaluations of residential buildings with only air heating indicate that the occupants perceive the bathroom temperatures as being too cold and bedrooms as too hot. However, the common heating system for residential passive houses in Norway is a simplified space heating distribution system, with floor heating in bathrooms, radiators in living rooms and a one zone mechanical ventilation system with a heating coil and heat recovery. This is a solution which in principle can facilitate a larger degree of thermal zoning within the building. [52]

Despite this, studies of Norwegian residential passive houses indicate that the occupants prefer lower bedroom temperatures than what is achieved and that it is problematic to attain this due to the one zone mechanical ventilation system [53]. A study performed by Berge et. al. investigated the perceived thermal environment in 62 residential passive houses with the most common heating and ventilation system in Trondheim. A survey based on the well-established 7-point scale for evaluation of the indoor climate in accordance with NS-EN 15271:2007 showed that the occupants were generally satisfied with the thermal conditions in the living room and bathrooms in both summer and winter. However, the thermal conditions in the bedroom were stated to be too warm for 50 % of the occupants during the winter and for 89 % of the occupants during the summer. This often resulted in window ventilation to achieve the desired temperature, which in turn leads to an excessive energy use for heating. The desired bedroom temperature ranged between 12-20 °C. The study pointed out the supply of a constant air temperature to the bedrooms as one of the major obstacles to attaining desired temperature conditions. [52]

A study by Thomsen et. al. interviewed 32 residents of passive houses and 6 residents of houses according to the technical building works regulation (TEK) of 2010 which revealed that the desired temperature in bedrooms ranged between 15-19 °C and the general indoor temperature between 22-24 °C [54]. Georges et. al. performed a qualitative study of two apartments in a building block in the same area as the work of Berge et. al. with the same heating concept. The study investigated this topic by applying building simulations, field measurements and interviews of occupants. The occupants' satisfaction on the thermal environment was in good agreement with the study of Berge et. al. and Thomsen et. al., with an indication that temperature zoning for the bedrooms is desirable. [55]

Strategies to achieve thermal zoning are insulation of bedroom walls, control strategies and multizone ventilation. The aforementioned study by Georges et. al. applied different strategies in the simulation tool IDA ICE to achieve thermal zoning in the bedrooms. The investigated strategies involved the efficiency of the heat recovery, SPT for the heating battery, SPT for space heating and opening of doors and windows. With an SPT of 21 °C for space heating, a bedroom temperature around 18 °C was achieved with about 20 % extra energy use for heating. Lower bedroom temperatures than this would require window opening for several hours or a significant reduction of the heat recovery efficiency, resulting in a very high energy use for space heating. [55]

A master thesis carried out by Selvnes at NTNU in 2017 examined different strategies to achieve thermal zoning of bedrooms. Different scenarios with building structures from heavy to light was simulated, and the results showed that the lightest building structure was more responsive to the outdoor temperature. The thermal resistance of the inner bedroom walls was also examined. The results showed that low outdoor temperatures contribute to thermal zoning, but that adding extra insulation on typical Nordic inner walls will not improve the thermal zoning further. Thermal inertia was however confirmed to have a larger impact on thermal zoning than thermal resistance of the internal constructions, especially for achieving very low bedroom temperatures. Solar and internal heat gains were also revealed to be the dominant factors for preventing thermal zoning, especially with milder outdoor temperatures. Solar shading is therefore an important aspect to study to achieve thermal zoning. The results also showed that the supply air temperature have a great impact on the bedroom temperature, and that an extra heat loss could be added by supplying air with lower temperature than the bedroom temperature. By adding an extract air terminal from the bedroom, the energy efficiency increased. [56]

3 Modelling Approach

To evaluate the energy flexibility of Norwegian residential buildings, a representative building model must be chosen. This chapter describes the applied simulation tool and the selected building models. Furthermore, the approach for modelling IHGs, the selected RBC strategies and the method for evaluating the bedroom temperatures is presented. Finally, the selected KPIs to describe the flexibility potential of the buildings are presented.

3.1 Building Performance Simulation Tool

IDA Indoor Climate and Energy (ICE) 4.7 is the building performance simulation tool used for this thesis. IDA ICE is a dynamic building simulation software developed by EQUA Simulation AB. It gives detailed whole-year, multi-zone calculation of the thermal indoor climate and the energy performance. It has high input possibilities where control strategies and thermal mass can be accounted for. This enables the software to do simulations with high accuracy. IDA ICE is also completely transparent which means that every equation, variable and parameter can be logged and studied in detail for each component. The accuracy of IDA ICE is validated according to NS-EN 15265. The climate files in IDA ICE are based on weather data developed by the American Society of Heating, Refrigeration and Air-Conditioning (ASHRAE) and the National Climatic Data Center, but other climate files can also be used. [57]

3.2 Description of the Evaluated Building Model

The choice of building model is based on the findings in the literature study and aims to represent the largest possible share of the building stock. Since the Norwegian residential building stock is dominated by SFH, this building type is chosen for the building model. Two construction modes and two levels of insulation are modelled, to represent both an older part of the building stock and passive house standard with different thermal mass. This is done to evaluate the potential for energy flexibility of buildings within different age segments, but also to illustrate the potential of a building stock moving towards a more energy efficient standard.

The building models are based on the work of Selvnes [56]. The model applied is a two-storey SFH with a total heated floor area of 160 m^2, extracted from the Norwegian house manufacturer Mesterhus. Some adjustments have been made to the models to better represent the two different segments of the building stock. An illustration of the building model from IDA ICE is shown in Figure 3.1.
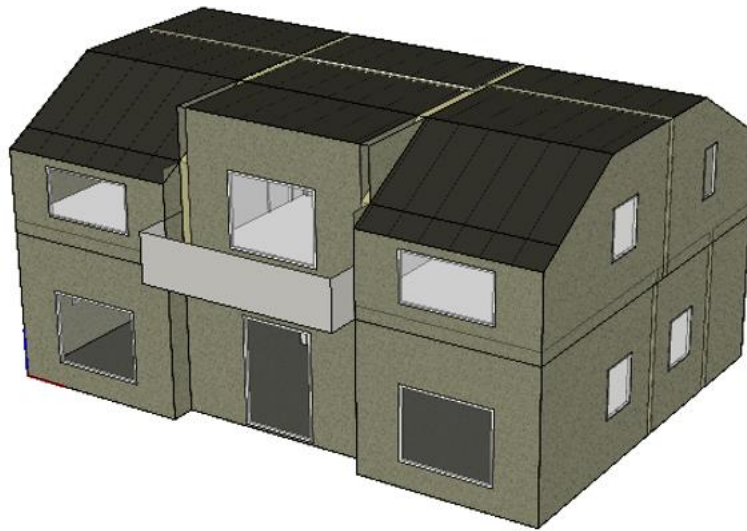
Figure 3.1 3D figure of the model building from IDA ICE showing the southwest facade.

The building model consists of nine zones, representing the rooms in the building. The floor plan is shown in Figure 3.2. The dark grey internal walls represent the load bearing internal walls, while the light grey is dividing walls. Zone 1, i.e. the kitchen and living room, has an open floor plan. Zone 2 is the hallway, which has an open staircase to the second floor. This is modelled as a single zone over the two storeys, with no floor. The dashed line between zone 2 and zone 7 illustrates that the zones are not separated by a wall.

(a) First floor   (b) Second floor
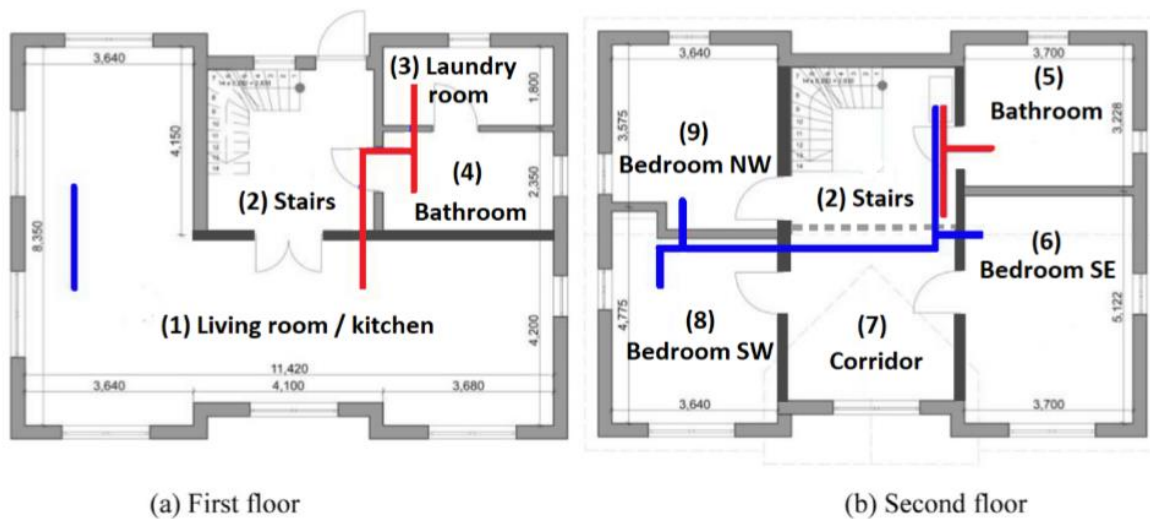
Figure 3.2 Floor plan of the model, showing the different zones and the supply and extract ducts for the ventilation system [53].

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3.2.1 Location and Climate

The location for the building is in Oslo, which has four clearly defined seasons, with relatively cold winters and warm summers. The yearly mean temperature in Oslo is 6.1 °C, which is the average of the daily mean temperatures over a thirty-year period, and the DOT is -19.8 °C [58]. The climate datasets accessible from IDA ICE are weather files based on a typical mean year (TMY). This means that the climate files are given for typical real months, but they may not be from the same year. This climate file is used for determining the power demand of the heating system, and for validation of the models to see that the energy need for heating is within the acceptable range.

If price-based RBC strategies or KPIs based on price are to be used, with actual electricity prices for a given year, a climate file for the given year must be used for the simulations. Climate files can be created from historical climate databases with measurements from weather observing stations. One example of this is eKlima, which is the Norwegian Meteorological Institutes database. For this thesis, a climate file from 2016 has been used in the simulation, retrieved from the climate web tool "Shiny Weather Data". This is a weather tool developed by a Ph.D. candidate at Mälardalen University in Sweden. The climate data is from the Swedish Meteorological and Hydrological Institute and Copernicus Atmosphere Monitoring Service. The online tool is based on gridded, historical meteorological datasets, and by transforming, merging and formatting them into time series they can be used for energy and hygrothermal building modelling and simulations. From the website, users can create actual climate files for any location in North Europe, in file formats used by common building simulation tools, such as IDA ICE. [59]

3.2.2 Construction Modes and Insulation Levels

As explained in section 2.4, the properties and connections of the materials used for the building structure will have a large influence on how much heat the building structure can accumulate, and thus on the dynamics of the indoor temperature. To evaluate differences in flexibility potential for different construction types, the implementation of RBC strategies is done with a light wooden construction mode (LCM) and a heavy masonry construction mode (HCM). Table 3.1 shows the heat storage capacity of the building structure and U-value of the internal walls and floors for the HCM and LCM.

Table 3.1 Heat storage capacity and average U-value for the internal structures for light construction mode (LCM) and heavy construction mode (HCM).

Construction mode	Heat storage capacity [MJ/K]	$U_{int.wall}$ [W/m^{2}K]	$U_{int.floor}$ [W/m^{2}K]
HCM	86	2.84	1.60
LCM	14	0.25	0.21

These construction types will thus have different time constants. The material layers from the IDA ICE models for the building parts of the LCM and HCM are given in Table 3.2.

Table 3.2 Construction specification for the heavy construction mode (HCM) and light construction mode (LCM). The materials are listed from inside to outside.

	Building part	Material layers
	External wall	Plasterboard, block of concrete, insulation, coating on walls
	Internal load bearing wall	Plasterboard, block of concrete, plasterboard
HCM	Roof	Plasterboard, wood/insulation, plywood
	Internal floor	Wood, concrete screed, concrete, plaster board
	External floor	Ceramic tiles, concrete screed, insulation, concrete slab
	External wall	Plywood, wood/insulation, woodfibre
	Internal load bearing wall	Plasterboard, wood/insulation, plywood, plasterboard
LCM	Roof	Plasterboard, wood/insulation, plywood
	Internal floor	Wood, plywood, wood/insulation, plaster board
	External floor	Ceramic tiles, concrete screed, insulation, concrete slab

In addition to two construction modes, two different thermal resistance levels are evaluated to represent an old and segment of the Norwegian building stock and a building with passive house (PH) standard. To change the performance of the building envelope, the thickness of the insulation level has been changed until the desired U-value is reached.

The building chosen to represent the older age segment of the building stock has been modelled according to the specifications for the example building of the SFH from 1981 to 1990 in the TABULA (TB) typology project, described in section 2.1 [9]. The specifications from the TB example building from 1981 to 1990 in its original state is used, i.e. without any refurbishment measures executed. This is assumed to be representative for a significant share of the Norwegian building stock. The specified U-value for the external floor in the chosen typology is 0.57 W/m^{2}K, facing a non-heated basement [9]. Since the building model does not have a basement, the U-value for the external floor is set according to TEK87, i.e. 0.20 W/m^{2}K [60]. The TB example building and TEK87 do not provide a normalized thermal bridge factor, and this is therefore set according to TEK10.

The other evaluated insulation level is set according to the Norwegian PH standard, NS 3700. The minimum requirements for thermal resistance of windows and doors, air tightness, normalized thermal bridge factor and heat recovery efficiency is met. In addition, the thermal resistance of the roof, external walls and the external floor is in the range of the typical requirements given by the standard. The building envelope properties for the two insulation levels are given in Table 3.3. [61]

The PH buildings are modelled with a balanced ventilation system with heat recovery and supply air temperature of 19 °C, where it is assumed a temperature rise of 1 °C by the fan. The ventilation

airflow rates are in accordance with the requirements given in TEK17. The most common ventilation system for buildings built in the 1980s is natural ventilation supplied with a mechanical exhaust system from rooms with high pollutant loads and moisture like kitchen and bathrooms [9]. Air is supplied through vents in outer walls and over windows and is highly dependent on natural driving forces. Modelling the natural principles accurately in IDA ICE is difficult, and therefore, for simplicity the TB buildings are modelled with balanced ventilation system without heat recovery.

Table 3.3 U-values for the external construction, air tightness at 50 Pa, normalized thermal bridge factor and ventilation heat recovery efficiency for the insulation level for PH building and the TB building.

Insulation level	U_{roof} [W/m²K]	$U_{ext.wall}$ [W/m²K]	$U_{ext.floor}$ [W/m²K]	$U_{Windows}$ [W/m²K]	n_{50} [h⁻¹]	Ψ'' [W/m²K]	η_{HR} [%]
TB	0.36	0.32	0.20	2.80	4	0.05*	0
PH	0.10	0.10	0.09	0.8	0.6	0.03	85

* Assumed similar to TEK10 [56]

With the two construction modes and the two insulation levels, a total of four different building types is evaluated. These are the TB building with LCM (TBL), the TB building with HCM (TBH), the PH building with LCM (PHL) and the PH building with HCM (PHH).

3.2.3 Heating System and Validation of Heating Demand

The heating system consists of electric radiators and electric floor heating in the bathrooms and the technical room. The installed capacity in each zone is dimensioned according to inputs from NS 3031 with a heat load simulation with ideal heaters with a constant SPT 21 °C and the DOT for Oslo. The capacity of each radiator is chosen according to manufacturer data, with an efficiency of 100 % [62]. The total sum of the installed capacity for the whole building only differs from the heat load simulation with around 1 % for the TB buildings and 3-4 % for the PH buildings. The difference is higher for the PH buildings as the magnitude of the power demand is much lower. The radiators are located centrally in the zones and below windows.

The investigation of the flexibility potential of the building types is done with both a P-controller and a thermostatic controller on the electric radiators. The P-controller is not a common controller on electric radiators but is used to be able to interpret how the different parameters are affecting the heating system in a more detailed manner. This is because a thermostatic controller is assumed to lead to a more unpredictable operation of the electric heating system. The thermostatic controller will however represent a more realistic scenario as this is the most common controller type used in electric radiators in a residential building. The P-band or deadband for the P-controller or thermostatic controller is simulated with 1 °C.

To check that the building types are representative of their age segments, test simulations are conducted to verify that the net energy need for space heating complies with the respective building

types. To ensure that the energy performance of the TB buildings is within a reasonable range, the net energy need for heating with an SPT of 21 °C is compared with the specified net energy need from the chosen TB example building [9].

For the models with an insulation level according to the Norwegian passive house standard, the net energy need is verified against the requirements given in NS 3700. This standard gives the maximum allowed demand for space heating, and with the given floor area of the model building and the mean yearly temperature of the location, the maximum heating demand can be calculated according to Equation (4) [61]. The validation of the passive house is tested with a climate file of a typical meteorological year (TMY) and an SPT of 21 °C, according to NS 3031 [44].

$$Q_{heating} = 15 + 5.4 \cdot \frac{(250 - A_{fl})}{100} + (2.1 + 0.59 \cdot \frac{(250 - A_{fl})}{100}) \cdot (6.3 - t_{ym}) \tag{4}$$

NS 3700 also has requirements for the energy supply source, where the delivered energy from electricity and fossil fuels have to be less than the net energy need, subtracted 50 % of the net energy need for DHW. This means that if 51 % of the energy need for DHW is supplied from a renewable energy source, the space heating system can be all-electric. [61]

3.3 Modelling Occupant Behavior and Internal Heat Gains

As explained in section 2.6, it is expected that the IHGs from occupants, lighting and equipment have an impact on the flexibility potential, especially for the PH buildings. Therefore, four scenarios of occupant behavior and load profiles are investigated in this thesis. The evaluated profiles are the ones provided by NS and TS, in addition to profiles generated from stochastic models distributed in time (SM_t) and distributed in both time and space (SM_{ts}). Furthermore, the aggregated effect of a neighborhood is investigated, and therefore 20 different SM_{ts} profiles are generated.

The base case is the profiles given in NS, where the IHGs are static, i.e. not distributed in time or space. The load profiles given in TS are also investigated, where the values for IHGs from equipment and lighting are dynamic but have a fixed schedule. The standards assume that 100 % of the input power for lighting is dissipated as heat, while for equipment this share is 60 % [44]. The profile of the total IHGs for NS and TS is shown in Figure 2.6.

In addition to the profiles given in NS and TS, stochastic IHG profiles are implemented into the model buildings. The yearly profiles for lighting and equipment are retrieved from models used in the study by Sartori et. al. [42], which is developed by Rangøy and Dar [49]. The daily average load profile for lighting and appliances is illustrated in Appendix A. The load profile for appliances is multiplied by 0.6 to get the yearly IHG profile. Since there is currently no stochastic occupancy model compatible with Norwegian data, an occupancy profile with an hourly resolution is created manually. The occupancy, appliance, and lighting profiles are all generated for a four-person household.

The self-made occupancy profile does not contain as frequent fluctuations as the lighting and appliance profiles. However, a separation is made between weekdays and weekends and in addition, there are variations in the occupancy for the summer, winter and spring/autumn months. The occupancy profiles for a weekday and weekend during the winter is shown in Appendix A. It is assumed that the residents have a traditional working schedule, as this is expected to represent a large share of the population. This means that the occupancy is high in the morning and afternoon/evening on weekdays. The heat emitted by the occupants is set to 1 met, i.e. seated quiet resting activity level. Furthermore, the occupancy profile is made to match the daily average shape of the stochastic profiles for equipment and lighting as good as possible. It is also checked that the occupancy profile does not eliminate the peaks when the IHGs are added together. This is illustrated in Appendix A, which shows the IHGs for one day separated into lighting, electrical appliances and occupancy.

When the IHG profiles for occupancy, lighting, and appliances are added together, the yearly average value is modified to match the average IHGs from NS. The daily IHG profiles evaluated are illustrated in Figure 3.3, where the yearly average of the stochastic profile is shown along with the maximum and minimum values. This shows that even with a relatively flat occupancy profile, there is a large variability in the IHGs, especially during the day where there are incidents of very high peaks compared to the average value.
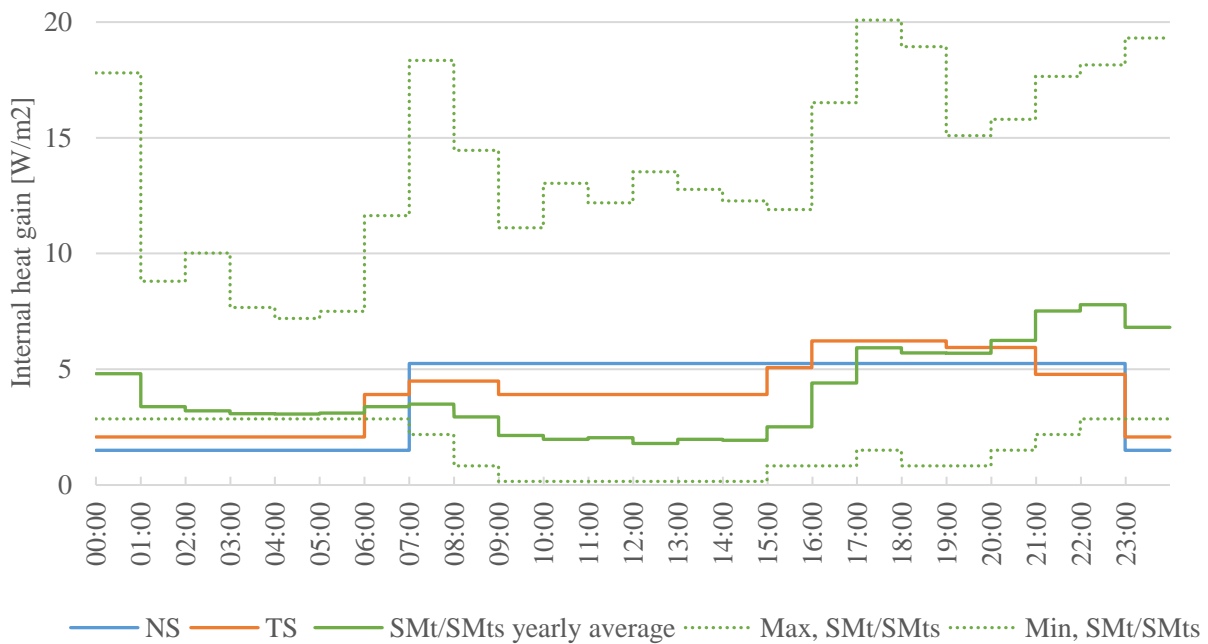

Figure 3.3 The evaluated internal heat gain profiles. Showing the total sum of lighting, equipment and occupancy.

The distribution of the stochastic IHG profile in space is done by creating an hourly schedule for each zone in the building assigned to a percentage share of the total IHGs. Thus, the SM_{ts} profile is the same as the SM_t, the only difference is that the SM_{ts} is distributed to different zones.

The distributed percentages are the same each day, but since the IHGs from lighting, appliance, and occupancy are variable, the total IHGs in each zone change every day. The distributed percentages in the different zones are illustrated in Appendix A. The yearly average heat gain is 5.8 W/m^2 for the kitchen/living room, ~4.8 W/m^2 for the bedrooms and ~1.1 W/m^2 for the bathrooms. This distribution is in good agreement with the space distributed IHGs used in a study by Georges et. al [63]. Figure 3.4 illustrates the yearly average IHGs profile in the South-East bedroom (bedroom SE) for SM_t and SM_{ts} for comparison. There is no IHGs from 10:00-21:00 in the bedrooms with SM_{ts} IHGs as it is for simplicity assumed that the bedrooms are not used as workspace and consequently no heat gains from equipment, lighting or occupancy occur during this period.
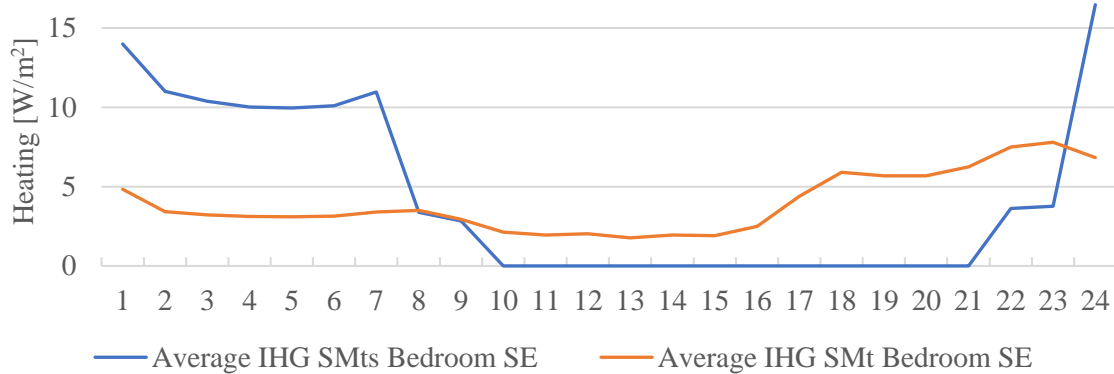
Figure 3.4 Internal heat gain profiles in bedroom SE distributed in time (SMt) and distributed in time and space (SMts).

To be able to evaluate the stochastic nature of a neighborhood, 20 SM_{ts} profiles are generated. The same occupancy profile is used in all profiles because of time limitation and the assumption that the stochastic profiles for appliances and lighting together with the occupancy would result in the desired variable profiles, with stochastic peaks. The IHGs from the 20 stochastic profiles are manually adjusted so that the sum of the yearly average IHGs for all 20 profiles is equal to that of NS, with a maximum and minimum of +9 % and -13 %, respectively.

3.3.1 Implementation of Internal Heat Gain Profiles in IDA ICE

Since the IHG profiles from NS and TS are the same for each day of the year, while the stochastic profiles vary from day to day, the methods applied for implementing these in IDA ICE are different. The IHGs from NS and TS are implemented for occupants, electrical appliances and

lighting separately. The occupancy profile is flat for both NS and TS, and the input required by IDA ICE is the number of occupants per square meter. The IHGs for lighting and appliances are implemented as schedules in each zone. In IDA ICE, schedules are smoothed by default to reduce the computational time [57]. This means that instead of the instant changes that are implemented in the schedule, the signal is ramped up or down towards the next value.

In IDA ICE, custom control strategies can be implemented for different devices in the building [57]. The stochastic IHG profiles are implemented in the central zone controller and are coupled to lighting. This is done by creating a text file containing the sum of all IHGs for the respective zones each hour for the year. IDA ICE interpolates the values that are provided in the text file, and to ensure that the values are not significantly changed, the output from IDA ICE is compared to the input in the text file. For the aggregated results, each of the 20 profiles is implemented in the IDA ICE models to be able to study the impact multiple stochastic IHG profiles have on the operation of local distribution grids, as it is important to include the variability of multiple individual houses to represent the time-coincident demand. This is done in 20 separate simulations (i.e. not one simulation with the average of the 20 IHG profiles) to include the effects the sudden IHG peaks have on the heating system.

3.4 Description of Investigated Rule-Based Control Strategies

To evaluate the flexibility potential for the different building types, two RBC strategies are applied in this thesis, off-peak hour control strategy (OPCS) and spot price control strategy with an overruling of the control strategy at night (SPCS). In addition, a parametric study and strategies to achieve thermal zoning are tested. This results in a total of 14 scenarios with the two CSs as a basis, and these are summarized later in section 3.7.

The OPCS strategy is based on the average electricity consumption for residential buildings on a weekday, as described in section 2.3. Based on this the peak hours for electricity consumption are defined to be between 07:00-09:00, and 17:00-19:00, which also is in good agreement with the average spot price for 2016 in Figure 2.4. The SPT for the electric radiators is therefore decreased to 19 °C during these hours to reduce the electricity consumption in the peak hours. One hour before the peak hours the SPT is increased to 23 °C to activate the thermal mass to postpone or avoid the restart of the electric radiators. The SPT is 21 °C otherwise, and the fixed schedule for SPT with OPCS is shown in Figure 3.5. The SPT schedule is set based on the recommended operative temperature limits given by the Norwegian technical regulation from 2017 (TEK17) in section 13- 4 "Thermal Indoor Climate" [64]. For the activity group "light work" the lower and upper limits are 19 °C and 26 °C, respectively. In addition, daily or periodic temperature fluctuations over 4 K are also claimed by TEK17 to give unacceptable discomfort. The temperature interval is therefore set to be ± 2 K from 21°C.
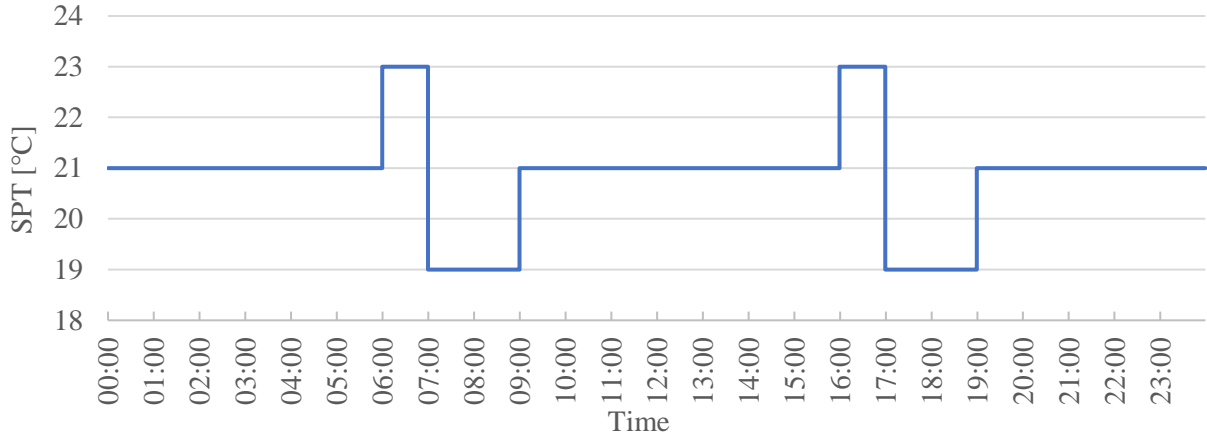
Figure 3.5 RBC strategy based on pre-defined peak hours (OPCS).

The SPCS is based on the same RBC strategy as the aforementioned study in subsection 2.5.2 by Clauß et. al [36], where the SPT is controlled by thresholds set for high and low electricity prices for each day. The low and high thresholds are set to 25 % and 75 % of the difference between the minimum and maximum day-ahead spot price, retrieved from NordPool.

Since the nighttime is characterized with a low electricity demand the spot price is relatively low, as seen in Figure 2.4. The SPCS strategy would initially exploit this low price to increase the SPT, which is presumed to lead to higher energy consumption and energy cost as it did in the study by Clauß et. al. [36]. The SPCS is therefore set to only operate between 06:00 and 23:00 and is overruled to be 21 °C otherwise. The electricity price, low-price and high-price thresholds and the resulting SPT are illustrated for January 1st in Figure 3.6. With a high and low threshold of respectively 75 % and 25 %, the lowest average SPT during the year occur around 08:00-09:00 and 18:00-19:00. This is in good agreement with the pre-defined peak hours used in the OPCS and confirms that the spot price generally correlates with the stress on the grid as described in subsection 2.2.
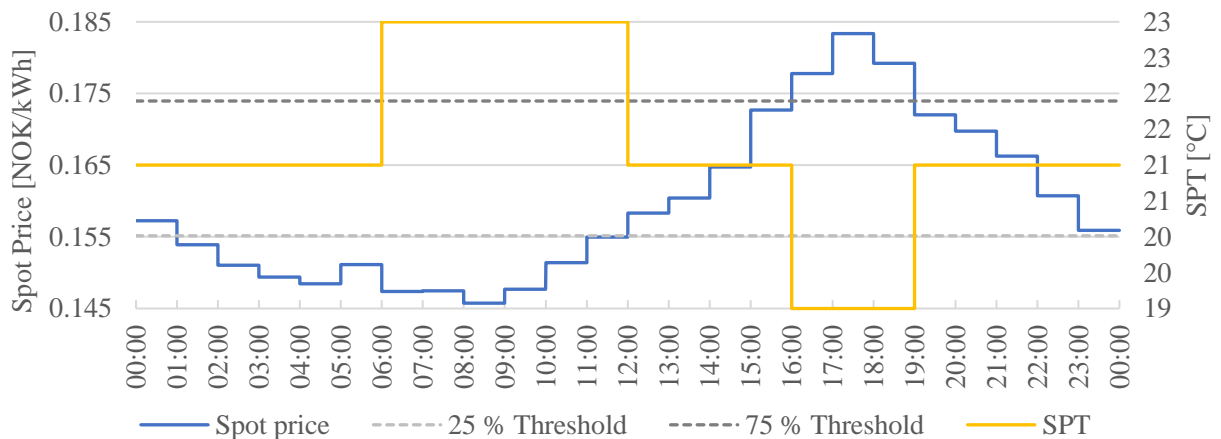
Figure 3.6 RBC strategy based on spot price (SPCS) for 1st of January.

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Both control strategies are implemented in the heating control macro in IDA ICE, where control strategies of the radiators can be customized. To ensure that the radiators start to react immediately when the SPT is changed, there is no time delay of the controllers. The OPCS is given by a schedule. As mentioned previously, there is a degree of smoothing by default in IDA ICE. This is however not the case with the SPT schedule of OPCS, as this schedule is implemented at the advanced level, and the smoothing is set to zero to achieve an immediate change in SPT as soon as the peak hours start.

With the SPCS, the SPT for each hour is determined by the input of spot price and high and low thresholds for the respective hour. In IDA ICE, these hourly inputs are interpolated. This means that if the spot price goes above the high threshold from one hour to the next, the change in SPT will happen sometime in between these hours.

3.4.1 Parametric Study of Control Strategies

To realize the full flexibility potential the four building types has to offer, the control strategies should ideally be adjusted to each of the building types separately. Therefore, the impacts of adjusting the control strategies in accordance with the building construction properties are investigated. It is also of interest to study how the results of the OPCS and SPCS change with different parameters to evaluate the sensitivity of the CSs. These evaluations are done only with thermostatic radiator control and IHGs from TS. This is because dynamic IHGs are expected to better represent reality, while at the same time the fixed IHGs of TS makes it easier to interpret how the changed parameters affect the flexibility potential. The deadband (DB) is expected to have an impact on the heating systems behavior when the CSs are applied. Therefore, the first parameter that is evaluated is with the DB of the radiators increased to 2 °C.

For the OPCS, the duration of the pre-heating period is evaluated. For the TB buildings, the pre-heating period is increased from one hour to two hours, to evaluate if this leads to a larger share of peak-shifting. For the PH buildings, the opposite is done, i.e. the pre-heating peak is reduced to 30 minutes. This is done to investigate if it is possible to achieve a high degree of peak shifting, whilst at the same time reduce the yearly energy use. For the SPCS, the sensitivity of the lower and higher thresholds for low and high spot price is changed from 25-75 %, to 20-80 % and 30-70 %. Furthermore, the SPCS is evaluated with no overruling of the CS in the night. The changed parameters and adjustments made to the CSs are summarized below:

- OPCS and SPCS: Increase of DB to 2 °C
- OPCS: Changed duration of pre-heating period
- SPCS: Change of price thresholds and no overruling of the CS at night

3.5 Evaluation of Bedroom Temperatures

As explained in section 2.7 occupants often want lower bedroom temperatures, and the variation of SPT to achieve energy flexibility may have a negative influence with regards to the occupant satisfaction. Therefore, the effect of the OPCS and SPCS on the bedroom temperatures is evaluated. This is done for the heating season, which in this thesis is defined to be from October to April. As the different IHG profiles also are expected to be of significance, the evaluation is also done for all profiles. The bedroom SE has been chosen for this evaluation. This is the largest bedroom, and as it is expected to be a double bedroom, the supply air from the ventilation system is twice as high for this bedroom than the other two. This is because technical regulation provides minimum requirements for supply of fresh air per person in bedrooms [64].

Furthermore, the CSs are decoupled from the bedrooms, i.e. the bedrooms have a constant SPT, to evaluate how this affect the temperatures in the bedroom. This is done by comparing the temperature in bedroom SE for when the bedroom radiator is coupled and decoupled to the CSs. The decoupled strategy is investigated with a constant SPT of both 21 °C and 16 °C. The U-values of the internal constructions of the different construction modes will be a contributing factor to how much heat is transferred to the bedrooms and are listed in Table 3.1.

The focus of these investigations is to see how the utilization of thermal mass to offer flexibility to the grid will affect the temperatures in the bedrooms, and how the potential for offering flexibility is reduced when the bedrooms are decoupled from the CSs. Thus, no other strategies are implemented to achieve thermal zoning other than adjustments of the OPCS and SPCS. As explained in section 2.7, the effect of open doors and windows will be a major influence on the temperatures. However, with the scope of this thesis, strategies concerning schedules of open windows and doors are not evaluated. Thus, the windows and doors are always closed.

3.6 Key Performance Indicators to Evaluate the Flexibility

The results of the RBC strategies are evaluated in terms of total energy consumption for heating, costs, in addition to an evaluation of the ability for peak-shifting. For every building type with every IHG profile, a reference case with constant SPT of 21 °C is simulated to compare the result with the CS. This temperature corresponds to the recommended minimum dimensioning temperature during the heating season, at the highest comfort level, in NS-EN 15251 [34]. Based on the reference simulation with the same parameters, some KPIs are selected to evaluate the flexibility potential. These are the relationship between the reference simulation with constant SPT and with the implemented CS. Thus, there are separate reference simulations for all building types with different IHG profiles, radiator control, and all evaluated parameters.

The change in energy use is showed as the relationship between the yearly energy consumption for the reference case and with the RBC strategy, given by Equation (5). The calculations for energy use is based on the hourly average power consumption from IDA ICE.

$$q_{tot} = \frac{Q_{RBC}}{Q_{ref}} \qquad (5)$$

The energy use for heating during the pre-defined peak hours (i.e. 07:00-09:00 and 17:00-19:00) is also evaluated and is given by the relationship between the energy consumption during the four peak hours (ph) of the day for the reference case and with CS, as seen in Equation (6).

$$q_{ph} = \frac{Q_{ph,RBC}}{Q_{ph,ref}} \qquad (6)$$

The change in peak power demand is represented by the relation between the maximum peak power during the entire year for the two cases, as shown in Equation (7). The generated result files from the IDA ICE simulations are given with a variable timestep. To retrieve the accurate peaks for the whole year and in the pre-defined peak hours, MATLAB is used. This script calculates both the peak during the entire year, in addition to the maximum peak occurring each hour of the year. When investigating the aggregated result of 20 simulations with different IHG profiles, the MATLAB script interpolates the power used for heating with a one-minute time interval. This ensures that the peak power consumption is occurring in the same one-minute interval for all 20 simulations.

$$p = \frac{P_{RBC}}{P_{ref}} \qquad (7)$$

To evaluate the peak-shifting potential the peak demand during the hours with reduced SPT are investigated throughout the year. The potential of peak demand reduction during these hours is given by the relation of the maximum peak occurring during these four hours for the whole year for the reference case and with RBC strategy, as shown in Equation (8).

$$p_{ph} = \frac{P_{ph,RBC}}{P_{ph,ref}} \qquad (8)$$

The change in annual costs for heating with the RBC strategy is also considered. This is done by multiplying the hourly power consumption for heating with the respective electricity spot price for 2016, retrieved for Nord Pool Spot [18]. The relation between the electricity price for the reference case and the RBC case is given by Equation (9).

$$c = \frac{\sum_{i=1}^{8784} Q_{RBC,i} \cdot sp_{el,i}}{\sum_{i=1}^{8784} Q_{ref,i} \cdot sp_{el,i}} \qquad (9)$$

3.7 Summary of Modelling Approach

The two main CSs, along with the names and parameters that are changed in the parametric study and the decoupling of bedrooms are listed in Table 3.4. All parameters that are changed are listed here.

Table 3.4 Names and parameter settings for all investigated control strategies.

Control Strategies	Deadband/ P-band	Duration pre-heating	Price Threshold	Overruling nighttime	Bedrooms Decoupled
OPCS	1	1 h	-	-	No
OPCS$_{db2}$	2	1 h	-	-	No
OPCS$_{ph0.5}$	1	0.5 h	-	-	No
OPCS$_{ph2}$	1	2 h	-	-	No
OPCS$_{bdc21}$	1	1 h	-	-	Yes (SPT 21 °C)
OPCS$_{bdc16}$	1	1 h	-	-	Yes (SPT 16 °C)
SPCS	1	-	25-75 %	Yes	No
SPCS$_{db2}$	2	-	25-75 %	Yes	No
SPCS$_{nor}$	1	-	25-75 %	No	No
SPCS$_{20-80}$	1	-	20-80 %	Yes	No
SPCS$_{30-70}$	1	-	30-70 %	Yes	No
SPCS$_{bdc21}$	1	-	25-75 %	Yes	Yes (SPT 21 °C)
SPCS$_{bdc16}$	1	-	25-75 %	Yes	Yes (SPT 16 °C)
SPCS$_{nor+bdc16}$	1	-	25-75 %	No	Yes (SPT 16 °C)

The research approach is illustrated in Figure 3.7. This shows all the investigated scenarios, and is done for all four building types (TBL, TBH, PHL, and PHH).

Part 1: Evaluation of control strategies and radiator control

OPCS		SPCS	
P-controller	Thermostatic controller	P-controller	Thermostatic controller
NS	NS	NS	NS

Part 2: Evaluation with dynamic IHG profiles (TS, SMt and SMts)

OPCS		SPCS	
P-controller	Thermostatic controller	P-controller	Thermostatic controller
TS	SMt	SMts	TS	SMt	SMts	TS	SMt	SMts	TS	SMt	SMts

Aggregated

Aggregated

Part 3: Parametric study

OPCS (thermostatic controller)	SPCS (thermostatic controller)
TS	TS

| Duration of pre-heating | Evaluation of deadband | Evaluation of thresholds | No overruling at night | Evaluation of deadband |

Part 4: Control strategies impact on bedroom temperatures

Evaluation of Bedroom Temperatures with CSs and all IHG profiles

Decoupling the bedrooms from the CS

OPCS (thermostatic controller)	SPCS (thermostatic controller)
SMts	SMts

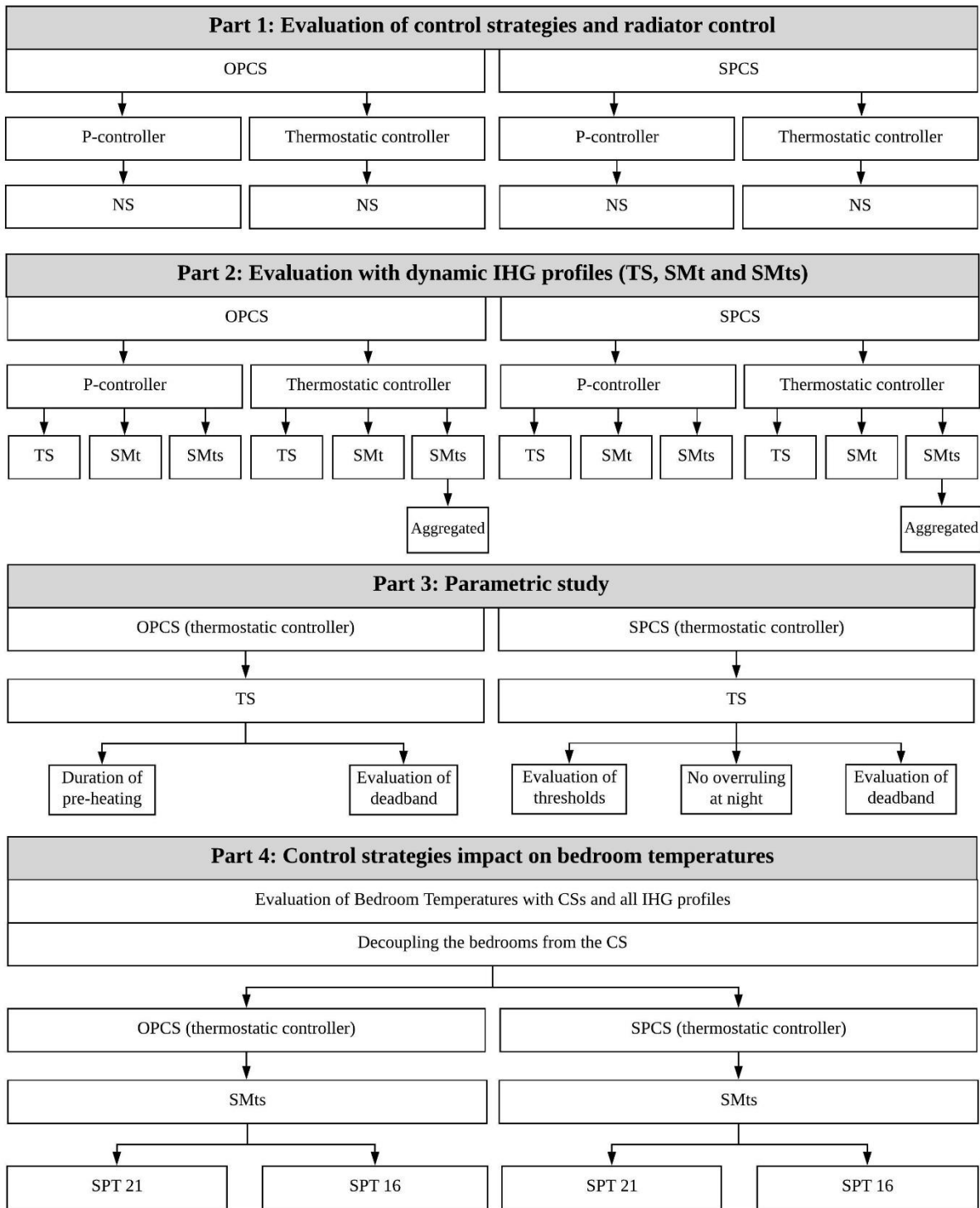| SPT 21 | SPT 16 | SPT 21 | SPT 16 |

Figure 3.7 Research approach.

4   Results

This chapter will present the results from the simulations in IDA ICE. The results are divided into four main sections. First, the results of the two CSs are presented and compared, and the influence of radiator controller is evaluated. The following section presents the results with dynamic IHG profiles and their influence on the flexibility potential is assessed. This section also includes aggregated results with 20 different space and time distributed stochastic IHG profiles. This is followed by a parametric study where the influence of electric radiator settings and parameters in the two CSs are evaluated. Finally, the last section addresses the issue with thermal zoning of bedrooms.

4.1   Evaluation of Control Strategies and Impact of Radiator Controller

To illustrate how the construction mode and insulation level affects the flexibility potential, the two CSs are in this section first examined with NS IHGs. The results with OPCS are presented first, followed by the SPCS. The heating power and air temperature profile during a cold day is presented for each building type with both CSs to help understand the KPIs. After the CSs are presented, an evaluation of the peak power consumption in the pre-defined peak hours is presented, in addition to an investigation of the impact of varying climatic boundary conditions.

As mentioned, the results of the CSs are in this section only presented with NS IHGs. The results of the reference simulations with a constant SPT of 21 °C are shown in Table 4.1, which shows the total energy use (Q_{tot}), energy use during the peak hours (Q_{ph}), peak power consumption during the year (P), peak power consumption during the pre-defined peak hours (P_{ph}) and yearly costs based on the spot price (C). Note that capital letters are used for exact values, while lowercase letters are used for the KPIs. The resulting energy use for the TB buildings is about 11 times higher than for the PH buildings. Table 4.1 also shows the difference between P-controllers and thermostatic controllers on the radiators. These references are the basis for the calculation of the KPIs with NS IHGs and the respective radiator controller. Thus, the energy and power performance of the reference will have a significant effect on the magnitude of energy and power that can be reduced when the CSs are implemented. In general, the thermostatic controllers result in increased peak power consumption, also in the peak hours. However, the energy consumption during peak hours is lower with thermostatic controllers than P-controllers for all building types except the TBH.

Table 4.1 Energy and power performance for the reference cases (constant SPT of 21°C) with NS IHGs for the four building types with P-controller (PC) and thermostatic controller (TC).

		Reference cases							
		TBL		TBH		PHL		PHH	
		PC	TC	PC	TC	PC	TC	PC	TC
Q_{tot}	[kWh/m^2]	178.3	177.4	175.2	174.8	16.0	15.3	15.3	14.3
Q_{ph}	[kWh/m^2]	28.3	27.7	27.8	28.7	2.4	1.8	2.2	1.3
P	[W/m^2]	76.3	82.9	74.8	82.2	15.2	20.7	13.9	18.5
P_{ph}	[W/m^2]	70.9	82.9	69.9	82.2	13.3	20.7	11.8	17.7
C	[NOK/m^2]	48.5	48.2	47.8	48.0	4.5	4.2	4.3	3.8

4.1.1 Off-peak Control Strategy

The heating power and temperature with the OPCS are presented for the kitchen/living room. This is chosen because it is the largest zone and represents the largest share of energy consumption for heating. In Figure 4.1 the heating power with P-controller and mean air temperature in the kitchen/living room with OPCS are illustrated for 22nd of January. This is the day with the coldest outdoor temperature of the year. The heating power drops to zero immediately after the SPT is reduced, but for the TB buildings, the heating power starts to increase quite rapidly again due to the simultaneous temperature drop. As opposed to the TB buildings, the heating power is zero for both PH buildings during the peak hours.

The temperature fluctuations for the LCMs are larger than for the HCMs because of the difference in thermal mass. For the TB buildings, this causes the TBH use significantly less energy for heating in the peak hours as more thermal energy is stored in the construction from the pre-heating. For the PH buildings, the peak power occurring after the pre-defined peak hours (rebound peak) is more significant for the LCM as the air temperature is lower at the end of the pre-defined peak hours. Furthermore, the air temperature does not reach 23 °C during the pre-heating for the PHH nor the PHL. This is because the PH buildings have less installed radiator capacity. Due to the higher radiator capacity, the TB buildings can heat up the zone faster, even though the heat loss is higher. Nevertheless, the temperature does not reach 19 °C during the pre-defined peak hours for neither of the PH buildings. This indicates that the duration of the pre-heating period might be reduced without significant impact on the reduction of heating power in the peak hours.
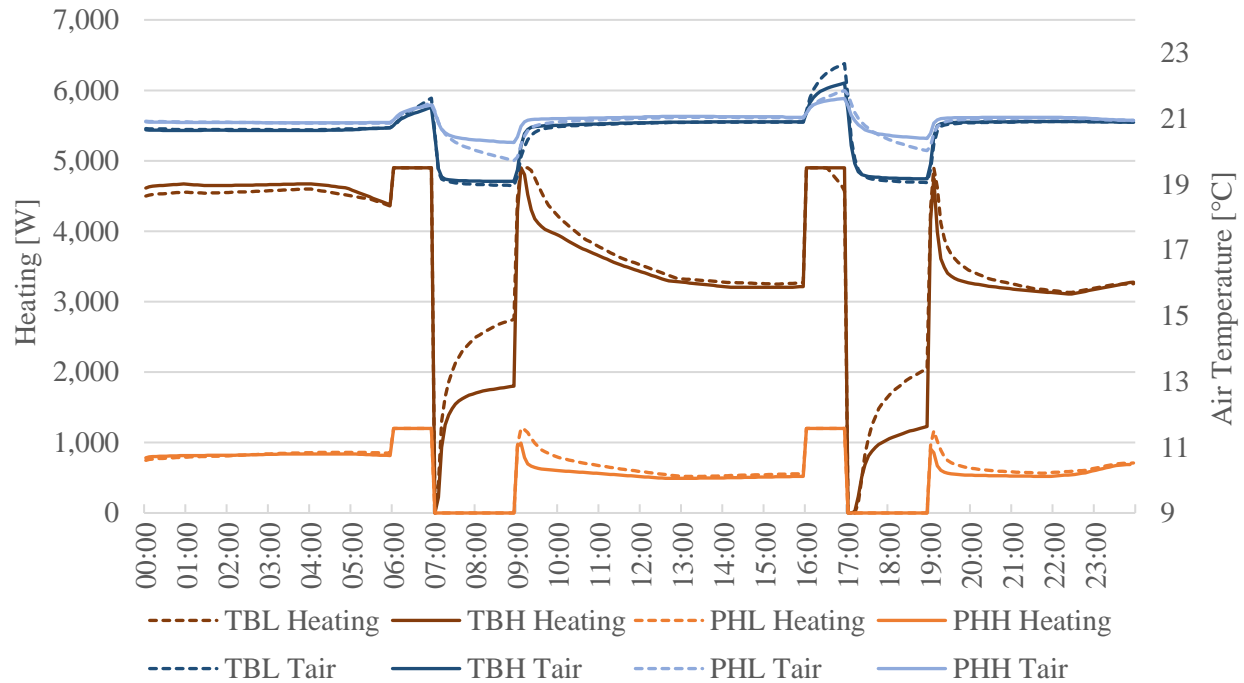
Figure 4.1 Comparison of the heating power and air temperature on a cold day in January in the kitchen/living room with OPCS (P-control and NS IHGs).

The energy flexibility with OPCS is evaluated with the KPIs which are shown in Table 4.2 for all building types. A KPI of 1.000 means that there is no change from the reference with constant SPT for the respective building type. The KPIs are presented with a P-controller along with the percentage difference of the equivalent KPIs with a thermostatic controller. It is clear that the OPCS results in a significant reduction of energy use and peak power use in the peak hours of the year. The indicators show that the PH buildings achieve a complete reduction of the energy and power consumption in the peak hours, as opposed to the TB buildings. On the other hand, the PH buildings also have a higher relative increase in yearly energy use and peak power consumption, especially the PHH.

The increase in energy use causes an increase in annual costs for the PH buildings with OPCS, whereas the costs for the TB buildings are decreased. The TBH achieves a better result than the TBL in terms of shifting energy and power use. This can be seen as the TBH has a slightly higher relative increase in yearly energy use, but the indicators q_{ph} and p_{ph} are significantly lower. The TBH also achieves more significant cost savings than the TBL. When evaluating the difference between the construction modes, the HCM has the highest potential for energy and power shifting for the TB buildings. However, for the PH buildings where both construction modes achieve a complete reduction of power consumption during peak hours, the HCM is less beneficial due to the high increase in yearly energy and peak power use.

The type of radiator controller is found to have an impact on the KPIs. With thermostatic radiator control, the p-indicator is decreased for all building types. This is because the references have a

higher peak power, as the radiator output is either 0 % or 100 %. The magnitude of the peaks occurring is however the same as, or higher than with P-controllers. Since the TB buildings have a heating demand during the peak hours, the p_{ph}-indicator is much higher with thermostatic radiator control, as can be expected. This is because when the temperature drops beneath the DB, the radiators start to operate at full capacity, as opposed to a gradual power increase with a P-controller, as illustrated in Figure 4.1. At the same time, the thermostatic radiator control results in a better q_{ph}-indicator compared to proportional control.

Table 4.2 KPIs with OPCS, with P-control (PC) and the percentage change with thermostatic control (TC). IHGs according to NS. Reference values are listed in Table 4.1.

Key Performance Indicator	OPCS							
	TBL		TBH		PHL		PHH	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.018	0 %	1.019	0 %	1.067	0 %	1.080	0 %
q_{ph}	0.132	-41 %	0.067	-64 %	0.000	0 %	0.000	0 %
p	1.086	-8 %	1.100	-9 %	1.350	-26 %	1.512	-25 %
p_{ph}	0.639	+81%	0.454	+92 %	0.003	0 %	0.000	0 %
c	0.996	-1 %	0.933	0 %	1.033	+2 %	1.051	+1 %

Since the heating season for the PH buildings is significantly shorter than for the TB buildings there are several days where the SPT is increased to 23 °C, increasing the energy use for heating, without a saving when the SPT is decreased to 19 °C. This is because there is no heating demand for the reference case in the first place. Therefore, the relative increase in energy use in the pre-heating periods is much larger than for the TB buildings.

4.1.2 Spot Price Control Strategy

The heating power and temperature profiles for the same cold day in January with SPCS are illustrated in Figure 4.2 for the kitchen/living room. Here, the heating power is high in the peak hours from 17:00-19:00, which contributes to a poorer result for the KPIs measuring the peak hours. The SPT for this chosen day is only reduced to 19 °C from 08:00 to 10:00, while it is increased to 23 °C from 12:00 until the SPT is overruled to 21 °C during the nighttime.
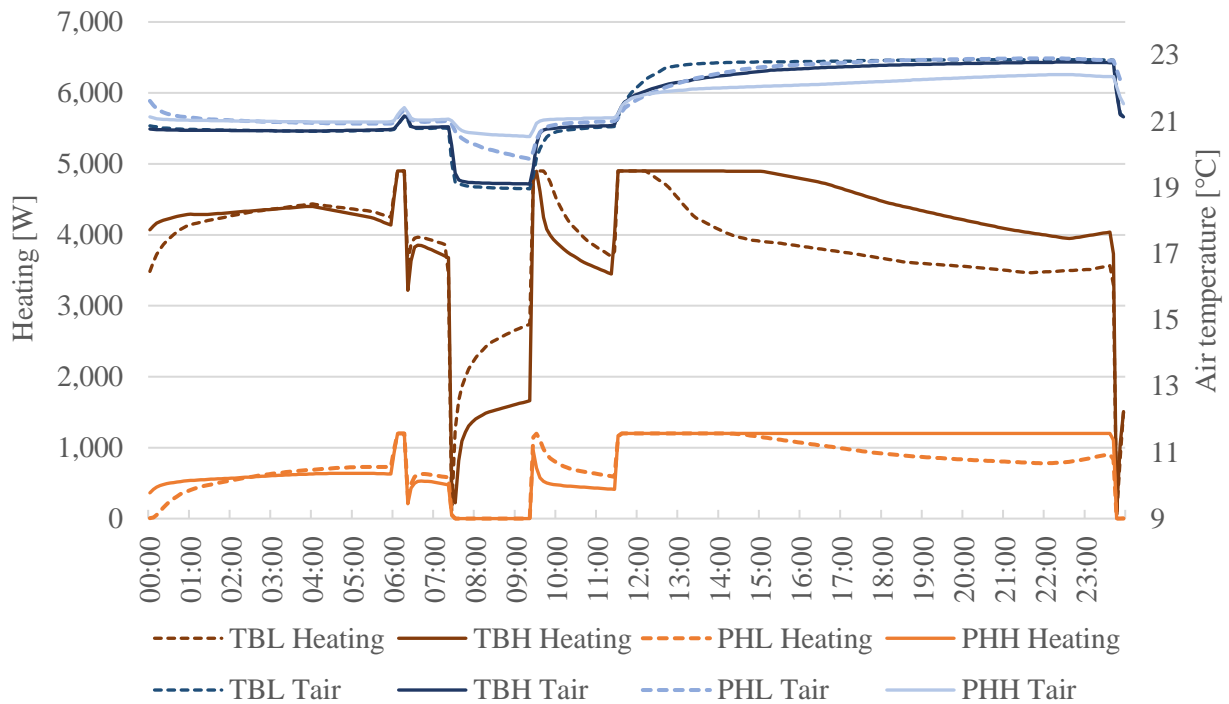
Figure 4.2 Comparison of the heating power and air temperature on a cold day in January in the kitchen/living room with SPCS (P-control and NS IHGs).

This day illustrates that for periods with a long duration of increased SPT, the total energy use for the heavy buildings are much higher than for the light buildings because the light buildings will reach the SPT faster and thus use less energy for heating. The radiators in the PHH is at maximum capacity until the SPCS is overruled at night.

The energy flexibility of the buildings with SPCS is evaluated by the KPIs which are given in Table 4.3 with P-control, along with the percentage difference with thermostatic control. The TB buildings achieve the best results measured in KPIs. The yearly costs are reduced for both TB buildings, which also have small changes in the yearly energy use compared to the reference simulation. The PH buildings have increased costs and increased energy use. Thermostatic radiator control result in the same relative cost saving for the TB buildings, and a further increase of relative costs for the PH buildings. The high q_{tot}-indicator for the PH buildings indicates that the reason these buildings do not achieve cost reduction is a result of an overall increase in energy use.

Compared to the OPCS, the SPCS leads to an even larger increase in yearly energy use for the PH buildings, but a reduction for the TB buildings. Here, the TBL achieves a small reduction of energy use compared to the reference with constant SPT. However, the TBH still has a larger reduction of energy costs. An explanation for this is that the TBH also has the highest reduction of energy use in the peak hours when the spot price is generally high. The thermostatic control results in a considerable increase of the q_{ph}-indicator for the PH buildings. Especially for the PHH, where the

q_{ph}-indicator is increased with 45 % compared to a P-controller, this results in an indicator value of 0.967.

Table 4.3 KPIs with SPCS, with P-control (PC) and the percentage change with thermostatic control (TC). IHGs according to NS. Reference values are listed in Table 4.1.

Key Performance Indicator	SPCS							
	TBL		TBH		PHL		PHH	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	0.993	0 %	1.003	0 %	1.072	+1 %	1.121	+4 %
q_{ph}	0.673	-4 %	0.599	-6 %	0.642	+ 28 %	0.665	+45 %
p	1.086	-8 %	1.100	-9 %	1.362	-27 %	1.512	-25 %
p_{ph}	1.169	-14 %	1.176	-15 %	1.552	-36 %	1.775	-33 %
c	0.974	0 %	0.964	0 %	1.024	+ 2 %	1.042	+5 %

To further explain the behavior of the heating system in the different buildings with SPCS, Figure 4.3 illustrates the daily average percentage difference in heating power compared to the references with constant SPT for all four building types with P-control. The building performance with SPCS is very dependent on the insulation level, and this figure clearly shows why the KPIs are much better for the TB buildings. In average, there are two periods during the day when the difference is negative, and mostly around 08:00-09:00 and 17:00-18:00, which correspond well with the peak hours of the OPCS. During these periods, the PH and TB buildings achieve approximately the same relative power reduction. However, in the periods with increased energy use the relative increase of the PH buildings is significantly higher. This is due to the low heating demand of the reference with constant SPT. Because of the increased heating in the evening, the PH buildings also have a considerable reduction of energy use throughout the night when the spot price is generally low. Some differences can also be observed between the construction modes. Generally, the LCMs have a higher heating demand than the HCMs during the day and a lower during the night.
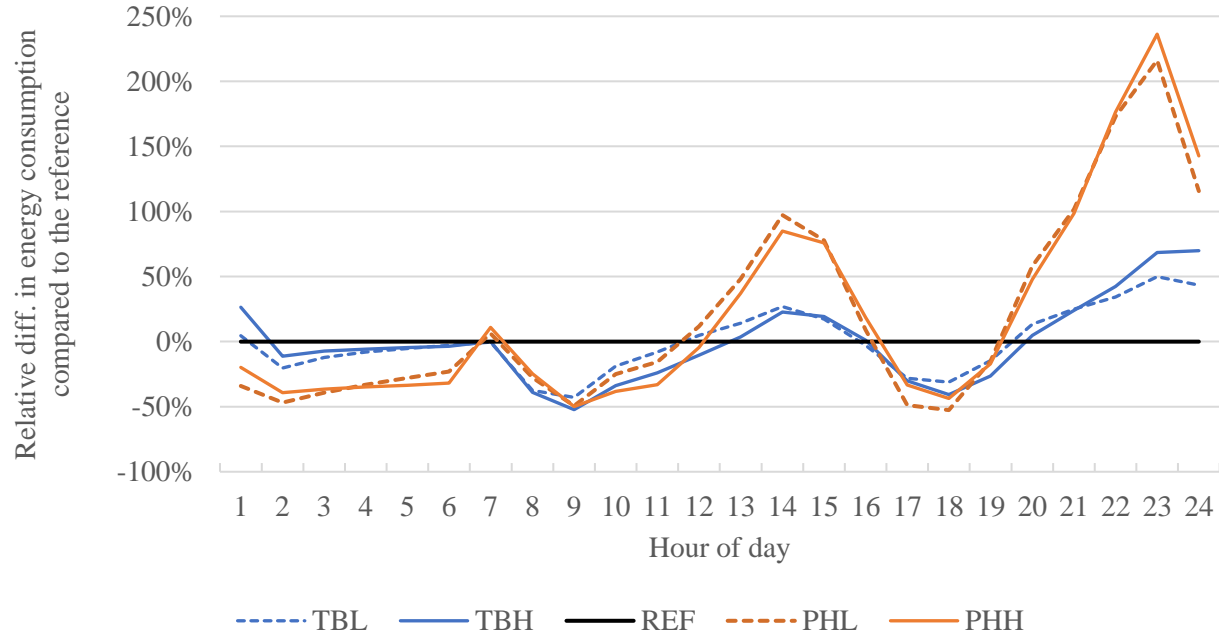
Figure 4.3 Daily average difference in energy use for heating with SPCS compared to the references with constant SPT (NS IHGs).

4.1.3 Investigation of Peak Power Use in Pre-defined Peak Hours

As the KPIs related to the peak hours are used for measuring the power shifting potential for the CSs and the p_{ph}-indicator only represent one occurrence of the largest power consumption in the peak hours during the whole year, it is of interest to investigate how the two CSs affect the power use in all of these hours. Figure 4.4 shows the sorted peak power use occurring in all the defined peak hours of the year in descending order, i.e. 1464 hours, for the TB buildings with both a P-controller and a thermostatic controller for both CSs. The amount of energy and power use shifted in the peak hours are significantly lower with the SPCS than with the OPCS. This is expected since the pre-defined peak hours only represent the general trend of the electricity price and stress on the grid, while there are variations in when the actual peak hours occur from day to day. The figure also reflects the performance of the thermal mass, as TBL always have a higher heating demand in the peak hours than the TBH. There is also a noticeable difference in maximum heating power between a P-controller and a thermostatic controller. The results show that the radiators with a thermostatic controller in general have more hours with a higher heating power than with a P-controller, but in return have fewer peak hours with a heating demand.

The trend observed in Figure 4.4 is the same for the PH buildings, but the slope of both the SPCS and the reference curve is much steeper. As illustrated by the KPIs, the OPCS results in zero power use during the pre-defined peak hours for the PHL and PHH.
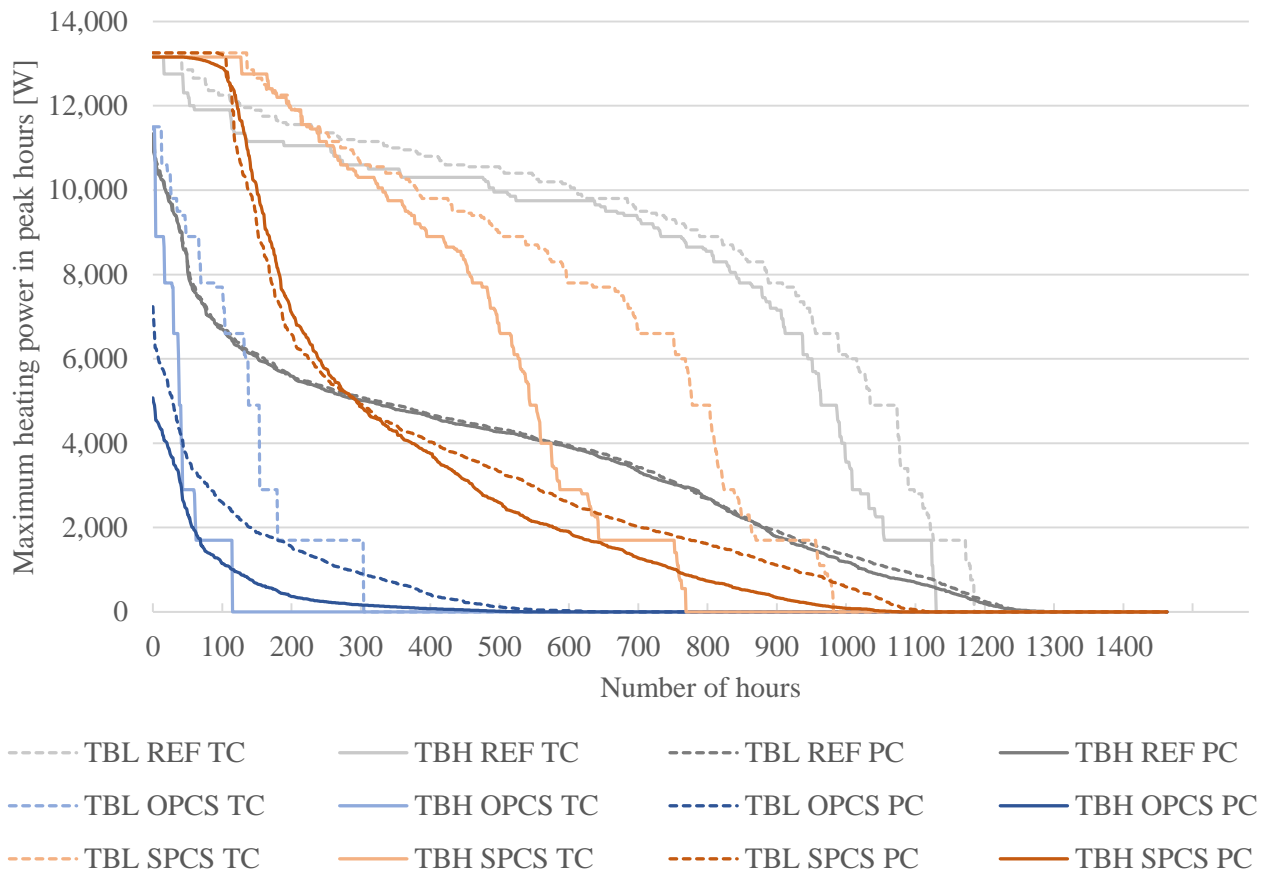
Figure 4.4 Load duration curve showing the maximum peaks occurring in the pre-defined peak hours for the TB buildings with constant SPT, OPCS and SPCS. Given with both P-control (PC) and thermostatic control (TC) (NS IHGs).

4.1.4 Impact of Climatic Boundary Conditions on the Flexibility Potential

As recommended in the study by Fischer et. al., presented in subsection 2.5.2, it is important to be aware of the robustness of RBC strategies with varying boundary conditions. As the outdoor temperature is expected to be one of the main influences, the performance of the CSs is evaluated when they are applied for a shorter period, i.e. the CSs are not applied for the warm months. This is because the CS might cause an unnecessary increase in energy use without significant benefits in terms of peak reduction in the summer months as these months have low or none energy use for heating. Hence the extra energy use for pre-heating will not be fully exploited in the peak hours. The resulting yearly average power use for each hour of the day of the chosen heating season is compared with the power use of the respective reference scenario with constant SPT for the same period.

Figure 4.5 shows the yearly average difference in heating power for the PHL building with constant SPT compared to OPCS and SPCS. The illustrated scenarios are with CSs implemented for the

whole year, from November to March and from December to February. Since the capacity for offering flexibility is greater when the reference has a high heating demand, the KPIs calculated only from December to February are significantly improved for the PH buildings. However, as can be seen from Figure 4.5, by only applying CSs in the coldest months result in a considerably less amount of energy reduced in the peak hours during the year. Even though the KPIs would be improved, the total magnitude of energy and power reduced in the peak hours would be decreased by not applying CSs outside the winter season. On the other hand, when the CS is applied from November to March, the sum of reduced energy in these hours is very close to that for the whole year for both CSs. At the same time, the energy used during the heating periods is reduced. This shows that the PH buildings may achieve almost the same magnitude of energy and power reduction during peak hours in addition to a lower increase in annual energy use when the CSs are not applied in the warmest months.
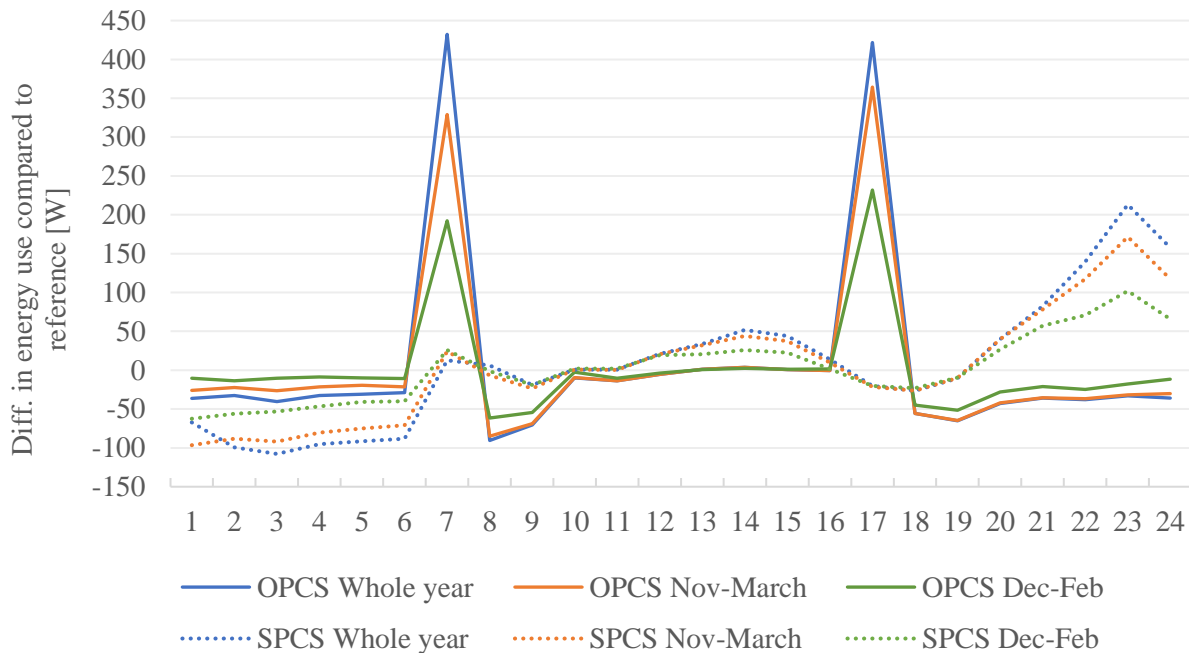
Figure 4.5 PHL: Average difference in heating power with OPCS and SPCS compared to the reference with constant SPT for different periods.

Even though the TB buildings have a high heating demand for most of the year, the CSs are investigated with a heating season from September to May, i.e. the three warmest months are not included. The result of this with OPCS is that the average energy use in the pre-heating hours is reduced for the TB buildings as well. A consequence of only applying the OPCS in the heating season is that the energy reduced in peak hours is slightly less which results in a somewhat poorer q_{ph}-indicator. This means that by only applying the OPCS in the heating season will result in better KPIs for q_{tot} and c, as the energy savings in the pre-heating period is larger than the reduced savings in the peak hours, and that the q_{ph} will be somewhat poorer. With the SPCS there are less noticeable changes when the CS is only applied during the heating season.

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4.2 The Influence of Dynamic Internal Heat Gains on Flexibility Potential

In this section, the influence of dynamic IHGs is presented. First, the differences for the reference simulations with constant SPT are presented before the results of the CSs with dynamic IHGs are evaluated. These results are only presented with P-controllers to make it easier to interpret the influence of the different IHG profiles on the heating system. However, all IHG-profiles are also simulated with thermostatic radiator control. At the end of this section, the aggregated result of 20 simulations with different stochastic profiles is presented.

The different IHG profiles that are investigated result in changes in the energy and power consumption for the reference cases with constant SPT, that will also have an impact on the KPIs. As this section only presents the most significant findings, the results of the reference simulations and the KPIs for all building types with the four investigated IHG profiles are given in Appendix B and Appendix C, respectively. This is given with both thermostatic and proportional radiator control. Thus, all KPIs can be translated to the energy and power consumption with the CSs.

For the references with constant SPT all three dynamic IHG profiles lead to the most considerable changes in energy use for heating for the PH buildings, but the trends in the changed performance are generally the same for the PH and TB buildings. As the dynamic IHG profiles have the same yearly value as NS, there are small differences in the yearly energy consumption with all profiles. Regarding the energy consumption during peak hours, the TS IHG profile leads to a small reduction, whereas the stochastic profiles result in a noteworthy increase. The same can be said for the peak power consumption during peak hours. The most significant increase in peak power consumption during the peak hours is with the SM_t IHGs, which result in an increase of 17-22 % for the PH buildings compared to results with the NS IHGs. This is because the stochastic profiles usually have a higher contribution of IHGs after the defined peak hours, especially in the evening. In average the IHGs from the stochastic profiles are below that of NS and TS in the peak hours in the morning, and lower than that of NS in the evening, as illustrated in Figure 3.3.

Figure 4.6 illustrates how the different IHG profiles affect the heating system when the SPT is constant on a cold day in January in the PHL. Figure 4.6 clearly illustrates that the IHG profile from TS has an earlier "start-up" than the profile from NS, and the heating power with IHGs from TS will start to drop earlier than the heating system with IHGs from NS. The IHGs from NS also have the highest heat gains from 07:00-15:00, when the SM_t and SM_{ts} have the lowest heat gains. There is a significant difference between the SM_t and the SM_{ts} profiles, especially in the afternoon/evening when the IHGs are highest. This is because when the gains are high in all zones at the same time with SM_t, this will cause a reduction in heating power in all zones at the same time. For the SM_{ts}, some zones will not have as high share of IHGs at this time and thus have a heating demand to keep the desired SPT, while other zones will have a high share of internal heat gains and the radiator will switch off. Thus, the whole building will have a higher heating power during this period. This day is opposite from the average of the stochastic IHG profiles, as there are high IHGs in the peak hours.
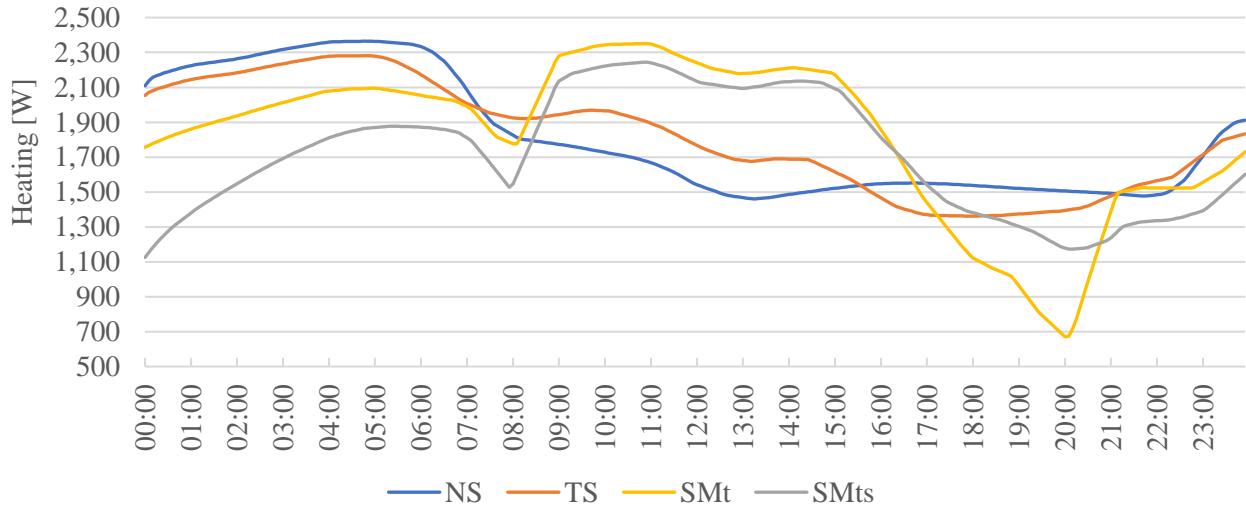
Figure 4.6 PHL: Energy use for heating during one cold day with constant SPT with IHG profiles from NS, TS, SMt and SMts.

## 4.2.1 Control Strategies with Dynamic Internal Heat Gain Profiles

The dynamic IHG profiles TS, SM_t, and SM_{ts} are implemented in the models together with the CSs to examine how the IHGs affect the performance of the control strategies. The results are evaluated with the help of the KPIs which are based on the reference simulation of the respective IHG profile and building type, i.e. there are separate references for all building types with all four IHG profiles and radiator control type. Thus, the KPIs only show how the CSs change the energy use, power use and yearly costs relative to the reference with constant SPT for the respective building type with a specific IHG profile and radiator control. Therefore, the magnitude of the reduced energy use during peak hours are also compared with all IHG profiles at the end of this section. As mentioned, all KPIs with the different IHG profiles for the four building types are tabulated in Appendix C.

The dynamic IHG profiles lead unsurprisingly to very small changes in the energy flexibility performance for the TB buildings with both CSs. The most noticeable difference is observed for p_{ph}-indicator, where the dynamic profiles lead to a slightly increased p_{ph}-indicator with OPCS, and slightly decreased p_{ph}-indicator with SPCS. However, since the changes are so small, the KPIs with dynamic IHG profiles are only presented for the PH buildings.

With the OPCS the dynamic IHG profiles result in the most prominent changes in the peak power indicators for the PH buildings. Since the reference simulation with TS IHGs has the lowest peak power consumption during the year, the difference when implementing the CSs is larger. Regarding the power consumption during the peak hours, the stochastic profiles result in a slight power use in the PHL with P-control, as opposed to the results with NS and TS IHGs. This is occurring right before the end of the peak hours, i.e. close to 09:00 and 19:00 on cold days. This show that the temperature in some zones in the PHL drops below the SPT at the end of the pre-defined peak periods, and thus the radiators start to operate. This is never the case for the PHH.

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The changes in both energy indicators and price indicator are small, however with the SM_{ts} IHG profile, there is a slight improvement compared to the NS IHG profile.

The most significant changes of KPIs with dynamic IHG profiles are observed with the SPCS in the PH buildings. The performance indicators with NS and dynamic IHGs for the PH buildings are illustrated for SPCS in Figure 4.7 along with the reference values for the dynamic IHGs. The reference values with NS IHGs are listed in Table 4.1. This show that with the stochastic profiles, all KPIs are improved, compared to NS and TS profiles. The only scenario where the CSs does not result in increased costs for the PH buildings is with the SPCS and space and time distributed IHGs. Thus, the PH buildings can shift a larger share of the energy and power use with the stochastic IHG profiles. The new peak power consumption is occurring in the peak hours, making the p_{ph}-indicator larger than p for NS and TS IHGs, since the peak power consumption for the reference case is lower in these hours because of the distribution of IHGs.
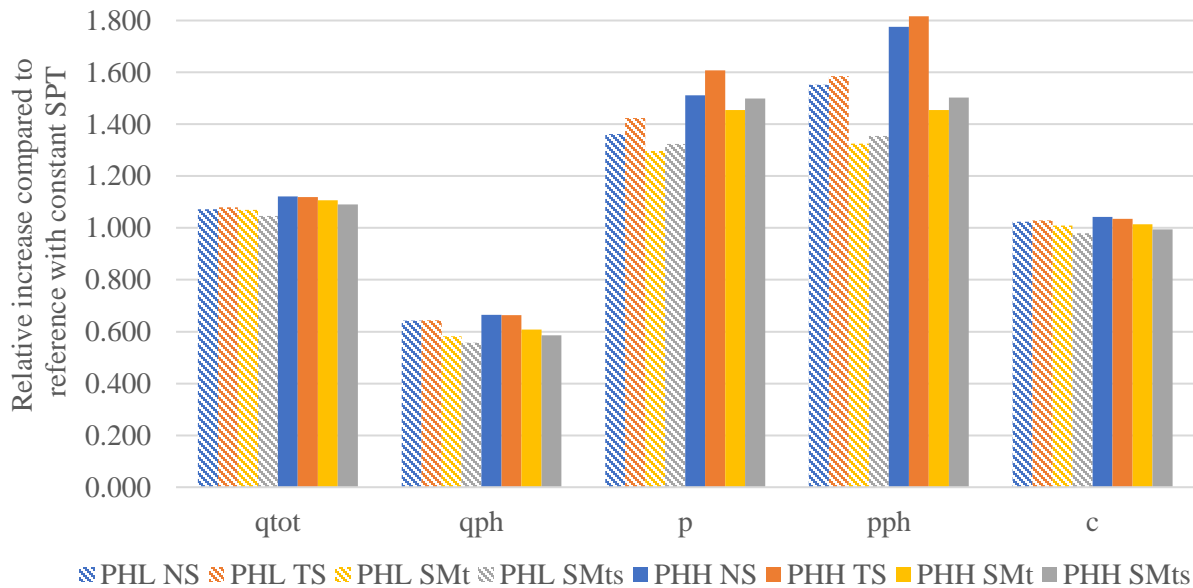
Reference	Qtot [kWh/m²]			Qph [kWh/ m²]			P [W/ m²]			Pph [W/m²]			C [NOK/m²]		
values	TS	SMt	SMts	TS	SMt	SMts	TS	SMt	SMts	TS	SMt	SMts	TS	SMt	SMts
PHL	15.9	15.8	16.1	2.3	2.7	2.8	14.6	16.0	15.6	13.1	15.6	15.3	4.6	4.7	4.8
PHH	15.2	15.1	15.2	2.1	2.4	2.6	13.1	14.5	14.0	11.6	14.5	14.0	4.4	4.4	4.5

Figure 4.7 KPIs for PHH and PHL with SPCS and IHGs from NS, TS, SMt and SMts with proportional controller. Reference values used for calculation are tabulated.

As explained in section 4.2, the energy and power use during the peak hours for the references with constant SPT is highest with the stochastic IHG profiles. Consequently, the capacity for shifting the consumption is larger with these IHG profiles. When investigating the magnitude of the energy that is reduced in the peak hours for both CSs and all four building types it is clear that the stochastic profiles result in the highest amount of energy reduction in these hours. Figure 4.8

shows the difference in specific energy use during peak hours from the reference cases and with the OPCS and SPCS throughout the year for the PH buildings. This is given both with thermostatic control and proportional control of the radiators. The stochastic profiles always result in the largest amount of energy shifted in the peak hours, and the SM_{ts} is the profile with the highest amount of reduced energy. The results show that the difference between the NS/TS IHGs and the stochastic IHG profiles is much more significant with thermostatic controllers.

Figure 4.8 Yearly difference in energy use during peak hours from the reference and with OPCS and SPCS for the PHL and PHH with thermostatic controller (TC) and proportional controller (PC).

The same is illustrated for the TB buildings in Figure 4.9. This shows that the order of magnitude of energy reduced for the TB buildings is almost three times higher than the PH buildings. The relation between the energy reduced in the peak hours is generally the same when comparing NS against the dynamic IHGs in the TBL building. This is however not the case with the TBH building, here the thermostatic controller results in a noticeable larger energy saving with SM_{ts} IHGs. A thermostatic controller generally results in larger energy savings for both TBL and TBH, and especially with SM_{ts} IHGs for the TBH building.
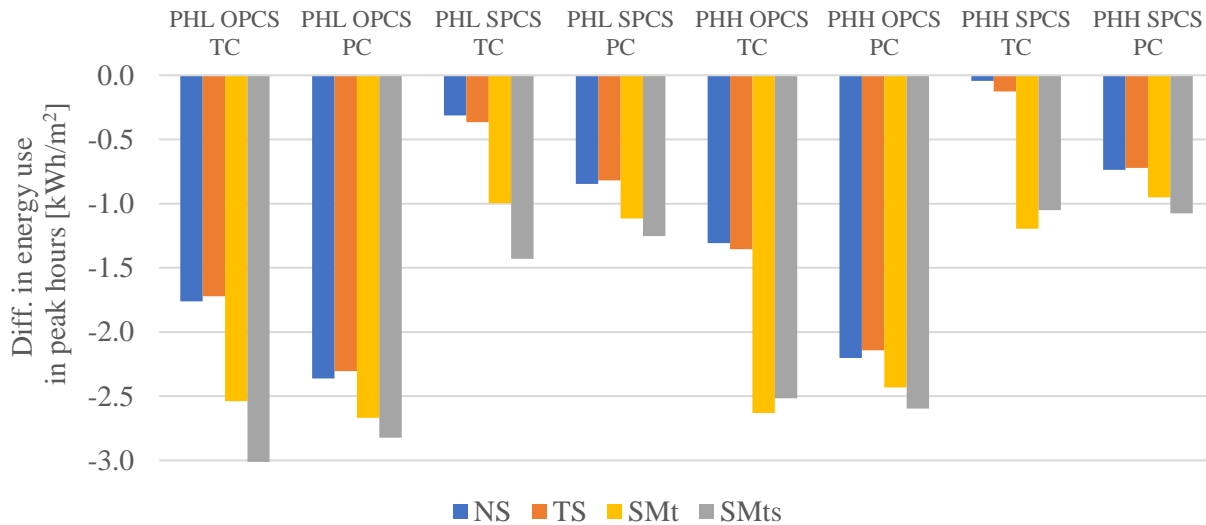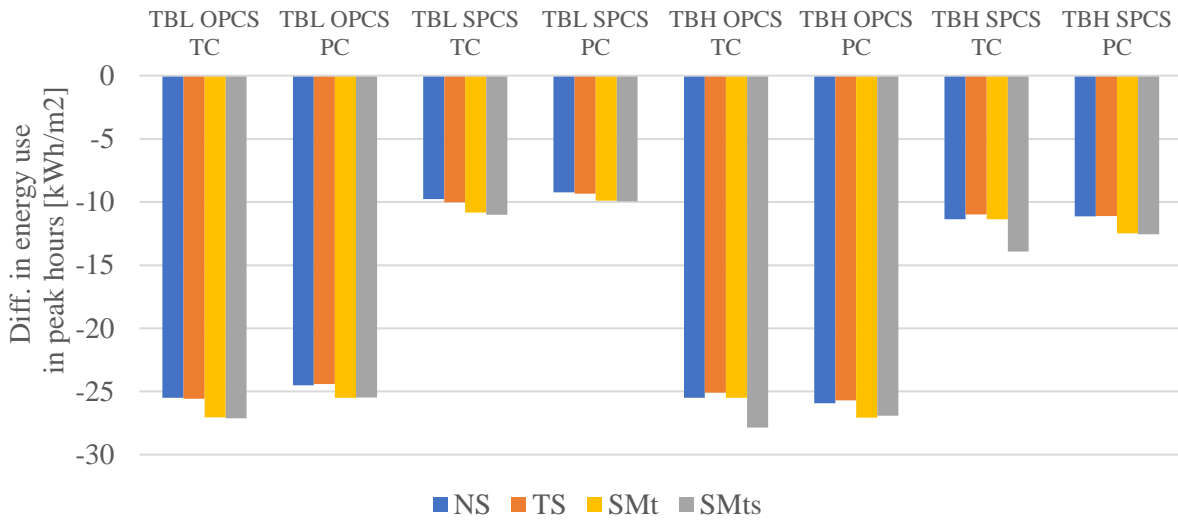
Figure 4.9 Yearly difference in energy use during peak hours from the reference and with OPCS and SPCS for the TBL and TBH with thermostatic controller (TC) and proportional controller (PC).

4.2.2 Aggregated Results with Several Stochastic Internal Heat Gain Profiles

To evaluate the effects the two CSs may have on a larger scale, simulations are conducted with 20 different SM_{ts} IHG profiles. To achieve the most realistic result, this is done with thermostatic controllers. As mentioned in section 3.3, the average yearly sum of IHGs from all 20 profiles is adjusted to match that of NS. The resulting performance indicators based on the average values of the 20 simulations and with a thermostatic controller are shown in TABLE, along with the maximum and minimum values of the 20 simulations. This is given for the PHL and the TBL. The KPIs for the HCMs are given in Appendix D.

The KPIs for the aggregated result are given in Table 4.4 for the PHL and the TBL. This show that the results are in the same range as with one SM_{ts} profile. However, the p-indicator is larger than for one SM_{ts} profile. This is because the interpolated 1-minute values of the 20 simulations for the reference cases is lower than for one simulation. This means that for the reference cases with constant SPT, all the 20 buildings do not have the peak power consumption during the same minute. Since the CS makes sudden changes occur in the buildings simultaneously, all buildings have the peak power consumption at the same time with the CSs. For the OPCS, this always happens in the pre-heating hours. Thus, the peak power performance indicators based on aggregated results with thermostatic radiator control are more similar to the results with a P-controller. The largest variation between the minimum and maximum values is observed in the PHL. It is generally the peak power indicators that have the largest variability.

Table 4.4 KPIs for the aggregated result of 20 different SMts profiles with OPCS and SPCS for the TBL and PHL, along with the percentage maximum and minimum KPI values.

Key Performance Indicator	TBL				PHL			
	OPCS		SPCS		OPCS		SPCS	
q_{tot}	1.011	0 %	0.989	0 %	1.045	+1/-1 %	1.054	+1/-1 %
q_{ph}	0.087	+2/-2 %	0.632	+1/0 %	0.000	0 %	0.522	+6/-2 %
p	1.017	0/-2%	1.017	0/-2 %	1.227	0/-29 %	1.227	0/-29 %
p_{ph}	0.928	0/-6 %	1.069	0/-6 %	0.000	0 %	1.227	0/-32 %
c	0.986	0 %	0.969	0 %	0.991	+1/-1 %	0.981	+1/-1 %

The average power use for heating of the aggregated results is shown in Figure 4.10 for 22nd of January with thermostatic radiator control. This is compared to the average aggregated results with the same SM$_{ts}$ profiles with a P-controller. This shows that the aggregated energy use of a neighborhood is very similar with a thermostatic controller and with a P-controller. It is assumed that with even more simulations with different SM$_{ts}$ IHG profiles, the results with the thermostatic controller would be smoother. The most significant difference with a thermostatic controller compared to the P-controller is the rebound peak with OPCS. The aggregated result with the P-controller results in a more distinct rebound peak after the pre-defined peak hours. This is because in some of the zones, especially the ones with floor heating (technical room, baths), the air temperature will not drop below 20.5 °C during the peak hours. If the temperature in these zones is between 20.5 °C and 21 °C, the P-controller will start to operate, whilst the thermostatic controller will wait until the temperature is below 20.5 °C. The results for TBL show the same trend for P-controller and thermostatic controller as the PHL, and the figure can be found in Appendix D. However, in contrary to the PHL the difference in the rebound peak between a P-controller and a thermostatic controller is insignificant. This is because the temperature drop in the peak hours is higher for the TB buildings. The thermostatic controller and P-controller will then operate with a 100 % output at the same time, and result in the same magnitude in rebound peak.
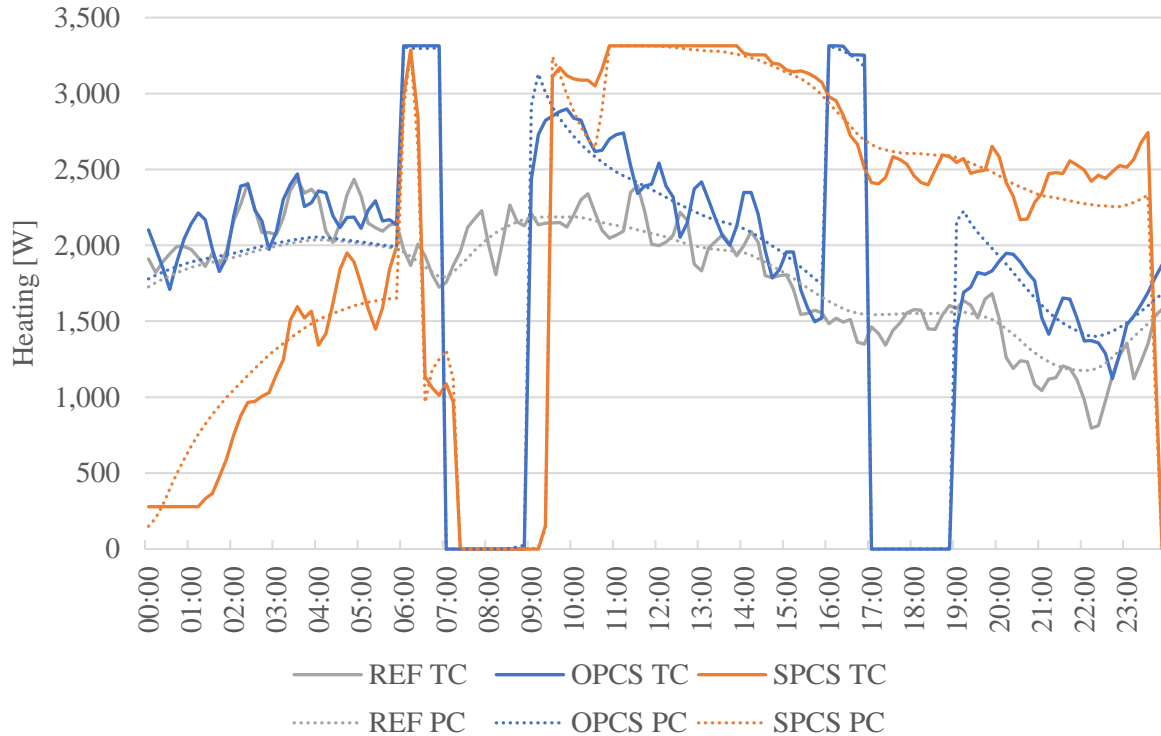
Figure 4.10 PHL: Average heating power of the 20 SM_{ts} profiles with thermostatic controller compared with P-controller. Given for one cold day for the reference (constant SPT), OPCS and SPCS.

4.3 Parametric Study

In this section, different parameters are changed, or adjustments are made to the CSs to evaluate the effects this has on the KPIs and the heating system. The KPIs are calculated with the reference simulations with constant SPT with the same IHG profile, radiator control type, and parameter settings. All results in this section are presented with the TS IHG profile and thermostatic controller. First, the effects of an increased DB are evaluated for both CS. In the following subsections, adjustments are made for the two CSs separately. The resulting KPIs for all investigated cases can be found in Appendix F.

4.3.1 Increased Deadband

The first parameter evaluated is the effect of a wider DB. A DB of 2 °C allows the temperature to drop to 18 °C in the pre-defined peak hours before the radiator is switched on instead of 18.5 °C as was the case with a DB of 1 °C. The change of DB has the most significant effect on the KPIs in the PH buildings. The KPIs for the OPCS$_{db2}$ and SPCS$_{db2}$ are shown together with the previous results with 1 °C DB in Figure 4.11 along with the reference values. With the OPCS$_{db2}$, the PH buildings still achieve a complete reduction of power use during peak hours. In addition, the KPIs regarding yearly energy consumption and costs are improved. The reason for this is mainly that the relative increase in energy consumption in the pre-heating hours is lower with a DB of 2 °C.

The SPCS$_{db2}$ improves the indicators mostly for the PHH. For this building, the c-indicator is reduced with a larger DB, whereas the q$_{tot}$-indicator is increased. Thus, the increased DB results in more energy shifted from high-price hours to low-price hours for the PHH with SPCS. When studying the average daily energy consumption, it is clear that the increase of DB with SPCS causes a high increase in energy use during the night for the PHH, as opposed to the PHL. Since the temperature fluctuations are slower in the PHH, the increase of DB causes the radiators to operate for a longer time during the night to reach the higher limit of the DB.
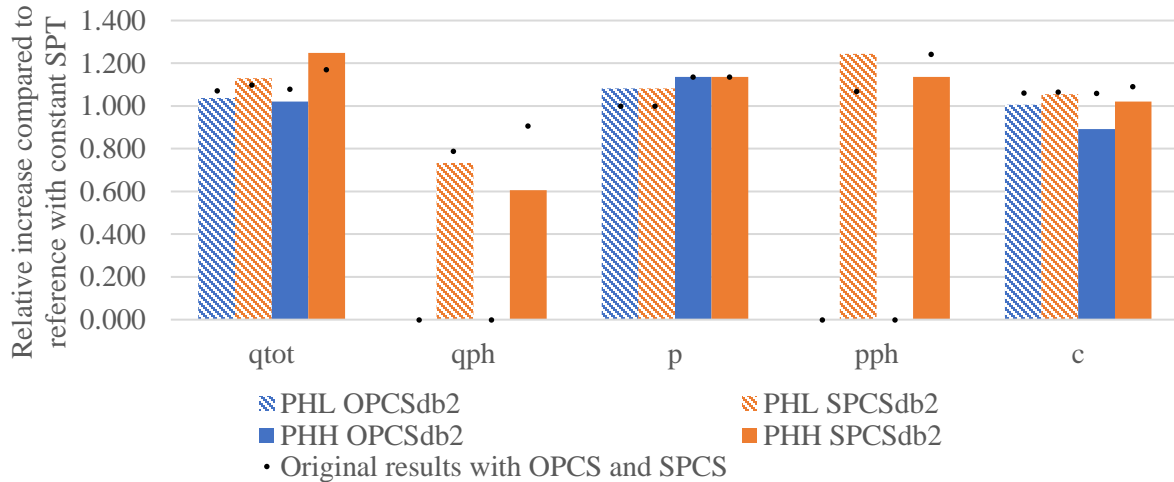
Reference values	Qtot [kWh/m²]		Qph [kWh/ m²]		P [W/ m²]		Pph [W/m²]		C [NOK/m²]	
	DB1	DB2	DB1	DB2	DB1	DB2	DB1	DB2	DB1	DB2
PHL	14.9	14.4	1.7	1.7	20.7	19.2	19.4	16.7	4.1	4.0
PHH	14.0	13.3	1.4	2.3	18.5	18.5	16.9	18.5	3.8	4.1

Figure 4.11 PH: KPIs with a deadband of 2 °C (OPCS$_{db2}$ and SPCS$_{db2}$) compared to 1 °C (OPCS and SPCS) with TS IHGs and thermostatic controller. Reference values used for calculation are tabulated.

Since the KPIs only measure the effects of the CSs relative to the reference cases with constant SPT, the increase of DB is also investigated with the magnitude of peak power use during the peak hours. Figure 4.12 shows the sorted peak power consumption occurring in the peak hours for the PH buildings with the SPCS and SPCS$_{db2}$. The PH buildings only have a power use for approximately 160 to 240 of the 1464 peak hours of the year. In terms of KPIs, the PHH achieved the best results. However, in terms of peak power use during the peak hours, the PHH has an increased peak power use during most of these hours with the wider DB. Thus, the improvement of the KPIs is due to a higher power and energy consumption for the PHH reference case. The difference in peak power consumption with the SPCS and SPCSdb2 is highest for the PHL, but for this building, the number and magnitude of peaks are lower with a DB of 2 °C.
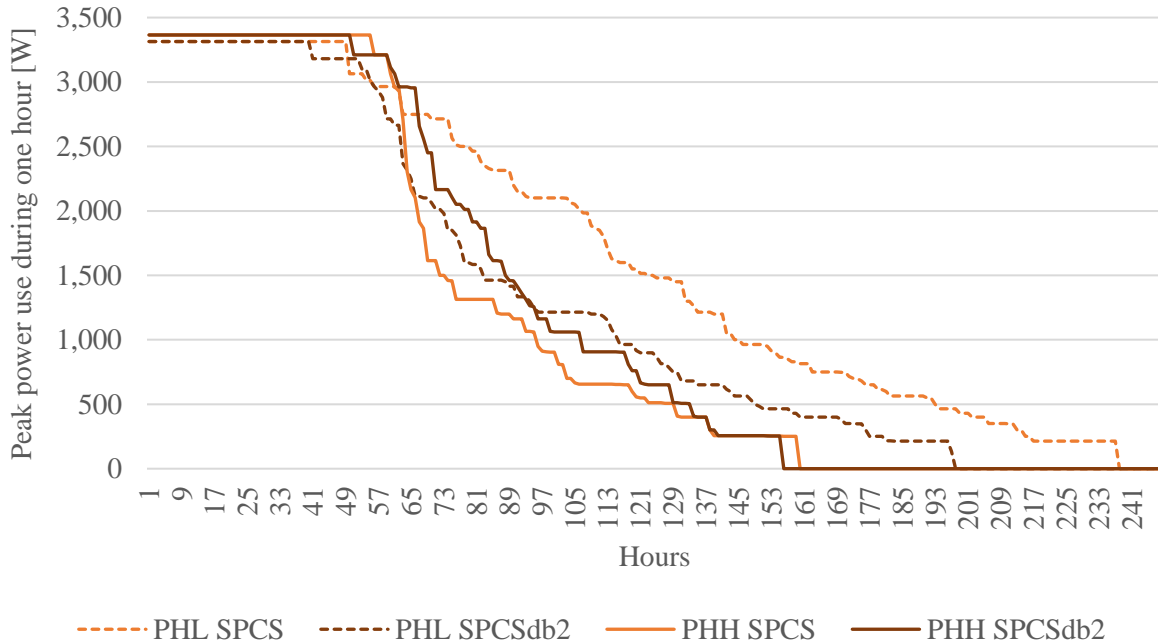
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Figure 4.12 Load duration curve showing the maximum peaks occurring in the pre-defined peak hours for the PH buildings with SPCS and a deadband of 1 °C (SPCS) and 2 °C (SPCS$_{db2}$).

For the TB buildings, the change of DB results in a significant improvement of the energy shifting potential for the TBH. The p_{ph}-indicator for the TBH building with OPCS$_{db2}$ is reduced with 20 % compared to the original OPCS. The changes in KPIs are less for the TBL. However, the peak power and energy consumption occurring in the peak hours is reduced for both TB buildings with a wider DB. This is illustrated in a load duration curve in Appendix E for both CSs, along with the KPIs with a DB of 2 °C.

4.3.2 Off-peak Control Strategy with Changed Duration of Pre-heating Period

This subsection presents the results of prolonging and shortening the pre-heating period of the OPCS for the TB buildings and PH buildings, respectively. The resulting KPIs with a pre-heating period of 2 hours for the TB buildings and 30 minutes for the PH buildings are shown in Appendix F. When changing the pre-heating duration from 1 hour to 2 hours for the TB buildings, the peak shifting potential is significantly improved. The performance indicator q_{tot} and c increase with 3 % and 2 %, respectively. The prolonged pre-heating period has however reduced q_{ph} by about 30 %. Thus, the prolonged pre-heating is very beneficial for the TB buildings. As the reduction of the q_{ph} is ten times greater than the increase of q_{tot}, a much larger share of the energy use in the peak hours is shifted.

The change of pre-heating duration for the PH buildings to 30 minutes results in no changes for the p_{max}, p_{ph} and q_{ph} performance indicators. However, the q_{tot} and c are improved, where the reduction is approximately 4-5 % and 6-7 %, respectively. Thus, the shortening of pre-heating

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period leads to a better result in terms of annual energy use and costs, without compromising the peak-shifting potential. Evaluation of the yearly average energy use shows that the consumption during the pre-heating period is drastically reduced. The cost performance indicator is reduced for both the PHL and PHH compared to a pre-heating period of 1 hour. With 30 minutes pre-heating, the PHH achieves reduced costs compared to the reference with constant SPT.

4.3.3 Spot Price Control Strategy Without Overruling at Night

The overruling of the SPCS at night is done to reduce the energy consumption for heating. However, it is interesting to evaluate the performance of the SPCS without overruling ($SPCS_{nor}$), The resulting KPIs with this strategy are compared with the results of the original SPCS.

As expected, there is an increase in total energy use for all building without overruling during nighttime, especially for the PH buildings. For the TB buildings the increase is of 5-7 %, and for the PH buildings, it is 25-43 %, where the HCMs have the highest increase. Consequently, the cost also increases without overruling the CS during nighttime. However, the relative increase in costs compared to the increased energy use is quite small. This is because the extra energy use mostly occurs during the night when the spot price generally is low.

With the $SPCS_{nor}$ the energy use during the pre-defined peak hours is considerably reduced for all building types. Figure 4.13 and Figure 4.14 show the percentage difference in average energy use each hour for SPCS and $SPCS_{nor}$ compared to the reference case with constant SPT for the TB buildings and PH buildings, respectively. The extra heating during the nighttime contributes to a lower heating demand during the day. Thus, the KPIs q_{ph} and p_{ph} are better with no overruling. The PH buildings have an especially significant reduction of power use during the day, from 06:00-20:00. The TBH also achieves reduction during this period.
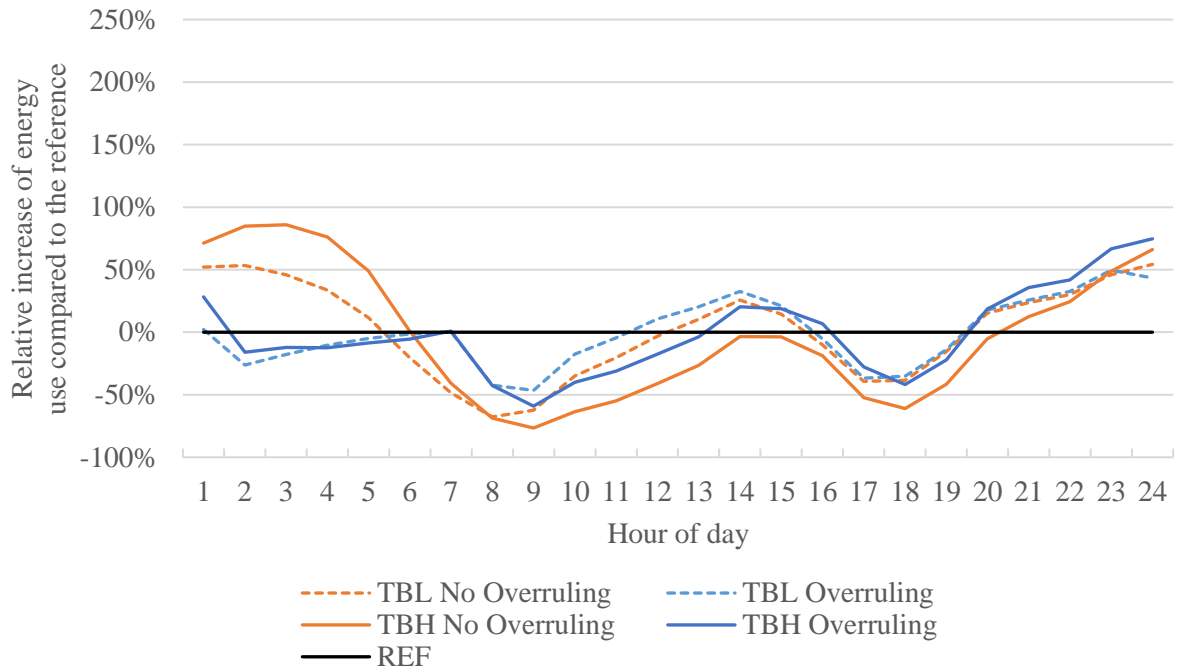
Figure 4.13 TB: Daily average difference in energy use for heating with SPCS and SPCS$_{nor}$, compared to the references with constant SPT (TS IHGs).
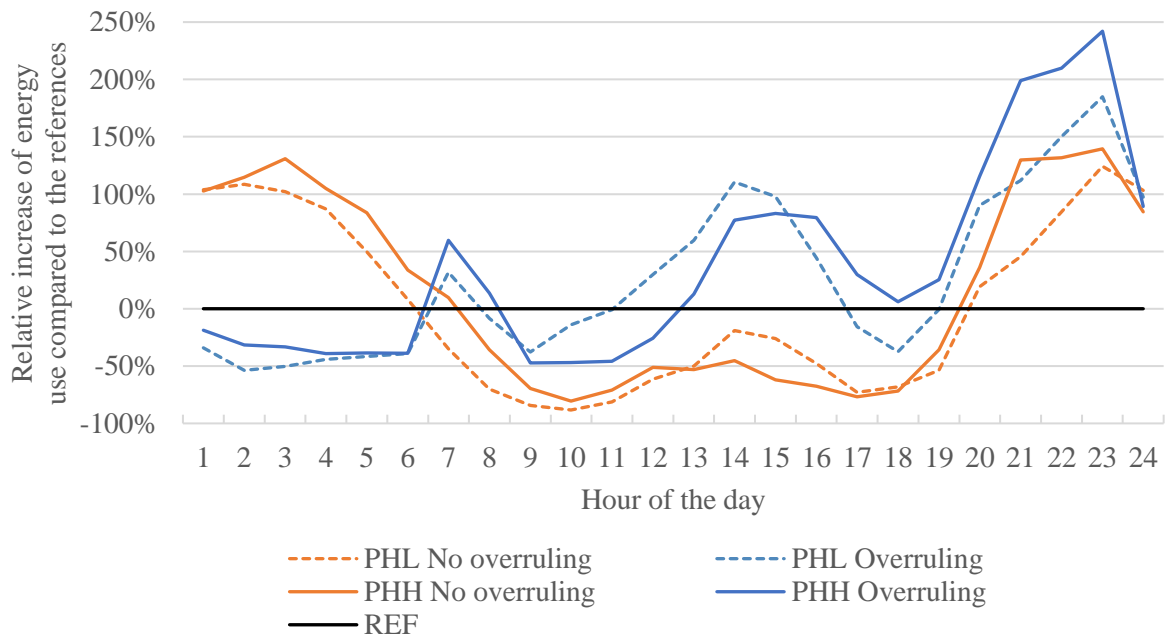

Figure 4.14 PH: Daily average difference in energy use for heating with SPCS and SPCS$_{nor}$, compared to the references with constant SPT (TS IHGs).

4.3.4 Sensitivity Analysis of Thresholds for the Spot Price Control Strategy

The influence the price thresholds have on the performance of the SPCS is investigated in this section. The average SPT and the percentage of hours in each temperature interval with the three evaluated thresholds, i.e. 25-75 % (original case), 20-80 % and 30-70 %, are shown in Table 4.5.

Table 4.5 SPT with different high and low-price thresholds for the SPCS.

Control Strategy	Average SPT [°C]	Hours with SPT 23 °C	Hours with SPT 21 °C	Hours with SPT 19 °C
SPCS$_{25\text{-}75}$	20.65	10.1 %	84.5 %	5.4 %
SPCS$_{20\text{-}80}$	20.71	8.8 %	86.6 %	4.6 %
SPCS$_{30\text{-}70}$	20.63	11.4 %	82.3 %	6.3 %

The different threshold scenarios do not result in very significant changes of the KPIs for the TB buildings. The largest change from the original threshold is found for q_{ph}-indicator for the TBH building. This is increased with both the SPCS$_{20\text{-}80}$ and the SPCS$_{30\text{-}70}$, but only with 3 % and 1 %, respectively. The KPIs for all thresholds scenarios are illustrated in Appendix F.

The KPIs for the PH buildings with the three SPCS threshold scenarios along with the references are shown in Figure 4.15. The SPCS$_{20\text{-}80}$ achieves the best results measured in the KPIs. The relative increase in annual energy use is reduced, and there are small changes during the pre-defined peak hours. The annual costs are also reduced with this threshold scenario. The SPCS$_{30\text{-}70}$ leads to worse KPIs regarding energy use, especially in the pre-defined peak hours, and also costs. The two peak power indicators remain unchanged when changing the price thresholds for both PH construction modes.

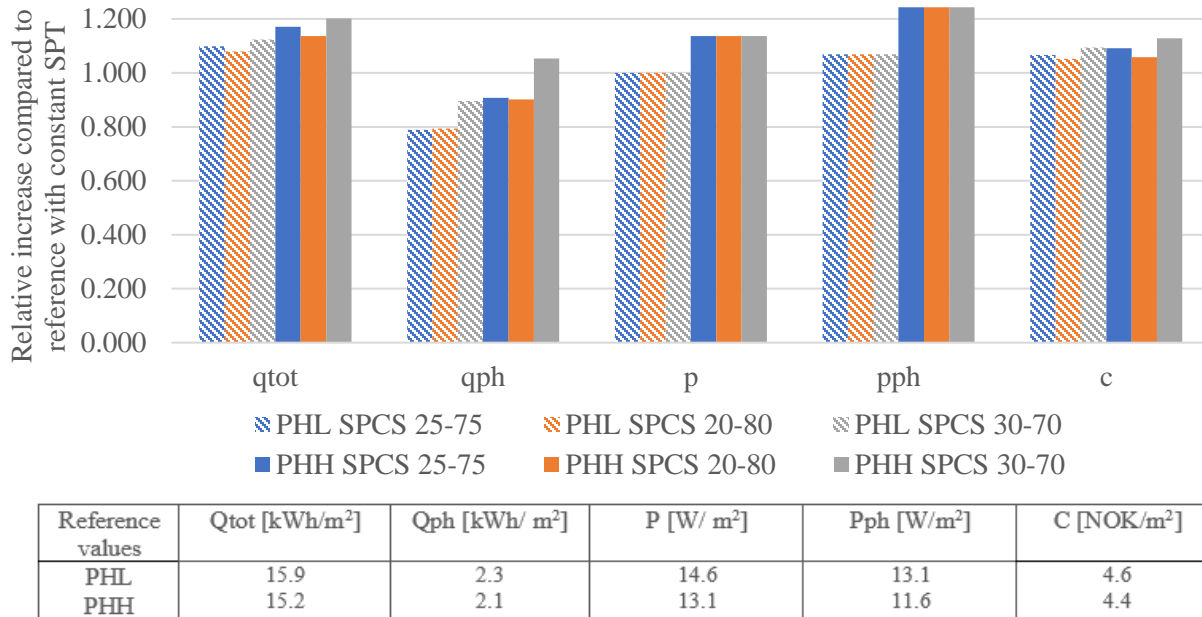| Reference values	Qtot [kWh/m²]	Qph [kWh/m²]	P [W/m²]	Pph [W/m²]	C [NOK/m²]
PHL	15.9	2.3	14.6	13.1	4.6
PHH	15.2	2.1	13.1	11.6	4.4

Figure 4.15 PH: Key performance indicators for SPCS with price thresholds of 25-75 %, 20-80 % and 30-70 %. Reference values used for the calculation are tabulated.

4.4 Evaluation of Bedroom Temperatures

As presented in section 2.7, occupants are often dissatisfied with bedroom temperatures in the cold months as well as the warmer months. Therefore, the influence of the IHGs, OPCS, and SPCS on the bedroom temperature is investigated. This is done during nighttime, i.e. between 23:00 to 07:00, in the defined heating season from October to April. To evaluate if the dynamic IHG profiles and control strategies affect the bedroom temperature differently with varying climatic boundary conditions, one of the coldest and mildest months of the heating season is evaluated. Therefore, the average temperature during the night is investigated separately for January and April.

In the last part of this section, the CSs are decoupled from the bedrooms. This is done both with a constant SPT of 21 °C ($OPCS_{bdc21}$ and $SPCS_{bdc21}$) and 16 °C ($OPCS_{bdc16}$ and $SPCS_{bdc16}$) in the bedrooms and only for the SM_{ts} IHG profile. The resulting KPIs are evaluated to see to what extent the energy flexibility is reduced by excluding the bedrooms. In addition, a new evaluation of the bedroom temperature during the heating season is made, to see whether this strategy improves the temperature.

4.4.1 Impact of Internal Heat Gains

The average operative temperature in the bedroom SE with the different IHG profiles is studied from 23:00 to 07:00 in January and April and is tabulated in Table 4.6. This is done without CSs to isolate the effect of the IHG profiles. Since the radiators are controlled by measurements of the air temperature, the operative temperature is higher in January for the TB buildings than the PH

buildings. This is because the radiators have a larger capacity in the TB buildings, and thus the share of radiative heat is higher.

Investigation of the temperatures for the reference cases with constant SPT shows that the dynamic IHGs barely affect the average monthly bedroom temperature in both January and April in the TB buildings, as the temperature difference is only $\pm$ 0.1 °C compared to NS IHGs. For the PH buildings, the dynamic IHGs only cause significant differences in bedroom temperatures in April. As no strategies are implemented to reduce the temperature in warmer months, the average operative temperature is between 1 and 3 °C higher than the SPT in April for the PH buildings with all IHG profiles. The highest average temperature is with the SM_{ts} IHGs which is 0.9 °C and 0.6 °C above the temperature with NS IHGs for the PHL and PHH, respectively. This is also the case during the entire heating season, i.e. from October to April. The percentage of time with different temperature intervals in bedroom SE in the PH buildings from 23:00-07:00 during the heating season is given in Appendix G. This is given for all IHG profiles, and clearly shows that the SM_{ts} profile leads to a significant increase of hours with too high temperatures.

Table 4.6 Average operative temperature between 23:00-07:00 in bedroom SE in January and April for the reference cases with constant SPT.

	January			
	TBL	TBH	PHL	PHH
NS	21.7 °C	21.7 °C	20.9 °C	21.0 °C
TS	21.7 °C	21.7 °C	20.8 °C	21.0 °C
SM_t	21.7 °C	21.7 °C	20.8 °C	20.9 °C
SM_{ts}	21.6 °C	21.7 °C	20.9 °C	20.9 °C
	April			
	TBL	TBH	PHL	PHH
NS	21.4 °C	21.4 °C	22.5 °C	22.1 °C
TS	21.4 °C	21.4 °C	22.6 °C	22.2 °C
SM_t	21.4 °C	21.4 °C	22.8 °C	22.2 °C
SM_{ts}	21.3 °C	21.3 °C	23.7 °C	22.8 °C

4.4.2 Impact of Control Strategies

Overall, the implementation of CSs results in slightly increased bedroom temperatures. The changes in the average operative temperature caused by the CSs during January and April are shown in Appendix G. The average temperature in the TB buildings is close to the SPT in both January and April. Additionally, the implementation of the CSs leads to insignificant changes in the average temperature. For the PH buildings, neither of the CSs contribute to very significant changes in the average temperature in January. The highest increase is found in the PHL with SM_{ts} IHGs. Here, the CSs cause the average temperature during the night to increase by 0.6 °C, i.e. to 21.5 °C.

In April, the PH buildings have a more significant increase of bedroom temperature caused by the CSs. The temperatures are already high in this month, and especially with space and time distributed IHGs. It is also observed that the CSs, in general, leads to more dramatic increases of temperatures for the PHH than the PHL in April. Nevertheless, the highest temperatures are observed in the PHL. The worst case, i.e. with SM_{ts} IHGs, results in an average temperature of 23.9 °C and 23.3 °C during the night for the PHL and PHH, respectively. This is almost the same for the two CSs, although the temperatures are slightly higher with SPCS.

Since the PHL building has the highest bedroom temperatures, the effect of distributing the IHGs in space is shown for this building. Figure 4.16 shows the average operative temperature for the bedroom SE in January and April in the PHL with OPCS and SPCS. This is given with stochastic IHG profiles, i.e. SM_t and SM_{ts}. In January the OPCS leads to increased temperatures during the day but does not affect the temperatures during the night. The SPCS however, leads to a significant increase in the operative temperature in the evening, and it stays high during the night. With the SPCS in January, the effect of space distributed IHGs is very noticeable, as the temperature is significantly higher with the space distributed IHG profile. In comparison, this difference in heat gains during the night is negligible with the OPCS. This indicates that the changes caused by the IHGs are more significant when the temperature is high, since the SPCS often result in an SPT of 23 °C during the evening until it is overruled.

In April, the operative temperature is very high, and the average is never below 22.5 °C. When compared with January, it is clear that the temperature is barely affected by the CSs, but rather the by IHG profiles and the solar heat gains. The only observable influence of the CSs are some spikes caused by the pre-heating in the OPCS, but the effect of this is eliminated during the night. The SM_{ts} IHG profile results in a more stable operative temperature throughout the day, and the temperature is significantly higher than with the SM_t during the evening and night.
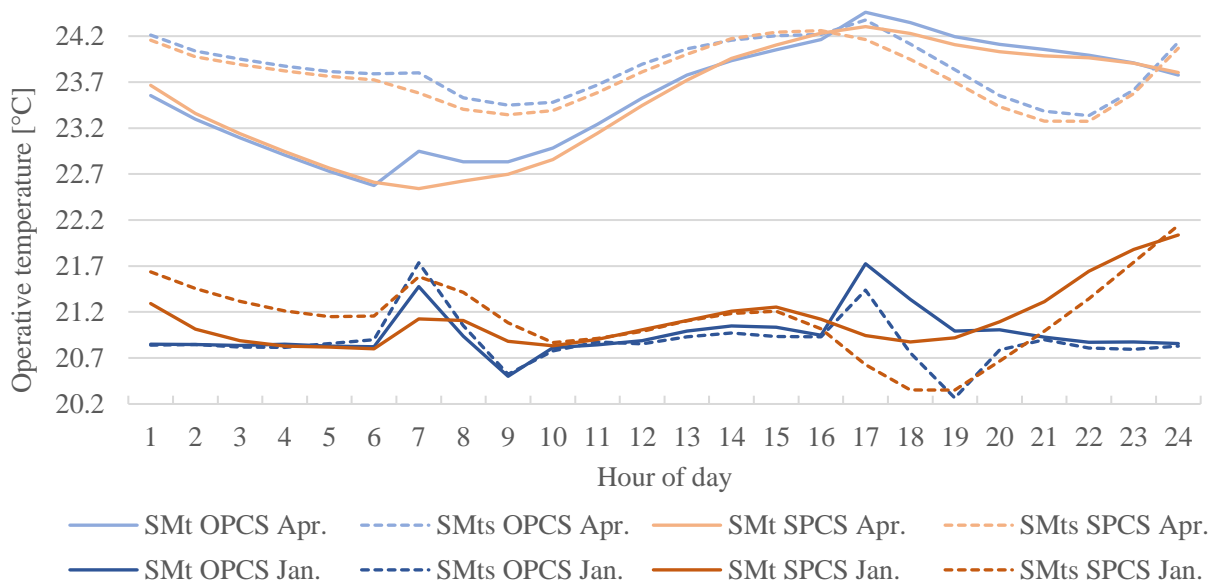

Figure 4.16 PHL: Average daily operative temperature in January and April in bedroom SE with OPCS and SPCS for the IHG profiles SMt and SMts.

4.4.3 Strategies to Reduce Bedroom Temperatures

To avoid unnecessary increase of bedroom temperatures, the CSs are decoupled from the bedrooms. Both a constant SPT of 21 °C and 16 °C in bedrooms are investigated. The results are presented only for the SM_{ts} IHG profile, as this is the profile with the most impact on the bedrooms, in addition to the profile that resulted in the highest temperatures. The bedroom temperatures are evaluated for the defined heating season from October to April. Finally, at the end of this subsection, an evaluation of the KPIs with decoupled bedrooms is presented.

With a constant SPT of 21 °C in the bedrooms, the operative temperature in bedroom SE in the TB buildings is studied during nighttime for the heating season. This is illustrated in Appendix G. The results show that for all scenarios the temperature is between 20-22 °C for more than 80 % of the time and that OPCS and SPCS increase the temperature. However, when the bedrooms are decoupled ($OPCS_{bdc21}$ and $SPCS_{bdc21}$) the temperatures are approximately the same as with the reference cases with constant SPT in all zones.

Figure 4.17 shows the percentage of time with different temperature intervals in bedroom SE in the PH buildings during nighttime for the heating season. When evaluating the temperature in the bedroom, it is clear that decoupling the bedrooms from the CS has a positive effect in reducing the bedroom temperatures. For the PH buildings, larger differences can be observed between the two construction modes. In general, the PHH has fewer hours with the highest and lowest temperature intervals, as it is less responsive to the outdoor temperature. For around 70 % of the time, the operative temperature is between 20 °C and 22 °C in the PHL.

The SPCS leads to the highest increase in bedroom temperatures, especially for the PHL, and the operative temperature is above 22 °C for more than 50 % of the heating season. The $SPCS_{bdc21}$ results in a significant improvement of this, and with this strategy the share of time over 22 °C is reduced to about 30 %. For the PHH, there are fewer hours with too high temperatures when the CSs are included the bedrooms but decoupling the bedrooms do not have the same effect as in the PHL. A reason for this is that the U-value of the internal constructions of the PHL is much lower than for the PHH, as shown in Table 3.1. Thus, the heat transfer from the zones below is much higher in the PHH and decoupling the bedrooms from the CSs is not as effective.
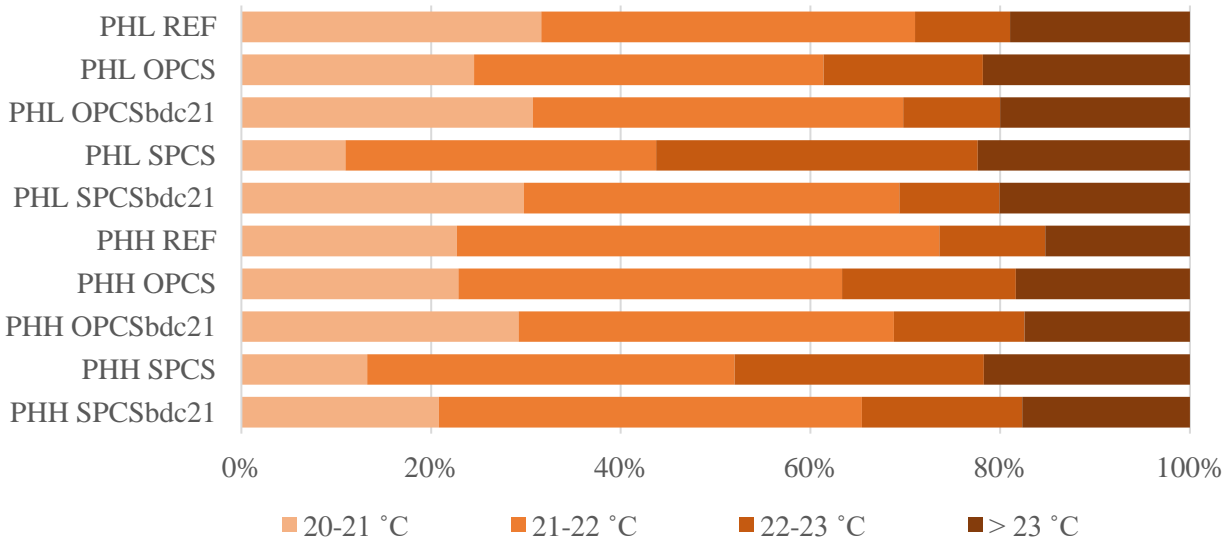
Figure 4.17 PH: Temperature duration in Bedroom SE at night in the heating season for the references with constant SPT, the original CSs and the CSs with decoupled bedrooms with an SPT of 21 °C.

When decreasing the SPT in the bedrooms to 16 °C, the TB buildings achieve temperatures close to the SPT for most of the heating season. The time distribution of the operative temperature with an SPT of 16 °C in the bedrooms is shown in Appendix G for the TB buildings. With OPCS$_{bdc16}$ and SPCS$_{bdc16}$, the bedroom temperature in the TBL building is below 17 °C for almost 100 % of the time between 23:00-07:00 in the heating season. The temperature is higher in the TBH building, but a temperature is below 17 °C is achieved for minimum 70 % of the time. The temperature is also studied when the SPCS is not overruled during nighttime (SPCS$_{bdc16+nor}$). This leads to a lot of hours with an SPT of 23 °C in the rest of the building, and the results show that this increases the bedroom temperature slightly, especially for the TBH.

Figure 4.18 shows the percentage distribution of the operative temperature in bedroom SE between 23:00 and 07:00 in the heating season for the PH buildings, included the OPCS$_{bdc16}$ and SPCS$_{bdc16}$. The SPCS$_{bdc16+nor}$ is also evaluated. The reference for these cases is with a constant SPT of 16 °C in the bedrooms and 21 °C in the rest of the zones. The reduction of the SPT to 16 °C does not contribute to a reduction of the highest temperatures for the PH buildings. This indicates that the temperature of 23 °C is due to other factors than the heating system SPT, such as internal and solar heat gains. Nevertheless, there is a reduction of the time within the medium-high temperature intervals, especially for the PHL. With the SPT of 16 °C, the bedroom radiators are off during the entire year for the PHH. Still, only the PHL achieves temperatures close to the SPT, and only for a very small share of the time. One main reason for this, especially for the colder months, is that the ventilation supply air temperature is 20 °C. Thus, even with no heat from local heating units, the heat from the supply air and other zones will keep the bedrooms warm.

The strategies with decoupled bedrooms do result in higher temperatures compared to the reference. However, the OPCS$_{bdc16}$ achieve temperatures below 21 °C for around 50-60 % of the

time compared to around 30 % of the time with OPCS$_{bdc21}$. This is not the case for SPCS$_{bdc16+nor}$, where the bedroom temperatures increase more. This increase is very high for the PHH, due to the high U-value of the internal structures.
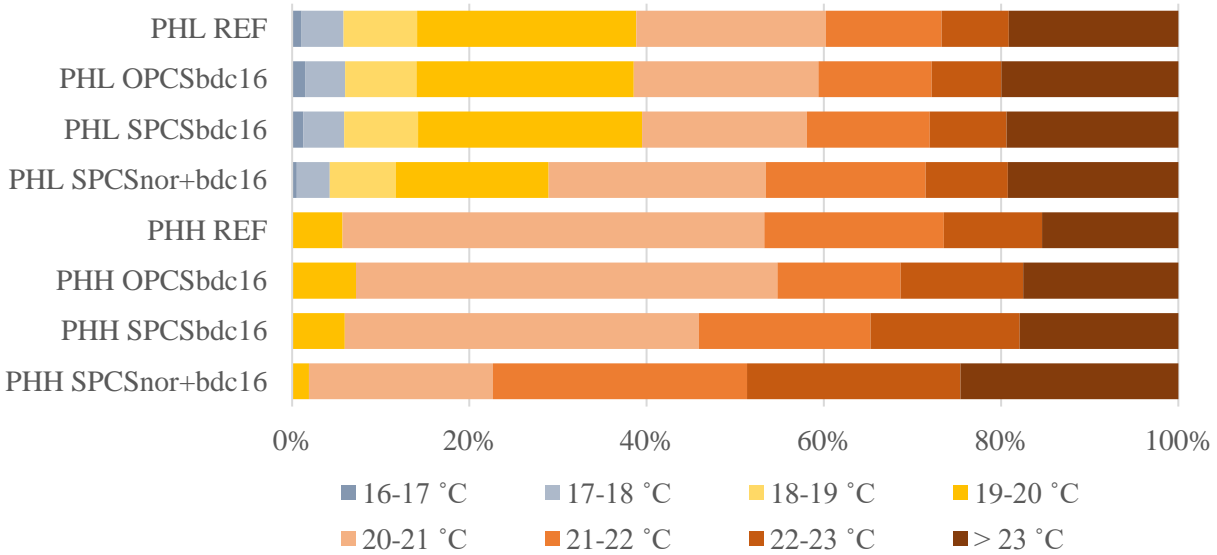

Figure 4.18 PH: Temperature duration in Bedroom SE at night in the heating season for the references with constant SPT, the original CSs and the CSs with decoupled bedrooms with an SPT of 16 °C.

By decoupling the bedrooms from the CSs the amount of energy and power shifted is reduced, as the radiators in the bedrooms will operate with a constant SPT of 21 °C or 16 °C during the peak hours. Thus, the performance indicator q$_{ph}$ is generally increased. This is illustrated in Figure 4.19, which show the q$_{ph}$-indicators with OPCS$_{bdc21/bdc16}$ and SPCS$_{bdc21/bdc16}$. The black marks show the q$_{ph}$-indicator with the original OPCS and SPCS. The KPIs for OPCS$_{bdc16}$ and SPCS$_{bdc16}$ are calculated with a reference with a constant SPT of 16 °C in the bedrooms and 21 °C in the other zones. The q$_{ph}$-indicator for the PH buildings is close to zero with an SPT of 16 °C since the radiators do not need to operate to maintain this temperature in the bedrooms. The other KPIs are barely affected by the decoupled strategies, except for the PH buildings with the OPCS$_{bdc21}$, where the p$_{ph}$-indicator is increased compared to the OPCS. All the KPIs of the decoupled strategies compared to the original OPCS and SPCS are illustrated in Appendix G.
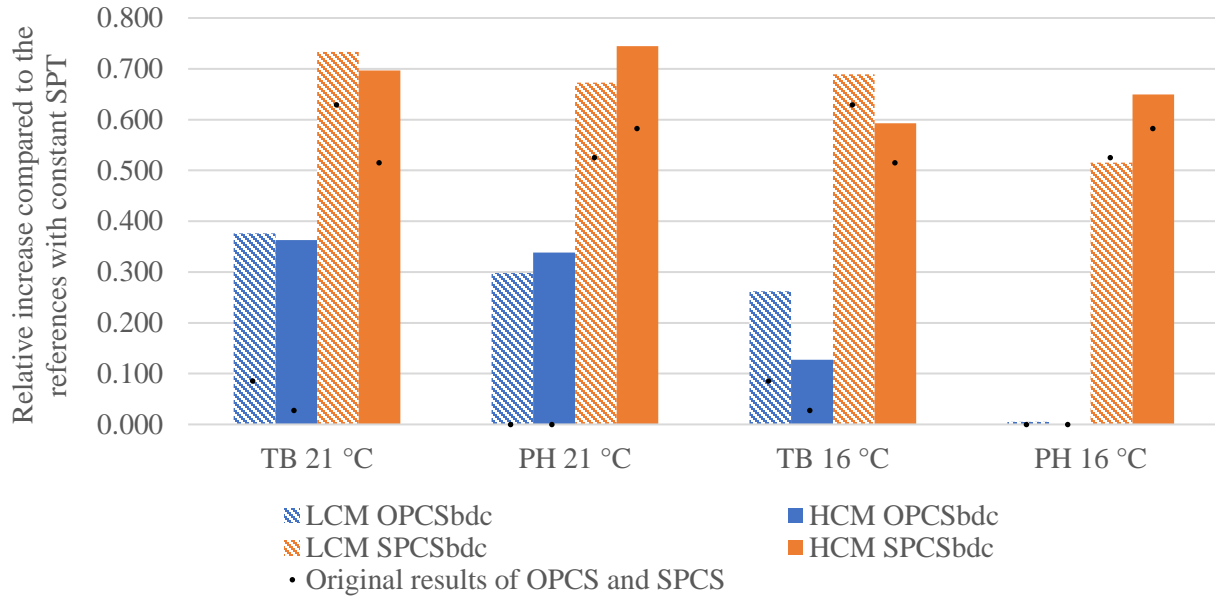
Figure 4.19 The KPI showing energy use during peak hours (q_{ph}) with $OPCS_{bdc21/bdc16}$ and $SPCS_{bdc21/bdc16}$. Original results of the OPCS and SPCS are illustrated with black marks.

5 Discussion

The objective of this thesis is to evaluate the energy flexibility that Norwegian residential buildings can provide to the electricity grid. To be able to represent a large part of the buildings stock, four different building types have been investigated, with two levels of insulation and two construction modes. Two different RBC strategies have been implemented to evaluate the flexibility potential. Furthermore, critical aspects such as the influence of dynamic IHG profiles and the conflict between the desire to provide flexibility and occupant preferences concerning bedroom temperatures have been investigated. In addition to this, a parametric study has been performed to evaluate how changes in parameters of the RBC strategies and the electric heating system affect the flexibility.

Overall, both RBC strategies show potential for shifting the power and consumption use to off-peak hours for all building types. This section provides a discussion of the effectiveness of the RBCs and trade-offs when offering flexibility, potential for improvement, impacts the chosen research approach has on the results and further work that requires investigation.

5.1 Evaluation of the Chosen Key Performance Indicators

There are several ways to characterize a building's ability to offer flexibility, and currently there are no standard defined metrics to do so. For this thesis, the flexibility potential is presented as the relative change of energy and power use and costs compared to a reference simulation of the same building type with a given IHG profile. Thus, the KPIs illustrate the influence of the implemented control strategies (CS) for each respective investigated case. They do not illustrate the magnitude of energy and power use that can be shifted for the different building types with different IHG profiles, but only the changes compared to the reference. However, the KPIs are selected to illustrate the difference in the share of energy and power shifted and the share of total increased energy and power consumption for the specific cases. In addition to the thermal properties of the building, this share is shown to be highly dependent on the available capacity for the reference case, i.e. the energy and power consumption in the defined peak hours.

Another approach would be to measure the effects of the CSs against the reference value of NS IHGs. This would bring forward a comparison the influence of the IHG profile, but not the actual energy and power consumption shifted with dynamic IHGs. Thus, the KPIs are applicable for evaluating the flexibility for a specific IHG profile and to compare the flexibility potential with different IHG profiles as was the objective of this thesis. Furthermore, the appendix contains all reference values with constant SPT and all KPIs for the CSs with different IHG profiles. This makes it possible to calculate the magnitude of energy, power or cost with the different CSs with different IHG profiles.

Another aspect with the KPIs is that the peak-indicators, i.e. p and p_{ph}, are based on the maximum peak occurring within each of the peak hours. Thus, these indicators show the relation between the maximum peaks that occur during the defined time period for the reference case and with CS, but not at which point in time during the defined time frame the peaks occur. Thus, they show the relation of the worst case between the reference and with CS. However, when they are seen

together with the energy indicator and price indicator, this provides a relatively comprehensive picture of the changes caused by the CSs. Another approach could have been to include the time duration with the maximum power in the peak hours and present this as a KPI. The maximum power in the peak hours was however presented in a load-duration curve, which is considered to illustrate this aspect sufficiently.

The KPIs depicting the shift of power and energy consumption during peak hours, i.e. q_{ph} and p_{ph}, are somewhat insufficient for measuring the effects of the spot price control strategy (SPCS). This is because the increase and decrease of SPT changes from day to day, and thus makes it is difficult to measure the accurate effects. It is still chosen to present these KPIs for the SPCS as they can be used to compare the effects of the two CSs. Another approach to illustrate the shifting potential could have been to illustrate the ratio between the total increase of energy use and costs.

Even though the selected KPIs for this thesis have some shortcomings, the KPIs along with the figures and tables are still believed to provide a comprehensive characterization of the building models ability to offer energy flexibility. As mentioned in section 2.5, the IEA EBC Annex 67 defines the three general properties of communicating energy flexibility; capacity that can be shifted, time aspects and costs. When presenting the results with the selected KPIs and illustrations of the heating system response to the implemented CSs, these three parameters are considered to be thoroughly investigated.

5.2 Assumptions and Simplifications Regarding the Applied Building Model

All results in this thesis are based on results from simulations in the building performance simulation tool IDA ICE. The results from IDA ICE and other detailed tools should be read with a critical mind, as these software tools have a high input rate, forcing simplifications to be made. IDA ICE is a tool that has a large number of input choices and require relatively high expertise to use to get trustworthy results. However, as long as the user understands the way the modelling and calculations are executed in the tool and states the assumptions made, the results are trustworthy.

In addition, it is important to be aware of simplifications done in the IDA ICE calculation steps in order to point out weaknesses in the results. As mentioned, by default IDA ICE applies a level of smoothing of the implemented schedules to reduce numerical errors. For this thesis, this applies to the IHG schedules for appliances and lighting of NS and TS, as the stochastic IHG profiles are implemented as a text file in the custom control.

Other factors that are assumed to have an effect on the results are simplifications made when modelling the buildings. A substantial simplification of the TB buildings is the implemented ventilation system, which is a balanced mechanical ventilation system with no heat recovery. Ideally, it should be naturally ventilated, supplied with mechanical exhaust ventilation. Here, the air change rate is highly dependent on outdoor conditions, buoyancy and wind pressure. It is believed that the air change rate is higher with the implemented balanced ventilation system. As there is no heat recovery, this simplification is presumed to increase the energy use for heating compared to a natural ventilation system. Another assumption that has been made is that the normalized thermal bridge factor is the same as that of TEK10 and that the U-value of the floor is

different from that presented in the TABULA example building. However, the resulting energy demand for heating is in the same range as presented for the example building in the TABULA project, and the building is assumed to be representative of its age segment. Regarding the PH buildings, the heating demand fulfills the passive house requirements. However, the passive house standard also requires a certain share of renewable energy supply. Therefore, a direct electric heating system is not common in passive houses.

The electric radiators are dimensioned according to a heat load simulation with DOT which is in accordance to common practice, and the capacity is selected based on the nearest radiator size on the market. This approach has been applied due to difficulties in determining a realistic capacity of an all-electric heating system. It is dependent on whether a safety factor is applied which results in an over-dimensioned system, or if the occupants buy the radiators themselves. It is also assumed that with the common practice, radiator capacity is rather over-dimensioned than under-dimensioned. The potential for the buildings to offer flexibility to the grid will be highly restricted by the heating system capacity. Especially the TB buildings, which do not reach the SPT of 23 °C in the pre-heating hours and require heating power in the hours with reduced SPT. Radiators with higher capacity would most likely result in a larger share of energy shifted for the TB buildings and would be an interesting parameter to study. However, this has not been done in this thesis due to time limitations and other priorities for the parametric study. It is assumed that the effects of an over-dimensioned heating capacity would result in KPIs with a higher p-indicator and a lower p_{ph}-indicator, as the power consumption will increase in the pre-heating hours which could contribute to a lower power consumption in the peak hours.

The modelling of the material layers for the different construction modes is also a factor that is expected to influence the energy flexibility potential, given the thermal connection with the indoor air. Thus, it could have been of interest to evaluate the effect the material layer order of concrete and insulation in the HCM has on the structural storage capacity. This is only evaluated with the insulation layer further towards the outside, and the concrete layer further in to exploit the thermal properties of concrete. It would be interesting to see how the energy flexibility potential would be if the insulation layer is placed further in, and the concrete layer further towards the outside. In addition, the thermal connection of the surfaces inside the building have not been considered. This could have been a parametric study, with the purpose of determinig the effect different materials on the inner structures have on the thermal energy storage and energy flexibility.

5.3 Modelling of Occupant Behavior and Internal Heat Gains

As one objective of this thesis is to evaluate the influence IHGs may have on the flexibility potential, four different IHG profiles are implemented in the building models. The IHGs implemented from NS and TS are done according to common practice, whereas the stochastic IHG profiles are partially retrieved from domestic electricity demand models and partially self-made. The IHG profiles for lighting and appliances are based on the models developed by Richardson et. al. and calibrated by Rangøy. This is assumed to be one of the most applicable domestic electricity demand models for Norwegian residential buildings, and it has been applied in several other studies, as mentioned in section 2.6. Since modelling of realistic occupant behavior is a complex

topic, varying from building to building and dependent on a range of factors, several simplifications are done when modelling the IHGs from occupants. This also applies to the distribution of IHGs to different zones, i.e. for the stochastic profiles that are distributed in both time and space. The methodology for modelling the stochastic internal heat gain profiles will be further discussed in this section.

The stochastic internal heat gain profiles are only generated for four-person households which was decided based on the number of bedrooms in the selected building model. It is however also possible that this building model type would be occupied by a single person, two persons or three persons, as this is highly dependent on their life status. As the study by Dar et. al. identifies household size as a major influence on the gap between predicted and actual energy use of buildings, a parametric study could be done to evaluate the effect on energy flexibility with fewer or more occupants to evaluate the sensitivity of the magnitude of internal heat gains.

Furthermore, different profiles with a varying number of occupants would also be beneficial for the aggregated results, as it is unlikely that all households would consist of four persons in the 20 simulated cases. To get a more realistic aggregated result, the time and space distributed stochastic profiles with different numbers of residents could have been made according to the distribution of household sizes of Norwegian residential buildings. Nevertheless, as the magnitude of IHGs during the entire year is different from profile to profile, the aggregated results of the 20 simulations are done with variability in both magnitude and timing of IHGs. At the same time the average sum of all 20 IHG profiles equals that of NS. Therefore, the IHG profiles applied to get the aggregated results are still assumed to be sufficient to illustrate the behavior of a neighborhood.

Since the model used to generate stochastic load profiles was claimed to not generate realistic occupancy profiles for Norwegian household, this was only used to generate profiles for lighting and appliances. Thus, a pragmatic profile was self-made based on reasonable assumptions due to time limitations. Since the main objective with the stochastic IHG profiles is to create a degree of random and variable IHGs to evaluate the influence on the flexibility, this was assumed sufficient for the objective of this thesis. It requires a lot of data and processing to create realistic occupancy profiles based on Norwegian statistics, and thus simplifications had to be done. The occupancy schedule is also created in accordance to the average daily load schedule for appliances retrieved from the stochastic model. This contributes to a certain degree of correlation between the schedule for occupancy and appliance. The desired stochasticity with rapid fluctuations in IHGs is achieved with the profiles for appliances and lighting, and it is checked that the designed occupancy does not flatten the total IHG profile too much.

The yearly occupancy profile is made with a traditional working schedule in mind, as this is expected to cover a larger share of the population. A more irregular working schedule based on shifts and/or home staying could also be made to evaluate the impact this has on the total IHGs, and thereafter evaluate if it should be tested with an RBC strategy as well. Another approach could have been to use the occupancy model generated from the model based on Norwegian TUS data even though this was not recommended by the developer. This would however give an occupancy schedule connected to the gains from appliances and lighting. Due to time limitation and lack of experience with the programming language Visual Basic for Applications (VBA), this schedule

was not retrieved. In addition, this occupancy schedule only contains "active occupancy", i.e. occupants asleep are not included and had to be included manually.

The space distribution of the stochastic IHG profiles is also simplified and made based on assumptions. The method of creating a percentage share of total IHGs in each zone for 24 hours does not allocate the IHGs to appliances and lighting in the correct magnitude. I.e. there might be more gains distributed to the living room/kitchen than what the realistic gains would have been if all kitchen/living room appliances were in use with full lighting and occupancy. Another approach could therefore be to allocate the appliances and lighting units from the inventory used in the stochastic model to suitable zones. Then the gains could be distributed as a percentage according to the assumed maximum heat gain that could occur in each zone. This would have to be done according to the maximum value that occurs during the entire year, and the distribution schedule would also have to reflect the variability during the day. This was presumed to be too complex and time consuming in proportion to the result, especially for 20 profiles as the appliances are allocated for each profile. In addition to the assumption of traditional working schedules it is assumed that there is no work station in the bedrooms, and therefore no IHGs are emitted in the bedrooms from 10:00-21:00. This may be somewhat unrealistic but is nevertheless expected to be representative for a large share of households. However, the average heat gains in the kitchen/living room, bedrooms and bathrooms were distributed so that they are in agreement with the study of Georges et. al, as mentioned in section 3.3.

The generated stochastic IHGs for appliances and lighting most often do not contribute during the night. In the self-generated occupancy profiles, the activity level from the occupants is set to be seated quiet resting, and the daily average is equal to that of NS and TS. The heat emittance from the self-made occupancy profile is however very high at night, as it is assumed that all occupants are at home and in bed, but with the same heat emitted as a seated person. This causes the IHGs in the night to be quite high, compared to NS and TS, which is flat and based on a daily average. Since sedentary occupants are used, the magnitude of the IHGs during the night is probably a bit too high, as the heat dissipated from a sleeping person is lower. Therefore, a more realistic approach would be to reduce the IHGs from occupants during the night and slightly increase it during the day.

5.4 Evaluation of the Control Strategies

With the aim of identifying the energy flexibility potential of the building types, two RBC strategies are selected and implemented in the building models. Only RBCs are evaluated and not MPC strategies as this is not the scope of the thesis. The study of Fischer et. al. found that the MPC outperforms the RBC in terms of cost, efficiency and comfort. Still, the choice between an RBC strategy and an MPC strategy should be determined based on the complexity of the building model and computational costs. This should be done with regards to the potential load shifted and the vulnerability of the local grid against the complexity of the controller. To achieve a significant shifting of power and energy use and at the same time minimize the trade-offs, there are many considerations to take when implementing RBC strategies. Considerations should be taken regarding building characteristics, heating system parameters and thermal comfort of occupants.

Therefore, it is useful to discuss the benefits and disadvantages of the implemented RBC strategies, along with suggestions for improvements.

The temperature level and interval of ±2 K is decided according to the recommendations from TEK17 for thermal indoor climate, and the CSs are therefore considered to be in a range with adequate thermal comfort. However, the CS operate down to an *air* temperature of 19 °C as the sensor in the radiator controller measures the air temperature, while the lower recommended limit for thermal comfort in TEK17 is an *operative* temperature of 19 °C. This means that when the SPT is 19 °C, the operative temperature in the zone will often be slightly higher as thermal radiation is included. Due to the small time constant of the TB buildings they will reach an air temperature of 19 °C significantly more often than the PH buildings. Therefore, the thermal comfort is most critical for these buildings as the lower temperature limit will be reached frequently during winter season. The lower temperatures in the peak hours are not considered to be as critical for the PH buildings because of the much slower temperature drop. However, for these buildings the hours with temperatures that are too high are more problematic. This is a general problem in the summer months for the PH buildings when no shading is implemented to reduce the solar heat gains, but the results show that the OPCS contribute to more hours with too high temperatures.

The temperature interval for both CSs with a basis of 21 °C may be somewhat low, as it is revealed through interviews by Georges et. al. and Thomsen et.al that residents often prefer a higher indoor temperature in occupied zones. The standard SPT of 21 °C is based on NS 3031, but a higher SPT of 22 °C might be more realistic. The SPT would then vary from 20-24 °C with the CSs. This would in addition prevent the operative temperature to reach the lower limit of 19 °C in the TB buildings. This could have been evaluated in the parametric study, as the interviews indicate that if a higher SPT is used, the occupants' willingness to reduce the SPT in peak hours to offer flexibility might be increased.

Since the OPCS is based on pre-defined peak hours retrieved from the average daily electricity consumption profile, the successfulness of this strategy in terms of peak shifting depends on the actual peaks on the grid occurring during these hours each day. This is not realistic, and therefore this CS might, some days, contribute to more stress on the grid if the pre-heating or rebound peak occurs in the actual peak hours. Since the pre-heating and rebound peaks are of significant magnitude, this is a weakness of this RBC. If this strategy is implemented in several buildings, these peaks would occur simultaneously for all buildings, as illustrated in Figure 4.10. This is an example of trade-offs between simple and less computationally demanding RBC strategies and MPC strategies.

The length of the pre-defined peak hours for the OPCS is limited to two hours, as this is assumed to cover large parts of the peak hours. However, a longer duration would increase the probability that the actual peaks occur in the pre-defined peak hours. In addition, consideration is taken to restrict the duration of reduced SPT due to thermal comfort, especially for the TB buildings because of the rapid temperature drop. This is not the case for the PH building as the higher insulation level prevents the rapid temperature drop. Therefore, the duration of the SPT reduction could have been longer for these buildings. This could also have contributed to less probability of

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the rebound peak occurring in the actual peak hours on the grid. It is however beneficial to have the same schedule for both insulation levels for comparison reasons. Therefore, two hours was a compromise to keep some degree of thermal comfort in the TB building while having a reasonable duration of reduced SPT to achieve a degree of peak shifting.

The OPCS should ideally be optimized to fit the different insulation levels and construction modes to get the best energy flexibility performance. The duration of the pre-heating is therefore tested in the parametric study for the two insulation levels, but not the duration of the pre-defined peak hours with reduced SPT. This could also have been done in the parametric study, especially for the PH buildings which managed to have a 100 % reduction in the pre-defined peak hours. Also, since the average electricity consumption for residential buildings shows that the peak is longer during the evening, it could be interesting to examine the flexibility potential for OPCS with a prolongation of the SPT in late peak hour.

The SPCS is only evaluated with the spot prices for 2016. Since the control principle would be the same for input data from any other year, it is presumed that this is enough to show the influence of the control strategy. The sensitivity analysis of the SPCS was only examined for a broader threshold interval of 20-80 % and a narrower interval of 30-70 % for when the SPT is changed from 21 °C. It could also be evaluated for a higher and lower threshold interval of for example 30-80% and 20-70%, where the higher interval of 30-80 % would give more hours with a lower SPT and fewer hours with a high SPT, and vice versa for a lower interval.

The SPCS increase and decrease the SPT according to the spot price and is therefore not set to pre-heat the rooms before reducing the SPT as the OPCS does. The SPT is most often 21 °C before an increase or decrease in SPT, but occasionally there is a rapid drop or raise in the spot price and the SPT might go from 23 °C to 19 °C and the desired pre-heating occur. This is however not controlled. Neither does the SPCS have a limit of maximum duration with low or high SPT which might affect the thermal comfort significantly. This could be controlled by either overruling the CS in the hour before the SPT is 19 °C since the SPSC is assumed to have the spot prices 24 hours in advance. Another solution could be to adjust the higher temperature level to 22 °C for the PH buildings since they are prone to overheating and thus too long periods with 23 °C is undesirable. This is not as critical for the TB buildings as they have a faster temperature drop. However, the lower temperature limit could be adjusted up to 20 °C to avoid too long periods with a temperature of 19 °C. This would result in worse KPIs for the TB buildings as the energy savings would be less. For the PH building, it might result in better KPIs as the extra energy use with low spot price would decrease, and not necessarily increase in the hours with high spot price, because of the slower temperature drop.

5.5 Evaluation of the Results

Both CSs manage to shift a significant amount of power and energy use. However, significant differences are observed between the two evaluated insulation levels. This is in accordance with the findings in literature, i.e. the study by Le Dréau and Heiselberg. The findings in this thesis correspond with the study, as the buildings with a high level of insulation have a higher potential

for shifting its energy and power use. However, the buildings with a low thermal resistance have a higher capacity for heat storage and conservation for short periods of time, in terms of the magnitude of energy and power.

The radiator controller is found to have an impact on the energy and power shifting potential. With the OPCS, the KPIs for the pre-defined peak hours are not changed for the PH buildings, which achieve a complete reduction of energy and power use. However, for the TB buildings, the thermostatic controller leads to an increased power use during peak hours, but at the same time a decreased energy use. The deadband/P-band of the respective controllers can be a major influence of these results. Here, the deadband/P-band is 1 °C and when the SPT of 19 °C during the peak hours is reached, the radiators with a proportional controller will start to operate earlier than with a thermostatic controller. This is because the thermostatic controller will start up as soon as the temperature is outside the deadband, and consequently the radiators are on for a shorter duration, but the power use is higher as the output is either 0 % or 100 %.

The duration of the heating demand throughout the year for the two insulation modes is very different. As in compliance with the study by Fischer et. al. [36] the climatic conditions affect the performance of the RBC strategies. The high energy use for heating in the milder months is one reason why the KPIs regarding the yearly energy use and costs (q_{tot} and c) often are better for the TB buildings. Thus, excluding the CSs in the warmest months to reduce the increase of yearly energy use and costs is mainly of interest for the PH buildings. As the PH buildings have a low energy use in the warmer months, the total capacity for energy and power reduction is relatively small. In addition, the grid is experiencing the highest amount of stress mainly during the winter season. Therefore, with the objective to reduce energy and power consumption in accordance with the needs of the electricity grid, the coldest months are the most critical. However, as the investigation of excluding months from the CSs only is tested for some months to illustrate the potential of doing this, the chosen months could be optimized. The results are also only valid for the year 2016, and as the temperatures will change from year to year, the evaluation should ideally be done with a TMY climate file to be more general and applicable for several years.

The implementation of dynamic IHGs in the models is most significant for the PH buildings as expected based on the findings in the literature. Even though the KPIs are relative to the reference simulation with constant SPT, there is an observable difference between different IHG profiles, and especially for the PH buildings. In general, the stochastic IHG profiles result in a larger energy and peak shifting potential for all building types, both measured in KPIs and magnitude. As the sum of the yearly IHGs is the same as for NS and TS, it illustrates that the timing of the internal gains has a significant influence on the available capacity for peak and energy shifting, especially for the PH buildings. Even with the simplifications done when modelling the stochastic profiles, as discussed earlier, these are assumed to represent a more realistic occupancy behavior. Thus, the results indicate that the potential for Norwegian residential buildings to offer flexibility by use of thermal mass might be under-estimated when applying the current common practice of modelling IHGs. When investigating the KPIs of the aggregated results with 20 different stochastic IHG profiles, the results indicate the same as with the one profile.

The aggregated behavior of 20 simulations with the thermostatic controller is very similar to that with a P-controller. Thus, if the number of evaluated buildings is large enough when investigating the aggregated effect of applying CS, the choice of radiator controller can be of little impact for the results. Therefore, the more predictable behavior with a proportional radiator control can be used to illustrate an aggregated result of many buildings. It is however observed that the aggregated result for the PHL with a thermostatic controller results in less significant rebound peaks than with proportional controllers. For less insulated buildings, this is not the case, as the high heat loss usually cause the temperature to drop to the reduced SPT during the peak hours. Therefore, when the SPT increases again, the temperature is outside the P-band/DB and the heating system with both controller types will start to operate with a 100 % output and give approximately the same heating demand curve. The results show that this is not the case for the PHL buildings as the temperature is within the P-band/DB of the increased SPT after the period with reduced SPT. Consequently, the thermostatic controller will not start to operate immediately, as opposed to the P-controller. However, this effect will be very dependent on the applied CS, especially the magnitude of the SPT change, versus the level of insulation of the evaluated building type and the DB of the radiator. It is reasonable to assume that if the DB range was smaller, the aggregated rebound peak with a thermostatic controller would be more similar to the result with proportional radiator control with a P-band of 1 °C for the PH buildings.

The parametric study was undertaken with thermostatic controllers and TS IHGs. This was done to represent what is assumed to be the most realistic radiator control and IHGs that are dynamic, and at the same time with a fixed schedule, to make it easier to interpret the impact of the changed parameters. However, as the different IHG profiles have shown to have an effect on the flexibility potential this should also be tested with other IHG profiles.

The two construction modes are affected differently by the increase of DB. A wider DB results in improved KPIs for the PHH which is mainly due to a higher energy and power consumption in the peak hours for the reference case, which increase the potential for reduction. For the PHL, a wider DB results in less energy and power use during the peak hours in the reference simulation in contrary to the PHH, and thus have a lower shift capacity. The increased DB only influence the p_{ph} indicator for the TBH buildings, which is noticeably reduced with a wider DB. Thus, the effects of the DB of the electric radiators are very dependent on the construction mode and insulation type of the investigated building. However, the results with the DB of 1 °C is expected to be the most realistic, and due to the accurateness of new electric radiators on the market, it could also be of interest to investigate an even lower DB than 1 °C.

As investigated in the study by Le Dréau and Heiselberg, for short-term storage of heat in the thermal mass, buildings of different thermal properties achieve the best results with different approaches. This is in good agreement with the resulting KPIs in this thesis when the duration of pre-heating is adjusted in accordance with the thermal properties of the building. The longer time constant of the PH building is shown by the fact that these buildings achieve a complete reduction of energy use during the pre-defined peak hours with the OPCS. The results of the parametric study for OPCS show that this is also achieved when the pre-heating is reduced to 30 minutes. For the TB buildings, the reduction of energy and power use in these hours were reduced considerably

with an increased pre-heating period. However, this is only investigated with thermostatic radiator control. It can be assumed that the change of pre-heating duration could lead to an increased energy consumption during the peak hours with proportional controllers. This is because the radiators generally stay off longer with a thermostatic controller than a P-controller because of the characteristic of the DB, given that the size of the DB/P-band is the same.

The choice of overruling the SPCS was done based on the findings by Clauß et. al., which showed that an RBC based on the electricity spot price with high and low thresholds resulted in a considerable increase in energy use. However, when evaluating the results of the SPCS and SPCS$_{nor}$ in this thesis, it is clear that the control strategy without overruling the SPT to 21 °C at night significantly outperforms the other in terms of reducing the level of stress on the grid. Thus, the choice of overruling the SPCS at night resulted in a lower increase of overall energy use, but the potential in offering flexibility when required is also reduced. As several studies have pointed out, it is important to be aware of the trade-offs when offering flexibility. For this RBC, it is essential to find an optimal approach that considers the overall increase in energy use and amount of energy and power that can be reduced at high-price hours. An approach could be to overrule the SPT for a shorter duration than done in this thesis.

Regarding the sensitivity of the thresholds of the SPCS, the parametric study showed that for the PH buildings, the SPCS$_{20-80}$ results in a slightly lower increase in energy consumption, without a significant increase in the measured peak hours compared to SPCS$_{25-75}$. However, the results are very dependent on the number of hours with increased or decreased SPT when the thresholds are changed. Table 4.5 shows the percentage of hours within each of the SPT, and that hours with SPT of 23 °C was the one with the most variation when changing thresholds. This is reflected in the results, as the SPCS$_{20-80}$ achieved a reduction of overall energy use, but on the expense of less energy saved in peak hours. With the SPCS$_{30-70}$ the increase of hours with an SPT of 23 °C is greater than the increase of hours with an SPT of 19 °C which is reflected in worse results in all KPIs.

The investigation of bedroom temperatures is only done for bedroom SE. This is the largest bedroom and has the highest supply air rate. As the supply air has an influence on the temperature, it is assumed that the effect of the IHGs and CSs would have been more visible for the two other bedrooms. However, the result shows that the temperature is affected by the CSs and IHGs in this bedroom even though it was expected to have the least influence here. All three bedrooms have two external walls, but with different orientation and consequently different solar heat gains which might affect the bedroom temperatures. For the decoupling of the bedrooms from the CSs an influence of choosing the bedroom SE might be that the other two bedrooms share an internal wall, while the investigated bedroom is sharing a wall with the upstairs bathroom. Thus, it is likely that this bedroom will be more influenced by the changes of SPT in the other zones than the other bedrooms.

The selected months for investigating the impact of the IHGs are January and April. These are chosen with the aim of representing the difference for a very cold month and a mild month in the defined heating season. It is assumed that for the summer months, the outdoor temperature and

solar gains would be so high, that the effect of the IHGs would be smaller and more difficult to interpret, especially for the PH buildings.

As the PH buildings are equipped with an electric radiator in each bedroom, the space heating solution is not very representative of common Norwegian passive houses, which usually have a simplified space heating system with water-based heating. However, the main focus is to investigate how the IHGs and CSs are affecting the indoor temperature. Even though the heat balance of the bedrooms would have been different with another space heating solution, the influence of these factors is assumed to be the same. For the TB building, the same applies to the ventilation system, which is assumed to increase the heating need. Thus, if the TB buildings were modelled with natural ventilation, it is expected that the bedroom temperatures would be higher.

When the CSs are decoupled from the bedrooms, the buildings with HCM was significantly more affected by the changes of SPT from the other rooms. It is hard to separate the influence of the difference in thermal mass and thermal resistance for the internal constructions for this case. Therefore, this could be investigated further with the same construction type and different levels of insulation on the internal constructions, as Selvnes found the influence of the thermal inertia to be of importance.

As found in the thesis of Selvnes, the relative significance of the internal heat gains increases with increasing outdoor temperatures. I.e. the smaller the heat loss through the envelope is, the higher impact the IHGs have on the bedroom temperature. This result is in good agreement with the findings in this study which can be seen from the average daily operative temperatures in the PHL building from January and April in Figure 4.16. For January, the impact of the CSs on the bedroom temperature is significant, and there are small differences between the IHG profiles, SM_t and SM_{ts}. For April, the changes in temperature caused by the CSs are negligible, whereas the difference between the two IHG profiles is very significant. Thus, the impact of the control strategies on the bedroom temperature is negligible in milder months. However, if measures to reduce the bedroom temperatures, such as solar shading was implemented, the influence of the CSs is assumed to be higher.

If the CSs leads to too high temperatures, the occupants are prone to open windows. In the context of energy flexibility, this is especially critical since the energy used by increasing the SPT to store heat in the thermal mass will go straight out the window. Thus, in addition to increased energy use, it may also reduce the capacity of the building for shifting the energy and power consumption during peak hours. This is critical with the SPCS without overruling at night and for the PH buildings, and especially the PHH. Therefore, extra caution should be taken with regards to thermal insulation level and thermal mass before implementing this CS.

5.6 Economical Aspects

As mentioned in subsection 2.5.2, there are currently ongoing discussions in Norway with regards to power demand tariffs. The proposition of a power demand subscription would restrict the control strategies for peak shifting and promote the strategies for peak reduction, and as mentioned, this proposition has met a lot of resistance. The suggestion of power demand tariffs by the "time of

use" model, i.e. pricing based on peak hours, would support the two classic forms of load management, peak shifting and peak reduction. As the RBC strategies presented in this thesis contributes to peak shifting, the "time-of-use" model would be beneficial for a possible implementation. It can be assumed that if this pricing scheme is implemented, the cost savings by the applied RBC strategies in this thesis would achieve greater cost savings.

To be able to implement DSM in the society, the occupants must accept to not be in charge of the temperature control in their home. There must be some sort of benefit for the occupants in terms of reduced cost as an RBC strategy to some extent of thermal comfort might be sacrificed. Thus, a CS with a reduced cost compared to the scenario with constant SPT is beneficial for this aspect. Both the OPCS and SPCS have a reduced cost for all building types when stochastic internal heat gains are implemented. However, the magnitude of the saved costs is relatively low, especially for the PH buildings. Thus, a different pricing scheme to further reward building flexibility would be of high importance for the implementation of RBCs. This means that the result of the ongoing discussion about the power demand tariff in Norway is very important concerning the realization of the type of RBC strategies evaluated in this thesis.

6 Conclusion

The objective of this thesis has been to evaluate the energy flexibility that Norwegian residential buildings can provide to reduce stress on the electricity grid. This has been done by applying rule-based control (RBC) strategies that adjust the set-point temperature (SPT) of a direct electric space heating system. Critical aspects with regards to utilization of the energy flexibility such as the influence of internal heat gains (IHG) and possible impacts of occupant preferences regarding thermal zoning of bedrooms are evaluated.

Two RBC strategies based on findings in literature have been chosen, one that applies a pre-defined schedule (OPCS), and one that applies the spot price (SPCS). These have been evaluated for a building model with two different insulation levels and two construction modes. The results show that all building types have potential to shift their energy and power consumption. The buildings with a high level of insulation achieved the most significant relative share of energy and power shifted. Even though the less insulated buildings have a lower peak shifting potential, the magnitude of the shifted energy and power is significantly higher. The high energy use of these buildings also leads to less significant trade-off effects, as the RBC strategies result in a low relative increase of overall energy and power use and a slight cost reduction compared to the highly insulated buildings. Furthermore, factors that improve the performance of the RBC strategies were found. With OPCS, determining the duration of pre-heating based on the building characteristic improved the results significantly. For SPCS, the choice of applying a fixed SPT during the night due to generally low spot price has significant impacts. By doing this the energy use is considerably reduced at the expense of available shifting capacity during the day. This was found to be especially significant for the highly insulated buildings and the heavy construction modes.

The largest potential for energy and power shifting was found to be with stochastic IHG profiles, which are assumed to be the most realistic representations of occupant behaviour. This indicates that the flexibility potential when utilizing the thermal mass is dependent on the timing of the IHGs, especially in highly insulated buildings. Thus, modelling IHGs according to the current practice might under-estimate the flexibility potential. The aggregated result with 20 different stochastic profiles supports this result. At a building level, the type of radiator control is found to have an impact on the energy and power shifting potential. Yet, the aggregated result with thermostatic radiator control indicates that the more predictable behaviour of proportional radiator control can be used to illustrate the behaviour of several buildings. However, the rebound peak was found to be slightly higher with a proportional controller when several highly insulated buildings were investigated.

The influence of IHGs and control strategies on the bedroom temperatures is larger in the highly insulated buildings. As the IHGs are more significant in milder months, the influence the RBC strategies have on the bedroom temperatures are lower. Decoupling the bedrooms from the RBC strategies improves the temperatures, especially in the colder months, but the potential for offering flexibility is also reduced. To what extent the bedroom temperatures are improved with this strategy is also dependent on the construction type of the building.

7 Further Work

This work could be further enhanced by including the DHW consumption. This way the energy flexibility of the entire heating system could be evaluated. Furthermore, stochastic DWH draw-off profiles based on Norwegian data should be implemented to get more realistic scenarios. When a DHW tank is implemented, the overall grid interaction with realistic load profiles should be evaluated as this would give a holistic view of the complete electricity demand of the building.

The stochastic IHG profiles used in this thesis should be improved by implementing more realistic occupancy profiles. As the current Norwegian TUS data implemented in the stochastic electricity demand model adapted by Rangøy is based on a person selection and not a household selection, this data was challenging to implement in the original demand model Richardson et.al. developed. Therefore, a self-made occupancy schedule was implemented. If or when Norwegian TUS data based on a person selection becomes available, this should be implemented in the Norwegian electricity demand model. This would result in more realistic IHG profiles with stochastic occupancy that would match the load profiles for appliances and lighting generated from the model.

The energy flexibility potential of a neighbourhood has only been evaluated with 20 different IHG profiles for the same building typology. This could be aggregated further with a combination of the different building types. In addition, the stochastic models could be generated for a different number of residents, since it is unlikely that all buildings have four residents. Then various combinations of different IHG profiles and building types could be investigated, which would allow for a more case-specific evaluation of the flexibility potential.

In this thesis, the energy flexibility is only evaluated with a direct electric heating system. This is not assumed to be a common solution in passive house buildings, and therefore evaluations should also be done with a more representative heating system. The heating system could e.g. be a hydronic heating system with a heat pump as this s claimed to be one of the most promising technology in combination with a TES for providing energy flexibility. Also, implementation of a photovoltaic system and/or solar collectors to the building model would be of interest as the energy flexibility potential concerning self-consumption and self-generation could be evaluated. Furthermore, the evaluations of the bedroom temperatures done in this thesis are only considered as a preliminary investigation to evaluate the effects of implementing RBC strategies. Therefore, further investigations with respect to the trade-offs between offering flexibility and occupant preferences regarding thermal zoning of bedrooms should be done.

8 Literature

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Appendix A: Modelling Stochastic Internal Heat Gain Profiles
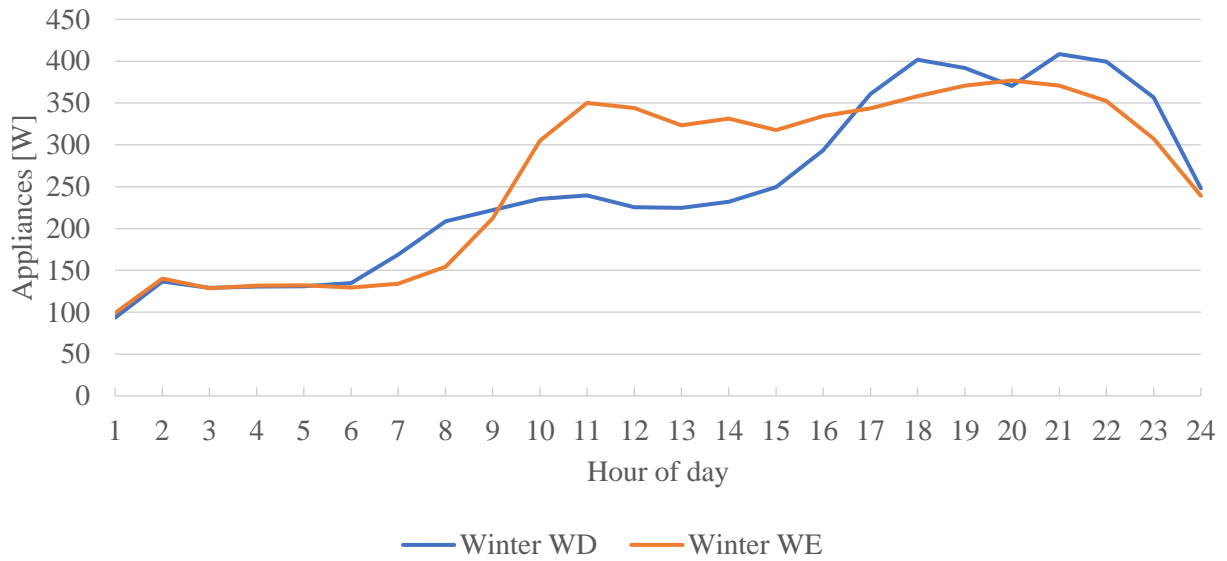
Figure A-1 Average load profile for appliances for the winter months generated from the stochastic model modified by Rangøy with Norwegian input data.
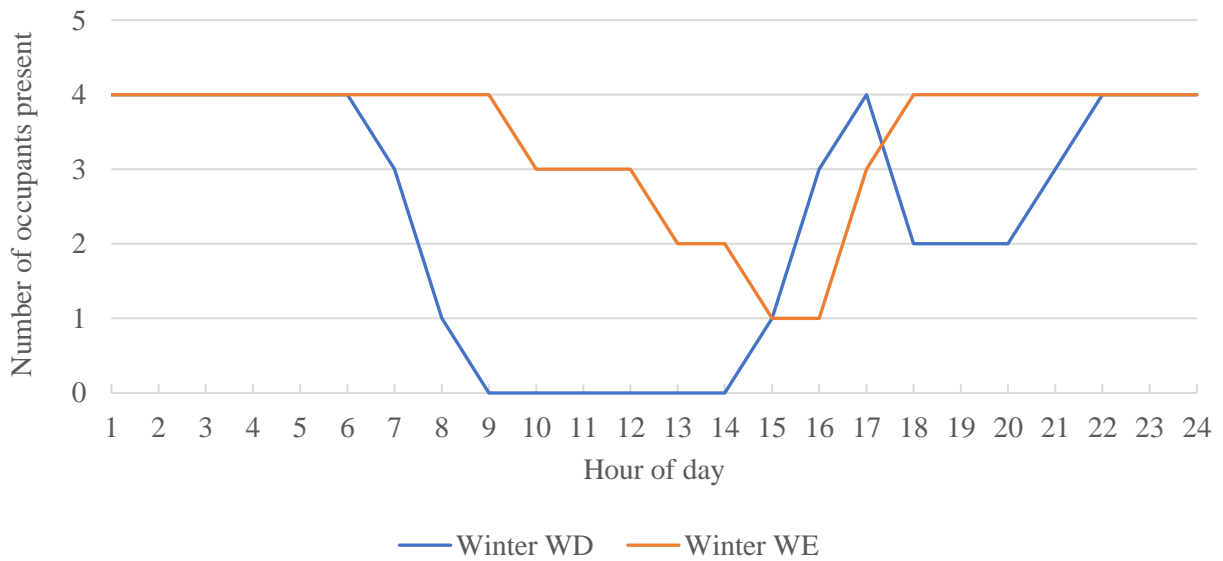
Figure A-2 Occupancy profile in the stochastic IHG profiles for weekdays and weekends in the winter.
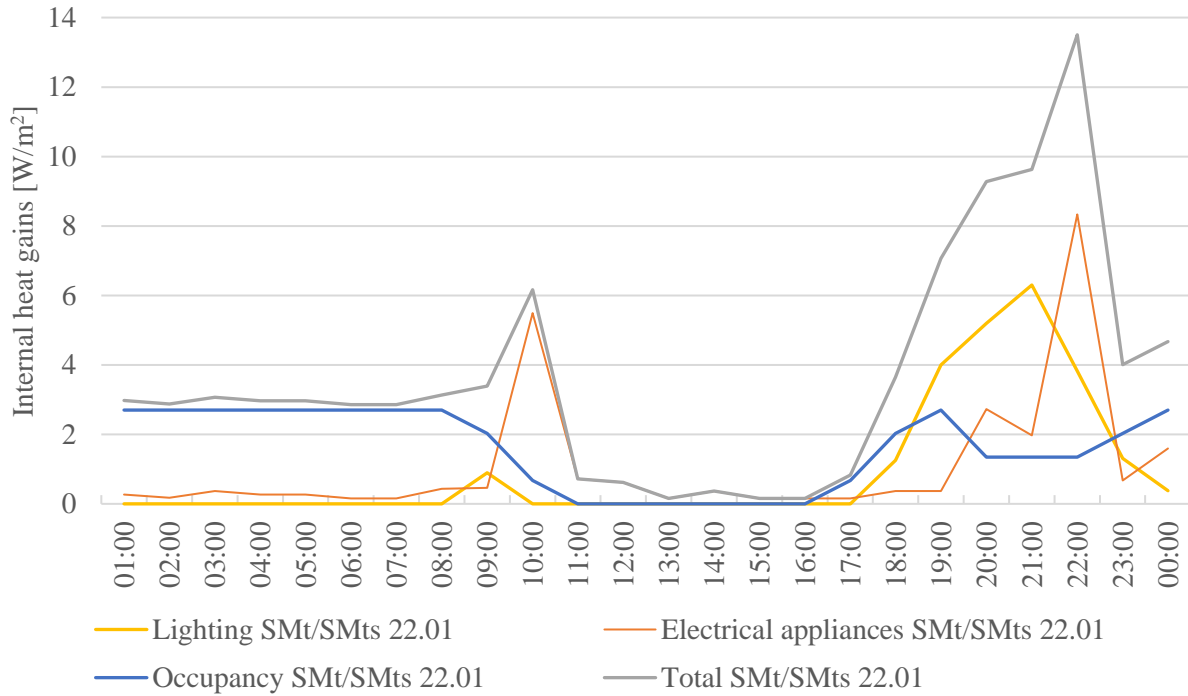
Figure A-3 The stochastic internal heat gains 22nd of January. IHGs from lighting and electrical appliances are retrieved from the stochastic model, occupancy is self-made.
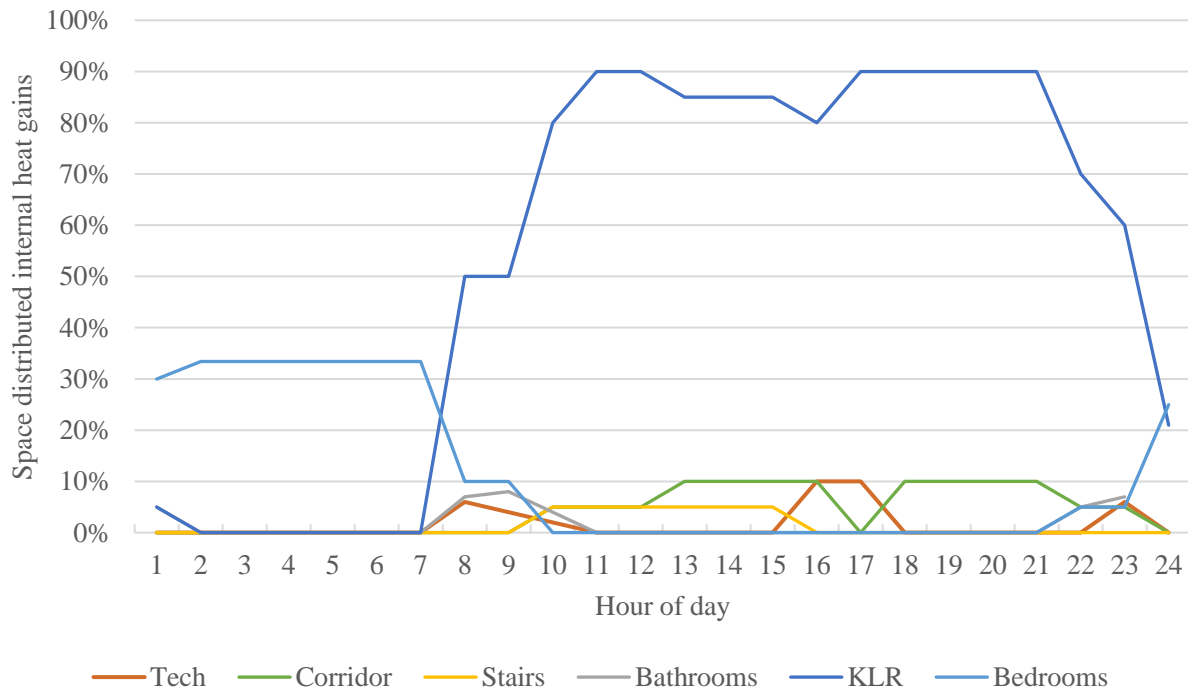
Figure A-4 The daily distribution of the stochastic IHGs to the different zones.

Appendix B: References with Different Internal Heat Gain Profiles

Table B-1 Energy and power performance for the reference simulations with constant SPT of 21 °C for four building types and 4 IHG profiles, with both P-controller (PC) and thermostatic controller (TC).

	TBL		TBH		PHL		PHH	
Total heating Q [kWh/m^2]								
	PC	TC	PC	TC	PC	TC	PC	TC
NS	178.3	177.4	175.2	173.6	16.0	15.3	15.3	14.3
TS	178.1	177.2	175.1	173.4	15.9	14.9	15.3	14.0
SMt	179.4	178.6	176.5	173.6	15.8	15.0	15.1	14.1
SMts	178.9	177.8	176.3	174.8	16.1	15.6	15.2	14.4
Heating during pre-defined peak hours Q$_{ph}$ [kWh/m^2]								
	PC	TC	PC	TC	PC	TC	PC	TC
NS	28.3	27.6	27.8	26.1	2.4	1.8	2.2	1.3
TS	28.1	27.7	27.5	25.7	2.3	1.7	2.1	1.4
SMt	29.6	29.4	29.1	26.1	2.7	2.5	2.4	2.6
SMts	29.6	29.8	29.2	28.7	2.8	3.0	2.6	2.5
Peak power P [W/m^2]								
	PC	TC	PC	TC	PC	TC	PC	TC
NS	76.3	82.9	74.8	82.2	15.2	20.7	13.9	18.5
TS	75.7	82.9	74.1	82.2	14.6	20.7	13.1	18.5
SMt	74.8	82.9	73.4	82.2	16.0	20.7	14.5	18.5
SMts	74.7	82.9	73.3	82.2	15.6	20.7	14.0	18.5
Peak power during pre-defined peak hours P$_{ph}$ [W/m^2]								
	PC	TC	PC	TC	PC	TC	PC	TC
NS	70.9	82.9	69.9	82.2	13.3	20.7	11.8	17.6
TS	70.4	82.9	69.5	82.2	13.1	19.4	11.6	16.9
SMt	73.6	82.9	72.3	82.2	15.6	20.7	14.6	18.5
SMts	72.4	82.9	72.3	82.2	15.3	20.7	14.0	18.5
Cost (spot price) [NOK/m^2]								
	PC	TC	PC	TC	PC	TC	PC	TC
NS	48.5	48.2	47.8	47.1	4.5	4.2	4.3	3.8
TS	48.6	48.3	47.9	47.2	4.6	4.1	4.4	3.8
SMt	49.3	48.9	48.6	47.1	4.7	4.4	4.4	4.2
SMts	49.1	48.8	48.6	48.0	4.8	4.7	4.5	4.3

Appendix C: KPIs with the Different Internal Heat Gain Profiles

Table C-1 Key performance indicators for OPCS and SPCS for the TB building with the four internal heat gain profiles NS, TS, SMt and SMts. Given with both P-control and thermostatic control.

Key Performance Indicator	NS		TS		SMt		SMts	
TBL OPCS								
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.018	1.013	1.017	1.012	1.016	1.009	1.018	1.011
q_{ph}	0.132	0.078	0.133	0.078	0.139	0.082	0.139	0.086
p	1.086	1.000	1.095	1.000	1.107	1.000	1.110	1.000
p_{ph}	0.639	0.868	0.651	0.868	0.741	0.868	0.723	0.868
c	0.996	0.990	0.995	0.988	0.994	0.985	0.995	0.986
TBH OPCS								
Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.019	1.016	1.019	1.017	1.018	1.016	1.018	1.013
q_{ph}	0.067	0.024	0.067	0.024	0.070	0.024	0.078	0.028
p	1.100	1.000	1.109	1.000	1.120	1.000	1.121	1.000
p_{ph}	0.454	0.870	0.515	0.870	0.503	0.870	0.537	0.870
c	0.993	0.990	0.993	0.989	0.991	0.990	0.991	0.984
TBL SPCS								
Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	0.993	0.991	0.993	0.991	0.990	0.988	0.991	0.989
q_{ph}	0.673	0.647	0.668	0.639	0.666	0.632	0.663	0.629
p	1.086	1.000	1.095	1.000	1.107	1.000	1.110	1.000
p_{ph}	1.169	1.000	1.177	1.000	1.127	1.000	1.145	1.000
c	0.974	0.974	0.974	0.973	0.971	0.970	0.971	0.970
TBH SPCS								
Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.003	1.001	1.002	1.002	0.995	1.001	0.997	0.994
q_{ph}	0.599	0.565	0.596	0.573	0.571	0.565	0.570	0.515
p	1.100	1.000	1.109	1.000	1.120	1.000	1.121	1.000
p_{ph}	1.176	1.000	1.182	1.000	1.138	1.000	1.137	1.000
c	0.964	0.963	0.963	0.962	0.949	0.963	0.950	0.945

Table C-2 Key performance indicators for OPCS and SPCS for the PH building with the four internal heat gain profiles NS, TS, SMt and SMts. Given with both P-control and thermostatic control.

PHL OPCS

Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.067	1.066	1.070	1.072	1.070	1.062	1.057	1.041
q_{ph}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
p	1.350	1.000	1.424	1.000	1.297	1.000	1.324	1.000
p_{ph}	0.003	0.000	0.002	0.000	0.076	0.000	0.057	0.000
c	1.033	1.049	1.047	1.061	1.037	1.027	1.011	0.986

PHH OPCS

Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.080	1.079	1.076	1.080	1.080	1.067	1.069	1.053
q_{ph}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
p	1.512	1.136	1.607	1.136	1.455	1.136	1.499	1.136
p_{ph}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
c	1.051	1.064	1.049	1.060	1.043	1.026	1.023	0.987

PHL SPCS

Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.072	1.078	1.080	1.099	1.070	1.075	1.047	1.049
q_{ph}	0.642	0.823	0.644	0.789	0.582	0.608	0.557	0.525
p	1.362	1.000	1.424	1.000	1.297	1.000	1.324	1.000
p_{ph}	1.552	1.000	1.585	1.069	1.326	1.000	1.355	1.000
c	1.024	1.046	1.029	1.066	1.009	1.016	0.980	0.976

PHH SPCS

Key Performance Indicator	NS		TS		SMt		SMts	
	PC	TC	PC	TC	PC	TC	PC	TC
q_{tot}	1.121	1.161	1.119	1.171	1.107	1.136	1.091	1.118
q_{ph}	0.665	0.967	0.663	0.908	0.608	0.546	0.586	0.582
p	1.512	1.136	1.607	1.136	1.455	1.136	1.499	1.136
p_{ph}	1.775	1.197	1.816	1.243	1.455	1.136	1.502	1.136
c	1.042	1.096	1.036	1.092	1.014	1.016	0.995	0.986

Appendix D: KPIs with Aggregated Stochastic IHGs

Table D-1 KPIs for the aggregated result of 20 different SMts profiles with OPCS and SPCS for the TBH and PHH.

Key Performance Indicator	TBH		PHH	
	OPCS	SPCS	OPCS	SPCS
q_{tot}	1.012	0.951	1.052	1.119
q_{ph}	0.028	0.522	0.000	0.577
p	1.018	1.018	1.291	1.291
p_{ph}	0.916	1.053	0.000	1.291
c	0.983	0.912	0.985	0.987
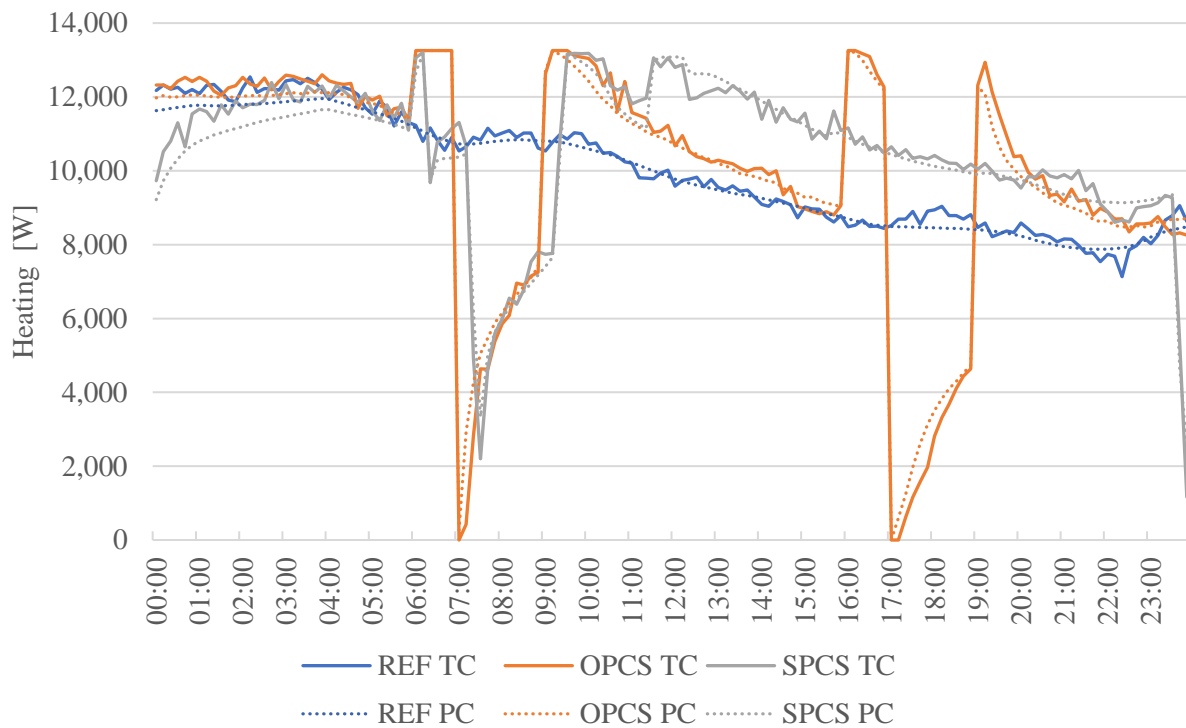
Figure D-1 TBL: Average power consumption of the 20 SM_{ts} profiles with thermostatic controller (TC) compared with P-controller (PC). Given for one cold day with REF, OPCS and SPCS.

Appendix E: Parametric Study
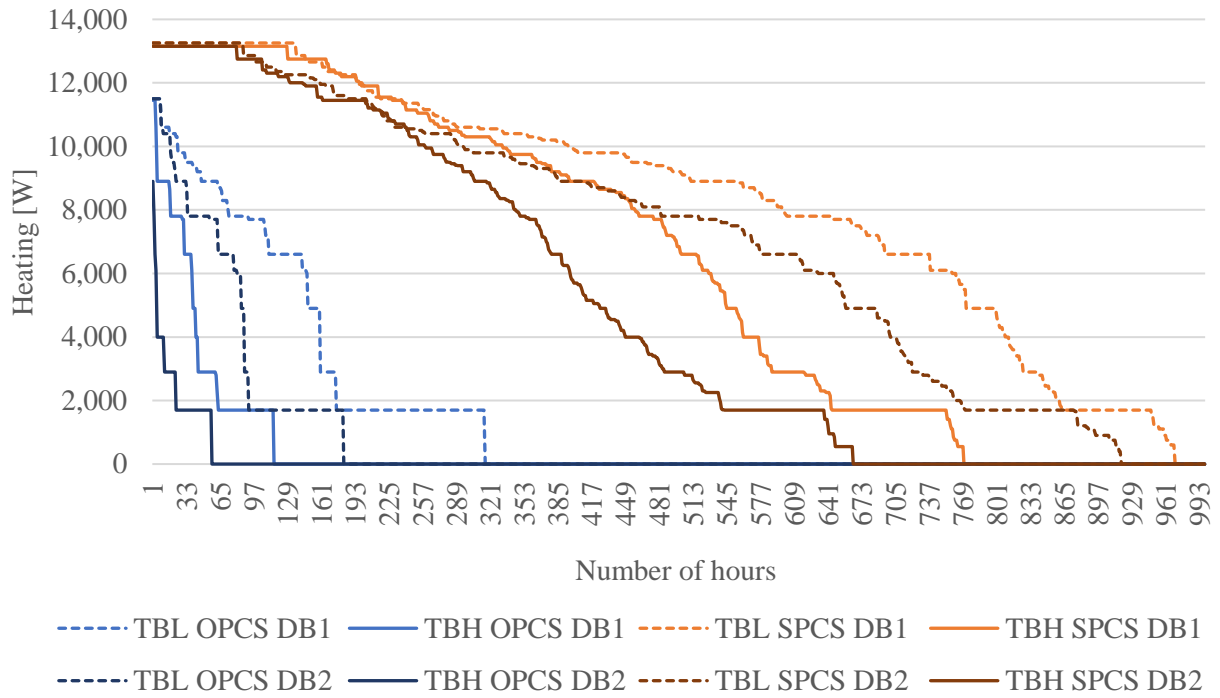
Figure E-1 The peak power occurring in the peak hours for TBL and TBH with OPCS and SPCS with a DB of 1 °C and 2 °C, sorted.

Appendix F: KPIs for the Parametric Study

Table F-1 TB: KPIs with a deadband of 2 °C compared to 1 °C with OPCS and SPCS. (TS IHGs, thermostatic controller).

Key Performance Indicator	TBL		TBH		PHL		PHH	
	OPCS	OPCS$_{db2}$	OPCS	OPCS$_{db2}$	OPCS	OPCS$_{db2}$	OPCS	OPCS$_{db2}$
q_{tot}	1.012	1.015	1.017	1.015	1.072	1.037	1.080	1.021
q_{ph}	0.078	0.057	0.024	0.008	0.000	0.000	0.000	0.000
p	1.000	1.000	1.000	1.000	1.000	1.082	1.136	1.136
p_{ph}	0.868	0.868	0.870	0.677	0.000	0.000	0.000	0.000
c	0.988	0.988	0.989	0.980	1.061	1.006	1.060	0.892
Key Performance Indicator	TBL		TBH		PHL		PHH	
	SPCS	SPCS$_{db2}$	SPCS	SPCS$_{db2}$	SPCS	SPCS$_{db2}$	SPCS	SPCS$_{db2}$
q_{tot}	0.991	0.991	1.002	1.008	1.099	1.131	1.171	1.248
q_{ph}	0.639	0.628	0.573	0.529	0.789	0.734	0.908	0.606
p	1.000	1.000	1.000	1.000	1.000	1.082	1.136	1.136
p_{ph}	1.000	1.000	1.000	1.000	1.069	1.244	1.243	1.136
c	0.973	0.972	0.962	0.958	1.066	1.055	1.092	1.021

Table F-2 KPIs for the parametric study with changed pre-heating period for OPCS, along with the KPIs from the original OPCS with a pre-heating of 1 hour. (TS IHGs, thermostatic controller).

Key Performance Indicator	TBL		TBH		PHL		PHH	
	OPCS	OPCS$_{ph2}$	OPCS	OPCS$_{ph2}$	OPCS	OPCS$_{ph0.5}$	OPCS	OPCS$_{ph0.5}$
q_{tot}	1.012	1.038	1.017	1.044	1.072	1.026	1.080	1.029
q_{ph}	0.078	0.055	0.024	0.018	0.000	0.000	0.000	0.000
p	1.000	1.000	1.000	1.000	1.000	1.000	1.136	1.136
p_{ph}	0.868	0.868	0.870	0.787	0.000	1.000	0.000	0.000
c	0.988	1.003	0.989	1.011	1.061	1.000	1.060	0.982

Table F-3 KPIs for the parametric study with and without overruling the SPCS from 23:00-06:00. (TS IHGs, thermostatic controller).

Key Performance Indicator	TBL		TBH		PHL		PHH	
	SPCS	$SPCS_{nor}$	SPCS	$SPCS_{nor}$	SPCS	$SPCS_{nor}$	SPCS	$SPCS_{nor}$
q_{tot}	0.991	1.047	1.002	1.071	1.099	1.352	1.171	1.495
q_{ph}	0.639	0.507	0.573	0.364	0.789	0.274	0.908	0.465
p	1.000	1.000	1.000	1.000	1.000	1.000	1.136	1.136
p_{ph}	1.000	1.000	1.000	1.000	1.069	1.069	1.243	1.243
c	0.973	0.996	0.962	0.976	1.066	1.168	1.092	1.299

Table F-4 KPIs for the parametric study with changed price thresholds for SPCS, along with the KPIs with the original SPCS with a threshold of 25-75 %. (TS IHGs, thermostatic controller)

Key Performance Indicator	TBL			TBH		
	SPCS	$SPCS_{20-80}$	$SPCS_{30-70}$	SPCS	$SPCS_{20-80}$	$SPCS_{30-70}$
q_{tot}	0.991	0.991	0.991	1.002	0.999	1.004
q_{ph}	0.639	0.638	0.639	0.573	0.602	0.582
p	1.000	1.000	1.000	1.000	1.000	1.000
p_{ph}	1.000	1.000	1.000	1.000	1.000	1.000
c	0.973	0.973	0.971	0.962	0.966	0.961
Key Performance Indicator	PHL			PHH		
	SPCS	$SPCS_{20-80}$	$SPCS_{30-70}$	SPCS	$SPCS_{20-80}$	$SPCS_{30-70}$
q_{tot}	1.099	1.079	1.124	1.171	1.137	1.201
q_{ph}	0.789	0.794	0.896	0.908	0.901	1.053
p	1.000	1.000	1.000	1.136	1.136	1.136
p_{ph}	1.069	1.069	1.069	1.243	1.243	1.243
c	1.066	1.052	1.093	1.092	1.059	1.128

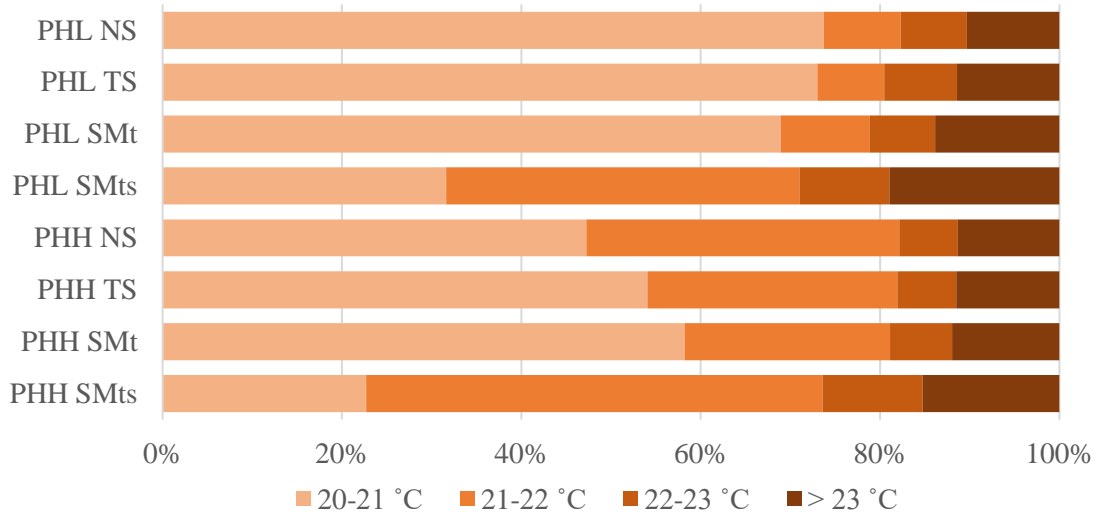# Appendix G: Bedroom Temperatures

Figure G-1 PH: Temperature duration in Bedroom SE in the night (07:00-23:00) in the heating season (Oct.-April) for the references with constant SPT with different internal heat gain profiles.

Table G-1 Change in average operative temperature between 23:00 and 07:00 for the bedroom SE in January and April with OPCS and SPCS.

|	January [°C]											
	TBL			TBH			PHL			PHH		
	REF	OPCS	SPCS	REF	OPCS	SPCS	REF	OPCS	SPCS	REF	OPCS	SPCS
NS	21.7	+0.2	+0.2	21.7	+0.1	+0.1	20.9	+0.1	+0.2	21.0	+0.1	0.0
TS	21.7	+0.2	+0.2	21.7	+0.2	+0.2	20.8	+0.1	+0.2	21.0	+0.1	0.0
SMt	21.7	+0.2	+0.2	21.7	+0.1	+0.1	20.8	+0.1	+0.3	20.9	+0.1	0.0
SMts	21.7	+0.2	+0.3	21.6	+0.1	+0.2	20.9	+0.1	+0.6	20.9	0.0	+0.3
	April [°C]											
	TBL			TBH			PHL			PHH		
	REF	OPCS	SPCS	REF	OPCS	SPCS	REF	OPCS	SPCS	REF	OPCS	SPCS
NS	21.4	0.0	+0.2	21.4	0.0	+0.2	22.5	+0.3	+0.3	22.1	+0.6	+0.6
TS	21.4	0.0	+0.2	21.4	0.0	+0.3	22.6	+0.3	+0.2	22.2	+0.6	+0.6
SMt	21.4	0.0	+0.2	21.4	0.0	+0.2	22.8	+0.3	+0.3	22.2	+0.6	+0.6
SMts	21.3	0.0	+0.3	21.3	0.0	+0.3	23.7	+0.2	+0.2	22.8	+0.4	+0.5
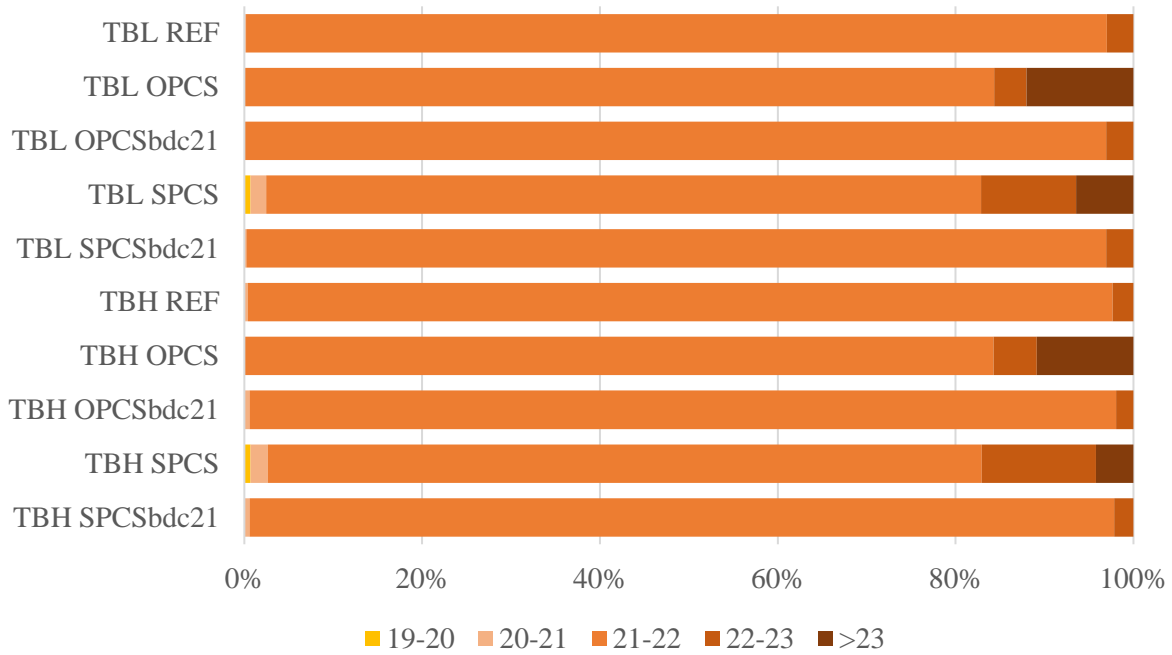
Figure G-2 TB: Time distributed operative temperature at night in Bedroom SE in the heating season for ref. with constant SPT, the original CSs and the CSs with decoupled bedrooms with an SPT of 21 °C.
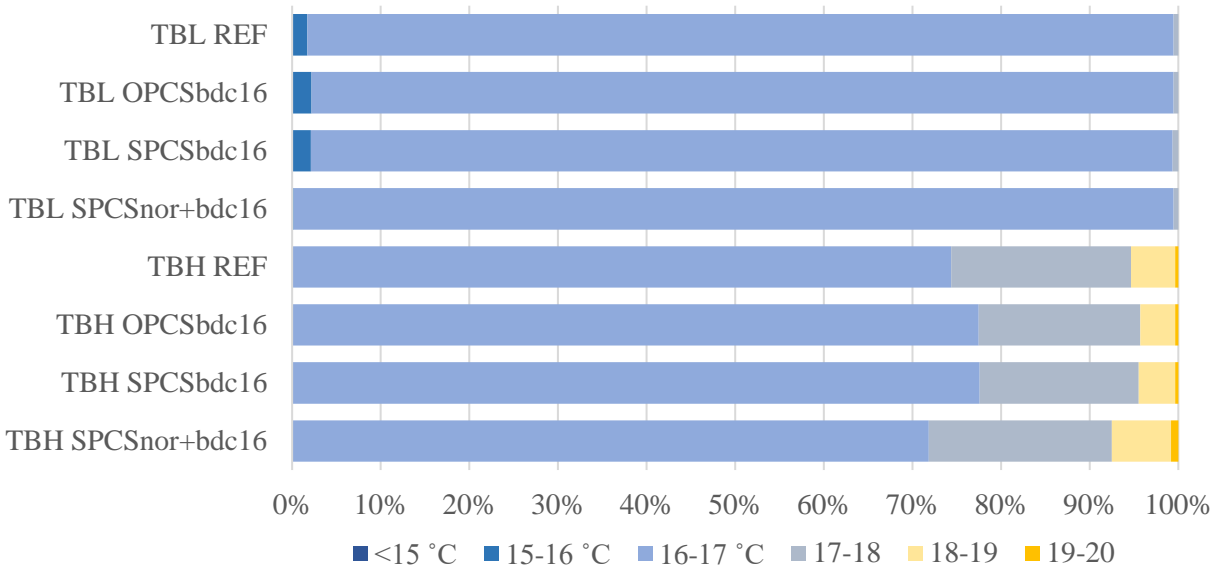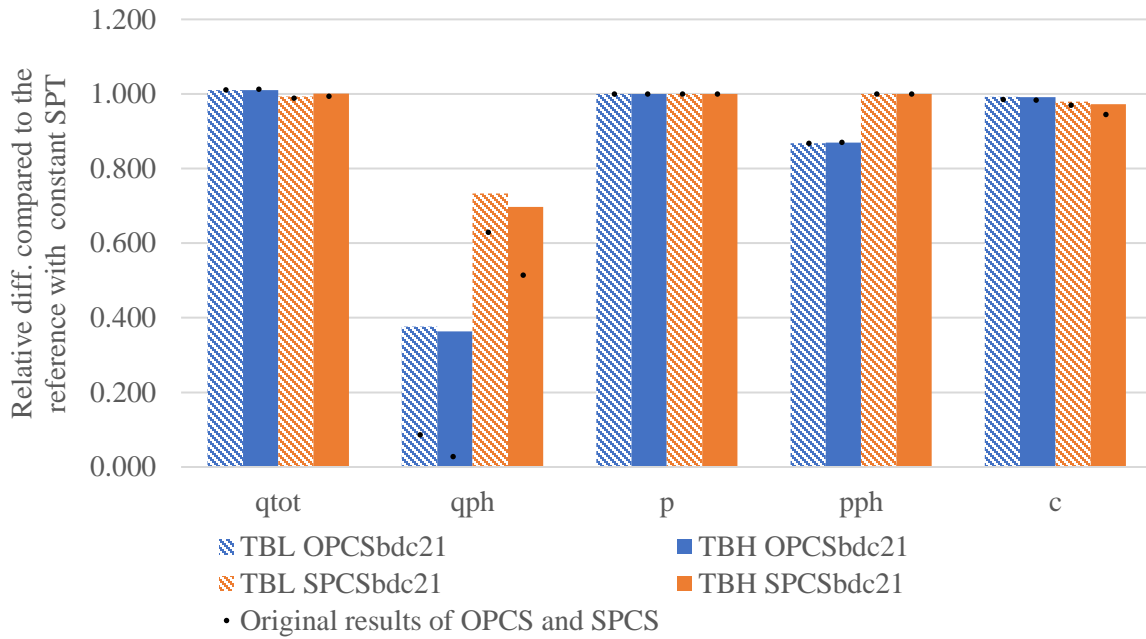

Figure G-3 TB: Time distributed operative temperature at night in Bedroom SE in the heating season for ref. with constant SPT, the original CSs and the CSs with decoupled bedrooms with an SPT of 16 °C.

Figure G-4 TB: Results of the OPCS and SPCS with a constant SPT of 21 °C in bedrooms with SMts. Original results with control strategy in all rooms are marked in black.
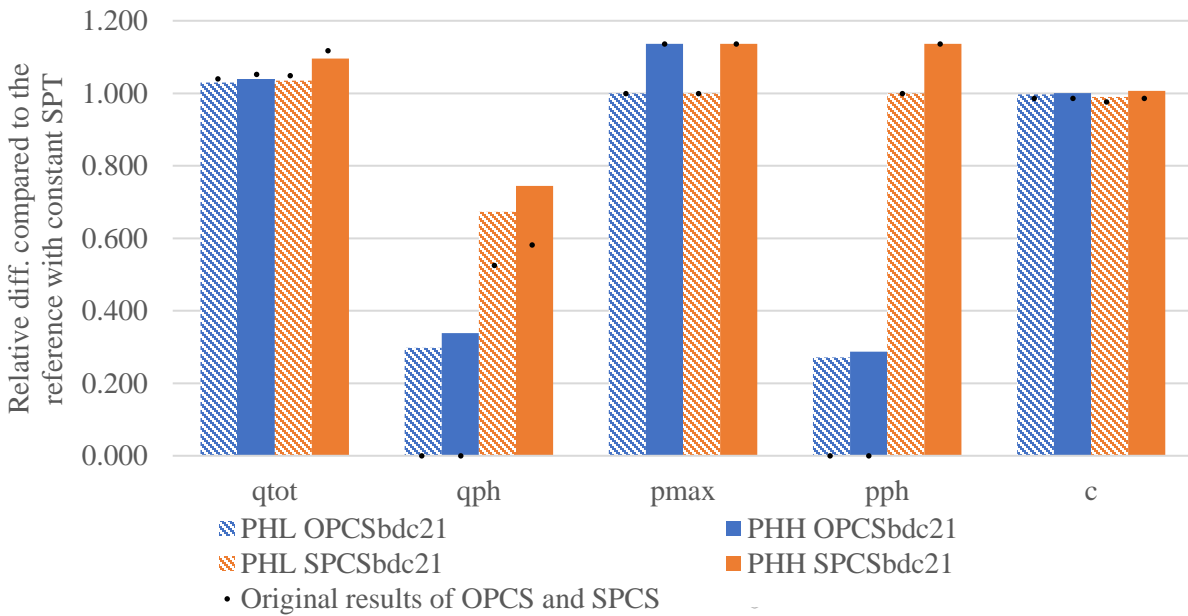

Figure G-5 PH: Results of the OPCS and SPCS with a constant SPT of 21 °C in bedrooms with SMts. Original results with control strategy in all rooms are marked in black.
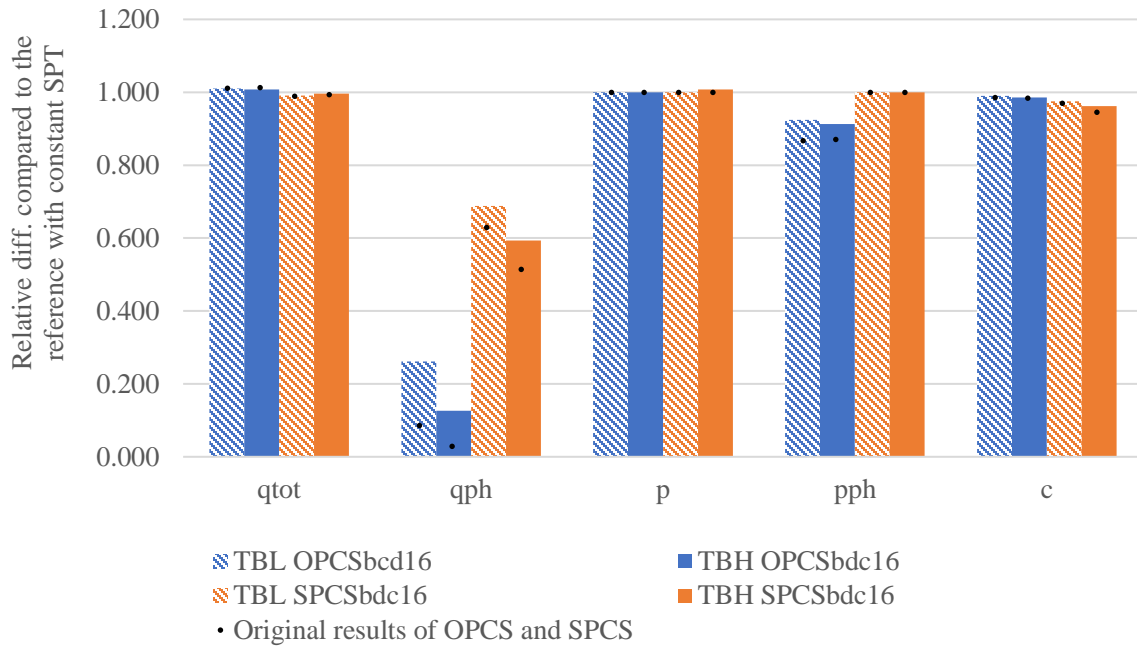
Figure G-6 TB: Results of the OPCS and SPCS with a constant SPT of 16 °C in bedrooms with SMts. Original results with control strategy in all rooms are marked in black.
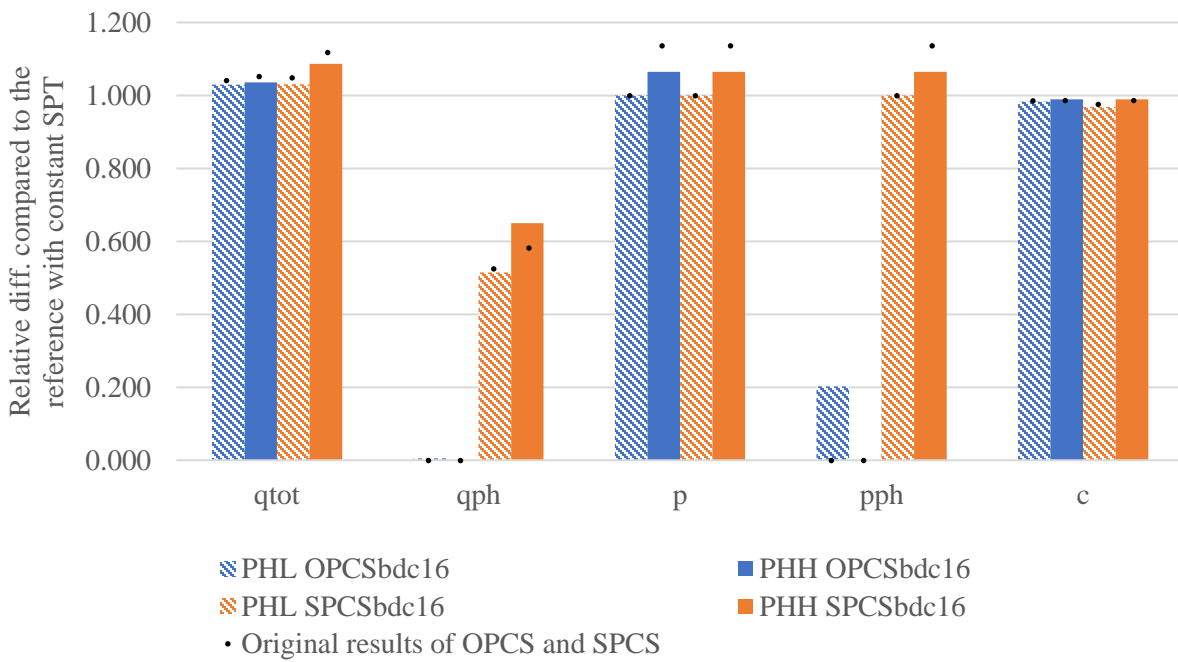

Figure G-7 PH: Results of the OPCS and SPCS with a constant SPT of 16 °C in bedrooms with SMts. Original results with control strategy in all rooms are marked in black.