Predictive Rule-Based Control to Activate the Energy Flexibility of Norwegian Residential Buildings: Case of an Air-Source Heat Pump and Direct Electric Heating

John Clauß[a,*], Sebastian Stinner[a], Igor Sartori[b], Laurent Georges[a]

[a] Norwegian University of Science and Technology, Kolbjørn Hejes vei 1a, 7034 Trondheim, Norway
[b] SINTEF Byggforsk, P.O. Box 124 Blindern, 0314 Oslo, Norway
[*] john.clauss@ntnu.no

Abstract

The building energy flexibility potential of a Norwegian single-family detached house is investigated using predictive rule-based control (PRBC) and building performance simulation (using IDA ICE). Norwegian timber buildings are lightweight and four different insulation levels are considered. Both on-off and modulating air-source heat pumps are analyzed and compared to direct electric heating which is the most common heating system for Norwegian residential buildings. A detailed model for both the heat pump system and the building is implemented, a level of detail not found in previous research on building energy flexibility. The three PRBC investigated have the following objectives: reduce energy costs for heating, reduce annual $CO_{2eq.}$ emissions and reduce energy use for heating during peak hours. This last objective is probably the most strategic in the Norwegian context where cheap electricity is mainly produced by hydropower. The results show that the price-based control does not generate cost savings because lower electricity prices are outweighed by the increase in electricity use for heating. The implemented price-based control would create cost savings in electricity markets with higher daily fluctuations in electricity prices, such as Denmark. For the same reasons, the carbon-based control cannot reduce the yearly $CO_{2eq.}$ emissions due to limited daily fluctuations in the average $CO_{2eq.}$ intensity of the Norwegian electricity mix. On the contrary, the PRBC that reduces the energy use for heating during peak hours turns out to be very efficient, especially for direct electric heating. For air-source heat pumps, the control of the heat pump system is complex and reduces the performance of the three PRBC. Therefore, results suggest that a heat pump system should be modeled with enough detail for a proper assessment of the building energy flexibility. First, by varying temperature set-points there is a clear interaction between the prioritization of domestic hot water and the control of auxiliary heaters which increases energy use significantly. Second, the hysteresis of the heat pump control and the minimum cycle duration prevent the heat pump from stopping immediately after the PRBC requires it. Finally, the paper shows that the influence of thermal zoning, investigated here by cold bedrooms with closed doors, has a limited impact on the building energy flexibility potential and the risk of opening bedroom windows.

Keywords: building energy flexibility, demand response, heat pump, predictive rule-based control, direct electric heating, $CO_{2eq.}$ intensity

1 Introduction

The transition to a sustainable energy system relies on the application of intermittent renewable energy sources. Demand side flexibility is essential to make full use of the electricity generated from intermittent renewable sources [1,2] and it can help balance the power grid and relieve it during grid peak hours [3]. Demand response measures can be applied to control the electricity use in a building depending on signals from the power grid and deploy demand side flexibility [4]. For heating systems in buildings, demand side flexibility can be seen as the margin by which a building can be operated while still fulfilling its functional requirements [5]. Numerous studies have been already conducted on building energy flexibility with focus on the heating system [2,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22]. In these studies, heat pump systems play a major role and the electrification of heating using heat pumps in combination with thermal energy storage has been recognized as a promising measure for increasing the flexibility potential [3,4]. This potential for a heat pump system is dependent on the type of buildings, the type of heat pump and thermal storage as well as the applied control strategy [10]. In the introduction, references are analyzed with respect to building energy flexibility.

Nomenclature

AHU	Air handling unit	*PH*	Passive house
ASHP	Air-source heat pump	*PI*	Proportional-integral
BAU	Baseline / Business as usual	*PMV*	Predicted mean vote
CBR	Closed bedrooms	*PPD*	Predicted percentage of dissatisfied
COP	Coefficient of performance	*PRBC*	Predictive rule-based control
CS	Control strategy	*PV*	Photovoltaic
CSC	Control strategy Carbon	Q_{Aux}	Auxiliary heater
CSP	Control strategy Price	*RTSP*	Reference temperature set-point
CSS	Control strategy Schedule	*RBC*	Rule-based control
DC	Doors closed	*S*	Safety margin factor
DE	Direct electric	*SH*	Space heating
DHW	Domestic hot water	*SP*	Spot price
DOT	Design outdoor temperature	*T*	Temperature
DR	Demand response	*TEK*	Norwegian building regulation
ER	Electric radiator	*TM*	Temperature measurement
FH	Floor heating	*TSP*	Temperature set-point
HP	Heat pump	U_{Total}	Total U-value of the windows including glazing and frame
HPT	High-price threshold		
HTSP	High temperature set-point	*V*	Volume
LPT	Low-price threshold	*w/o*	Without
LTSP	Low temperature set-point	*ZEB*	Zero Emission Building
MHP	Modulating heat pump	η_{HR}	Heat recovery efficiency
MPC	Model-predictive control	φ_{max}	Nominal space heating power, *kW*
n_{people}	Number of persons		
Net-ZEB	Net-Zero Energy Building	*Subscripts*	
OBR	Open bedrooms	*EW*	External wall
OHP	On/off heat pump	*h*	Heating
OTCC	Outdoor temperature compensation curve	*IW*	Internal wall
		max	Maximum
		min	Minimum

Regarding the thermal mass activation, Pedersen et al. [15] use an economic model-predictive control (MPC) to investigate the energy flexibility potential for different building insulation levels. Reynders et al. [6] make use of the structural thermal storage in residential buildings and quantify the energy flexibility in terms of available storage capacity, storage efficiency and power-shifting capacity. The thermal mass of a residential building is also used as short-term storage in the study by Le Dréau and Heiselberg [7]. They model two residential buildings with different insulation levels and quantify their flexibility potential. A flexibility factor is introduced to distinguish between electricity consumption during high-price and low-price hours.

Thermal zoning means that different indoor temperatures are applied to the various rooms in a building. The effect of thermal zoning on building energy flexibility has been investigated in a limited number of studies. In these studies, different temperature set-points (TSP) are defined for so-called day-zones and night-zones, where the TSP for the night zone is slightly lower than the TSP of the day zone [17,23,24]. Nevertheless, in other simulation studies, a single indoor temperature is considered for an entire dwelling. In Scandinavia, research nonetheless showed that many people prefer cold bedrooms which could limit the energy flexibility potential [25] with thermal mass activation. Berge et al. [26] conducted long-term measurements in highly-insulated apartments in Norway in combination with occupant surveys and found that extensive window opening was common to reach the desired lower temperatures in bedrooms. A limited number of papers has investigated the influence of the building insulation level (including partition walls), building thermal mass and the control of the heating and ventilation systems on the thermal zoning and the corresponding space heating (SH) needs [27,28,29].

The control of the heating system of a building is essential for deploying its energy flexibility potential. Even though MPC has been found to outperform non-optimal control strategies, MPC is more computationally expensive and more complex, essentially because a low-order model of the system to be controlled is required [10]. Compared to MPC, rule-based control (RBC) is based on a set of predefined rules to control the system. RBC is more straightforward to implement than MPC as it does not require a control model. Nevertheless, a careful design of the control rules is essential, which is not always obvious. RBC can be based on the prediction of the future boundary conditions, such as the hourly electricity price. It is then termed predictive rule-based control (PRBC). Fischer et al. [10] found that PRBC can be a promising alternative to MPC as it is simpler and still effective (providing the control rules are well defined). Several relevant studies confirmed that PRBC can decrease the energy costs for the building operation [18,30,31,32,33,34,35]. In order to define the PRBC rules, Georges et al. [36] introduced a lower and upper price threshold so that energy is stored during low-price periods and energy use is lowered during high-price periods. Alimohammadisagvand et al. [30] successfully implemented a price-based PRBC to control the thermal energy storage of a residential building heated by a ground source heat pump. Fischer et al. [32] used PRBC for scheduling the heat pump operation depending on predictions of the electricity price, PV generation and thermal loads of the building. Here, the heat pump was either run at times of high PV generation to maximize the PV self-consumption or at times of minimum electricity prices to charge the storage tank of the heat pump system. Dar et al. [33] investigated the energy flexibility of a Net-ZEB heated by an air-source heat pump. They concluded that the peak power can be reduced significantly with a well-tuned RBC. Regarding modulating heat pumps, MPC and RBC are significantly different. Most studies using MPC assume that the compressor power can be directly controlled which ignores the details of the built-in PI control of the heat pump. RBC rather adjusts the set-point to this PI controller.

In general, different objectives can be targeted in the context of building energy flexibility (either by using MPC or RBC). Besides reducing the energy costs, maximizing the use of renewable energy sources, increasing the self-consumption of the on-site PV generation and limiting the peak power are frequently discussed [5]. De Coninck et al. [37] increased the use of on-site renewable energy by controlling a heat pump by means of the power injection to the grid or overvoltage at the grid connection of the buildings. Vanhoudt et al. [8] investigated an actively-controlled heat pump and successfully limited peak power demands and maximized self-consumption of the on-site electricity generation. Vandermeulen et al. [38] controlled the heat pump in a Belgian residential building to maximize the electricity when there was a high level of renewable energy generation in the power grid. Hedegaard et al. [16], Pedersen et al. [15] and Knudsen et al. [39] minimized the emissions of carbon dioxide ($CO_{2eq.}$) related to the SH in Danish residential buildings. Knudsen et al. [39] found that in Denmark the electricity spot price and $CO_{2eq.}$ intensity of the electricity mix (also called the $CO_{2eq.}$ factor) are not strongly correlated. Thus, a control focusing on minimizing the energy costs for SH would not automatically minimize the related $CO_{2eq.}$ emissions.

As already mentioned, many studies consider heat pump systems as key technology for building energy flexibility. Nevertheless, studies which resort to a detailed modeling of the heat pump system consider a simplified building model (such as low-order resistance capacitance models) or do not consider the thermal mass activation [21,32]. On the contrary, existing studies with a detailed building model resort to a simplified model for the heat pump system. To the authors` knowledge, no study considers a detailed modeling for both the heat pump system and the building, which is done in this work.

This study investigates the energy flexibility potential of Norwegian residential buildings by controlling their heating system using PRBC. It considers the activation of the building thermal mass and a water storage tank. The performance of an air-to-water heat pump and direct electric heating is compared. The paper answers four original research questions:

- Q1: *What is the energy flexibility potential of PRBC in the specific context of Norway?* To answer this question, this study considers different building insulation levels starting from old building standards to Norwegian Passive Houses (PH) and Zero Emission Buildings (ZEB). Norwegian houses are mostly heated using direct electricity, meaning electric radiators for SH and an electric resistance in a storage tank for the domestic hot water (DHW) production [40]. Nevertheless, for buildings with enough insulation, heat pumps are also a popular solution. In Norway, buildings are typically lightweight timber constructions and most of the electricity in the power grid is generated by hydropower [41].

- Q2: *How does the thermal zoning impact the energy flexibility potential?* This problem has been addressed in a very limited number of studies only [17,23,24], whereas most studies assume the same indoor temperature in all the rooms of the building, including bedrooms. Nevertheless, it has been proven that many Norwegians like cold bedrooms (< 16 °C) and may open windows for several hours a day to reach the desired bedroom temperature. The risk of flushing the heat stored in bedrooms is more important with increasing insulation levels. It is thus important to determine how the thermal mass activation using PRBC influences bedroom temperatures.

  Q3: *How does the modeling complexity of the heat pump system influence the operation of the heating system and thus the energy flexibility potential?* Most of the studies found in the literature are based on simulations using models that significantly simplify the heat pump system for one or several of the following aspects: (1) the heat pump is not able to modulate or, on the contrary, it modulates perfectly between 0 and 100%; (2) minimum cycle durations and pause times are not used with the heat pump; (3) the storage tank is simplified by neglecting either thermal stratification or the details of the connections to the tank as well as the exact location of the temperature sensors in the tank; (4) the control of the auxiliary heater is idealized.

  Here, a detailed modeling of the heat pump system has been implemented in the detailed dynamic simulation software IDA Indoor and Climate (IDA ICE) to answer this question. To the authors` knowledge, this level of modeling detail for both the heat pump system and the building has not been proposed in the literature regarding building energy flexibility. Regarding the modeling of the heat pump system, the air-source heat pump (ASHP) is able to modulate continuously between 30% and 100%. It has an imposed minimum cycle and pause time and a realistic control to prioritize DHW over SH. The heat pump is connected to a detailed model of a storage tank with a realistic control of the auxiliary heaters. Even though the models for each component of the heat pump system (i.e. the heat pump, the tank or the SH distribution systems) are not the most sophisticated, the interaction between components and their control is particularly comprehensive.
- The proposed level of detail enables to answer a supplementary question. Q4: *How does PRBC influence the operating conditions of the heat pump in terms of duration and frequency of cycles as well as the seasonal performance factor*?

An indirect control is performed, meaning that a control (or penalty) signal from the grid is used as input to the PRBC to schedule the temperature set-point for the SH and DHW systems. These changes of temperature set-points enable heat to be stored in the thermal mass of the building or in the storage tank (for DHW but also for SH in the case of the ASHP). Three different control strategies are investigated to meet the specific objectives: (1) decrease the energy costs for heating using the day-ahead spot price for electricity as the input control signal [42], (2) decrease the $CO_{2eq.}$ emissions related to heating using the hourly $CO_{2eq.}$ intensity of the Norwegian electricity mix as input control signal and (3) decrease electricity use for heating during typical peak hours for Norwegian residential buildings [43].

The paper is organized as follows. Section 2 provides an overview of the methodology and a detailed description of the building as well as its heating and control systems. Demand response controls are defined in Section 3 while Section 4 introduces the key performance indicators. Results are presented and discussed in Section 5.

2 Methodology and test case

As this work involved detailed modeling a comprehensive description of the building and its heating system is necessary. Therefore, a real building is used as a test case for our investigations. Even though this case is specific, it has been selected as representative for Norway and provides enough technical information to build a reliable simulation model of the heat pump system.

The Living Lab is a ZEB residential building with a heated area of 105 m² located on the Gløshaugen campus in Trondheim (Norway). The building floor plan is shown in Fig. 1. Common rooms consist of the Living Room, Kitchen and the Living Room North. Detached single-family houses represent a large share of the Norwegian building stock. The building has a highly-insulated envelope and a lightweight timber construction [44]. SH and DHW production is performed by a heat pump and solar thermal collectors connected to a single storage tank. This is a common heating strategy applied in Norwegian ZEB, see e.g. [45]. The on-site electricity generation from photovoltaic panels is designed to compensate for the $CO_{2eq.}$ emissions embodied in the building materials as well as for emissions generated from the operational phase over the complete building lifetime. The climate of Trondheim is also relevant for Norway in general.

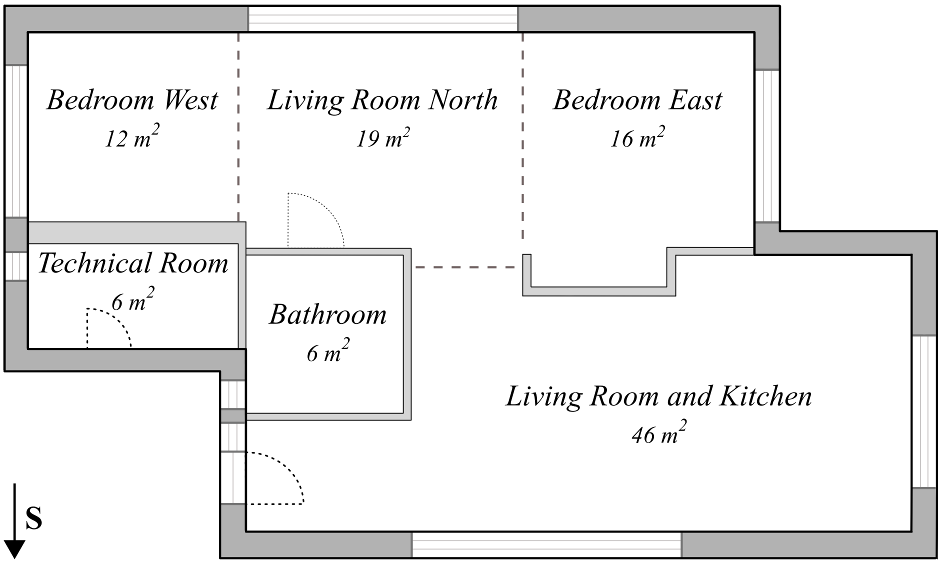

Fig. 1. *Floor plan of the studied building.*

A detailed multi-zone model of the Living Lab has been created using the software IDA ICE version 4.8. IDA ICE is a dynamic building simulation software which applies equation-based modeling [46]. It allows investigation of the detailed dynamics of the components of the energy supply system and enables the user to evaluate the indoor climate as well as the energy use of a building. IDA ICE has been validated in several studies [47,48,49,50,51].

Starting from a detailed model of the ZEB Living Lab, a sensitivity analysis can be performed to investigate the impact of building parameters on the energy flexibility potential. First, the influence of the thermal performance of the building envelope is investigated, here by changing the insulation levels. Second, both on-off and modulating heat pumps are both considered as well as the use of direct electric heating. The potential of energy flexibility is investigated by comparing three different PRBC to the reference scenario which applies constant temperature set-points for SH and DHW.

As the weather- and grid-related data are correlated (such as the spot price and $CO_{2eq.}$ intensity), historical data from 2015 have been used for simulations.

2.1 Building envelope

Four different performance levels of the building envelope are investigated; here, these are termed the building insulation levels. In addition to the PH and ZEB levels, the requirements of two older Norwegian building regulations, TEK87 and TEK10, are considered. For each performance level, Table 1 provides an overview of their thermal characteristics taken from [52].

Except for the TEK87, all the building insulation levels require balanced mechanical ventilation. The air handling unit (AHU) has a rotary heat wheel with heat recovery effectiveness (η_{HR}). According to the building regulations, the constant air volume ventilation has a nominal airflow rate of 120 m^3/h. Natural ventilation was usually applied in TEK87 buildings. For the sake of the simplicity, natural ventilation is modeled as balanced mechanical ventilation with a η_{HR} of 0%.

For the ZEB insulation level, the multi-zone IDA ICE model of the building envelope heated by an electric radiator has been calibrated with measurement data from a dedicated experiment conducted in April and May 2017 [53]. It was found that the model correctly predicted the short-term thermal dynamics of the building and the temperature differences between rooms [54].

Table 1. *Summary of building envelope properties and energy system characteristics for different building insulation levels (EW – external wall, IW – internal wall, HR – heat recovery, U_{Total} is the total U-value of the windows including the glazing and the frame).*

Component	**Parameter**	**Unit**	**Building insulation type**			
			PH	**ZEB**	**TEK10**	**TEK87**
Building envelope	U_{EW}	W/(m²·K)	0.10	0.16	0.22	0.35
	U_{IW}	W/(m²·K)	0.34	0.34	0.34	0.34
	U_{Roof}	W/(m²·K)	0.09	0.11	0.18	0.23
	U_{Floor}	W/(m²·K)	0.09	0.10	0.18	0.30
Infiltration		ACH	0.6	0.7	2.5	3.0
Thermal bridges		W/(m²·K)	0.03	0.045	0.03	0.05
Windows	U_{Total}	W/(m²·K)	0.8	0.8	1.2	2.1
AHU	η_{HR}	%	85	85	70	0
Heat pump	Q_h (A7/W35)	kW	5.1	5.1	5.1	-
	COP	-	4.57	4.57	4.57	-
Water tank	DHW	l	215	215	215	215
	SH	l	243	275	382	-
	$Q_{Aux,DHW}$	kW	3	3	3	-
	$Q_{Aux,SH}$	kW	9	9	9	-
Heat distribution system	FH	W/m²	40	45	78	-
	El. Radiator	W/m²	40	45	78	93
Solar thermal	Collector Area	m²	-	4	-	-
SH needs		kWh/m²	34	48	91	172

2.2 Heating system

Two different heating systems have been considered. First, an ASHP is connected to a water storage tank used for both SH and DHW. For the ZEB insulation level, the heat pump is assisted by 4 m² of solar thermal collectors (in line with the most common concepts of Norwegian ZEB). With the ASHP, the SH distribution is performed using floor heating (FH). The peak and back-up heating is done by electric resistances. The layout of the heat pump system is presented in Fig. 2. Second, the building is heated by direct electricity, meaning electric radiators for SH and a resistance in a storage tank for DHW.

2.2.1 Power sizing

The heat pump is sized according to "bivalence point" principle, which is recommended by heat pump manufacturers [55,56,57]. For a design outdoor temperature (DOT) of -19 °C, the ZEB has a nominal SH power (φ_{max}) of 3.6 kW, whereas the DHW heating power is 1.4 kW. The selected heat pump is a Hoval Belaria SRM 4 [58] working in bivalent mono-energetic mode at low outdoor temperatures [55]. The heat pump power has been selected for a bivalence outdoor temperature of about -9 °C. In that way, the heat pump is able to modulate between 30% and 100% for outdoor air temperatures between 5 °C and -9 °C. This temperature range represents most of the SH season in Trondheim. This leads to a nominal capacity (A7/W35) of 5.1 kW (COP 4.57) for the ZEB case. As smaller heat pumps are difficult to find on the market, the same heat pump capacity is used for the PH case. For the sake of the simplicity, the same power is also applied for the heat pump in the TEK10 case. Even though the φ_{max} of the TEK10 building is 5.6 kW, it can still be supplied by the selected heat pump, the ASHP is just operated more often at a full speed. On/off auxiliary heaters are installed at the top layer of the SH and DHW parts of the tank to ensure that the required water distribution temperatures are always met. The auxiliary heater in the DHW tank has a capacity of 3 kW, whereas the auxiliary heater for the SH tank has a capacity of 9 kW [59]. The capacities of both auxiliary heaters are chosen according to the manufacturer data of the storage tank which is installed in the ZEB Living Lab.

2.2.2 Heat pump system

The heat pump system is introduced first. The FH system consists of seven circuits with at least one circuit per room. The nominal SH power of each room is calculated for a DOT of -19 °C in order to determine the nominal power of each floor heating circuit. This power is adjusted for each building insulation level. The FH supply temperature is adapted using an outdoor temperature compensation curve (OTCC).

The modeling of the components is not the most detailed but the modeling of the interaction between components and their control is particularly comprehensive. Several studies [60,61,62] provide detailed descriptions of the heat pump model which is embedded in IDA ICE. The heat pump model is steady-state with a heat exchanger model for the condenser and evaporator as well as a correction for part load operation. The model parameters are calibrated using manufacturer data at full load [63] according to the methodology reported by Niemelä et al. [61]. The water in the SH tank is heated when flowing through the heat pump condenser (i.e. a direct connection). The heat pump can reach a desired supply temperature either by (1) running the heat pump at full load and adjusting the water flow rate of the circulation pump or by (2) running the circulation pump at nominal speed and adjusting the heat pump compressor speed. In SH mode, the mass flow is constant and a PI control adjusts the compressor power to reach a temperature set-point measured in the SH storage tank. Parameters of the PI control are tuned using SIMC tuning rules (Skogestad Internal Model Control) [64]. Regarding DHW, the heat pump is first operated at full load and the mass flow is adjusted by a P-controller in order to meet a given temperature set-point at the outlet of the condenser. As soon as the circulation pump runs at full speed, the heat pump compressor speed is adjusted. The heat pump is connected to the DHW tank through a heat exchanger. Then, the supply temperature of the heat pump is slightly higher than the temperature set-point in the DHW storage tank. In this study, the default heat pump model in IDA ICE (called ESBO plant) has been extended in to order to account for additional physical phenomena. First, the heat pump modulates continuously between 30% and 100% of the nominal compressor capacity while it cycles on-off below 30%. Second, a minimum run and pause time has been implemented (here taken at 10 minutes) in order to prevent on-off cycling from occurring too frequently. Third, a realistic prioritization of the DHW over the SH production is implemented so that the heat pump cannot support SH when producing DHW. Few studies about building energy flexibility considered DHW prioritization (e.g. [17]). All these three actions require supplementing an anti-windup to the PI control in order to prevent the saturation of the integral action.

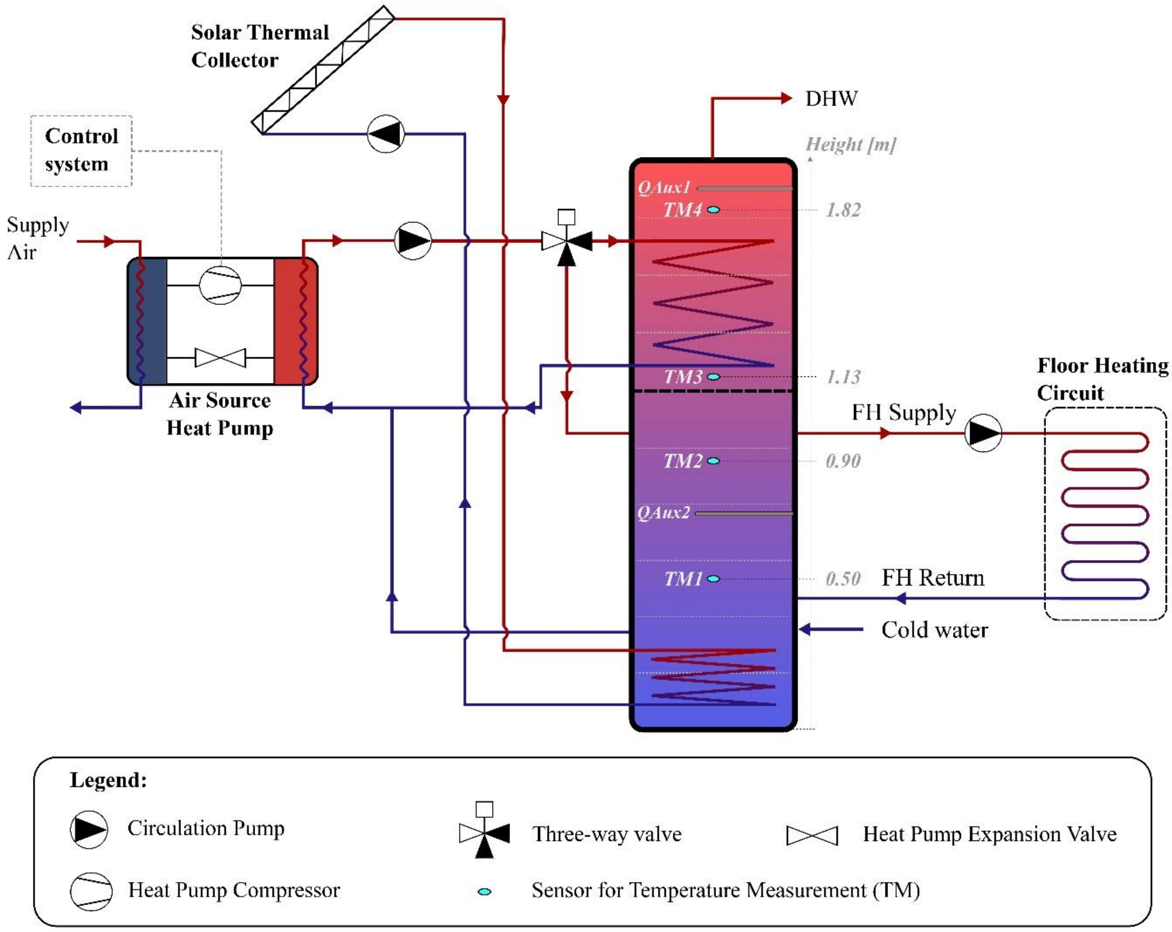

***Fig. 2.** Configuration of the heating system in the ZEB case.*

Furthermore, it is worth mentioning that the DHW prioritization and the minimum run and stop times may lead to the violation of the temperature set-points for SH. Then, auxiliary heaters have to compensate. To the author`s knowledge, these physical effects have hardly been taken into account in other studies.

IDA ICE has a one-dimensional model of a stratified tank that accounts for the heat conduction and convection effects in the tank. The storage tank is divided into ten horizontal layers: the DHW part consists of the four upper layers and the SH part of the six lower layers. The required DHW storage volume is dependent on the number of people and on a safety margin S, which is set to 125% for a low number of people [65]. The storage volume for DHW is calculated by:

$$V_{DHW} \cong S \cdot 65 \cdot n_{people}^{0.7} \qquad [l] \tag{1}$$

The dimensioning of the SH buffer tank is not only dependent on the type of heat pump and its power but also on the temperature of the heat distribution system as well as the thermal inertia of the building. According to [65], the recommended storage volume for SH is:

$$V_{SH} \cong 81.54 + 53.8 \cdot \varphi_{max} \qquad [l] \tag{2}$$

Following Eqs. (1) and (2), the storage volume for DHW tank is kept constant for all building insulation levels while the volume for SH is adapted for each case (as φ_{max} changes). Even though the overall tank volume changes, the same aspect ratio of the water storage tank is kept as well as the relative position of the connection to the tank in order to maintain similar stratification effects.

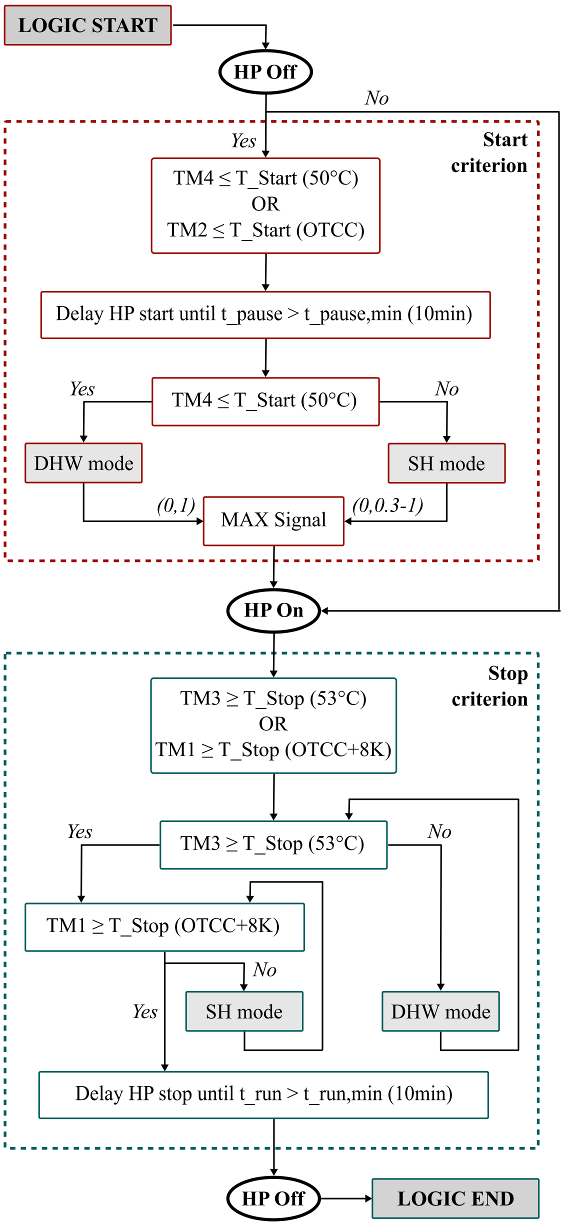

Fig. 3. *Principle of the temperature-based heat pump control.*

The operation of the heat pump as well as both auxiliary heaters is based on measured water temperatures in the tank. The principle of heat pump control is presented in Fig. 3. There are four temperature sensors in the water tank. Each part of the tank (i.e. the DHW and SH parts) has two sensors to control their charging. The heat pump is started as soon as the temperature in the upper layer of the respective tank part drops below a certain set-point. It runs until the set-point for the sensor in the lower layer of the tank part is reached. For the reference control scenario, called BAU (business-as-usual), the temperature set-points to start and stop DHW heating are set to 50 °C and 53 °C, respectively. The temperature set-points for the SH tank vary as a function of the OTCC. The stop criterion of the SH hysteresis is set to OTCC + 8 K. A hysteresis of 8 K gives enough storage to prevent the heat pump from cycling too frequently, even during mild outdoor temperatures (and thus low OTCC), but a large dead-band leads to reduced energy efficiency.

With a bivalent heat pump system, the control of the auxiliary heaters should be clearly defined as the auxiliary heater operation can have a strong impact on the total electricity use for heating [21,66]. The temperature set-points of both electric auxiliary heaters are set 3 K below the start temperature of the heat pump. In that way, the heat pump is started when the temperature drops below a certain threshold. If the heat pump cannot cover the heat demand and the tank temperature continues to decrease, the auxiliary heater eventually starts. The auxiliary heaters are controlled by a thermostat with a dead band of 4 K.

2.2.3 *Direct electric heating*

An electric resistance heater with a power of 3 kW is used for DHW heating whereas electric radiators are used for SH. One electric radiator is placed in each room with a power equal to the nominal SH power of the room.

2.3 *Boundary conditions*

The heat gains from electrical appliances, occupants and lighting are 17.5, 13.1 and 11.4 kWh/(m^2·year) respectively, according to Norwegian technical standard, SN/TS 3031:2016 [67]. Schedules for electrical appliances are based on SN/TS 3031:2016, whereas the schedules for occupancy and lighting are taken from prEN16798-1 and ISO/FDIS 17772-1 standards [68,69]. The internal gains are uniform in space. The hourly profiles over a day are presented in Fig. 4. The occupancy profiles are treated as deterministic daily profiles [68], where 0 means absence and 1 full presence. A fraction of 0.5 means that the building reaches 50% of full occupancy. The daily profile for DHW consumption is taken from SN/TS 3031:2016 [67], see Fig. 4., with an annual energy use of 25 kWh/(m^2·year). All profiles have an hourly resolution and are applied for every day of the year.

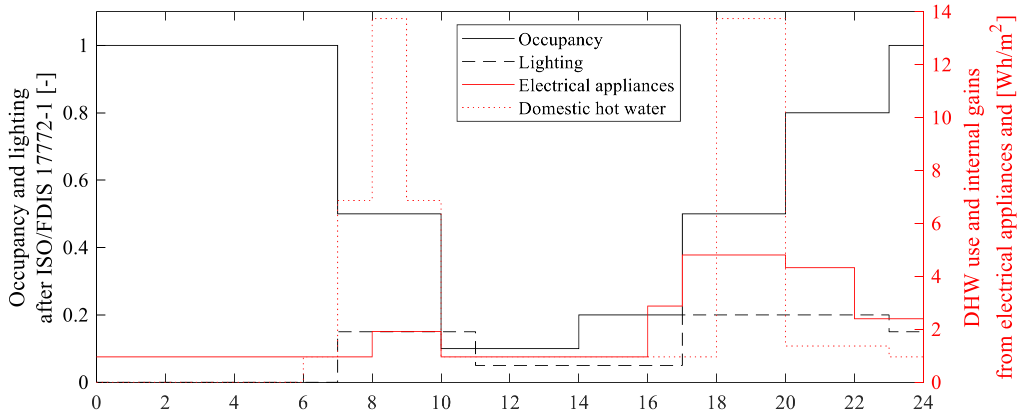

Fig. 4. *Daily profiles for DHW use and internal heat gains from electrical appliances, occupancy and lighting*.

Using the Predicted Mean Vote (PMV) method, indoor operative temperature set-points can be defined depending on the activity and clothing level of the occupants [70]. According to EN15251:2007 [71], a minimum and maximum indoor operative temperature of 20 °C and 24 °C correspond to a Predicted Percentage Dissatisfied (PPD) < 10% and -0.5 < PMV < +0.5 in residential buildings for an activity level of 1.2 MET and a clothing factor of 1.0 clo. With thermal activation, indoor operative temperatures are varied between 20 °C and 24 °C. When thermal zoning is investigated, a temperature set point of 16 °C is used in bedrooms to account for the temperature preferences of many Norwegians.

Hourly weather data is taken from [72] and includes dry-bulb air temperature, relative humidity, wind direction and speed as well as direct and diffuse solar radiation on a horizontal plane. NordPool provides hourly day-ahead spot prices for each bidding zone, including the bidding zone of the Trondheim area (NO3) [42]. It is used as an input signal for the price-based control and to calculate energy costs for heating. The hourly average $CO_{2eq.}$ intensity is determined according to the methodology proposed in [41] based on the hourly generation from each generation technology. The method considers the electricity imports to the bidding zone. The hourly $CO_{2eq.}$ intensity of the electricity mix is used as control signal to decrease annual $CO_{2eq.}$ emissions. Weather data, spot prices and $CO_{2eq.}$ intensity of the electricity mix in NO3 are correlated so that historical data from 2015 for the city of Trondheim is applied.

3 Simulation scenarios

3.1 Demand response control scenarios

The baseline scenario (called BAU), maintains a constant indoor temperature of 21 °C and constant temperature set-points for the heating system throughout the whole year. The start and stop temperatures for DHW heating are 50 °C and 53 °C, respectively. These constant set-points are chosen as the baseline scenario because this is the most common way to control heating systems in Norwegian residential buildings. For the three demand response (DR) control strategies, all the set-points for SH are either increased by 3 K or decreased by 1 K whereas the set-points for DHW heating are either increased by 10 K or decreased by 5 K. Regarding the DR for DHW heating, increasing the TSP by 10 K leads to an upper temperature boundary of 63 °C, which is just below the maximum supply temperature that the heat pump is able to deliver. Temperature set-points that are related to DHW heating are the start and stop temperatures (of the hysteresis), as well as the supply temperature of the heat pump. Temperature set-points that are related to SH are the room temperature, the start and stop temperatures of the hysteresis as well as the FH supply temperature. With DR, annual energy savings could occur if temperature set-points are frequently lower than values of the BAU control. The first DR control scenario is based on the time-varying spot price. Electricity prices vary throughout a day so that energy costs could be reduced if the heating system is operated outside high-price periods. Two different algorithms can be applied for the price-based control. The second DR scenario considers the dynamic $CO_{2eq.}$ intensity of the electricity mix in the NO3 bidding zone. The $CO_{2eq.}$ intensity gives an indication of the carbon intensity in the fuel type which has been used for electricity generation. It can thus be used to maximize the consumption of electricity generated from non-fossil fuels. The rules for the control strategies based on the spot price and $CO_{2eq.}$ intensity are similar. In the Norwegian electricity grid, a major concern regarding residential buildings is the maximum power and electricity use during peak hours. In the last DR scenario, the control reduces the energy use for heating during peak hours and flattens the consumption profile.

3.2 PRBC using the spot price (Control Strategy Price, CSP)

The price-based control signal is calculated in two different ways (a) the spot price for the next 24 hours is divided into three price segments, where the set-points are adjusted depending on the spot price of the current hour, or (b) additionally to the three price segments, the control checks whether the spot price is increasing or decreasing with time.

3.2.1 Version a (CSP-a)

This price-based PRBC uses a 24-hour sliding horizon to determine a high-price threshold (HPT) and low-price threshold (LPT). At each hour, the current spot price is compared to these thresholds. Taking SP_{max} and SP_{min} as the maximum and minimum prices for the next 24h, LPT has been selected to $SP_{min} + 0.3\ (SP_{max}-SP_{min})$ and HPT to $SP_{min} + 0.75\ (SP_{max}-SP_{min})$. The temperature set-points for DHW and SH are adjusted depending on the current spot price. If the price of the current hour is below the LPT, the temperature set-points are increased. If the current spot price is above the HPT, the set-points are decreased to delay the start of the heating, whereas if the spot price of the current hour is between the LPT and HPT, the temperature set-points remain equal to BAU. The performance of the control is sensitive to the selection of LPTs and HPTs. Table 2 shows the influence of the thresholds on the number of hours at a respective temperature set-point. Generally, the higher the LPT, the more hours with an increased temperature set-point occur during a year. On the contrary, the lower the HPT, the more hours with decreased temperature set-points occur. An analysis of the price thresholds found that this control strategy may charge the thermal storage many hours before the next high-price period. Therefore this leads to an unnecessary increase in annual heating energy use.

3.2.2 Version b (CSP-b)

The control signal is here determined based on the three price segments, as defined in CSP-a, but, additionally, the control checks if the spot price is increasing or decreasing with time. If the current spot price is between the LPT and HPT and the spot price is increasing in the next two hours, the temperature set-point is increased (Fig. 5).

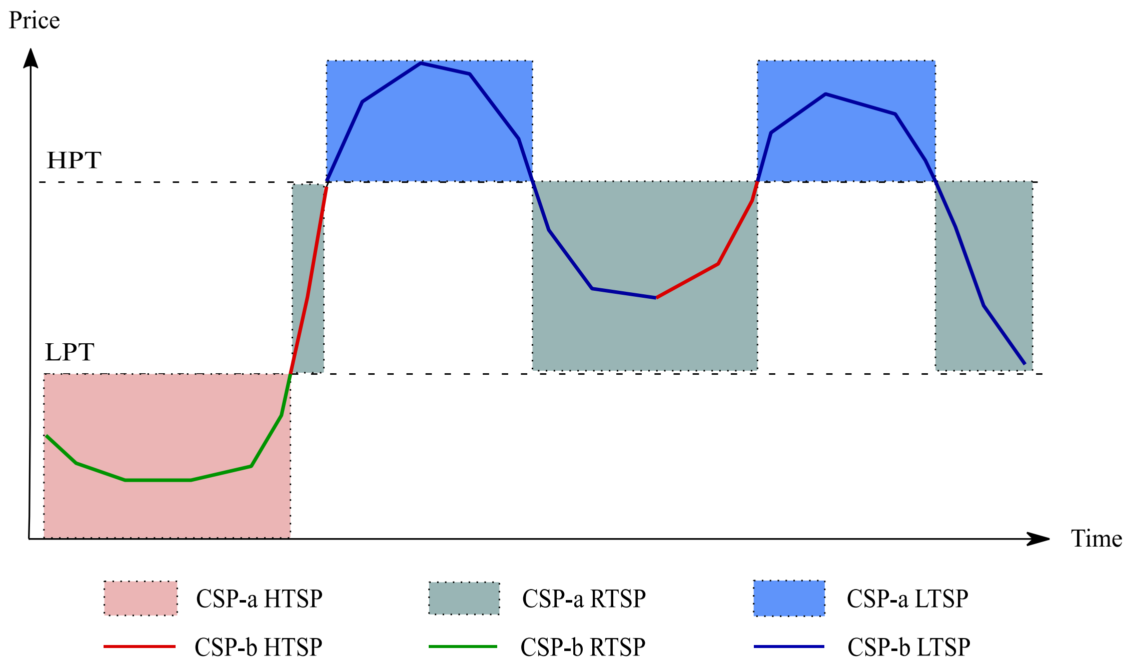

Fig. 5. *Principle of the determination of the price-based control signal after CSP-a and CSP-b (HTSP is high temperature set-point, RTSP is reference temperature set-point, LTSP is low temperature set-point).*

If the current spot price is between the LPT and HPT and the price is decreasing in the next two hours, the TSPs are decreased. Contrary, if the current spot price is between LPT and HPT and the price is increasing in the next two hours, the TSPs are increased. Unlike CSP-a, this logic aims at charging the thermal storages right before high-price periods. The duration for an increased temperature set-point depends on the difference between the two price thresholds. The larger the difference between the thresholds, the longer the period for charging a thermal storage. An LPT of 30% and an HPT of 75% are chosen for determining the CSP-b control signal. Comparing CSP-a and CSP-b in Table 2, it is obvious that the temperature set-points are decreased for more hours during a year (2728 vs. 4423) and increased less often (3012 vs. 1326) using CSP-b.

Table 2. *Influence of the low-price and high-price thresholds on the control signal in terms of number of hours per set-point segment (LTSP is low temperature set-point, RTSP is reference temperature set-point, HTSP is high temperature set-point).*

LPT&HPT [%]	**CSP-a**			**CSP-b**		
	t_{LTSP} [h]	t_{RTSP} [h]	t_{HTSP} [h]	t_{LTSP} [h]	t_{RTSP} [h]	t_{HTSP} [h]
20&75	2728	3690	2342	4805	2341	1614
25&75	2728	3350	2682	4607	2681	1472
30&75	**2728**	**3020**	**3012**	**4423**	**3011**	**1326**
35&75	2728	2695	3337	4242	3336	1182
40&75	2728	2334	3698	4043	3697	1020
30&60	3765	1984	3011	4879	3010	871
30&65	3433	2316	3011	4737	3010	1013
30&70	3098	2651	3011	4585	3010	1165
30&80	2369	3380	3011	4256	3010	1494
30&85	2030	3719	3011	4112	3010	1638

3.3 PRBC using $CO_{2eq.}$ intensity (Control Strategy Carbon, CSC)

The principle of the $CO_{2eq.}$-based control strategy is similar to the price-based control strategy CSP-b, but aims at reducing $CO_{2eq.}$ emissions. A high-carbon threshold of 70% and a low-carbon threshold of 30% are chosen based on a sensitivity analysis. It can be seen from Fig. 6 that low spot prices occur at times of high average $CO_{2eq.}$ intensity, thus leading to contradictory control objectives. Norway usually imports electricity during the night, giving a higher $CO_{2eq.}$ intensity, whereas the hydropower plants run during the day to balance supply and demand, leading to a lower $CO_{2eq.}$ intensity.

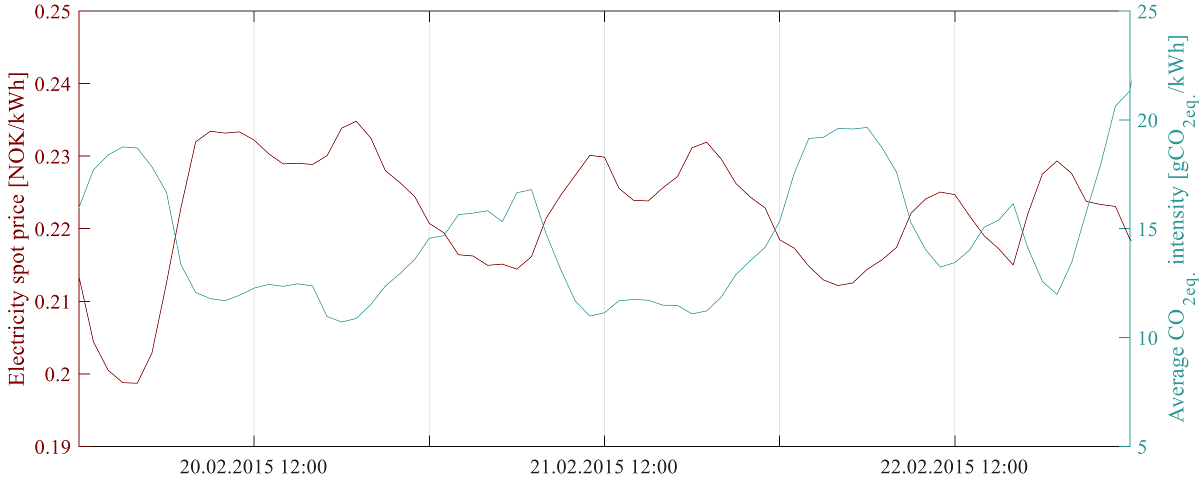

Fig. 6. *Spot price* [42] *and average* $CO_{2eq.}$ *intensity* [41] *in bidding zone NO3 during an exemplary period in 2015.*

A control scenario which makes use of the lowest $CO_{2eq.}$ intensity of the electricity mix (corresponding to CSC-a) would therefore lead to increased heating electricity use during peak periods. This situation is specific to Norway because $CO_{2eq.}$ intensity and peak power are usually highly correlated in other European countries, such as Germany. To prevent increased energy use during peak hours, the implemented $CO_{2eq.}$-based control signal is also determined according to version b of CSP, here corresponding to CSC-b.

3.4 Schedule-based control (Control Strategy Schedule, CSS)

The temperature set-points are changed based on a schedule. Knowing the hourly profile of typical electricity use for Norwegian households [43], peak hours can be defined and electricity use during these hours decreased by charging the heat storages before the daily peak periods. Typical peak hours occur between 7 a.m. and 10 a.m. and between 5 p.m. and 8 p.m. Temperature set-points are increased three hours before a defined peak period and decreased during peak periods. Three hours of pre-heating are chosen to make sure that the time period is sufficiently long to charge both the storage tank and the building thermal mass, even during the coldest outdoor temperatures.

3.5 Consequences of DR on the heating system

When changing temperature set-points during DR control, it should be ensured that the use of the heat pump is prioritized over auxiliary heaters. Therefore, auxiliary heaters should be controlled carefully. First, the temperature set-point for auxiliary heaters is not increased when the temperature set-points for the heat pump are increased. Second, the SH-related set-points are increased only if the heat pump is not heating DHW. Otherwise, when the heat pump heats DHW, higher SH-related set-points would lead to a faster cooling down of the SH tank, eventually leading the auxiliary heater to start before the heat pump has finished producing DHW.

Fig. 7 illustrates the principle of the CSP-b control during 48 hours of the heating season. Fig 7(a) presents the spot price signal as well as the LPT and HPT. Fig. 7(b) illustrates the temperatures in the DHW tank as well as the start and stop temperatures of the hysteresis. It can be seen that the set-points are changing depending on the price signal. It is clear from Figs. 7(c) and 7(d) that the SH-related set-points are increased only if the heat pump is not in DHW mode. For example, in the morning of 20 February, the DHW set-point is increased as soon as the spot price is increasing and is between LPT and HPT, whereas the SH-related set-points are not increased during that period. The modulation of the heat pump compressor is presented in Fig. 7(e) together with the heat emitted to the rooms and the power of the auxiliary heater. The compressor speed increases up to nominal capacity as soon as DHW heating is required. The temperature in the SH tank decreases when there is DHW heating because the heat pump cannot contribute to the heating of the SH tank at the same time. If the temperature in the SH tank drops too low, the electric auxiliary heater starts running. A combination of several design parameters influences the duration of the DHW mode and consequently determines whether the SH auxiliary heater has to be started: the capacity of the heat pump, the water volume to be heated up as well as the start and stop temperatures for DHW. Another reason for the SH auxiliary heater to operate when the heat pump is in DHW mode is related to the tank layout. The DHW is preheated by the SH tank so that the temperature in the SH tank is decreased by the fresh DHW inlet during a draw-off.

At the start of a DHW mode (e.g. afternoon of 19 February), the compressor speed increases to full load and the water circulates through the condenser at a low flow rate in order to reach the supply temperature set-point at the condenser outlet. When the maximum supply temperature allowed by the heat pump is reached, the water flow rate is increased whereas the compressor capacity is reduced. When the stop criteria for DHW is met, the heat pump switches to the SH mode and the compressor modulates continuously to keep the required FH supply temperature. As soon as the SH-related set-points are decreased, no more heat is emitted to the rooms and the SH tank is heated up until the stop criteria for the SH hysteresis is reached.

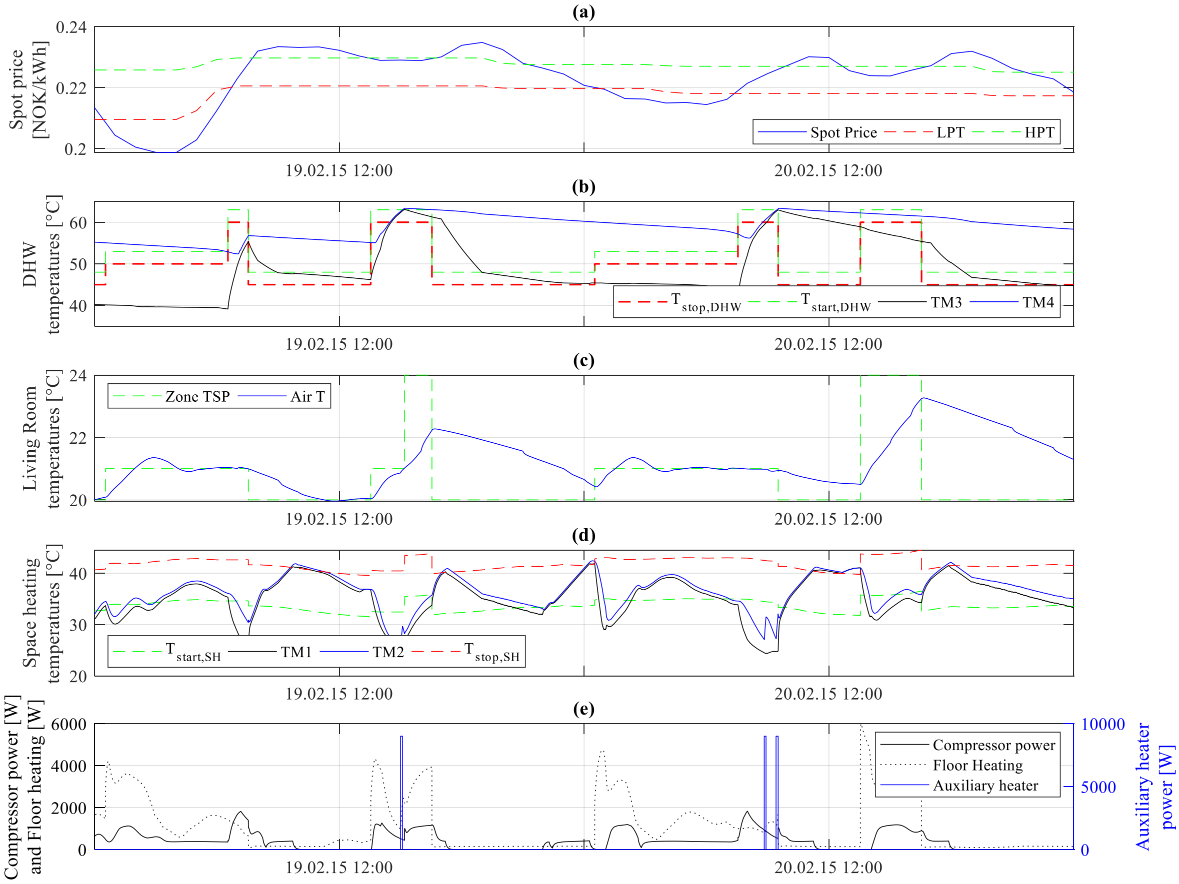

Fig. 7. *Illustration of the control principle using the CSP-b during a period of 48h:* $T_{start,SH}$ *and* $T_{stop,SH}$ *are the start and stop temperatures for SH.*

3.6 Thermal zoning

In the baseline case, all internal doors are open and the same indoor temperature set-point is applied to all rooms. Thermal zoning is achieved by closing internal doors to bedrooms. In this scenario, a constant heating temperature set-point of 16 °C is applied to both bedrooms, while the temperature set-point in the other rooms is controlled as in the baseline cases. Thermal zoning with cold bedrooms should lead to a reduction in electricity use for heating and a decreased load shifting potential. The heat storage capacity is decreased because the thermal mass of colder bedrooms does not contribute to thermal mass activation. All the simulation cases investigated are summarized in Fig. 8.

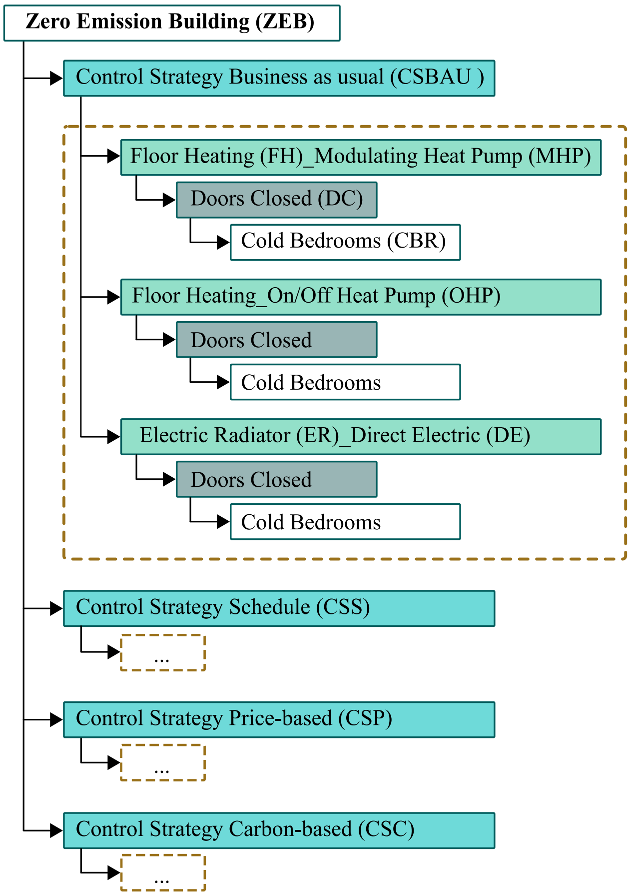

Fig. 8. *Structure of the different simulation cases.*

4 Introduction of performance indicators

Several performance indicators are evaluated and compared to quantify the effect of the different control strategies and construction types.

4.1 Energy related indicators

- *Electricity use for heating:* The electricity use for heating covers both SH and DHW. It includes the heat pump compressor (if applied), the electric resistances and electric radiators (if applied) and excludes the circulation pumps
- *Load shifting:* Load shifting from peak hours to off-peak hours can be expressed in terms of energy. The electricity use for heating is investigated for pre-peak, peak and after-peak hours where pre-peak hours are the three hours before each respective peak period and the after-peak hours are defined as the two hours after each respective peak period.
- *Annual heating costs:* The annual electricity costs for heating consist of hourly spot prices and additional fees, which depend on the size of the installed fuse as well as the energy use in the building. A single-family building usually has a 63A fuse with 230V. For this fuse, the price that has to be paid on top of the spot price is 0.40 NOK/kWh (in 2015) [73]. Two cost-scenarios are evaluated: (1) annual costs for heating including the electricity fee, and (2) annual costs for heating without considering the electricity fee.
- *Annual $CO_{2eq.}$ emissions:* The annual $CO_{2eq.}$ emissions due to the operation of the heating system are evaluated using $CO_{2eq.}$ intensity.

4.2 Heat pump-related indicators

- *Number of heat pump cycles per year or per month:* A low number of heat pump cycles is preferred as unnecessary on/off cycling reduces the lifetime of the compressor.

- *Seasonal coefficient of performance (SCOP):* This indicator characterizes the heat pump and does not consider the electricity use for circulation pumps.

5 Results and discussion

Results are presented first for the ZEB case and the generalization to other insulation levels is discussed later on. If not defined explicitly in the text, the price-based and carbon-based control scenarios correspond to CSP-b and CSC-b, respectively.

5.1 Power

The hourly averaged compressor power is shown in Fig. 9 for the modulating heat pump in a ZEB. Even though this single case is discussed here, it is representative and supports the main conclusions. In general, the heat pump hardly runs at full load for long periods but rather modulates at low compressor speeds. In the BAU scenario (Fig. 9 (a)), the heat pump is often run during peak hours because these hours also coincide with peak DHW demand. The CSP-b strategy (Fig. 9 (c)), enforces heat pump operation in early morning and early afternoon because spot prices are usually increasing at these times. The CSC-b strategy (Fig. 9 (b)) amplifies the heat pump operation during late evening and peak hours in the morning in close accordance with the typical daily fluctuations of the $CO_{2eq.}$ intensity.

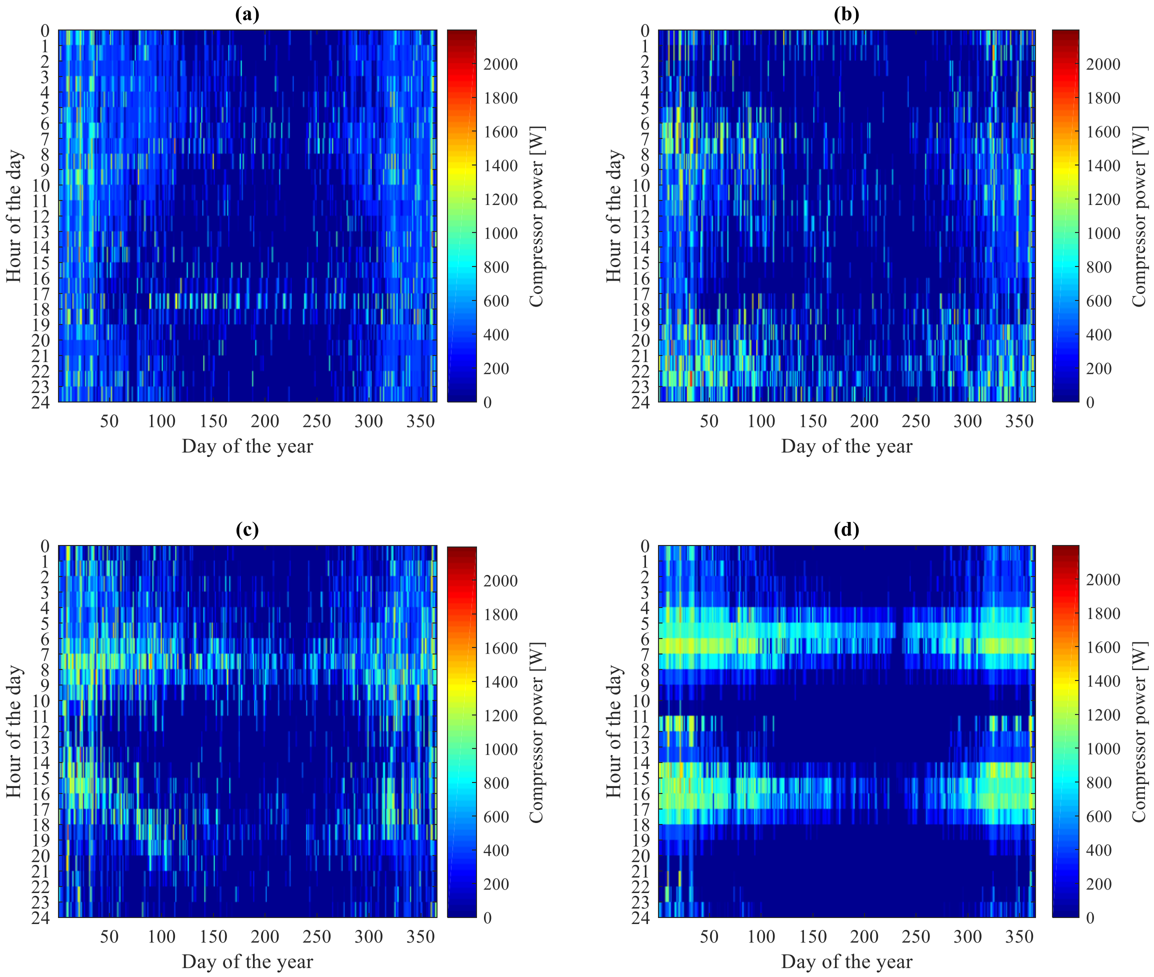

Fig. 9. *Carpet plot of the hourly averaged compressor power of the modulating heat pump in the ZEB: (a) BAU, (b) CSC-b, (c) CSP-b and (d) CSS.*

The CSS strategy (Fig. 9 (d)) enforces the heat pump operation during pre-defined periods. The heat pump operates not only during the hours of increased temperature set-points, but also continues its operation during the first hour of the peak periods. This is due to the hysteresis control of the SH tank which allows the heat pump to stop only if the stop temperature is reached, see e.g. Fig. 7(d) and (e). This creates a delay between the decision to reduce the SH temperature set-points and the time where the heat pump can actually be stopped. This effect cannot be captured by simplified models, which neglect the hysteresis. Compared to the BAU scenario, the heat pump modulates more often at higher compressor powers for CSC, CSP and CSS due to the higher temperature set-points.

The hourly averaged power of the heat pump system is illustrated in Fig. 10 for an entire year. The operation of the auxiliary heaters increases for all DR control strategies compared to BAU. It can be seen that the daily peak power occurs at different times of the day during the year for the different control strategies. Especially for the CSS, the auxiliary heaters operate just before the peak period starts.

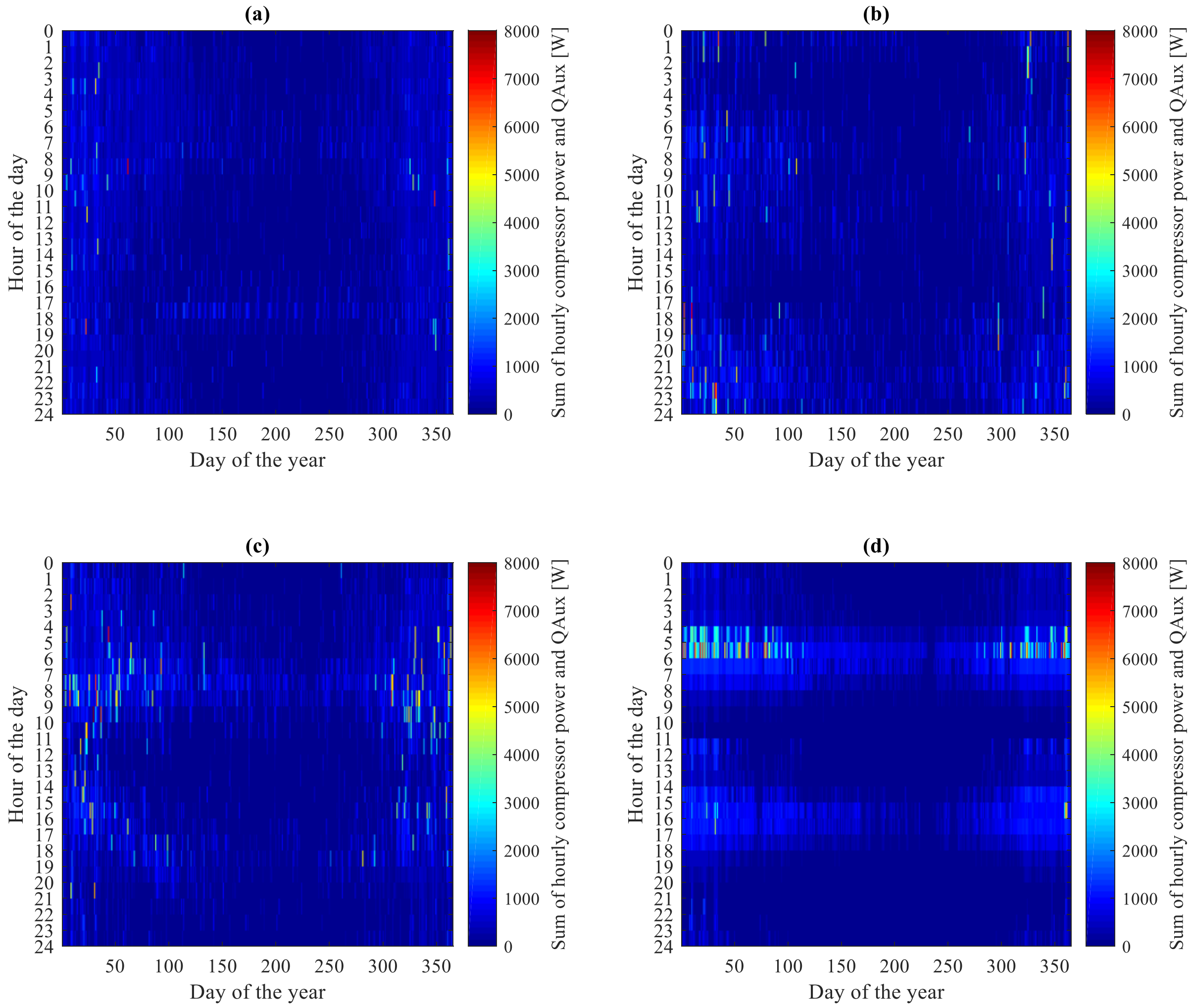

Fig. 10. *Carpet plot of the hourly averaged electrical power for heating including the modulating heat pump and electric auxiliary heaters (ZEB): (a) BAU, (b) CSC-b, (c) CSP-b and (d) CSS.*

5.2 Load shifting potential

Fig. 11 illustrates the influence of the control scenarios on the annual electricity use for heating during pre-peak, peak and after-peak hours for the different PRBC scenarios applied in the ZEB. Fig. 11(a) and (b) correspond to the modulating heat pump system whereas Fig. 11(c) and (d) correspond to the direct electric heating.

The case of direct electric heating is discussed first. The CSS control leads to a higher increase in electricity use during pre-peak hours compared to the CSP-b and CSC-b control scenarios. The CSS is extremely effective to reduce energy use during peak hours but may generate new peaks during pre-peak periods. CSC-b leads to increased electricity use during after-peak hours, but decreased use in pre-peak and peak periods. CSP-b leads to increased heating during pre-peak periods and reduced electricity use during peak periods. In conclusion, all controls reduce the energy use during peak hours, especially CSS. CSC-a on the contrary, would lead to increased electricity use during peak hours as well as after-peak hours. The annual electricity use for heating is increased slightly for the CSP-b and CSS controls compared to the references (BAU), whereas it is decreased for the CSC-b strategy (Fig. 11(d)).

For the case of a modulating ASHP, the CSS control is much less effective to reduce electricity use during peak hours. CSC-b has almost unchanged energy use during that time period while CSP-b has increased energy use during peak hours. Regarding CSP-b, an increased use of the auxiliary heater during peak hours, which is due to the strict prioritization of DHW heating for the heat pump, is indicated in Fig. 10(c). Furthermore, Fig. 10(d) shows a more frequent use of the auxiliary heater between 4 a.m. and 6 a.m. for CSS, thus leading to a strong increase in electricity use for heating during pre-peak hours (Fig. 11(a)).

There is an increase in the annual electricity use for heating for all three control scenarios. The reasons for increased electricity use for heating are the TSP variations for DHW heating and SH, hence increased thermal losses from the water storage tank and through the walls as well as the DHW prioritization for the heat pump. Because of the prioritization of DHW heating, the SH tank is less frequently charged to higher temperatures by the heat pump. Thus, the auxiliary heater is used more often for the CSC-b, CSP-b and CSS cases as the water temperature in the SH tank drops below the respective set-point for the auxiliary heater more frequently. It is obvious from Fig. 11 that a more regular use of the auxiliary heater will increase the amount of electricity used for heating. Better control for switching between the two heating modes is necessary considering the state-of-charge for the two parts of the tank. The increase in energy use for heating is not due to the complexity of the power modulation control: the results for the on-off heat pump have a similar trend regarding load shifting.

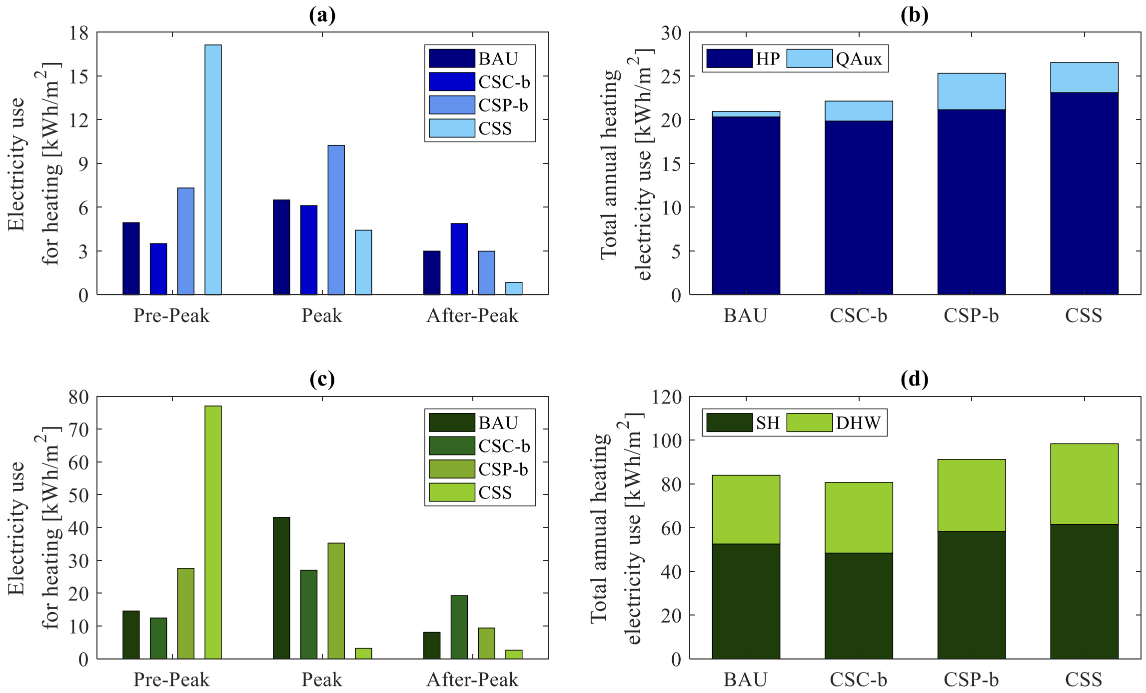

Fig. 11. *Electricity use for heating of the ZEB using a modulating heat pump (a, b) or direct electric heating (c, d).*

Fig. 12 presents the duration curves for the mean air temperature in the common rooms (Fig. 12(a)) and the upper half of the DHW tank (Fig. 12(b)). Generally, all three DR scenarios lead to higher mean indoor air temperatures.

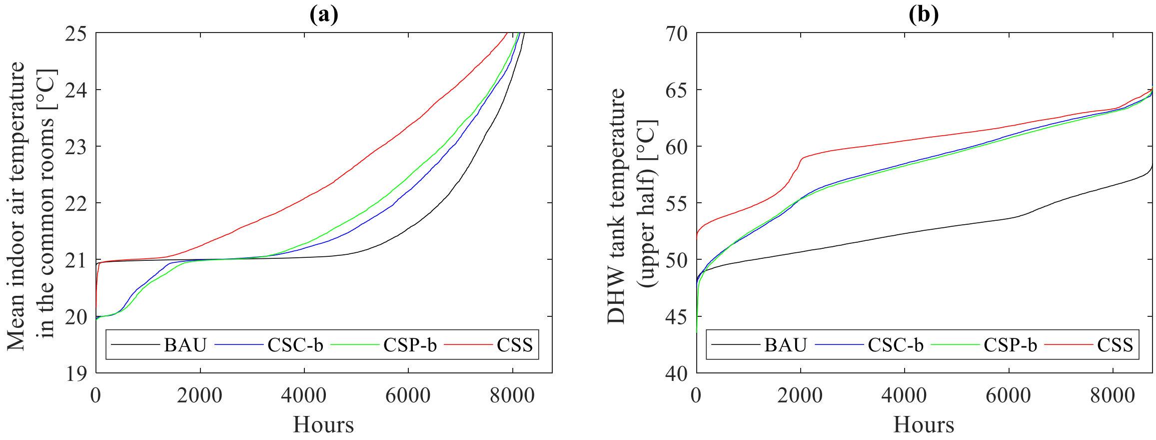

Fig. 12. *Duration curve for the mean indoor air temperature of the common rooms (a) and the upper half of the DHW tank (b) using the modulating heat pump in the ZEB.*

Fig. 12 shows an increasing trend for temperature duration curves starting with the lowest value at hour zero. This figure is used to show the number of hours that a temperature is below a certain value. For example, the mean indoor air temperature in the common rooms for CSS (red line in Fig. 12(a)) is below 24 °C for about 7000 hours. The TSP increases for a longer period for CSS, whereas CSC-b and CSP-b have shorter periods with increased set-points. The room temperature set-points are at 24 °C for 440 h for CSC-b, 750 h for CSP-b and 1250 h for CSS. The DHW duration curves for the three DR control scenarios are more similar, especially the duration curves for CSC-b and CSP-b. For both strategies, the control signals are determined using the same approach and the input signals (i.e. spot price and $CO_{2eq.}$ intensity) have similar trends (Fig. 6).

5.2.1 Annual heating costs

Table 3 presents the annual heating costs. Regarding the ASHP, the annual heating costs are increased by up to 25% for the CSS. The CSP-b leads to 21% increase in electricity costs. The effect of a lower spot price is outweighed by the increased electricity use. Regarding the direct electric heating case, the CSP-b leads to slightly higher heating costs (+5%), even though the electricity use is increased by 13%. Cost savings are influenced by the fee for the grid connection. The cost savings are higher when the grid connection fee is not included in the cost analysis. The price-based control strategy CSP-a leads to much higher heating electricity use and annual heating costs than CSP-b. Even though CSP-a makes use of the lowest spot prices, it leads to higher energy costs because it also involves longer periods with increased temperature set-points. On the contrary, the temperature set-points are increased for shorter periods using CSP-b which charges the thermal storages right before high-price periods. In other words, the averaged electricity price consumed by CSP-a is lower (NOK/kWh) whereas energy costs are lower for CSP-b (NOK).

Table 3. *Annual heating costs for the modulating ASHP and direct electric heating for the ZEB case.*

	ASHP						**Direct electric heating**					
	Heating		**Costs**				**Heating**		**Costs**			
	E_{Use}		with el. fee		w/o el. fee		E_{Use}		with el. Fee		w/o el. Fee	
	kWh	%	NOK	%	NOK	%	kWh	%	NOK	%	NOK	%
BAU	2199	-	1364	-	484	-	8809	-	5393	-	1869	-
CSC-b	2323	+6	1442	+6	513	+6	8464	-4	5183	-4	1797	-4
CSP-a	3057	+39	1828	+34	605	+25	10659	+21	6310	+17	2046	+9
CSP-b	2657	+21	1648	+21	585	+21	9572	+13	5796	+7	1967	+5
CSS	2786	+27	1704	+25	590	+22	10324	+17	6172	+14	2042	+9

This suggests that applying a PRBC to reduce energy costs for heating does not work in Norway. In fact, spot prices do not fluctuate as much during the day as in other countries. A price-based control is more favorable in countries with greater price fluctuations. For instance, the same building and price-based controls have been tested for Denmark, using actual weather data, hourly spot prices and $CO_{2eq.}$ intensities for Aarhus in 2015. Using direct electric heating, it has been found that the electricity use increased by 19%, whereas the cost was lowered by 9% for the CSP-a case. CSP-b increases the electricity use by 8%, while annual heating costs remained the same. This emphasizes that the applied control has to be adjusted for the respective region and its spot price fluctuations. In comparison, other studies suggest that applying an MPC could reduce energy costs for SH by 14% for a residential building heated by electric radiators and located in Aarhus [39].

5.2.2 *Annual $CO_{2eq.}$ emissions for heating*

Table 4 presents a comparison for the carbon emissions for all control strategies for the ZEB case. CSC-b leads to slightly reduced annual carbon emissions for direct electric heating, whereas it does not reduce the carbon emissions for the ASHP. Compared to the spot price, the fluctuations in $CO_{2eq.}$ intensities are rather small compared to other European countries. Thus, the emission savings of CSC-b reported for direct electric heating are closely related to the decreased electricity use. CSC-a leads to higher $CO_{2eq.}$ emissions than CSC-b. CSC-a consumes electricity with lower emissions per $kWh_{heating}$ but this gain is outweighed by the increased electricity use during low-carbon hours.

Table 4. *Annual carbon emissions for the tested control strategies for the ZEB case*

	ASHP					**Direct electric heating**				
	BAU	CSC-a	CSC-b	CSP-b	CSS	BAU	CSC-a	CSC-b	CSP-b	CSS
Emissions kg]	27	30	28	31	33	101	101	96	109	120
Emissions [%]	-	+11	+4	+15	+22	-	0	-5	+8	+19
Emissions per $kWh_{heating}$ [g/kWh]	12.1	10.2	12.1	11.5	11.8	11.5	10.1	11.4	11.4	11.6

5.2.3 *Influence of insulation levels*

The electricity use for heating during pre-peak, peak and after-peak hours for different insulation levels is illustrated in Fig. 13. The results are shown for the cases with direct electric heating.

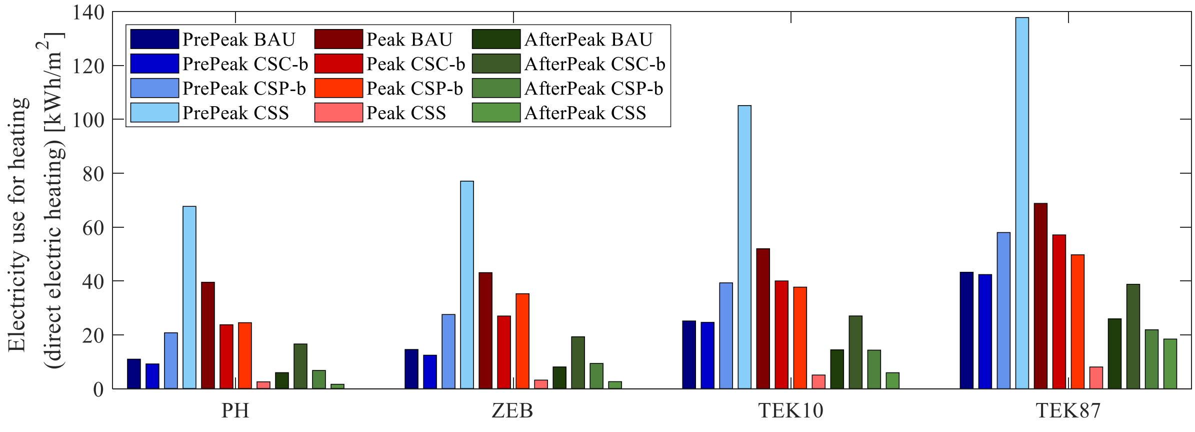

Fig. 13. *Heating electricity use for the cases with direct electric heating and different insulation levels.*

It is obvious that there will be increased electricity use with decreased insulation level. In absolute terms, Fig.13 shows that the reduction of energy use during peak hours is larger for buildings with poorer insulation when using the CSS control. For other controls, this reduction is almost left unchanged. On the contrary, in relative terms, the energy use during peak hours is slightly increased with poorer insulation for all DR controls compared to BAU, see Table 5. This can be explained by the better storage efficiency with higher insulation levels. This storage efficiency is defined as the relative increase in energy use when storage is activated compared to BAU [6,74].

***Table 5**. Influence of the control strategy (CS) on the reduction of electricity use for heating during pre-peak, peak and after-peak periods for the four building insulation levels and direct electric heating.*

	Building	Control strategy			
		BAU	CSC-b	CSP-b	CSS
$E_{PrePeak,CS}/E_{PrePeak,BAU}$ [-]	PH	1	0.84	1.89	6.17
	ZEB	1	0.85	1.89	5.29
	TEK10	1	0.98	1.56	4.18
	TEK87	1	0.98	1.34	3.19
$E_{Peak,CS}/E_{Peak,BAU}$ [-]	PH	1	0.60	0.62	0.07
	ZEB	1	0.63	0.82	0.07
	TEK10	1	0.77	0.73	0.10
	TEK87	1	0.83	0.73	0.12
$E_{AfterPeak,CS}/E_{AfterPeak,BAU}$ [-]	PH	1	2.78	1.14	0.28
	ZEB	1	2.38	1.16	0.32
	TEK10	1	1.87	0.99	0.41
	TEK87	1	1.49	0.84	0.71

5.3 Influence on energy system performance indicators

For the ZEB insulation level, Fig. 14 presents the number of heat pump cycles per month for the modulating and the on/off ASHP. The calculation of the cycle length only considers when the heat pump is turned on. The year can be typically divided into two periods. From October to April, both SH and DHW are important while, between May and September, the DHW needs are dominant. In this last period, the number of heat pump cycles is similar between the DR control strategies as well as between the on-off and modulating heat pumps (i.e. in the range of 40 to 100 cycles per month). On the contrary during the period when SH needs are significant, the number of heat pump cycles differs between cases. The trend is analyzed below and is partly explained by the outdoor temperature.

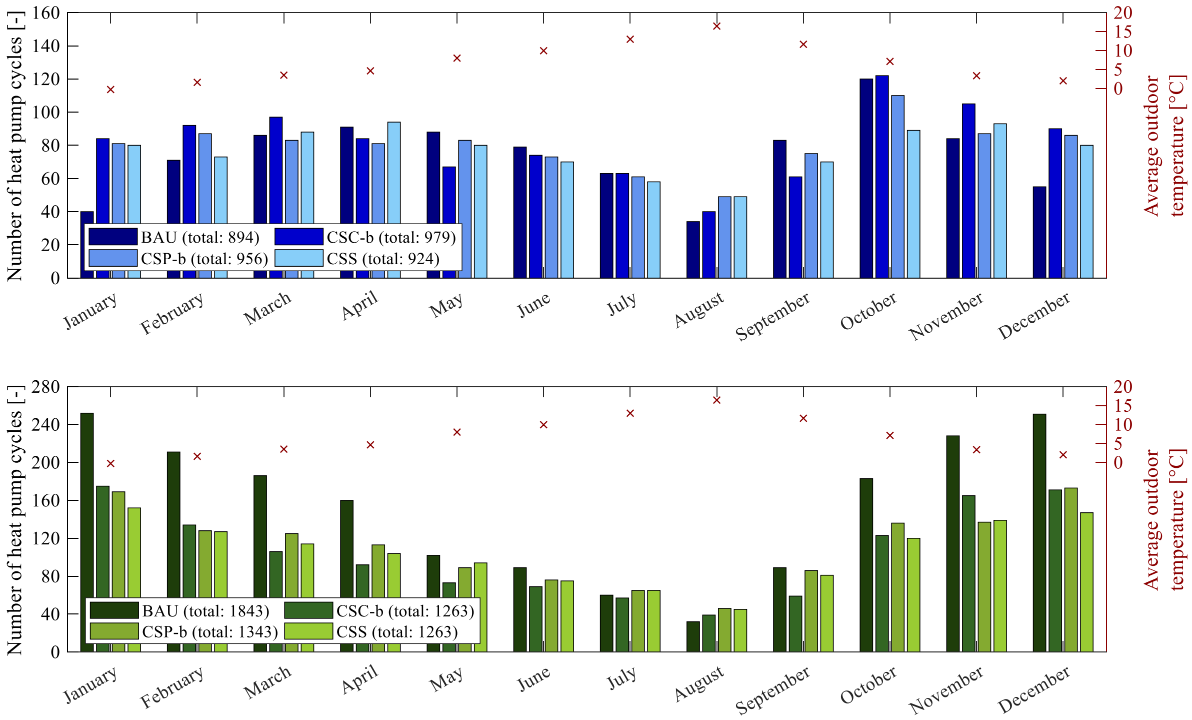

***Fig. 14.** Influence of the control strategies on the number of heat pump cycles for a modulating and an on/off ASHP and the ZEB case.*

Regarding the BAU control, the number of heat pump cycles for the modulating heat pump increases with the rising outdoor temperature from January to April, whereas an opposite trend can be seen for the on/off heat pump. The modulating heat pump cycles less often with colder outdoor temperatures due to the power sizing procedure. The heat pump is sized in order to operate continuously for outdoor temperatures that are typical for winter. Above these temperatures, the modulating heat pump behaves more like an on/off heat pump and has shorter cycles for heating the storage tanks. For the BAU case, the benefit of a modulating heat pump compared to an on-off heat pump is clear in terms of heat pump cycles.

For the three DR controls, they lead to a decreased number of cycles for the on-off heat pump compared to the BAU control. The DR controls with fluctuating temperature set-points lead to less frequent and longer cycles. For the modulating heat pump, DR controls do not significantly change the number of cycles except in the colder months of the year (i.e. January and December) when the number of cycles is increased compared to BAU. During these months, the heat pump is sized to operate continuously so that the DR controls interrupt this continuous operation. For an entire year, the DR controls do not significantly alter the number of cycles of the modulating heat pump.

Fig. 15 compares the total number of heat pump cycles and the average heat pump cycle length for one year between the different building insulation levels. Following the conclusions in the last paragraph, the advantage of the modulating compared to the on-off heat pump is less important when using DR controls than when using the BAU. Comparing building insulation levels, the total number of heat pump cycles is similar, but the average duration of a cycle is different. The SH tank volume is smaller for higher insulation levels because of lower nominal SH power, see Eq. (2). As the heat pump capacity is the same for all three cases, the average cycle length is shorter for higher levels of insulation. It is obvious that proper sizing of the heat pump system (i.e. both the heat pump and storage tank) is essential.

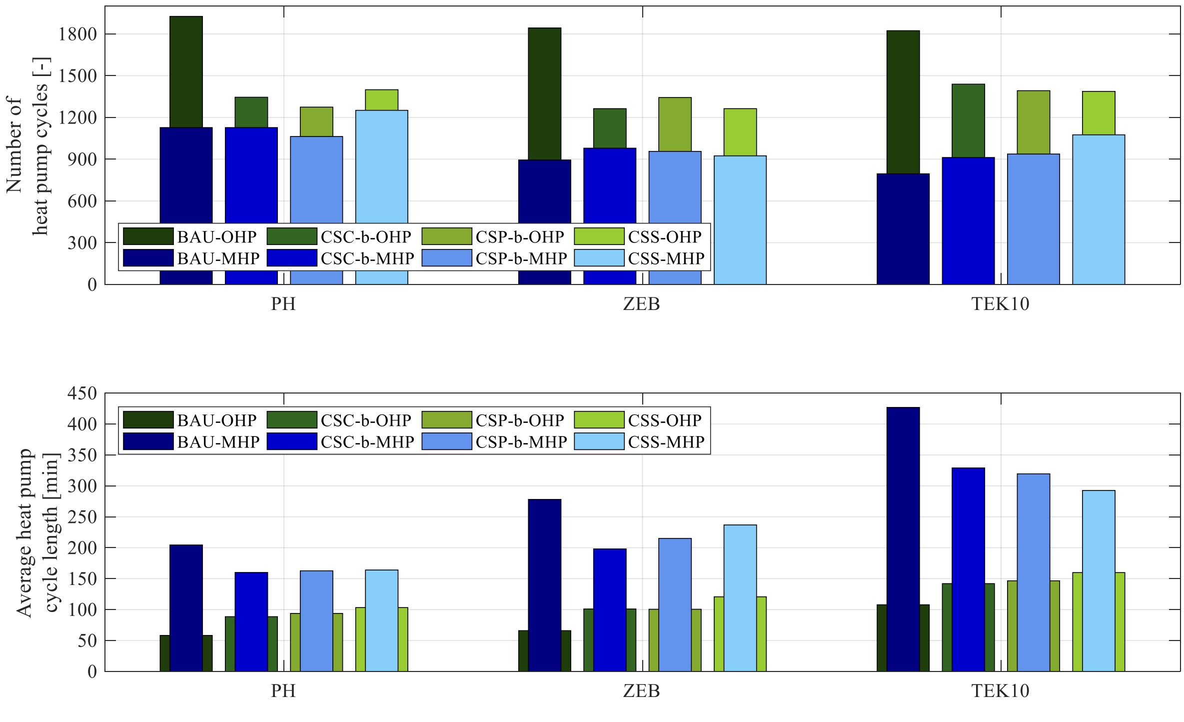

Fig. 15. Influence of the building insulation level on the total number of heat pump cycles per year for a modulating (MHP) and an on/off ASHP (OHP).

For the same heat pump control and building insulation level, DR controls do not alter the SCOP more than 20% taking the BAU control as a reference (Appendix, Table **A1**A1). It confirms that the increase in the electricity use when applying DR control is mostly due to the operation of the auxiliary heaters and not the degradation of performance of the heat pump.

5.3.1 Effect of thermal zoning

Fig. 16 illustrates the duration curve for the mean indoor air temperature of bedrooms for two building insulation levels, the PH and TEK87 cases. A longer heating season for TEK87 compared to PH is obvious. Comparing the PH and TEK87 buildings, the bedroom temperature is evidently colder for the less insulated building. Furthermore, the bedroom temperature in the PH is always above 16 °C meaning that no SH is required in these rooms, whereas SH is applied in the TEK87 building to keep a minimum temperature of 16 °C. For the PH, a highly-insulated external wall, effective heat recovery of the ventilation air in combination with the internal heat gains may lead to bedroom temperatures above 16 °C during winter.

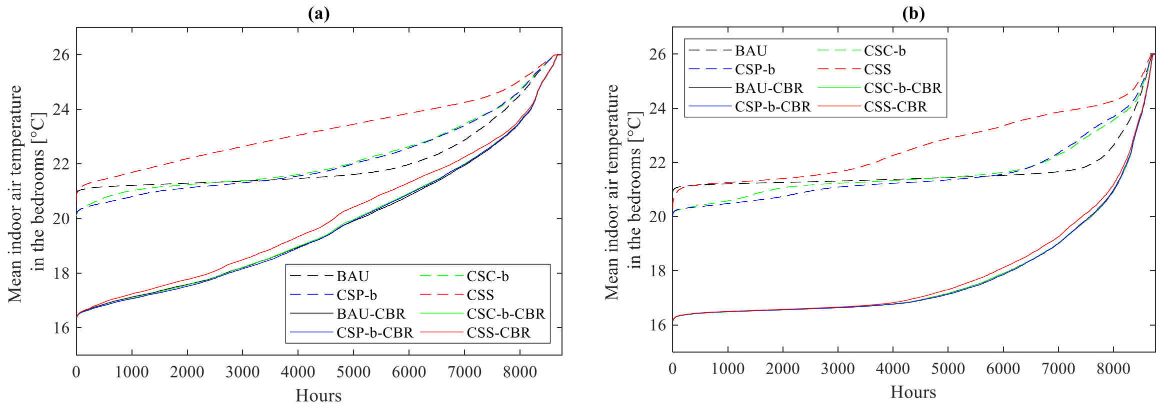

Fig. 16. *Duration curve for the indoor air temperature in bedrooms for the (a) PH and (b) TEK87 buildings with direct electric heating: dashed lines show the reference case with open bedroom doors; solid lines show the cases with closed bedroom doors (CBR) and 16 °C as the temperature set-point.*

Using the thermal zoning strategy, duration curves show that the temperature of bedrooms is independent of the DR control strategy applied in the common rooms (such as the living room). It means that DR controls will not increase the risk that occupants open windows to reduce temperature of bedrooms and thus flush out the heat stored in the building. For the baseline strategy with open internal doors, there is efficient heat exchange between rooms. In addition, the same temperature set-point is applied for all rooms. Therefore, the temperature in the building is almost uniform. For instance, the dashed lines in Fig 16(a) are similar to the mean temperature of the common rooms shown in Fig 12(a).

Table 6 presents the influence of thermal zoning on selected performance indicators for the ZEB case. The electricity use for heating is decreased by roughly 10% for all control scenarios. This leads to a similar reduction in the energy costs for heating and the $CO_{2eq.}$ emissions. Nevertheless, the influence of thermal zoning on the energy use during peak periods differs among the control scenarios. For the CSS, the thermal zoning strategy does not change the energy use during peak hours: this quantity is reduced by 93% with open and closed internal doors. On the contrary, the thermal zoning strategy slightly reduces the load shifting potential for the other DR controls. In conclusion, the thermal zoning strategy is a way to investigate the influence of the users' behavior. Results show that thermal zoning generally has an impact on the building energy flexibility, but these variations are relatively limited (up to 10% reductions).

Table 6. *Influence of thermal zoning with cold bedrooms on selected key performance indicators for the ZEB and electric radiator cases (OBR means open bedroom doors, CBR means closed bedroom doors and CS means control strategy).*

	BAU		**CSC-b**		**CSP-b**		**CSS**	
	OBR	CBR	OBR	CBR	OBR	CBR	OBR	CBR
E_{Use} [kWh]	8809	8169	8464	7744	9572	8620	10324	9357
Costs [NOK]	5393	5000	5183	4742	5796	5216	6172	5598
$CO_{2eq.}$ [kg]	101	93	96	88	109	99	120	109
$E_{Peak,CS}/E_{Peak,BAU,OBR}$	1	0.97	0.63	0.59	0.82	0.72	0.07	0.07

6 Conclusions

This work investigates three types of predictive rule-based control (PRBC) to perform the demand response for heating a Norwegian residential building. The single-family detached house has a lightweight timber construction and four different insulation levels are evaluated. Unlike other studies, a detailed model of an air-source heat pump (ASHP) system has been implemented to obtain realistic operation of the system. There is a comparison of an ASHP modulating between 30% and 100% of the compressor power and an on-off ASHP. Furthermore, direct electric heating is investigated as this is the most common heating system for residential buildings in Norway. The three PRBC strategies are designed to reduce (a) energy costs for heating using the hourly spot prices as input, (b) the annual $CO_{2eq.}$ emissions for heating using the hourly $CO_{2eq.}$ intensity of the electricity mix in Norway and (c) the energy use during peak-load hours using a pre-defined schedule. In the Norwegian context, reducing the energy use during peak-load hours is probably the most important objective for control, as bottlenecks in the distribution grids are expected in the near future. On the contrary, Norwegian electricity currently has a relatively low price and $CO_{2eq.}$ intensity compared to other European countries.

The first research question (Q1) evaluated the energy flexibility potential of PRBC in the specific context of Norway. The price-based PRBC leads to increased heating costs even though it aims to avoid heating during high-price periods. The potential cost savings for the tested PRBC are outweighed by the increase in electricity use for heating. Generally, price-based PRBC is more profitable in electricity markets such as Denmark with greater daily fluctuations in the electricity price. It has been shown that the investigated price-based controls, which do not lead to cost savings in the Norwegian context, result in cost savings if they were applied to the same building in Denmark. The carbon-based PRBC is associated with higher electricity use during early mornings and late evenings. As for the price-based control, increased energy use and limited daily fluctuations of the $CO_{2eq.}$ intensities (compared to other European bidding zones) limit the reduction of the annual $CO_{2eq.}$ emissions. Reductions can only be achieved when there is direct electric heating, not the ASHP. The schedule-based control proved to be very efficient to reduce the energy use for heating during peak hours, especially for the direct electric heating. In the case of the heat pump, the reduction is significantly lowered due to the complexity of the heat pump control (see Q3 below). In the Norwegian context, the schedule-based control manages to significantly reduce the energy use during peak hours, which is a main goal. By definition, PRBC is based on predefined control rules that may not be optimal. For energy costs and $CO_{2eq.}$ emissions, it should therefore be investigated whether model-predictive control could generate significant benefit even though the price and $CO_{2eq.}$ signals have limited fluctuations in Norway.

The second research question (Q2) investigates the influence of thermal zoning on the energy flexibility potential. Energy flexibility has been evaluated for warm and cold bedrooms with open and closed doors, respectively. Lower temperature in bedrooms reduces the annual electricity use for heating (typically by 10%) compared to a uniform temperature in the building. It leads to a similar reduction in the energy costs for heating and annual $CO_{2eq.}$ emissions. For DR controls, the results found that thermal zoning has a limited effect on the reduction of energy use during peak periods. For colder bedrooms with closed doors, it is shown that the bedroom temperatures are not strongly dependent on the heating control strategies applied in the other rooms. These are important conclusions because it suggests that energy flexibility potential is moderately impacted by thermal zoning which is an important aspect of user behavior. In addition, the risk of open bedroom windows to keep bedroom cold will not be increased by the different DR controls. In Norway, buildings are often constructed in wood which leads to thermal insulation in partition walls to limit the sound propagation. The conclusion may be different for construction modes with non-insulated partition walls, such as concrete.

The third research question (Q3) investigates the impact of the modeling complexity of the heat pump system on the energy flexibility potential. With DR controls using time-varying set-points, results show that the domestic hot water (DHW) prioritization, the minimum cycle length as well as the hysteresis between the start and stop temperatures (when the heat pump operates below its minimum power modulation capabilities) prevent the heat pump stopping immediately after it is required by the PRBC. This may also trigger the operation of the auxiliary heater too frequently and significantly increase the energy use for heating. These phenomena have a major impact on the performance of the DR controls. Compared to a simpler heating system, direct electric heating, the performance of DR controls with the ASHP is systematically lower. Modeling these details in a heat pump system are most often neglected in the literature but are important to predict the realistic energy flexibility potential. Finally, such detailed heat pump models can be used to optimize PRBC. For instance, improving the prioritization control strategy between DHW and SH should be considered to make maximum use of the heat pump and minimize the use of auxiliary heaters while respecting the temperature set-points.

The influence of the PRBC on the operating conditions of the heat pump in terms of duration and frequency of cycles is also addressed (Q4). The study confirms the advantages of a modulating heat pump over an on-off heat pump. For the reference case (BAU) with constant heating set-points, the modulating heat pump leads to roughly half the number of heat pump cycles throughout the year. Compared to BAU, the DR controls lead to a comparable number cycles for the modulating heat pump whereas an on-off heat pump will have fewer cycles with longer durations. As the number of cycles is related to the mechanical wear and the lifetime of the heat pump, an increased (or decreased) number of cycles correspond to a cost (or a saving) that needs to be investigated in future work.

Acknowledgements

The authors would like to acknowledge IEA EBC Annex 67 "Energy Flexible Buildings", IEA HPT Annex 49 "Design and Integration of Heat Pumps for nZEBs" as well as the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN). The contribution of Sebastian Stinner for this research was supported by a research grant from E.ON Stipendienfonds im Stifterverband für die Deutsche Wissenschaft (project number T0087/29896/17).

References

[1] Jensen SØ, Marszal-Pomianowska A, Lollini R, Pasut W, Knotzer A, Engelmann P, Stafford A, Reynders G. IEA EBC Annex 67 Energy Flexible Buildings. Energy Build 2017;155:25–34. doi:10.1016/j.enbuild.2017.08.044.

[2] Aduda KO, Labeodan T, Zeiler W, Boxem G, Zhao Y. Demand side flexibility: Potentials and building performance implications. Sustain Cities Soc 2016;22:146–63. doi:10.1016/j.scs.2016.02.011.

[3] IEA, Nordic Energy Research. Nordic Energy Technology Perspectives 2016 Cities, flexibility and pathways to carbon-neutrality. Oslo: 2016.

[4] Finck C, Li R, Kramer R, Zeiler W. Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems. Appl Energy 2017;209:409–25. doi:10.1016/j.apenergy.2017.11.036.

[5] Clauß J, Finck C, Vogler-Finck P, Beagon P. Control strategies for building energy systems to unlock demand side flexibility – A review. 15th Int. Conf. Int. Build. Perform. Simul. Assoc. San Fr. USA, San Francisco: 2017.

[6] Reynders G, Diriken J, Saelens D. Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. Appl Energy 2017;198:192–202. doi:10.1016/j.apenergy.2017.04.061.

[7] Le Dréau J, Heiselberg P. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 2016;111:991–1002. doi:10.1016/j.energy.2016.05.076.

[8] Vanhoudt D, Geysen D, Claessens B, Leemans F, Jespers L, Van Bael J. An actively controlled residential heat pump: Potential on peak shaving and maximization of self-consumption of renewable energy. Renew Energy 2014;63:531–43. doi:10.1016/j.renene.2013.10.021.

[9] Georges E, Cornélusse B, Ernst D, Lemort V, Mathieu S. Residential heat pump as flexible load for direct control service with parametrized duration and rebound effect. Appl Energy 2017;187:140–53. doi:10.1016/j.apenergy.2016.11.012.

[10] Fischer D, Madani H. On heat pumps in smart grids: A review. Renew Sustain Energy Rev 2017;70:342–57. doi:10.1016/j.rser.2016.11.182.

[11] Fischer D, Wolf T, Wapler J, Hollinger R, Madani H. Model-based flexibility assessment of a residential heat pump pool. Energy 2017;118:853–64. doi:10.1016/j.energy.2016.10.111.

[12] Lopes RA, Chambel A, Neves J, Aelenei D, Martins J. A literature review of methodologies used to assess the energy flexibility of buildings. Energy Procedia 2016;91:1053–8.

doi:10.1016/j.egypro.2016.06.274.

[13] Halvgaard R, Poulsen N, Madsen H, Jørgensen J. Economic model predictive control for building climate control in a smart grid. 2012 IEEE PES Innov. Smart Grid Technol., 2012, p. 1–6. doi:10.1109/ISGT.2012.6175631.

[14] Masy G, Georges E, Verhelst C, Lemort V. Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the Belgian context. Sci Technol Built Environ 2015;21:6:800–11. doi:10.1080/23744731.2015.1035590.

[15] Heidmann Pedersen T, Hedegaard RE, Petersen S. Space heating demand response potential of retrofitted residential apartment blocks. Energy Build 2017;141:158–66. doi:10.1016/j.enbuild.2017.02.035.

[16] Hedegaard RE, Pedersen TH, Petersen S. Multi-market demand response using economic model predictive control of space heating in residential buildings. Energy Build 2017;150:253–61. doi:10.1016/j.enbuild.2017.05.059.

[17] Péan T, Ortiz J, Salom J. Impact of Demand-Side Management on Thermal Comfort and Energy Costs in a Residential nZEB. Buildings 2017;7:37. doi:10.3390/buildings7020037.

[18] Stinner S, Huchtemann K, Müller D. Quantifying the operational flexibility of building energy systems with thermal energy storages. Appl Energy 2016;181:140–54. doi:10.1016/j.apenergy.2016.08.055.

[19] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. doi:10.1016/j.rser.2015.01.057.

[20] Oldewurtel F. Stochastic Model Predictive Control for Energy Efficient Building Climate Control. ETH Zurich, 2011.

[21] Salpakari J, Lund P. Optimal and rule-based control strategies for energy flexibility in buildings with PV. Appl Energy 2016;161:425–36. doi:10.1016/j.apenergy.2015.10.036.

[22] D'hulst R, Labeeuw W, Beusen B, Claessens S, Deconinck G, Vanthournout K. Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium. Appl Energy 2015;155:79–90. doi:10.1016/j.apenergy.2015.05.101.

[23] Reynders G, Nuytten T, Saelens D. Potential of structural thermal mass for demand-side management in dwellings. Build Environ 2013;64:187–99. doi:10.1016/j.buildenv.2013.03.010.

[24] Arteconi A, Patteeuw D, Bruninx K, Delarue E, D'haeseleer W, Helsen L. Active demand response with electric heating systems: Impact of market penetration. Appl Energy 2016;177:636–48. doi:10.1016/j.apenergy.2016.05.146.

[25] Georges L, Alonso MJ, Woods R, Wen K, Håheim F, Liu P, Berge M, Thalfeldt M. Evaluation of Simplified Space-Heating Hydronic Distribution for Norwegian Passive Houses. Trondheim: 2017.

[26] Berge M, Georges L, Mathisen HM. On the oversupply of heat to bedrooms during winter in highly insulated dwellings with heat recovery ventilation. Elsevier Ltd, 2016. doi:10.1016/j.buildenv.2016.07.011.

[27] Georges L, Wen K, Alonso MJ, Berge M, Thomsen J, Wang R. Simplified space-heating distribution using radiators in super-insulated apartment buildings. Energy Procedia 2016;96:455–66. doi:10.1016/j.egypro.2016.09.177.

[28] Georges L, Håheim F, Alonso MJ. Simplified Space-Heating Distribution using Radiators in Super-Insulated Terraced Houses. Energy Procedia 2017;132:604–9. doi:10.1016/j.egypro.2017.09.677.

[29] Selvnes E. Thermal zoning during winter in super-insulated residential buildings. Norwegian University of Science and Technology, 2017.

[30] Alimohammadisagvand B, Jokisalo J, Kilpeläinen S, Ali M, Sirén K. Cost-optimal thermal energy storage system for a residential building with heat pump heating and demand response control. Appl Energy 2016;174:275–87. doi:10.1016/j.apenergy.2016.04.013.

[31] Alimohammadisagvand B, Jokisalo J, Sirén K. Comparison of four rule-based demand response

control algorithms in an electrically and heat pump-heated residential building. Appl Energy 2018;209:167–79. doi:10.1016/j.apenergy.2017.10.088.

[32] Fischer D, Bernhardt J, Madani H, Wittwer C. Comparison of control approaches for variable speed air source heat pumps considering time variable electricity prices and PV. Appl Energy 2017;204:93–105. doi:10.1016/j.apenergy.2017.06.110.

[33] Dar UI, Sartori I, Georges L, Novakovic V. Advanced control of heat pumps for improved flexibility of Net-ZEB towards the grid. Energy Build 2014;69:74–84. doi:10.1016/j.enbuild.2013.10.019.

[34] Kandler C, Wimmer P, Honold J. Predictive control and regulation strategies of air-to-water heat pumps. Energy Procedia 2015;78:2088–93. doi:10.1016/j.egypro.2015.11.239.

[35] Pallonetto F, Oxizidis S, Milano F, Finn D. The effect of time-of-use tariffs on the demand response flexibility of an all-electric smart-grid-ready dwelling. Energy Build 2016;128:56–67. doi:10.1016/j.enbuild.2016.06.041.

[36] Georges E, Garsoux P, Masy G, DeMaere D`Aetrycke G, Lemort V. Analysis of the flexibility of Belgian residential buildings equipped with Heat Pumps and Thermal Energy Storages. CLIMA 2016 - Proc. 12th REHVA World Congr., Aalborg: 2016.

[37] De Coninck R, Baetens R, Saelens D, Woyte A, Helsen L. Rule-based demand-side management of domestic hot water production with heat pumps in zero energy neighbourhoods. J Build Perform Simul 2014;7:271–88. doi:10.1080/19401493.2013.801518.

[38] Vandermeulen A, Vandeplas L, Patteeuw D, Sourbron M, Helsen L. Flexibility offered by residential floor heating in a smart grid context : the role of heat pumps and renewable energy sources in optimization towards different objectives . 12th IEA Heat Pump Conf. 2017, Rotterdam, Netherlands: 2017.

[39] Dahl Knudsen M, Petersen S. Demand response potential of model predictive control of space heating based on price and carbon dioxide intensity signals. Energy Build 2016;125:196–204. doi:10.1016/j.enbuild.2016.04.053.

[40] Brattebø H, O'Born R, Sartori I, Klinski M, Nørstebø B. Typologier for norske boligbygg - Eksempler på tiltak for energieffektivisering. 2014.

[41] Clauß J, Stinner S, Solli C, Lindberg KB, Madsen H, Georges L. A generic methodology to evaluate hourly average CO2 intensities of the electricity mix to deploy the energy flexibility potential of Norwegian buildings. Proc. 10th Int. Conf. Syst. Simul. Build., Liege, Belgium: 2018, p. 1–19.

[42] Nord Pool Spot. www.nordpoolspot.com/historical-market-data 2016. www.nordpoolspot.com/historical-market-data.

[43] Rendum J, Vik AL, Knutsen AS. Innføring av AMS i norske husstander, og mulighetene dette gir for nettfleksibilitet. Norwegian University of Science and Technology, 2016.

[44] Goia F, Finocchiaro L, Gustavsen A. 7 . Passivhus Norden | Sustainable Cities and Buildings The ZEB Living Laboratory at the Norwegian University of Science and Technology : a zero emission house for engineering and social science experiments, Copenhagen: 2015.

[45] Kristjansdottir TF, Houlihan-Wiberg A, Andresen I, Georges L, Heeren N, Good CS, Brattebø H. Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway? Energy Build 2018;168:457–69. doi:10.1016/j.enbuild.2018.02.046.

[46] EQUA. EQUA Simulation AB 2015. http://www.equa.se/en/ida-ice.

[47] EQUA Simulation AB, EQUA Simulation Finland Oy. Validation of IDA Indoor Climate and Energy 4.0 with respect to CEN Standards EN 15255-2007 and EN 15265-2007. 2010.

[48] EQUA Simulation AB. Validation of IDA Indoor Climate and Energy 4.0 build 4 with respect to ANSI/ASHRAE Standard 140-2004. Stockholm: 2010.

[49] Achermann M, Zweifel G. RADTEST – Radiant Heating and Cooling Test Cases Supporting Documents. Luzern: 2003.

[50] Bring A, Sahlin P, Vuolle M. Models for Building Indoor Climate and Energy Simulation Models for Building Indoor Climate and Energy Simulation 1. Executive Background and Summary.

1999.
[51] Sahlin P. Modelling and Simulation Methods for Modular Continuous Systems in Buildings. 1996.
[52] Georges L, Iwanek T, Thalfeldt M. Energy efficiency of hydronic space-heating distribution systems in super-insulated residential buildings. Proc. 15th IBPSA Conf., 2017, p. 1852–61.
[53] Vogler-Finck P, Clauß J, Georges L, Sartori I, Wisniewski R. Inverse model identification of the thermal dynamics of a Norwegian zero emission house. In: Johansson D, editor. Springer Proc. Energy, Cold Clim. HVAC 2018 Conf., Springer Nature Switzerland AG 2019; 2018.
[54] Clauß J, Vogler-Finck P, Georges L. Calibration of a high-resolution dynamic model for detailed investigation of the energy flexibility of a zero emission residential building. In: Johansson D, editor. Springer Proc. Energy, Cold Clim. HVAC 2018 Conf., Kiruna, Sweden: Springer Nature Switzerland AG 2019; 2018. doi:https://doi.org/10.1007/978-3-030-00662-4_61.
[55] Stiebel Eltron. Planung und Installation: Wärmepumpen. 2013.
[56] Vaillant. Innovativ Heizen und Kühlen mit Wärmepumpen. 2017.
[57] Viessmann. Planungshandbuch Wärmepumpen. 2011.
[58] HOVAL. Dimensionierungshilfe für Wärmepumpenanlagen 2017. 2017.
[59] OSOHotwater. OSO Hotwater, "OSO Optima EPC series". Patent 328503, 02 2014, 2014.
[60] Niemelä T, Kosonen R, Jokisalo J. Comparison of energy performance of simulated and measured heat pump systems in existing multi-family residential buildings. 12th IEA Heat Pump Conf. 2017, Rotterdam, Netherlands: 2017.
[61] Niemelä T, Vuolle M, Kosonen R, Jokisalo J, Salmi W, Nisula M. Dynamic simulation methods of heat pump systems as a part of dynamic energy simulation of buildings. Proc. 3rd Ibpsa-engl. Conf. BSO 2016, Newcastle: 2016.
[62] Fadejev J, Kurnitski J. Geothermal energy piles and boreholes design with heat pump in a whole building simulation software. Energy Build 2015;106:23–34. doi:10.1016/j.enbuild.2015.06.014.
[63] Hoval. Luft / Wasser-Wärmepumpen. 2018.
[64] Skogestad S. PID-tuning using the SIMC rules. 2017.
[65] Fischer D, Lindberg KB, Madani H, Wittwer C. Impact of PV and variable prices on optimal system sizing for heat pumps and thermal storage. Energy Build 2017;128:723–33.
[66] Renaldi R, Kiprakis A, Friedrich D. An optimisation framework for thermal energy storage integration in a residential heat pump heating system. Appl Energy 2017;186:520–9. doi:10.1016/j.apenergy.2016.02.067.
[67] SN/TS3031:2016. Bygningers energiytelse, Beregning av energibehov og energiforsyning 2016.
[68] Ahmed K, Akhondzada A, Kurnitski J, Olesen B. Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standards. Sustain Cities Soc 2017;35:134–44. doi:10.1016/j.scs.2017.07.010.
[69] ISO17772-1. Energy performance of buildings - Indoor environmental quality - Part1: Indoor environmental input parameters for the design and assessment of energy performance of buildings. 2017.
[70] ISO7730:2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria 2005.
[71] Standard Norge. NS-EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics 2007.
[72] OpenStreetMap. Shiny weather data 2017. https://rokka.shinyapps.io/shinyweatherdata/ (accessed May 20, 2017).
[73] TrønderEnergi. Nettleie privat 2016. https://tronderenerginett.no/nettleie/privat/priser-fra-1.jan-2016. (accessed October 31, 2016).

[74] Reynders G, Diriken J, Saelens D. A generic quantification method for the active demand response potential of structural storage in buildings. 14th Int Conf Int Build Perform Simul Assoc 2015.

APPENDIX

Table A1. *SCOP for both heat pump cases for four investigated control strategies and all building insulation levels*

Building	Control strategy	SCOP	
		Modulating heat pump	**On-off heat pump**
PH	BAU	2.42	2.33
	CSC-b	2.32	2.12
	CSP-b	2.40	2.12
	CSS	2.12	1.91
ZEB	BAU	2.25	2.30
	CSC-b	2.35	2.15
	CSP-b	2.31	2.08
	CSS	1.97	1.84
TEK10	BAU	2.80	2.60
	CSC-b	2.75	2.39
	CSP-b	2.79	2.44
	CSS	2.55	2.02