13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Energy flexibility of capacity-controlled air-source heat pumps using rule-based control in residential nZEB

Lukas Rominger[a], John Clauß[b,c], Carsten Wemhoener[a*], Laurent Georges[c]

[a]IET Institute of Energy Technology, HSR University of Applied Sciences Rapperswil, Oberseestrasse10, 8640 Rapperswil, Switzerland
[b]SINTEF Community, Høgskoleringen 7B, 7034 Trondheim, Norway
[c]Norwegian University of Science and Technology, Kolbjørn Hejes vei 1a, 7034 Trondheim, Norway

Abstract

The reduction of operational heating costs by deploying the building flexibility is investigated using a predictive rule-based control and building simulations. This paper focuses on the applicability of a proposed price-based control strategy in different buildings and climate zones where also electricity spot prices differ. More specifically, the operational costs of a heat pump system in a Norwegian and Swiss residential single-family house are compared. The aim of the price-based control is to shift the operation of an air-to-water heat pump to times when electricity spot prices are low. The results show, that the success of the control strategy with regard to operational cost savings is highly dependent on the hourly fluctuations of the electricity spot price. Furthermore, it is shown that also the design of the heating system as well as the chosen temperature set-points of the control influence the outcome substantially. Results show, that a 5% cost reduction can be achieved even though the electricity use increases.

Keywords: heat pump system; price-based control; capacity-controlled heat pump

1. Introduction

With the growing share of renewable energies in the electricity mix, demand side flexibility gets more important to enable the full potential of the renewables [1][2]. Heat pumps are more often applied to heat buildings and their share among other building heating systems is growing, especially in highly energy-efficient buildings [3]. The application of capacity-controlled heat pumps has become more common during the last decade as the increased efficiency during part-load operation leads to distinct benefits compared to on-off heat pumps. Detailed studies on heat pump systems are usually performed for one specific country, whereas there is a lack of studies that evaluate similar control approaches for heat pump systems for different countries.

Clauß et al. [4] tested different price-based control strategies for heating a residential building located in Norway. In their study, they evaluated price-based heating control strategies for different building insulation levels. The implemented price-based control aims at reducing operational costs by deploying the energy flexibility potential of the building. To evaluate how the heating strategies proposed by Clauß et al. work for the Swiss climate and Swiss national boundary conditions, the control strategies are applied to a Swiss building. The Swiss building is described in detailed in Rominger et al. [5], where different building insulation levels and thermal masses have been applied to the Swiss building.

2. Methodology

Two different residential buildings have been simulated. In a previous study, Clauß et al [4] studied a Norwegian residential single-family house using the dynamic building performance simulation tool IDA ICE

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[*] Corresponding author. Tel.: +41 55 222 43 25
E-mail address: carsten.wemhoener@hsr.ch

Version 4.8 The Swiss residential building is simulated using Matlab Simulink and the CARNOT-toolbox [6]. A brief comparison of both buildings in presented in Table 1.

It is mentioned here that there are distinct differences for the building and heating, ventilation and air-conditioning (HVAC) system models for the original Norwegian study and the study performed in this paper. The main differences are the building location, the building size and thus the load profiles and the layout of the HVAC system. The original work of Clauß et al. [4] considers a water tank for space heating (SH). In this study, the heat pump is in many cases connected directly to the floor heating (FH) system.

However, the same heat pump, HOVAL Belaria SRM 4, is chosen for both studies. To be able to provide a meaningful comparison of the results from this work and the previous work by Clauß et al. [4], the U-values of the building envelopes are aligned, as also shown in Table 2. The same price-based control strategies are implemented in both studies to research the effect of the spot price signals on the operational costs. Furthermore, the temperature set-points (TSP) for SH and domestic hot water (DHW) heating are varied (1) within the same range (+10 K; -5 K for DHW) to compare both case studies and (2) within a lower range (+3 K; -3 K for DHW) to also show the influence of TSP choices on the energy system performance and operational costs. The TSP for SH depends on the fact whether a SH storage tank is used or not.

Table 1. Comparison of the case study buildings.

Parameter	Unit	Norwegian (Clauß et al. [4])	Swiss
Area	m²	105	200
Floors	-	1	2
Basement	-	No	Yes
Window fraction	%	10	29
Number of persons	-	4	4
Location	-	Trondheim, Norway	Zurich, Switzerland

Figure 1 Pictures of Norwegian building (left) and the drawing of the Swiss building (right)

2.1. Building envelope

The characteristics of the building envelope are according to the Norwegian passive house (PH) standard for residential buildings, NS 3700 [7]. This building standard also requires a balanced mechanical ventilation with a heat recovery effectiveness of the air handling unit of 85% at nominal conditions. The constant air volume ventilation has a nominal air flow rate of 120 m^3/h and a supply temperature set-point of 19 °C. The Norwegian PH building is a wooden lightweight building. For the Swiss PH, the same building structures are used as for the Norwegian PH, but the geometry of the building remains the same. However, the basement of the Swiss PH is a concreate construction. The Swiss heavyweight construction (HC) building is designed to meet the new building requirements of Switzerland MuKEn 2014 [8]. Except for the roof, everything is in heavyweight construction. Table 2 summarizes the building envelope and HVAC characteristics.

Table 2. Insulation level and HVAC characteristic

Component	Parameter	Unit	Building insulation type		
			Norwegian	Swiss	
			PH	PH	HC
Building envelope	$U_{\text{exterior Wall}}$	W/(m²K)	0.10	0.10	0.16
	$U_{\text{inner Wall}}$	W/(m²K)	0.34	0.34	0.70
	$U_{\text{Basement Wall}}$	W/(m²K)	-	0.17	0.17
	U_{Roof}	W/(m²K)	0.09	0.09	0.15
	U_{Floor}	W/(m²K)	0.09	0.09	0.71
	$U_{\text{Floor Basement}}$	W/(m²K)	-	0.17	0.17
Infiltration	$V_{\text{dot,i}}$	ACH	0.6	0	0
Air exchange	V_{dot}	m³/h	120	96	96
Thermal bridges	ψ	W/(m²K)	0.03	0.02	0.02
Windows	U_{Total}	W/(m²K)	0.8	0.8	1.0
AHU	η_{HR}	%	85	80	80
Water tank	DHW	l	215	500	500
	SH	l	243	243	243
	$Q_{\text{dot,Aux,DHW}}$	kW	3	0	0
	$Q_{\text{dot,Aux,SH}}$	kW	9	0	0
SH needs	Q_{SH}	kWh/(m²yr)	34	19	27

2.2. HVAC system

The HVAC systems of the previous work by Clauß et al. [4] and this case study are slightly different. The main difference is the use of a SH tank. In this case study, two system layouts have been considered: (1) the heat pump is directly connected to the heat distribution system and (2) the heat pump is connected to a SH tank, like in the Norwegian study.

The HVAC system simulated in this study consists of an air-source heat pump that is connected to a DHW storage tank, while the heat pump is directly connected to a FH system to provide SH. The heat pump runs at full load in DHW mode, whereas it modulates between 30 % and 100 % of the nominal compressor capacity in SH mode. Regarding DHW mode for the Norwegian case study, at the beginning of a heat pump cycle the heat pump is operated at full load and the mass flow through the circulation pump is adjusted by a P-controller to meet the temperature set-point at the condenser outlet. As soon as the mass flow is at its maximum, the speed of the heat pump compressor is adjusted to stay close to the required DHW temperature set-point. In the Swiss building the DHW storage is charged by step-charging with a constant mass flow. For the SH, the mass flow is kept constant for both building cases while the heat pump modulates to achieve the required floor heating supply temperature. For the Swiss case study, the FH supply temperature is kept constant throughout the whole year and is not dependent on the outdoor air temperature. A simplified sketch of the heating system configuration is presented in Figure 2.

For the case where a SH tank is used, the volume of the SH storage tank is aligned to the volume of the previous Norwegian case study, being 243 liters (l). However, the DHW storage tank of the Swiss buildings has a chosen capacity of 500 l, compared to 215 l for the Norwegian case study. To ensure a minimal tapping temperature of 45 °C, the heat pump switches on as soon as the temperature at a relative tank height of 0.8 drops below 50 °C. The heat pump is switched off again as soon as the temperature of 50 °C is reached at a relative tank height of 0.4. For the Swiss building, the internal heat exchanger is placed at the bottom of the DHW storage tank. The same strategy as for the DHW storage tank is used for the SH storage tank with a temperature set-point of 30 °C and relative heights of 0.8 and 0.2. For the cases without a SH storage, the heat

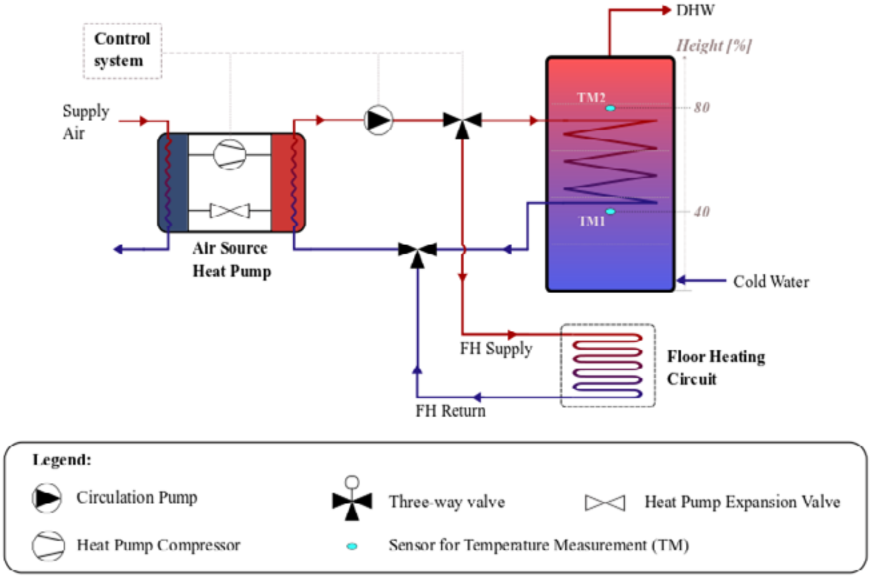

Figure 2. Configuration of the heating system

pump is switched on based on the room temperature. The temperature set-point (TSP) of the room is 21 °C with a hysteresis of 2 K.

2.3. Power sizing

The performance map of the selected air-source heat pump HOVAL Belaria SRM 4 is shown in Figure 3.

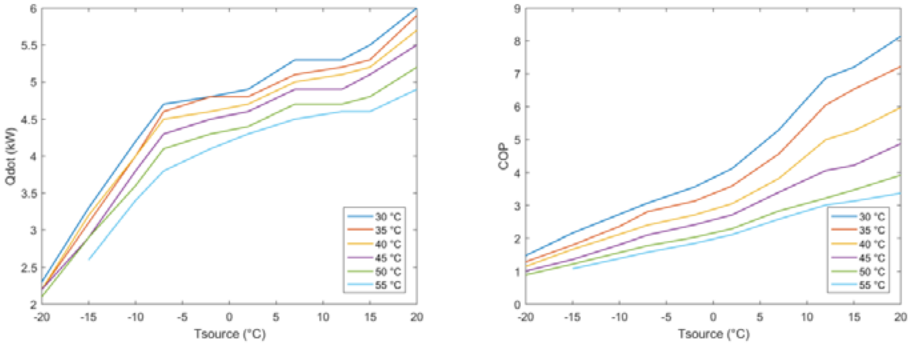

Figure 3. Performance map of HOVAL Belaria SRM 4 at 100 % compressor speed

The heat pump is designed for a monovalent operation, but it can be used as a bivalent/mono-energetic system where an auxiliary heater would cover peak loads. In Switzerland, a heat pump is designed for monovalent operation according to the building regulation, which does not allow bivalent heat pump systems with a direct electric heater. In Norway, a heat pump system can also be sized as a bivalent system. This difference will be important when comparing the price-based controls of both studies in Section 5.

For all cases, the same heat pump is used, although the heat pump is generally oversized for the PH cases. However, since there are no heat pumps on the market, which are significantly smaller than the chosen one, it seems to be a realistic assumption that this heat pump can also be applied to PH cases.

To simulate the inverter-controlled behavior, the heating capacity of the heat pump can be controlled from 30 % to 100 % of its maximal capacity, while the mass flow of the floor heating circuit is kept constant. The detailed control strategies are described by Clauß et al. [4] and Rominger et al. [5]. For the sake of simplicity, the COP increase during part-load operation is not modeled. The COP is held constant over the whole part-load range.

2.4. Boundary conditions

Weather data as well as electricity spot prices were taken for one year. In the previous study by Clauß et al. [4], simulations were performed for the year 2015, whereas this Swiss case considers the data for 2018. By using spot prices and weather data from the same year, it can be ensured that possible weather dependencies of the electricity price are taken into account.

For the Swiss cases the internal user profiles for occupancy and electric appliances (including lighting) are taken from the Reference Framework for System Simulations [9]. However, these profiles are scaled according to the pre standard SIA 2024 [10] for single-family houses.

Based on Fanger`s Predicted Mean Vote (PMV) / Predicted Percentage Dissatisfied (PPD) method, it is assumed that indoor operative temperatures can be varied between 20 °C and 24 °C while still keeping a similar comfort level. According to EN15251:2007 [11], this temperature range corresponds to $-0.5 < PMV < 0.5$ and a $PPD < 10\%$ for a clothing level of 1.0 and an activity level of 1.2 MET.

3. Simulation scenarios

3.1. Reference strategy

In the reference case, called business as usual (BAU), temperature set-points for DHW heating and SH are kept constant at all time at 50 °C and 21 °C, respectively. Constant temperature set-points are chosen for the reference scenario, because heating systems in residential buildings are usually controlled in this way.

3.2. Control Strategy Price, CSP

This work investigates demand response scenarios, where the DHW and SH set-points are modulated depending on the hourly spot price. Electricity spot prices vary throughout the day, which means that operational costs could be reduced, if a heating system is operated during low-price periods and/or if the operation during high-price periods is avoided. The TSPs for SH are either increased by 3 K or decreased by 1 K depending on the current spot price and the spot price trend for the next 24 hours. In the case without a SH storage, the switch-off hysteresis is decreased by 1 K during high-price periods. Therefore, the heat pump switches off earlier. On the contrary, the temperature set-point is increased by 1 K during low-price periods. Two temperature ranges for TSP variation are investigated for DHW: (1) the TSPs for DHW heating are increased by 10 K or decreased by 5 K, or (2) the TSPs are increased or decreased by 3 K respectively. The capacity control of the heat pump is not affected by the price signal.

To generate the price-based control signal, two principles are applied and compared, control strategy price principle (a), CSP-a and principle (b), CSP-b. Both principles are illustrated in Figure 4 [4]. The spot price of the prospective 24 hours can be divided into three price segments (i.e. low, medium and high price segments) using two price thresholds. The heating set-points can then be adjusted based on the spot price of the current hour relative to the price segment. A 24 hours sliding horizon is considered to determine a low-price threshold (LPT) and a high-price threshold (HPT). The determination of the thresholds follows the approach presented in [4]: describing the maximum and minimum spot prices for the next 24 hours as SP_{max} and SP_{min}, the HPT can be determined by $SP_{min} + 0.75\,(SP_{max} – SP_{min})$ and the LPT by $SP_{min} + 0.30\,(SP_{max} – SP_{min})$. The choice of thresholds is important for the operation of the heating system, as different thresholds will lead to a different number of hours per price segment and thus the respective heating set-points.

CSP-a aims at charging the thermal storage during periods with the lowest prices and simply increases TSPs when the current price is below the LPT and decreases TSPs as soon as the current spot price is above the HPT.

CSP-b aims at charging the thermal storages just before high-price periods. For this case, the control signal is also based on the three price segments and additionally considers whether the spot price will be increasing or decreasing in the next two hours. The TSPs are increased, if the current spot price is between the two thresholds and if the spot price is increasing the next two hours. On the contrary, the temperature set-points are decreased, if the current spot price is between the HPT and LPT and is decreasing the next two hours. The TSPs remain at the reference set-point if the current spot price is below the LPT.

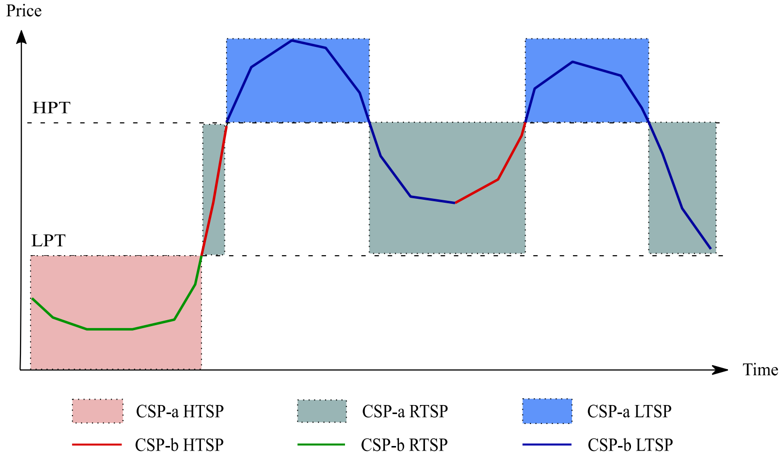

Figure 4. Determination of price-based control signals for control strategies CSP-a and CSP-b (HTSP – High temperature set-point, RTSP – Reference temperature set-point, LTSP – Low temperature set-point) [4]

4. Key performance indicators

The results are evaluated with the help of the following key performance indicators (KPI):

- Annual energy use for heating in kWh, consisting of the delivered electricity ($El_{del,i}$) to the heat pump compressor
- Annual heating costs for the operation of the heat pump system, calculated by

$$E_{Costs}\left[\frac{€}{year}\right] = \sum_{i=1}^{n} El_{del,i}[kW] \cdot 1h \cdot Spot\ Price_{el,i}\left[\frac{€}{kWh}\right] \qquad (1)$$

Other performance indicators such as primary energy or CO_2-emissions are not considered in this study.

5. Results

It is shown in Table 3 that CSP-a performs better than CSP-b for the Swiss case study, whereas in Norway CSP-b shows a better performance than CSP-a. For all cases, the used electrical energy increases with the CSP compare to the BAU. That is obvious, since TSP are increased to charge the thermal storages when electricity prices are low. Higher storage temperatures also lead to higher storage losses and lower COP for the heat pump (as a result of higher temperature lift).

It is possible to reduce the energy costs with CSP-a using the Swiss spot prices. Applying the Norwegian electricity spot prices to the Swiss building and energy system, the annual operational costs increase. It can therefore be concluded that CSP-a works well, if the spot price varies strongly enough. The Swiss spot price in 2018 has a difference from the average to the 0.75 quantile and the 0.25 quantile of 10.8 €/MWh respectively 11.0 €/MWh. Whereas the Norwegian spot price only varies 5.9 €/MWh respectively 6.0 €/MWh from the average spot price to the 0.75 quantile and the 0.25 quantile. However, also with the Swiss electricity prices, the measure of increase and decrease of the TSP is decisive for a decrease of the costs.

With the comparison between the Swiss PH with and without a SH storage it can be determined that the cost reduction is bigger without a SH storage tank. This is due to the fact that the thermal heat storage capacity to which the heat pump is connected to, is bigger for the building thermal mass compared to the SH storage tank, although the building thermal mass is also for the case with the SH storage tank indirectly connected to the heat pump. The higher thermal mass of the Swiss HC compare to the Swiss PH does not lead to an increase in cost savings. Furthermore, the Swiss electricity spot prices in combination with CSP-b do not cause cost savings.

In the Norwegian case study by Clauß et al [4], a bivalent heat pump system was used. They found that the electric auxiliary heater operated more often, if price-based control strategies were applied for both, SH and DHW heating, which was due to the fact, that the heat pump prioritized DHW heating over SH. If there was a demand for DHW and SH at the same time, the heat pump was heating DHW and the electric auxiliary heater provided SH.

Table 3. General Results (PH – Passive house, BAU – Business as usual, CSP – Control strategy price, SH – space heating, SPF – Seasonal performance factor, NSP – Norwegian spot price, SSP – Swiss spot price, Swiss HC – Swiss solid construction)

Set points	Building	Spot price	Control strategy	Electrical energy		Cost	
				kWh	%	NOK*/€	%
Variant 1 (TSPs for DHW +10 K or –5 K)	Norwegian PH	NSP	BAU	2199	-	484*	-
			CSP-a	3057	+39	605*	+25
			CSP-b	2657	+21	585*	+21
	Swiss PH with SH Storage	SSP	BAU	1741	-	93	-
			CSP-a	2050	+18	97	+4
			CSP-b	2006	+15	107	+15
	Swiss PH without SH storage	SSP	BAU	1760	-	95	-
			CSP-a	2063	+17	94	-1
			CSP-b	1992	+13	107	+13
	Swiss PH without SH storage	NSP	BAU	1760	-	744*	-
			CSP-a	2084	+18	816*	+10
			CSP-b	1974	+12	829*	+11
	Swiss HC without SH storage	SSP	BAU	2109	-	115	-
			CSP-a	2428	+15	116	+1
			CSP-b	2345	+11	127	+11
Variant 2 (TSPs for DHW +3 K or –3 K)	Swiss PH	SSP	BAU	1741	-	93	-
			CSP-a	1850	+6	90	-3
			CSP-b	1822	+5	95	+2
	Swiss PH without SH storage	SSP	BAU	1760	-	95	-
			CSP-a	1871	+6	88	**-7**
			CSP-b	1805	+3	95	+0
	Swiss PH without SH storage	NSP	BAU	1760	0	744*	-
			CSP-a	1897	+8	756*	+2
			CSP-b	1803	+2	747*	+0
	Swiss HC without SH storage	SSP	BAU	2109	0	115	-
			CSP-a	2226	+6	109	**-5**
			CSP-b	2162	+2	116	+1

6. Conclusions

The results of this paper show that a sufficient hourly fluctuation of the spot prices is necessary to achieve cost savings for the proposed demand response strategies. The additional energy use due to charging the thermal energy storages are only outweighed, if the difference in the electricity spot prices are sufficient. However, a stable electricity price indicates, that there is no incentive for a price-based control.

Since the total electrical power of all the electrical heat pumps in Switzerland is about 1.5 GW [12] and the maximal electricity power of the hydro storage power plants are 11 GW [12] it is hard to say how much the spot price would be influenced, if all heat pumps would use the CSP-a controller. In addition, the Swiss electrical grid is well connected with its neighbours, which makes it even more difficult to predict the influence of the CSP-a control on the spot price.

This study confirms the conclusions found by Fischer et. al. [13]. The success of a demand response strategy is highly dependent on the sensor position and the control strategy to run the heat pump. In the Norwegian case, with the lower sensor being positioned relatively high in the SH storage, the potential of shifting the load is limited. However, for the Swiss building and HVAC layout, the best results were achieved for a system without a SH storage tank. Due to the fact that the thermal mass of the building is bigger than the thermal mass of the water storage tank and the building thermal mass is directly accessible, more energy can be shifted for the case without a SH storage tank. For the Swiss PH with its lightweight structure there is no need of a SH storage tank regarding the run time of a capacity-controlled heat pump. Therefore, in this case an HVAC system layout without a SH storage tank is preferable.

Furthermore, the procedure/regulations for sizing a heat pump are an important factor that influences the success of a control strategy. For the Norwegian case study by Clauß et al. [4], the system was designed as a bivalent system with a direct electric heater as an auxiliary heater. On the contrary, building regulations in Switzerland do not allow bivalent sizing of the heat pump with a direct electric heater. Therefore, the efficiency loss due to higher TSPs is smaller in Switzerland than in Norway, where it is possible to run the heat pump and the direct electric heater at the same time to provide DHW heating and SH. Thus, for a bivalent heat pump system, the price-based control strategy should be improved to prevent the electric heater from switching on too frequently. Regarding the choice of the TSPs and their influence on the operational costs, it can be concluded that a too large TSP variation lowers the efficiency too much so that it impairs the operational cost savings. This also shows that the potential cost savings with a sensible heat storage is limited, due to the efficiency decrease with temperature increase. Therefore, a latent heat storage might be suitable to increase the flexibility and the operational cost savings, if the charging and discharging power of it is sufficient.

Acknowledgements

The authors would like to acknowledge the international research collaboration "IEA HPT Annex 49 - Design and Integration of Heat Pumps for nZEB" which provided the framework for this work. The support and funding of the IEA HPT Annex 49 by the Swiss Federal Office of energy SFOE is highly acknowledged.

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