12th IEA Heat Pump Conference 2017

Investigations of Different Control Strategies for Heat Pump Systems in a Residential nZEB in the Nordic Climate

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Abstract

The paper investigates different control strategies for a ground source heat pump of a Norwegian residential zero emission building, with detailed dynamic simulations (here using IDA ICE). These rule-based controls aim at activating the energy flexibility of the building to improve grid interaction, lower energy costs, perform load shifting and reduce energy needs. Three load shifting controls load the building before pre-defined peak hours based on the electricity grid, whereas three other control strategies are based on hourly electricity spot prices. One additional control promotes the PV self-consumption in order to improve the grid interaction. Investigations showed that none of the proposed controls was able to maximize all objectives at the same time. The controls for peak load shifting were able to activate the water storage tank, but did not manage to activate the thermal mass of the building. Price-based heating control strategies for temperature set-points for space heating and domestic hot water heating led to an increased energy consumption of up to 25% as well as increased operational costs for the heat pump, but also decreased the total annual heat pump run time above 30% part load ratio by 13%. The controls were able to shift the electricity consumption to low-price hours, but failed to achieve savings for annual operational costs. A control for improving the PV self-consumption increased the building´s self-generation by 9% (up to 61%) and the building´s self-consumption by 5% (to up to 28%).

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Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: nZEB, heat pumps systems, rule-based control, control strategies, grid interaction

1. Introduction

National building standards vary among European countries, partly due to different climate conditions. In cold climate countries like Norway, space heating needs are dominant over space cooling demands. According to the EPBD recast, all new buildings built after 2020 have to be nearly zero energy buildings [1]. The Norwegian Research Centre on Zero Emission Buildings (ZEB) focuses on the balance of CO_2 emissions rather than on primary energy. In Norway, the CO_{2eq} balance is typically promoted by (1) highly-insulated building envelopes in order to decrease space heating (SH) needs, (2) energy efficient thermal systems, as well as (3) covering the final energy use by renewable energy sources. A common approach for harvesting renewable energy is the use of heat pumps in combination with a geothermal energy storage and solar energy, solar thermal as well as photovoltaic.

The common approach for determining the energy needs of an nZEB applies fixed set-point temperatures for

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AHU	Air handling unit	NO3	Norwegian spot price bidding area
COP	Coefficient of Performance	nZEB	Nearly Zero Energy Building
CO_{2eq}	CO_2 equivalent	OP	Off-peak
DHW	Domestic hot water	PV	Photovoltaic
EPBD	European Performance of Buildings Directive	RBC	Rule-based control
FH	Floor heating	SFP	Specific fan power
GSHP	Ground source heat pump	SH	Space heating
HDS	Heat distribution system	SP	Spot price
hGHE	Horizontal ground heat exchanger	SPF	Seasonal performance factor
HVAC	Heating, ventilation and air-conditioning	t_{aa}	Average annual temperature
HRU	Heat recovery unit	TMY	Typical meteorological year
KPI	Key performance indicator	T_{SP}	Temperature set-point
LL	Living Lab	ZEB	Zero Emission Building
MPC	Model-predictive control		

the heating system (EN15251) so that constant indoor temperatures as well as domestic hot water (DHW) temperatures are met. In this way, the heating system does not take into account external physical variables for building control such as price variations or limitations of electrical power that can be delivered by the grid. Furthermore, the approach does not consider any flexibility of occupants to variations of the indoor temperature and neither that a heating system can have storage capacity.

A suitable control strategy for the heat pump system can improve the building performance significantly. Among others, such a control strategy can apply rule-based or model-predictive control (MPC). Rule-based control (RBC) uses pre-defined set points for temperatures, electricity CO_2 levels or prices for running the energy system in an efficient way. MPC applies a simplified building model for predicting future system states and optimizes an objective function over a sliding planning horizon. The objective function optimizes the schedule for a chosen parameter, for example minimum energy costs for operation. Both, rule-based control as well as MPC can lead to considerable energy and operation cost savings [2] [3].

In this paper, nine rule-based control strategies are investigated using detailed dynamic simulations (IDA ICE). Each control is applied to a Norwegian residential ZEB located in Trondheim and their performances are compared with regards to eight different key performance indicators (KPI). The terminology is taken according to NS-EN15603:2008 [4].

2. Description of residential ZEBs

2.1. Characteristics of the Living Lab

The studied building, shown in Figure 1, is a Norwegian residential zero emission building [5] constructed in Trondheim, Norway. The so-called Living Lab (LL) is a single-family building and is used for several interdisciplinary research studies [6], ranging from investigations of the occupant behavior to testing of different ventilation strategies or control strategies for the heating system. The Norwegian Research Centre on Zero Emission Buildings (ZEBs) focuses on the balance of CO_2 emissions during the building life cycle. Different performance levels have been defined depending on how many stages of the building life cycle are included in the emission balance [7]. The LL is designed to be a ZEB-OM meaning that on-site generation compensates for embodied emissions as well as emissions from the operation phase. The building envelope specifications follow the Norwegian passive house standard NS3700 [8] and are presented in Table 1.

The LL, which is located at the Gløshaugen Campus of the Norwegian University of Science and Technology (NTNU), has a floor area of approximately 100 m^2 and a volume of around 500 m^3 [5]. The building has four rooms (machinery room not part of the protected volume): two bedrooms, one bathroom and one large room combining a kitchen, a living room and a working space. The building has lightweight construction with a wooden frame construction.

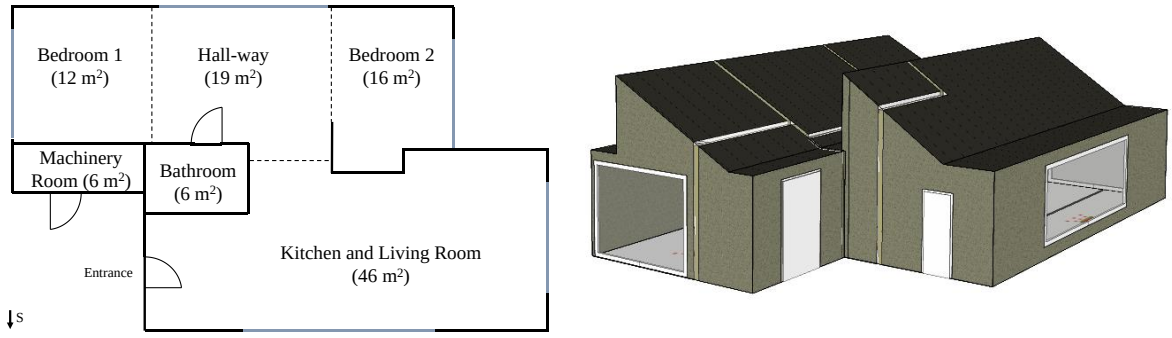
Table 1. Building envelope specifications of the Living Lab [9] and comparison of the U-value with NS3700.

Construction element	Construction element specification	Construction thickness [mm]	U-value $\left[\frac{W}{m^2K}\right]$	
			Living Lab	NS3700
External wall	Timber framed construction, mineral wool insulation, timber cladding	479	0.11	-
Internal wall	Timber cladding, mineral wool insulation	120	0.345	-
Floor	Raised timber framed construction, mineral wool insulation, parquet timber flooring	469	0.1	-
Roof	Timber framed construction, mineral wool insulation, integrated phase change material, in-roof photovoltaic panels	523	0.1	-
Window south side	Triple glazed unit with insulated aluminum frame, double skin	-	0.67	≤ 0.8
Window east/west side	Aluminum clad timber framed triple glazed units, integrated vacuum insulated panels	-	0.8	≤ 0.8
Window north side	Triple glazed unit with insulated aluminum frame, double skin	-	0.97	≤ 0.8
Air tightness $\left[\frac{1}{h}\right]$	0.5 ACH at 50 Pa	-	-	≤ 0.6
Thermal bridges $\left[\frac{W}{m^2K}\right]$	0.03	-	-	0.03

The maximum acceptable SH demand for a passive house is calculated following the standardized equation [8]

$$SH = 15 + 5.4 \cdot \frac{250 - A_{floor}}{100} + \left(2.1 + 0.59 \cdot \frac{250 - A_{floor}}{100}\right) \cdot (6.3 - t_{aa}) \quad (1)$$

leading to 26.9 kWh/(m²·a) for a floor area of 105 m² and an average annual temperature of 4.9 °C for Trondheim.



(a) (b)

Figure 1. (a) Floor plan (dashed lines show the delimitation of the modelled zones) and (b) sketch of the studied building

2.2. Energy system

A ground source heat pump (GSHP) connected to a horizontal ground heat exchanger (hGHE) and solar thermal collectors provides heating energy to a water storage tank (for both, space heating and DHW). All components are commercially available products. For such a highly-insulated building, the DHW demand is dominant over the space-heating needs [10]. The GSHP has 3.2 kW (0/35°C) nominal power and a COP of 3.7. If the water temperature has to be heated to 55°C, the nominal power and COP are 2.6 kW and 3.0 respectively. It is a one-stage heat pump cycle where the water is recirculated through the heat pump until it reaches 55°C. The water tank consists of a 240 litre DHW tank installed on the top of a 160 litre SH tank [11]. Depending on which part of the water tank is heated up, the temperature supplied by the heat pump changes. The total tank height is 1990 mm and the inner diameter is 580mm. Each of the tank parts has one auxiliary electric heating coil with a capacity of 3 kW [5]. The hGHE is a 150 m long surface collector field and is used as the heat source to the GSHP. The energy gained from the flat-plate solar thermal collector (STC) can either be used to recover the ground temperature of the hGHE or for heating the water in the tank. The STC is installed at the south façade and has an area of 4.2 m²

and an optical efficiency of 82%. The photovoltaic (PV) system consists of 48 polycrystalline panels and has a total installed power (DC) of about 12.5 kW. The panels have a rated efficiency of 16% [5]. There are two possible water-based heat distribution system (HDS) installed in the LL, a radiator with a design supply temperature of 55°C and a floor heating (FH) system with a design supply temperature of 33°C. On top of this, heating by ventilation air is also possible by increasing its temperature up to 40°C. There are eight different FH loops in the LL, which are usually used to heat up the building, and which can be run independently. The radiator, which is installed at the wall in the middle of the building, is only used, when FH is not used. The LL is equipped with a balanced mechanical ventilation system. The air handling unit (AHU) has a rotary heat wheel with nominal heat recovery efficiency of 85%. The AHU has a nominal flow rate of 120 m^3/h.

3. Rule-based control strategies

3.1. Working principle of rule-based controls

Rule-based control (RBC) strategies use pre-defined conditions (or decision rules) to change the current state of a system. Regarding HVAC systems, these pre-defined conditions can be set-points for indoor temperatures or indoor CO_2 levels. In case of a decreasing indoor temperature, the heating system is started as soon as a pre-defined set point for the lowest indoor temperature is reached and hence the zone is heated up. RBCs are commonly used for testing different scenarios in order to optimize the energy use of HVAC systems or to improve the energy flexibility towards the grid [2] [12]. The strategies can be easily implemented into dynamic building simulation tools, such as IDA ICE.

Regarding energy flexibility towards the power grid, RBC strategies can be coupled with electricity prices in order to investigate load-shifting scenarios where the electricity demand is moved to off-peak hours by activating thermal energy storages. The electricity prices follow the electricity production and can change significantly throughout the day. Practically, knowing these changes, RBC strategies can be used to preferentially run the heating system during low-price hours. Figure a shows the trend of the electricity spot price in Trondheim as well as the electricity production of the NO3 region throughout two exemplary days during 2015. Trondheim is situated in the NO3 region which is one of the five bidding areas of the power market in Norway [13]. Even though the electricity production of the grid is in the same range for the two exemplary days, the electricity price levels are significantly different (Figure a). The trend of the electricity production does not necessarily show a pre-dominant trend for the period of the year. In addition, RBC strategies considering these price variations can lead to economic savings for the electricity consumer. Low and high thresholds can be introduced in order to increase or decrease a temperature set-point depending on the spot price. The principle is illustrated in Figure b. Similar ideas have been proposed by Dar et al. [14] and Georges et al. [2] as a measure to describe flexibility of the heating system. In this study, it is examined how much energy flexibility can be provided by the GSHP in combination with a water storage tank depending on different control strategies. The corresponding cost savings for the building operation are also compared.

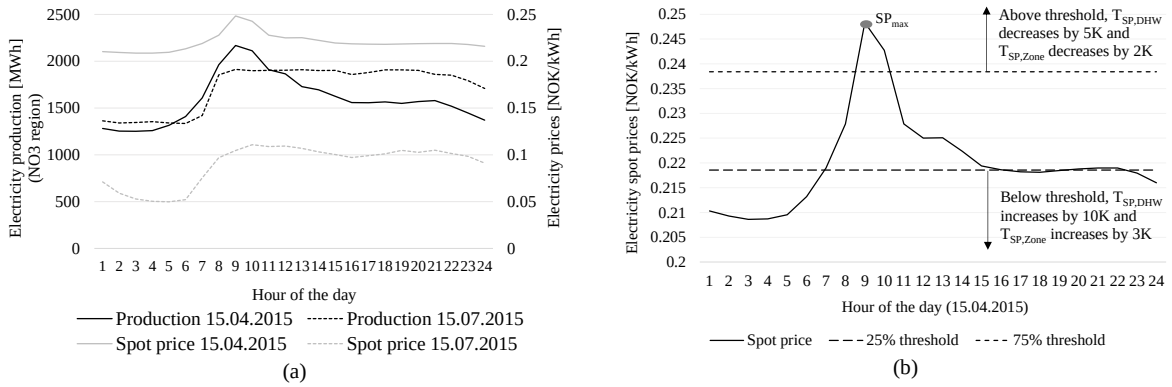


Figure 2. (a) Electricity spot prices throughout two exemplary days [13] and (b) principle of heating control based on electricity spot prices

3.2. Investigated strategies

Nine different rule-based control strategies for the heating system are investigated (here termed C1 to C9). C1 is a constant set-point heating and is used as the reference case since it is a common way to operate passive houses.

C2 investigates intermittent heating (time-scheduled set-points) even though it is usually not recommended for passive houses (due to the power needed to restart the building after a night setback). C3, C4 and C5 investigate peak-shaving strategies assuming that the peak in the power grid is between 7a.m. and 10a.m. C6, C7 and C8 are based on the electricity spot price with the aim of shifting the electricity consumption to low-price hours. C9 aims at increasing the PV self-consumption. The investigated control strategies are:

- C1, constant set-points (CS): The set-point of the indoor temperature is 21°C in the common rooms (hall-way and kitchen) and is kept constant at all times. The set-point temperature is 19°C for the bedroom and 24°C in the bathroom, considering the bathroom door is closed at all times. The set-point temperature for stored DHW is 55°C.
- C2, intermittent heating (IH): The indoor temperature set-point is 21°C during the day (6a.m.-10p.m.) and 18°C during the night for the common rooms. For the bathroom, it is 22°C during unoccupied times (0a.m.-5a.m. and 10a.m.-4p.m.), otherwise 26°C. The temperature set-point for the bedrooms is 16°C from 9p.m. to 6a.m. and 19°C during the day. The set-point temperature for the stored DHW is 55°C.
- C3 (OP/DHW): The DHW tank is pre-heated before typical peak hours. The set-point of the DHW tank is increased to 65°C during periods preceding peak power (5a.m.-6.30a.m.) and decreased to 50°C during peak periods in the grid (6.30a.m.-9.30a.m.). The temperature set-points for SH in the different zones are the same as in C1.
- C4 (OP/SH): The building thermal mass is activated before typical peak hours. The GSHP is supposed to run before the peak hours in the power grid (between 4a.m.-6.30a.m.) by increasing the SH set-point temperature in the common rooms by 3K. To decrease the consumption during peak power periods (7a.m.-10a.m.) the set-point temperature is decreased to 19°C. The DHW set-point remains at 55°C without any load shifting.
- C5 (OP/DHW&SH): This control combines C3 and C4 where both, the DHW storage tank and the thermal mass are activated.
- C6 (SP/DHW): The DHW tank is charged as a function of the electricity spot price. The control of the heat pump includes electricity day-ahead prices with constant thresholds for low prices and high prices for one full day. Each day at midnight the new thresholds are determined by taking into account the spot prices of the day ahead. The thresholds are set at 25% and 75% of the difference between the minimum and maximum spot price of the day above the minimum price of the day ahead, respectively (see Figure b). If the spot price of the current hour is below the daily low-price threshold, the upper temperature set-point of the DHW tank is increased from 55°C to 65°C. If the spot price of the hour is above the high-price threshold, the upper temperature set-point in the tank is decreased from 55°C to 50°C, so that the heat pump starts heating later and thus consumes less energy at high prices. If the spot price is between the two thresholds, the DHW set-point remains at 55°C. The temperature set-points for SH in the different zones are the same as in C1.
- C7 (SP/SH): The thermal mass is charged based on the electricity spot price. The same principle as for DHW heating in C6 is implemented for the zone heating. During high-price periods the set-point temperature is decreased by 2K and during low-price periods it is increased by 3K. This temperature control is done in the floor and kitchen. Even though the low prices typically occur during the night, a control for increasing the temperature set-point in the bedrooms is not desired for practical reasons. The DHW remains at 55°C.
- C8 (SP/DHW&SH): This control combines C6 and C7 allowing changes for both set-points. The principle is shown in Figure b.
- C9 (PV/SC): Increase of the water storage tank temperature based on on-site PV generation to increase electricity self-consumption. The temperature set-point of the water storage tank is increased by 10K as soon as the PV generation is above 860 W. This value is chosen to make sure that the heat pump runs continuously (without frequent on/off) which requires to run above 30% of the nominal compressor capacity. A power of 860 W considers electricity consumption for lighting, appliances and the compressor and was chosen because the software distributes on-site PV generation equally among all consumers.

4. Modelling approach

4.1. Simulation software tool

The building simulation is carried out in IDA ICE 4.7.1. IDA ICE is a dynamic multi-zone simulation software, which enables the user to investigate the energy consumption or the indoor thermal climate of a building. The software applies equation-based modelling [15].

4.2. Complexity of the model

The model of the building envelope can be validated by comparing the annual net SH needs [kWh/(m^2·a)] to the NS3700 standard. The SH demand of the building model of IDA ICE is 27.0 kWh/(m^2·a) and thus the envelope model is reasonably accurate compared to 26.9 kWh/(m^2·a) calculated in equation (1).

The parameters of the heat pump model should be optimized to be consistent with manufacturer data at nominal conditions. The best fit is obtained when the error between the computed condenser and compressor power and the manufacturer data is minimal. With the help of parametric runs in IDA ICE it is possible to change the parameters (termed B, C, E and F) of the IDA ICE heat pump model. The optimization is then done using GenOpt. Other assumptions and simplifications are presented in Table 2. In general, idealized models for the components of the energy system are applied.

Table 2. Modelling assumptions and simplifications of the study.

Parameter	Model assumption/simplification
Indoor temperature set point	Chosen manually, depending on the control strategy
Internal gains	According to NS3700
Occupant behaviour	Synthetic occupancy schedules and Finnish DHW consumption profiles are used
Energy system model	Hot water tank: idealized tank combining DHW and SH with a volume of 400 litres
	GSHP: IDA ICE heat pump model with continuous power modulation from 0 to 100% and no maximum temperature limitation; nominal capacity is 4.54 kW with COP 4 (not the real heat pump installed in the LL)
	PV: constant panel efficiency (16%) throughout the year
	Solar thermal: constant collector efficiency throughout the year
	HDS: only floor heating is applied
	AHU: real ventilation flow rates which were measured in the building
Weather data	TMY data from Trondheim (Værnes) is used
Electricity prices	Hourly electricity spot prices for Trondheim in 2015 plus additional fees on top of the spot price

4.3. Occupant behavior

Occupants have different behavior in terms of occupancy patterns, SH set-point temperature, DHW needs, lighting and electrical appliances, resulting in different energy usage. The Norwegian passive house standard NS3700 defines time-constant SH set-point temperatures as well as space-uniform internal gains (from lighting, electrical appliances and occupants) to determine the net SH needs. For a same thermal comfort level, set-point temperatures can deviate from these fixed standard values as long as the indoor operative temperature corresponds to the same PMV level [16]. In order to be more realistic, different occupancy profiles are defined for this study (see Table 3). These synthetic profiles are meant to describe a realistic day rhythm of a four-person-family. The parents are both working and the children are going to school.

Table 3. Synthetic occupancy profiles defined for this study.

Room	Occupancy	
	Weekdays	Weekends
Kitchen	Occupied from 7-9am (0.5) and 17-19pm (0.5)	Occupied from 9-11am (0.5), 13-14pm (0.5) and 17-20 (0.5)
Floor	Occupied from 7-9am (0.5) and 18-20pm (0.5)	Occupied from 9-11am (0.5), 13-14pm (0.5) and 18-21pm (0.5)
Bedrooms	Occupied from 22pm-8am (1)	Occupied from 22pm-9am (1)
Bathroom	Occupied from 7-9am (0.5) and 19-22pm (0.1)	Occupied from 9-11am (0.5) and 19-21pm (0.1)

A realistic DHW consumption profile is included in the model. It is based on hourly consumption profiles for DHW in detached houses in Finland [17]. Because of the similar climate conditions it is assumed that the same profile can be applied for Norway. Comparing it to other DHW consumption data found in [17], the chosen profile seems to be a representative user profile. The corresponding DHW demand for a 4 persons household adds up to 29.8 kWh/(m^2·a) which is comparable to the Norwegian Standard NS3700.

4.4. Presentation of the applied key performance indexes

Eight key performance indexes are used to evaluate the effect of the investigated control strategies:

- The net heating needs including SH and DHW presented in kWh/(m^2·a).
- The annual energy use for heating is the energy input to the heating system [4], here the delivered electricity to the compressor of the heat pump and the electric resistances.
- The energy costs during operation are based on the delivered and exported energy to the building. It results from the energy use for lighting, electrical appliances, fans and pumps as well as for the heat pump and the electricity production from PV. Two different cost scenarios are presented: one scenario without any feed-in tariff for the exported electricity from PV and one scenario with a feed-in tariff being the hourly electricity spot price. The energy costs are calculated for each hour *i* (n=8760 hours i.e. 1 year) by

$$E_{Cost}\left[\frac{NOK}{year}\right] = \sum_{i=1}^{n} E_{del,i.}\,[kW] \cdot 1h \cdot Price_{el.,i}\left[\frac{NOK}{kWh}\right] \quad (2)$$

  A negative cost means that money is earned by feeding electricity into the grid (for the cost scenario with a feed-in tariff). The variable electricity prices consist of the spot prices and additional fees. The additional costs depend on the size of the installed fuse of the building and on the energy consumption of the building. A single-family building usually has a 63A fuse with 230V. For this fuse, the energy price that has to be paid on top of the spot price is 0.40 NOK/kWh (in 2015) [18]. Both prices are considered in the energy cost analysis. The different heating scenarios will lead to different annual electricity costs, since the additional fee depends on the energy consumption.
- The amount of energy in kWh/(m^2·a) which is delivered to the building during the peak hours of the grid. Here, the peak hour period of the power grid is assumed to be between 7-10a.m.
- CO_{2eq} balance on the operation of the ZEB: the balance is based on the delivered and exported energy. For constant and symmetric (same for import and export) CO_{2eq} factors, the annual emissions can be calculated by

$$Em_{op}\left[\frac{kgCO_{2eq}}{m^2 \cdot a}\right] = f(i) \cdot (Q_{exp} - Q_{del}) \quad (3)$$

  where Q_{del} is the annual electricity delivered to the building, Q_{exp} is the annual exported electricity from the building to the grid and f(*i*) is the annual averaged CO_2 factor. The CO_2 factor is assumed to be 0.132 kgCO_2 eq./kWh which is commonly used by the Norwegian ZEB Centre [19]. If Em_{op} is positive, the building achieves a "plus energy" balance for operation.
- Two indexes are used to characterise the grid interaction of the building. The *load cover factor*, also known as "*self-generation*", is the percentage of the electrical demand, which is covered by on-site electricity generation [20]. It can be calculated by

$$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt} \quad (4)$$

  where τ is the time resolution, g (t) is the on-site electricity generation, l (t) is the energy load and t is total time of observation. The time resolution is one hour and the total time period is one year. The *supply cover factor*, also known as "*self-consumption*", is the percentage of the on-site generation that is used by the building [20]. It is calculated by

$$\gamma_{supply} = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} g(t)dt} \quad (5)$$

  For the calculation of both indexes, energy storage balances, S(t), and energy losses, ζ(t), are neglected.
- The accumulated run time of the heat pump (duration curve) shows how many hours of the year the heat pump is running on a part load higher than 30% of the nominal compressor power. Since the heat pump is here modelled with an idealized power modulation from 0 to 100%, the absolute number of these hours does not have real physical meaning and thus rather gives an indication whether a control promotes on/off cycling or a more continuous heat pump operation.

5. Results

Compared to the reference case C1, each of the control strategies C2-C9 focuses on the improvement of at least one of the KPIs. The results are presented in Table 4. The results show that a trade-off between the performance indicators has to be made. It is not possible to achieve the lowest energy consumption and have the lowest energy costs, but at the same time improve the potential for energy flexibility. Activating the building flexibility requires storing heat at a higher temperature which most often leads to an increased energy consumption. The annual energy consumption for heating has been lowest for C2 (IH) being 17.9 kWh/(m^2·a), corresponding to an energy saving of 8%, but C2 also showed an increased energy consumption during peak hours. The highest energy use for heating occurred for C8 (SP/DHW&SH) with 24.4 kWh/(m^2·a). Lower operational costs were achieved with C2 (IH) and C9 (PV/SC) (14%).

Table 4. Comparison of the investigated control strategies (green for best case, red for worst case).

	Net heating needs $\left[\frac{kWh}{m^2 \cdot year}\right]$	Heating energy use $\left[\frac{kWh}{m^2 \cdot year}\right]$	Energy costs during operation $\left[\frac{NOK}{year}\right]$		Energy delivered to the building 7-10 $\left[\frac{kWh}{m^2 \cdot year}\right]$	Accumulated heat pump run time at P > 0.3 P_{nom} $\left[\frac{h}{year}\right]$	CO_2 eq. balance $\left[\frac{kg\ CO_2}{m^2 \cdot year}\right]$	Grid interaction indexes	
			w/o feed-in tariff	with feed-in t.				Self-gen.	Self-cons.
C1-CS	56.7	19.4	1645	-69	4.52	3150	8.93	0.52	0.23
C2-IH	54.7	17.9	1588	-133	5.34	2520	9.13	0.53	0.23
C3-OP/DHW	56.7	19.6	1731	-33	3.90	3120	8.91	0.48	0.21
C4-OP/SH	60.8	20.8	1717	12	5.01	3280	8.74	0.51	0.23
C5-OP/DHW&SH	60.6	20.9	1792	38	4.43	3430	8.72	0.48	0.21
C6-SP/DHW	56.9	22.2	2078	266	4.32	2740	8.56	0.41	0.19
C7-SP/SH	61.7	21.3	1733	66	4.99	3550	8.67	0.51	0.23
C8-SP/DHW&SH	61.7	24.4	2207	401	4.76	2890	8.26	0.40	0.19
C9-PV/SC	56.7	22.2	1414	-153	4.37	3220	8.55	0.61	0.28

Using pre-defined schedules for loading the thermal mass and the water storage tank before peak hours in the grid only had a limited effect on the load shifting. Loads were shifted only, if the peak hours were actually within the pre-defined peak hour period. C3 and C5 indeed led to slightly decreased energy consumptions during these peak hours. With the default tank implementation in IDA ICE, C4 (OP/SH) did not manage to activate the thermal mass before peak periods but rather transferred the energy from the storage tank to the floor heating system.

All price-based control strategies generated a higher energy consumption, unfortunately leading to increased total energy costs. This is due to the control principle. The controller strictly increased or decreased the set-point of the temperature in the common rooms based on the price, which means that, for example, the zone set-point temperature was kept at 24°C all night long until the price was above the low-price threshold. This led to a significant increase in energy consumption that is not compensated by the low electricity price. Although the electricity consumption increased for the price-based controls, it can be seen from Figure 3 that the price-based controls were able to actively shift the electricity consumption to low-price hours. C9 (PV/SC) had the lowest delivered energy consumption because self-consumption of the on-site generated electricity was prioritized and thus operational costs based in delivered energy were decreased.

Generally, the running time of the heat pump (Figure 4Figure 3) using on/off cycles could be reduced when using a control that increases the temperature set-point for DHW heating compared to a control, which used constant standard set-point temperatures throughout the day for a whole year (C1). Due to the idealized power modulation assumed in the heat pump model, results of when the heat pump is operated below 30% of the nominal capacity cannot be interpreted as this would lead to on/off cycles in reality. This limitation will be addressed in further studies. It can be seen from Figure 4 that the control strategies with varying DHW set-points promote a more continuous operation of the heat pump. The Living Lab achieves a positive CO_{2eq} balance reaching values between 8.3 and 9.1 ($kgCO_{2eq}$)/(m^2·a) and hence the building generates more on-site electricity than it consumes. The magnitude of these values are in agreement with studies from other Norwegian ZEBs [21].

C2 has the best CO_{2eq} balance because it has the lowest energy consumption. The annual self-generation of the building is 0.52 meaning that 52% of the electricity demand of the building can be covered by on-site electricity generation. The annual self-consumption is 0.23 meaning that 23% of the on-site generated electricity are used by

the building. Only C9 (PV/SC) is able to significantly improve both grid interaction indexes leading to a self-generation of 0.61 and a self-consumption of 0.28. The range of these grid interaction indexes are in good agreement with comparable studies on other net zero energy buildings [22].

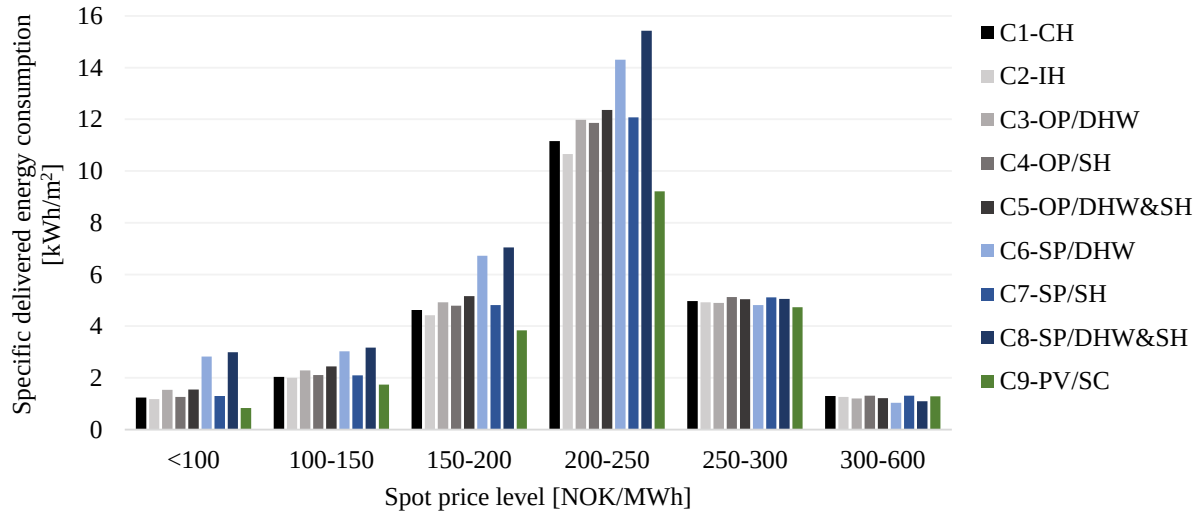


Figure 3. Specific delivered energy consumption per spot price level: average spot price during the space heating season was 210 NOK/MWh in 2015

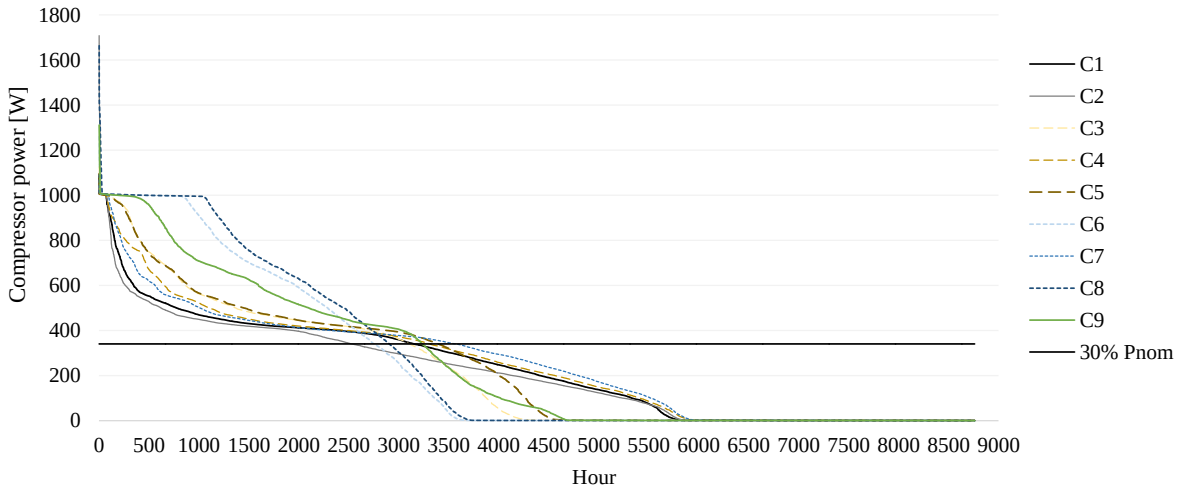


Figure 4. Duration curve of the heat pump (with idealized power modulation from 0 to 100%)

6. Discussion and conclusion

Nine rule-based control strategies for heating systems in a residential zero emission building have been investigated to assess their effect on different performance indicators. Three control strategies were based on pre-defined peak hours based on the power grid, whereas three other strategies were based on hourly electricity spot prices. One control promotes PV self-consumption in order to improve the grid interaction.

The controls for peak load shifting (C3-C5) managed to activate the water storage tank, but not the thermal mass of the buildings. Hence a better control for the activation of the thermal mass will be realized in the future. Furthermore, a control strategy based on the grid´s electricity generation will be implemented.

The price-based controls (C6-C8) successfully shifted the electricity consumption to low-price hours, but failed to achieve savings for annual operational costs. The control strategies with varying DHW set-points promoted a continuous heat pump operation and reduced the accumulated run time above 30% nominal capacity (C6 and C8).

Control strategy C9 proved to increase the self-generation as well as the self-consumption of the building and was thus able to improve the flexibility service to the grid.

Room temperature set-points of 19°C and 24°C were within the same PMV level (-1<PMV<1) (ASHRAE 55) and were thus assumed to be comfortable. Increased DHW set-points have a higher impact on load shifting than increased SH set-points due to the dominance of DHW needs in highly-insulated building envelope. The same control may not lead to similar conclusions for buildings with lower insulation levels. This study proves that a balance between a low energy consumption, energy costs, heat pump run time and a high load shifting potential has still to be found, for instance by advanced control strategies, such as MPC.

For further work, a more realistic heat pump control model will be implemented in this model. Up to now, the heat pump is used to heat up the DHW to 65°C, while in reality it would heat up the DHW to about 55°C and the last 10K temperature difference would be achieved by electrical resistance peak heating. Furthermore, a control based on the CO_2 intensity of the electricity generation in the power grid will be implemented in the model in order to address the aim of improving the CO_{2eq} emissions balance. Another control to be tested is the combination of C2 and the introduced price-based controls, as this will prevent high set-points during the night (usually low spot prices) and also to lower the number of start/stops of the heat pump. In addition, a sensitivity analysis against the lower and upper spot price thresholds (for the present price-based control) will be performed. Finally, the storage tank volume in combination with the heat pump capacity will be optimized for increased flexibility towards the grid.

Acknowledgements

This work has been performed in the framework of the IEA EBC Annex 67 Energy Flexible Buildings as well as IEA HPT Annex 49 Design and Integration of Heat Pumps for nZEB.

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