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Quantification of electrical load flexibility offered by an air to water heat pump equipped single-family residential building in Sweden

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Abstract

Heat pumps are widely used in Swedish single-family houses for space and water heating applications, of which the most common is air-to-water heat pumps. Today, there is an increase in the variability and uncertainty of electricity production due to an increment in the share of electricity generation by intermittent energy sources. Hence, as opposed to the conventional power system operation, there is variability and uncertainty in electricity consumption and production. One possible way of addressing the challenge of balancing the power system is by using heat pumps as a flexibility resource. In this regard, this study quantifies the flexibility potential by developing and integrating a mathematical model of an air-to-water heat pump with the thermal model of a building with a standard way of space heating i.e., radiator heating. The result from this study will provide an estimate of flexibility levels from space heating, in terms of varying levels of reduced electricity consumption as a function of indoor temperature, during different outdoor ambient temperatures. Furthermore, the result of this study helps in employing suitable measures for demand-side-management to support the power system during severe problems.

Keywords: Air-to-water heat pump, Flexibility, Single family residential building, Intermittent energy sources, Power system ;

1. Introduction

The role of electricity is significant for social and economic development. In Sweden, increasing emphasis to reduce greenhouse gas emissions has resulted in a transition of electricity production from conventional fossil fuel-based power plants towards renewable-based power plants[1] i.e., the share of electricity production from wind and solar is increasing. However, the electricity production from these sources is highly intermittent in nature. As a result, in the current power system, there is variability as well as uncertainty in both electricity consumption and production, as opposed to the conventional power system. Hence, one of the major challenges is to ensure the balance between the electricity supply and consumption for hassle-free operation of the power system, especially during power deficit conditions.

Currently, in the scientific literature, a holistic approach is adopted to address the challenge of ensuring the balance between electricity production and consumption in the current as well as future power systems. Most of the technologies like fuel cells and converters aim at making the electricity production side much stronger. However, they have limitations and involve high investment costs [2][3]. On the other hand, several studies focus on reducing electricity consumption during power deficit conditions, often known by the terms demand-side-management and flexibility studies.

Focusing on the total electricity consumption in Sweden, 58 % of it is from the residential and service sector [4]. Moreover, the total electricity consumption in single-family residential buildings is around 4 to 4.5 times higher compared to the multifamily dwellings [5] and mostly electricity is used for space as well as water heating applications, with an air source heat pump as the most common type [6]. The air source heat pumps are mainly of two types namely, air-to-air and air-to-water heat pumps. Another category of air source heat pump is the exhaust air heat pump (mainly air-to-air but air-to-water also available). This could be used for providing additional heating based on the insulation level and the needs of the building [7]. As water-based heating with radiators is the most common in Sweden, a single-family residential building equipped with an air-to-water heat pump, will be the focus of this article for quantifying the flexibility potential. In this study, flexibility refers to the reduction in the electricity consumption for space heating, to support the electric power system during power deficit conditions.

To use an air to water heat pump as a flexible load, it is important to have information regarding its performance, indicating the quantity of heat delivered, temperature at which heat is rejected, speed and electricity consumption of the compressor, during different outdoor ambient temperatures. Unfortunately, the heat pump manufactures will provide the relevant information only at standard Air Conditioning and Refrigeration (ARI) conditions, where the performance will be optimized. In this regard, in most of literature dealing with demand side management and flexibility studies, the model of air source heat pumps is simplified, where Coefficient of Performance (COP) is only considered as a constant value or as function of outdoor ambient temperature. Furthermore, the variable speed heat pump is assumed to be perfectly modulating between 0 and 100% as the limitations posed by the operating envelope of the compressor in terms of speed and condensor temperatures are not accounted [8][9][10].

Thus, with this background, the purpose of this article is to quantify the potential for flexibility from space heating in a building equipped with an air-to-water heat pump, by obtaining the heat pump's performance, considering the compressor's rating, and operating envelope during different outdoor ambient temperatures to fulfill different heating requirements in the building. The main contribution of this study is that the flexibility quantification serves as valuable information to ensure resilient operation of the electricity grid during power deficit conditions.

2. Methodology

This section describes the method to quantify the heat delivered by a variable speed air-to-water heat pump as a function of condensor and evaporator temperatures together with the speed of the compressor and outdoor ambient temperature, using vapour compression heat pump cycle. This will be followed by the description of the method to obtain the thermal model of a building.

2.1. Vapour compression heat pump cycle

The main components of a heat pump and its operation based on the actual vapour compression cycle, represented on a pressure-enthalpy diagram is shown in figure 1. The four processes involved in this cycle are heat absorption by the refrigerant in the evaporator, compression of the refrigerant by the compressor, heat rejection by the refrigerant in the condensor and the expansion of the refrigerant in the expansion valve.

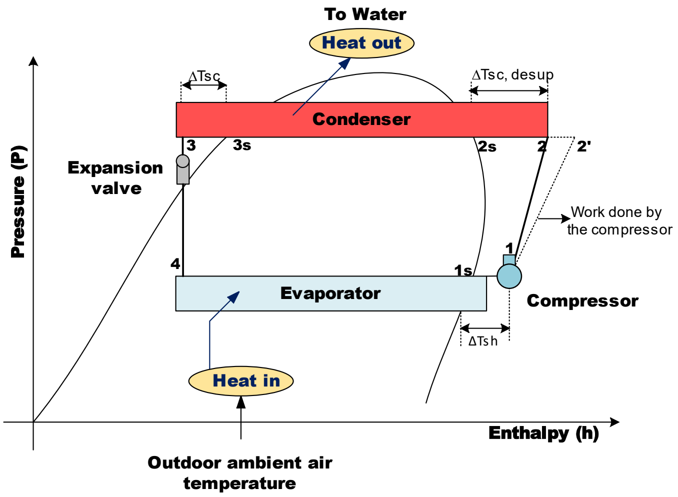


Figure 1: Vapour compression heat pump cycle

The procedure for evaluating the heat delivered and COP is as follows:

- The pressure in the evaporator is determined using the information of the temperature at which evaporation occurs and the quality (100% for saturated vapour (1s)) of the refrigerant.
- The temperature for superheating (ΔT_{sh}) is assumed to be 5K. The enthalpy 'h_1' is determined using the details of the superheated temperature of the refrigerant and the pressure in the evaporator (pressure is assumed to be constant in the evaporator). Also, the entropy and density are determined at the same condition.
- The process of compression is assumed to be isentropic. So, the entropy of the compressed vapour is assumed to be same as that of the vapour at the outlet of the evaporator.
- The pressure in the condensor(pressure is assumed to be constant in the condensor) is determined using the information of the temperature at which condensation occurs and the quality (0 for saturated liquid (3s)) of the refrigerant.
- The temperature of the compressed vapour is determined using the details of pressure in the condensor and entropy of the compressed vapour.
- The mass flow rate of the refrigerant in $\left(\frac{kg}{s}\right)$ is calculated as
$$\dot{m} = \frac{V_{dis}\,\rho_s\,f\,\eta_{\mathrm{vol}}}{10^6}$$
where, 'V_{dis}', 'ρ_s' , 'f' and 'η_{vol}' are the compressor displacement volume $\left(\frac{cc}{rev}\right)$, density at suction $\left(\frac{kg}{m^3}\right)$, compressor speed (Hz) and the volumetric efficiency respectively[11] .
- Using the information of the entropy and temperature of the compressed vapour, the enthalpy 'h_2' $\left(\frac{kJ}{Kg}\right)$is determined. The work done by the compressor to perform the compression is calculated using
$$\dot{W}_{comp} = \frac{\dot{m}(h_2 - h_1)}{\eta_{isent\_speed}}$$
where, '$\eta_{\mathrm{isent\_speed}}$' is the isentropic efficiency of the compressor for a given speed.
- The temperature for subcooling (ΔT_{sc}) is assumed to be 5K. The enthalpy 'h_3' is determined using the details of the temperature at which the refrigerant is sub cooled completely and the pressure in the condensor .
- The heat delivered at the condensor (kW) and the COP is calculated as

$$COP = \frac{Heat\ delivered}{Work\ done\ by\ the\ compressor} = \frac{\dot{m}\,(h_2 - h_3)}{\dot{W}_{comp}}$$

2.2. The compressor's operating envelope

The compressor is the heart of a heat pump. Manufactures of compressors will provide the operating envelopes indicating the conditions within which the compressors can operate safely, and performance is guaranteed. Before analyzing the vapour compression heat pump cycle, it is important to check if the operating point lies within the operating envelope, otherwise that operating point cannot be used, since the safe operation is not guaranteed outside the envelope.

2.3. Thermal dynamics in the building

With the knowledge of the physical and thermal properties of the building, the thermal mass (C) and the thermal resistance (R) are estimated. A simple way of modelling the thermal dynamics in a building, is in the form of an electric circuit, comprising of a resistance and a capacitance connected in series, powered by a heating system modelled as a current source. The ambient temperature which is an external condition is represented as a voltage source and is shown in figure 2.

The terms 'C_{tot}'and 'R_{tot}'are the total thermal mass and thermal resistance of a building respectively. 'P_{heat}' and 'T_{amb}' are the heat from the heating system and external ambient temperature respectively. The temperature of the room is represented by the voltage 'T_{r}' across the capacitor.

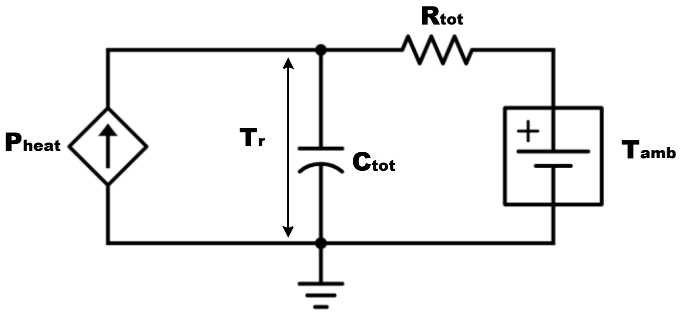


Figure 2: Simple thermal model of a building

3. Case study

This section deals with a brief description of the data considered for the modelling of a variable speed, air-to-water heat pump. This will be followed by a description of the thermal and physical properties of the building, for establishing its thermal model.

3.1. Air to water heat pump

The technical data of a variable speed compressor without enhanced vapour injection, from Copeland Emerson technology is considered for the validation of the model developed. The working fluid considered is the refrigerant 'R410a'. The relevant data together with the operating envelope considered for this study is provided in Table 1 and figure 3 respectively [12]. The operating envelope for this study, adapted for heating application, is considered based on two reasons, the first reason is that the minimum compression ratio should be greater than or equal to 2.3. This assumption is based on the experimental result obtained for Emerson's scroll compressors in [13] and [14]. The second reason is that for heating application, the condenser temperature should be at least 30℃.

Table 1. Technical data of variable speed compressor from Copeland Emerson [12]

Compressor Model	ZPV030	ZPV038
Power (kW)	2.98	3.73
Displacement $\left(\frac{cc}{rev}\right)$	30	38
Speed range (rpm)	900-7200	900-7200
Rated Capacity (kW)@ARI 60Hz	9.7	12.6
Power Input (kW)	2.98	3.80
COP (W/W)	3.25	3.3

3.2. Physical and thermal properties of the building

A single-family residential building in Gothenburg constructed between 1961 and 1975 with an average U-value (rate of heat transfer for climate shell) of $1\frac{W}{m^2\,K}$ and thermal mass of 21.6 $\frac{MJ}{K}$ is considered. The building is assumed have a floor area 125 m^2 and equipped with water radiators for space heating. Sanitary ventilation of $0.35\frac{l}{s\,m^2}$ is also accounted. The maximum supply temperature to the radiators is 55℃. The heating to this building will be provided from an air-to-water heat pump equipped with a variable speed ZPV030 compressor discussed above.

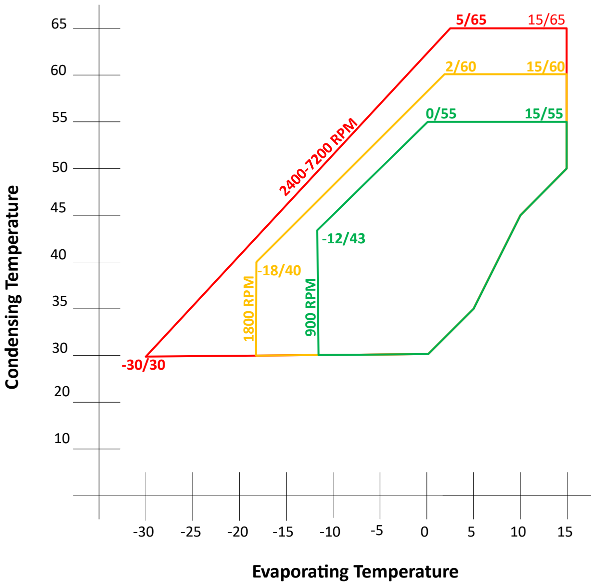


Figure 3: Operating envelope of scroll compressor adapted for the study [12]

4. Results

This section deals with the assumptions made for the analysis and validation of the results obtained from the steady state model of an air-to-water heat pump with ZPV030 and ZPV038 Copeland Emerson scroll compressors. Furthermore, it also deals with the quantification of the flexibility levels from space heating in a single-family residential building dealt with in section 3.2, equipped with an air-to-water heat pump having ZPV030 scroll compressor.

4.1. Validation of simulation result from the air source heat pumps with ZPV030 and ZPV038 scroll compressors @ARI 60 Hz

The following are the assumptions made in the model developed

- The volumetric efficiency 'η_{vol}' of the compressor is 83%
- The isentropic efficiency 'η_{isent}' is 65% at design conditions, considering the aspects of losses [15]
- For air source heat pumps, the temperature difference between evaporator and outdoor ambient temperature is between 5^0C and 8^0C [16]. In this study, a temperature difference of 8^0C is considered.
- The condensor temperature 'T_{cond}' required to heat the water to a desired temperature, is calculated as

$$T_{\text{cond}} = T_{\text{return}} + \frac{T_{\text{supply}} - T_{\text{return}}}{1 - e^{\left(\frac{-(T_{\text{supply}} - T_{\text{return}})}{\Delta T_{log.cond}}\right)}}$$

  where, 'T_{return}', 'T_{supply}' are the return and supply temperatures of the water from and to the heating circuit respectively. '$\Delta T_{log.cond}$' is logarithmic temperature difference of the heat exchanger and is assumed to be 4K.
- The isentropic efficiencies (η_{isent}) during different compression ratios for the Emerson's scroll compressor considered by comparing and analyzing the data available in [13] and [14], is shown in table 2.

Table 2: Variation of isentropic efficiency with respect to compression ratio

Compressor ratio	2.3	3	3.5	4	5	6	7	8	9	11	13.9
Isentropic efficiency	0.59	0.64	0.65	0.645	0.63	0.62	0.6	0.58	0.57	0.524	0.46

- The variation in isentropic efficiency with respect to the speed (f) of the compressor is estimated [17] as

$$\eta_{\text{isent\_speed}} = \eta_{\text{isent}} \left(-0.08 \left(\frac{f}{f_{60}} \right)^2 + 0.1411 \left(\frac{f}{f_{60}} \right) + 0.9337 \right)$$

where, 'f_{60}' is the frequency of the compressor at 60 Hz.

The simulation result is compared with the data provided in Table 1 and the observations are tabulated in Table 3. It is observed that the simulation result matches well with the data provided (@ARI 60Hz, i.e.,7°C evaporator temperature and 55°C condensor temperature).

Table 3. Comparison of the result obtained from the mathematical model with the technical data provided in [12]

Compressor Model	ZPV030		ZPV038	
	Given	Obtained	Given	Obtained
Speed (RPM)	3600	3600	3600	3600
Rated Capacity (kW) @ ARI 60Hz	9.7	9.85	12.6	12.47
Power Input (kW)	2.98	2.96	3.80	3.74
COP (W/W)	3.25	3.33	3.3	3.33

4.2. The COP as a function of outdoor ambient temperature and condensor temperature for an air to water heat pump with ZPV030 scroll compressor

The condensor temperature as a function of outdoor ambient temperature and COP for an air source heat pump under study is shown in figure 4. It is observed that for a given condensor temperature, as the outdoor ambient temperature increases, COP increases. It is interesting to observe that, at lower outdoor ambient conditions, the heat pump should be complemented with electric heating to deliver desired heat at high temperatures.

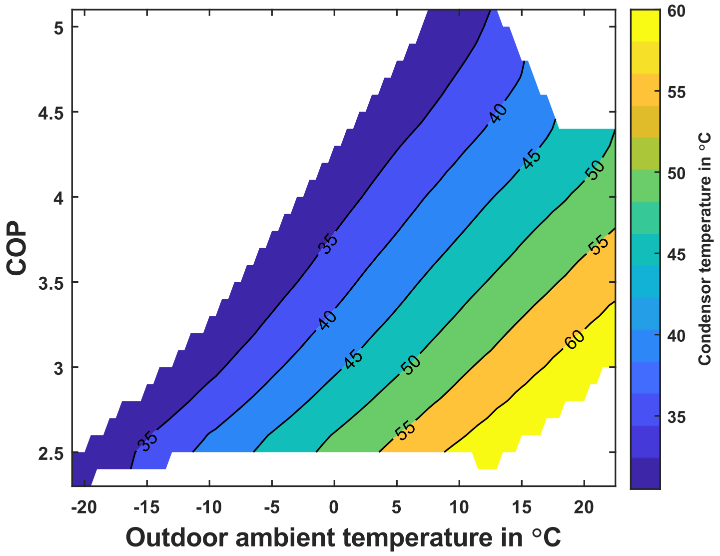
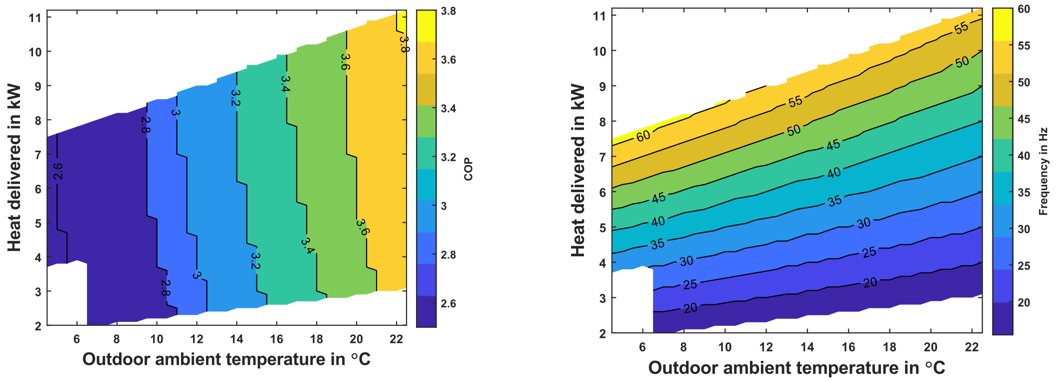


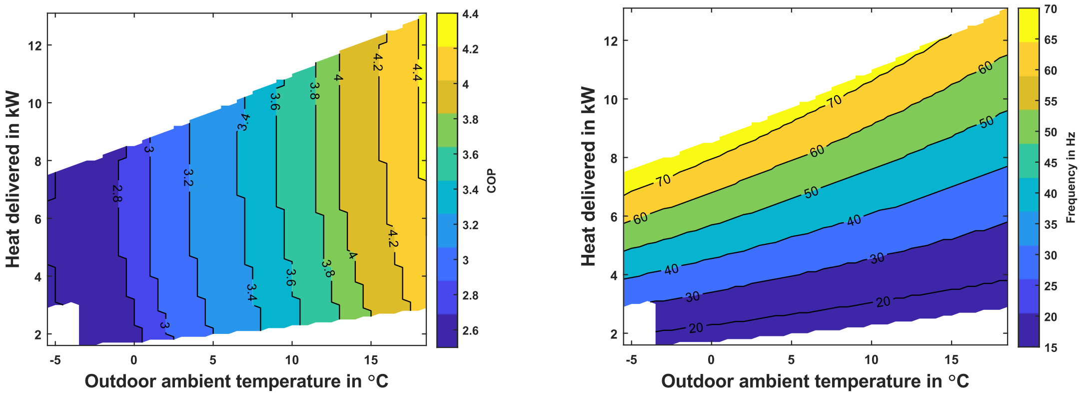
Figure 4: Condensor temperature as a function of outdoor ambient temperature and COP

4.3. The COP and speed as a function of heat delivered and outdoor ambient temperature for supplying water at 55°C, 45°C and 30°C.

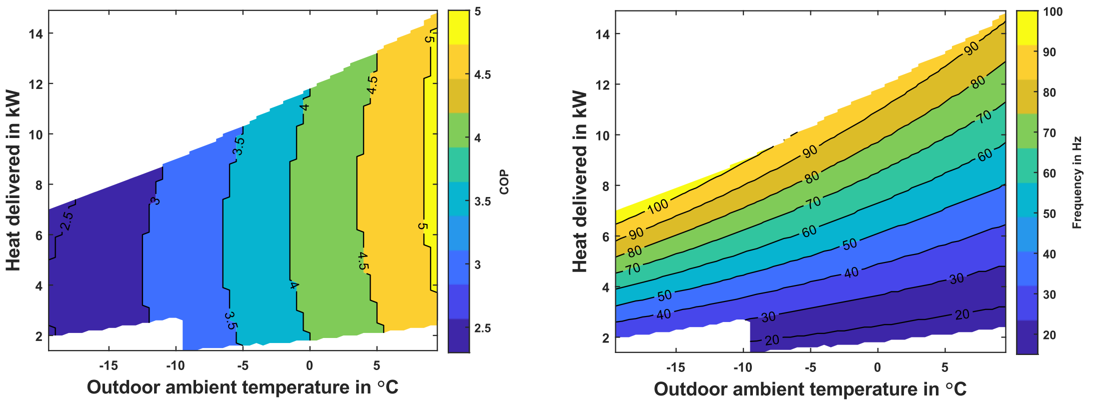
The maximum supply temperature to the panel radiator considered for the analysis is 55°C. However, depending on heating requirements during different outdoor ambient temperatures, the supply temperature of the water to the radiator can vary. In this regard, for the representation purpose, supply water temperatures of 30°C, 45°C and 55°C are selected. The COP and the speed as a function of heat delivered and outdoor ambient temperature, for supplying water at temperatures 55°C, 45°C and 30°C are shown in figure 5.



(5a) Heat delivering capability of the heat pump to deliver hot water at 55℃



(5b) Heat delivering capability of the heat pump to deliver hot water at 45℃



(5c) Heat delivering capability of the heat pump to deliver hot water at 30℃

Figure 5: Heat delivering capability of the heat pump to deliver hot water at 55℃, 45℃ and 30℃

The COP and amount of heat delivered increases with an increase in ambient temperature, as the temperature of the source increases. Furthermore, for a given ambient temperature, the heat delivered increases with a reduction in the supply temperature of the water.

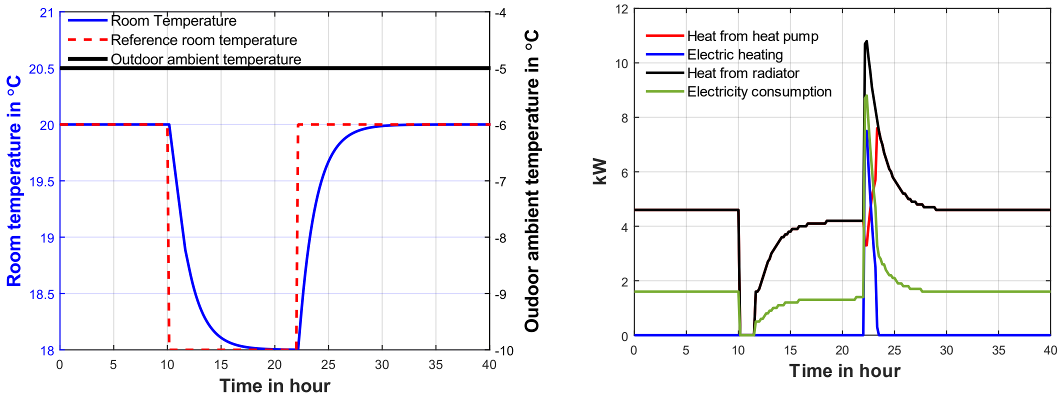
The change in COP at a given condensor temperature and ambient temperature, for delivering different heat loads is due to the variation in isentropic efficiency at different compressor speeds. It is also observed that the speed of the compressor is limited as the power consumption exceeds the rating of the compressor. However, as the supply temperature of the water is reduced, the heat pump can be operated at higher speeds.

4.4. Flexibility offered by the residential building by reducing the indoor temperature from 20℃ to 18℃ during different outdoor ambient temperatures

The outdoor ambient temperatures of -5℃, 0℃ and 5℃ are selected.

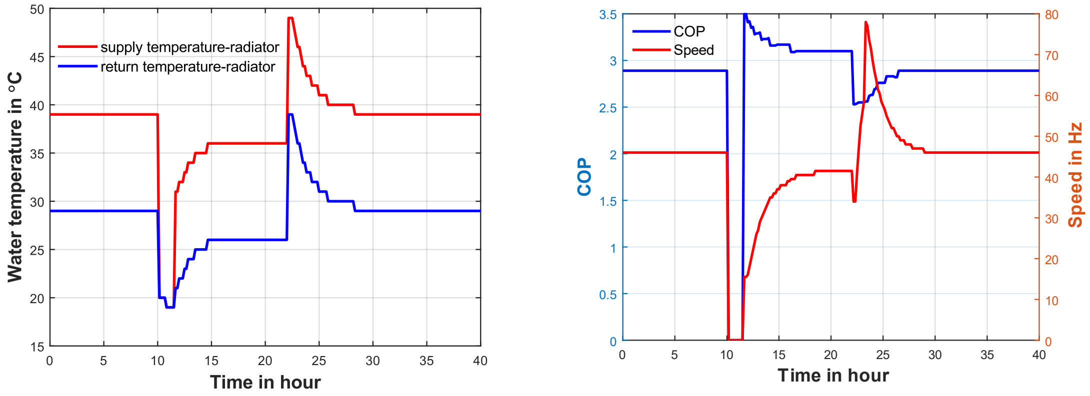
4.4.1. Flexibility offered by the residential building by reducing the indoor temperature from 20℃ to 18℃ during outdoor ambient temperature of -5℃

To maintain indoor temperature at 20℃, when the outdoor ambient temperature is -5℃, around 4.6 kW of heat is required. This heat is obtained by setting the supply temperature of the water in the radiators to 39℃ with appropriate mass flow rate to achieve the return water temperature of 29℃. The COP and speed of the heat pump at this condition is 2.89 and 46 Hz respectively. This is shown in figure 6.



(6a): Variation of indoor temperature

(6b): Heat delivered by the radiators, electric heater in the heat pump, the heat pump and electricity consumed



(6c): Supply and return temperatures of the water in the radiator together with the temperature of water supplied by heat pump

(6d): The variation in the speed and COP of the heat pump while maintaining desired indoor temperature

Figure 6: Thermodynamics in the building during outdoor ambient temperature of -5℃

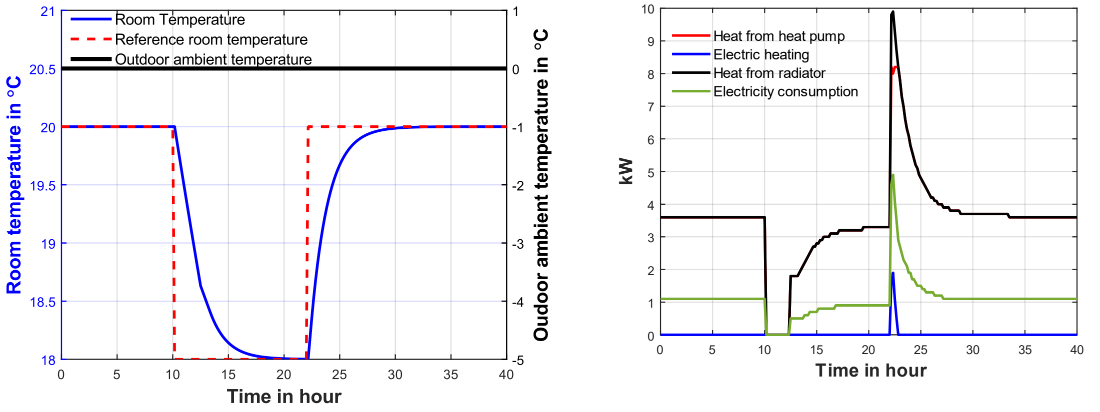
When the indoor reference temperature is changed to 18℃, there is no heating required for nearly 1.33 hours. After 1.33 hours until reference indoor temperature is reset, the heating requirement gradually increases for maintaining the indoor temperature at the desired level. During this period, it can be observed in figures (6c) and (6d) that, as the supply temperature of water increases, the COP reduces accordingly. When the new steady state has been reached, it is noticed that COP is 3.1 and is higher compared to the COP required for maintaining the indoor temperature at 20℃.

When the indoor reference temperature is reset to 20℃, it can be observed in figures (6b) and (6c) that there is a spike in electricity consumption due to spike in heating requirement. At outdoor ambient temperature of -5℃, the heat pump cannot heat the water to 49℃. In this situation, the heat pump heats the water to 42.5℃ and electric heater is used for heating the water up to 49℃. Correspondingly, it is observed that there is a sudden dip in the COP to 2.53 (to heat water to 42.5℃). As the heat requirement reduces and the supply temperature of water reduces, COP improves gradually, heating from electric heater also reduces and a new steady state is reached.

For 1.33 hours, no electrical energy is consumed by space heating, which corresponds to taking 2.13 kWh less electricity from the power grid, and this can be viewed as the flexibility service offered from the building. Furthermore, by continuing to maintain the indoor temperature at 18℃, the strain on the grid during power deficit conditions can be reduced as it is reflected in terms of reduced electricity consumption i.e., higher COP. However, when the temperature is reset to 20℃, initially there is a spike in electricity consumption.

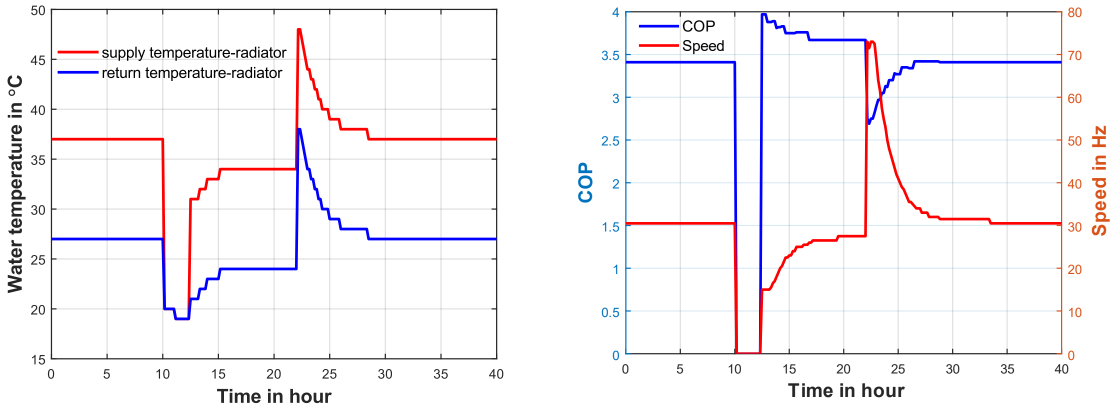
4.4.2. Flexibility offered by the residential building by reducing the indoor temperature from 20℃ to 18℃ during outdoor ambient temperature of 0℃

When the outdoor ambient temperature is 0℃, around 3.6 kW of heat is required to maintain indoor temperature at 20℃. This is achieved by setting the supply temperature of the water in the radiators to 37℃ with appropriate mass flow rate to achieve the return water temperature of 27℃. The corresponding COP and speed of the heat pump is 3.41 and 30.5 Hz respectively and is shown in figure 7.



(7a): Variation of indoor temperature

(7b): Heat delivered by the radiators, electric heater in the heat pump, the heat pump and electricity consumed



(7c): Supply and return temperatures of the water in the radiator together with the temperature of water supplied by heat pump

(7d): The variation in the speed and COP of the heat pump while maintaining desired indoor temperature

Figure 7: Thermodynamics in the building during outdoor ambient temperature of 0^0C

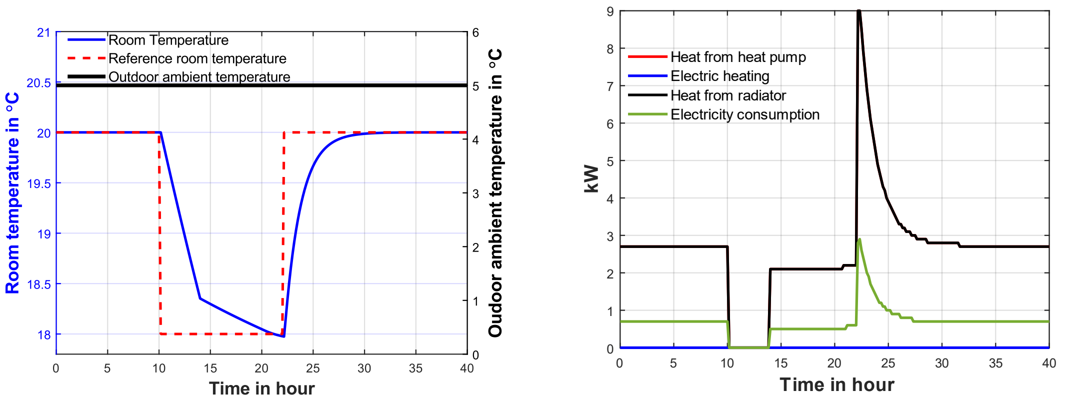
When the indoor reference temperature is changed to 18℃, there is no heating required for nearly 2.16 hours. After 2.16 hours until reference indoor temperature is reset, the heating requirement gradually increases for maintaining the indoor temperature at the desired level. During this period, the observations in figures (7b) and (7c) with respect to supply temperature of the water in radiators and COP is similar to as discussed in section 4.4.1.

When the indoor reference temperature is reset to 20℃, it can be observed in figures (7b) and (7c) that there is a spike in electricity consumption due to spike in heating requirement. At an outdoor ambient temperature of 0℃, the maximum heat this heat pump can deliver to heat the water at 48℃ is 8.2 kW. In this situation, the heat electric heater is used for providing extra heat of 1.6 kW. Correspondingly, it is observed that there is a sudden dip in the COP to 2.53 (to deliver heat of 8.2 kW). As the heat requirement reduces and the supply temperature of water reduces, COP improves gradually, heating from electric heater also reduces and a new steady state is reached.

For 2.16 hours, no electrical energy is consumed by space heating, which corresponds to taking 2.38 kWh less electricity from the power grid, and this can be viewed as the flexibility service offered from the building. Furthermore, by continuing to maintain the indoor temperature at 18℃, the strain on the grid during power deficit conditions can be reduced as it is reflected in terms of reduced electricity consumption i.e., higher COP. However, when the temperature is reset to 20℃, initially there is a spike in electricity consumption.

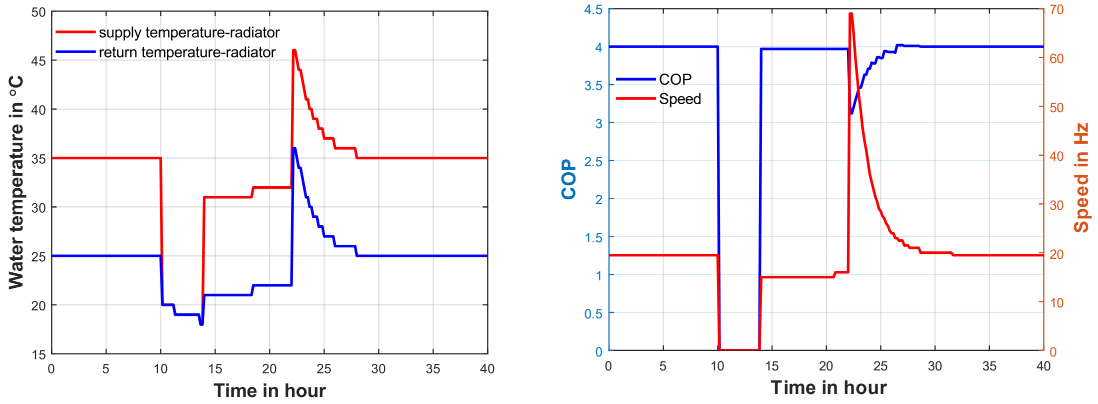
4.4.3. Flexibility offered by the residential building by reducing the indoor temperature from 20℃ to 18℃ during outdoor ambient temperature of 5℃

Around 2.7 kW of heat is required to maintain indoor temperature at 20℃, when the outdoor ambient temperature is 5℃. This is realized by setting the supply temperature of the water in the radiators to 35℃ with appropriate mass flow rate to achieve the return water temperature of 25℃. The COP and speed of the heat pump obtained at this condition is 4 and 19.5 Hz respectively. This is shown in figure 8.



(8a): Variation of indoor temperature

(8b): Heat delivered by the radiators, electric heater in the heat pump, the heat pump and electricity consumed



(8c): Supply and return temperatures of the water in the radiator together with the temperature of water supplied by heat pump

(8d): The variation in the speed and COP of the heat pump while maintaining desired indoor temperature

Figure 8: Thermodynamics in the building during outdoor ambient temperature of 5℃

When the indoor reference temperature is changed to 18℃, there is no heating required for nearly 3.5 hours. After 3.5 hours and some time before the reference indoor temperature is reset, around 2.1 kW of heat is provided as it is the minimum heat which the heat pump can provide at this condition. This heating is then gradually increased to 2.2 kW. During this period, the observations in figures (8b) and (8c) with respect to supply temperature of the water in radiators is similar to as discussed in section 4.4.1.

When the indoor reference temperature is reset to 20℃, it can be observed in figures (8b) and (8c) that there is a spike in electricity consumption due to spike in heating requirement. Correspondingly, it is observed that there is a sudden dip in the COP to 3.12. As the heat requirement reduces and the supply temperature of water reduces, COP improves gradually, heating from electric heater also reduces and a new steady state is reached.

For 3.5 hours, no electrical energy is consumed by space heating, which corresponds to taking 2.49 kWh less electricity from the power grid, and this can be viewed as the flexibility service offered from the building. Furthermore, by continuing to maintain the indoor temperature at 18℃, the strain on the grid during power deficit conditions can be reduced as it is reflected in terms of reduced electricity consumption i.e., higher COP. However, when the temperature is reset to 20℃, initially, there is a spike in electricity consumption.

5. Discussion

The result obtained in section 4 is consolidated in table 4. It can be observed that the flexibility in terms of power is high when the outdoor ambient temperature is -5℃ compared to 5℃. On the contrary, the flexibility in terms on energy is high during when the outdoor ambient temperature is 5℃ compared to -5℃. Furthermore, by maintaining the reference indoor temperature to a low value, the amount of energy offered as flexible service would be high, considering the contribution from several residential buildings. This can help the electricity grid to be more resilient by avoiding situations which can lead to severe problems during power deficit conditions.

Table 4: Flexibility offered from space heating by reducing the indoor temperature from 20^{0}C to 18^{0}C at steady state

Outdoor ambient temperature	Heat in kW to maintain indoor temperature @		COP to maintain the indoor temperature @		Time required for the indoor temperature to reach 18^{0}C from 20^{0}C in hours	Reduced power in-take during no space heating in kW	Reduced intake of electrical energy during no space heating in kWh	Electricity consumption by electric heating in kW
	20^{0}C	18^{0}C	20^{0}C	18^{0}C				
$-5^{0}C$	4.6	4.2	2.89	3.10	1.33	1.60	2.13	0
$0^{0}C$	3.6	3.3	3.41	3.67	2.16	1.10	2.38	0
$5^{0}C$	2.7	2.3	4.00	3.97	3.50	0.71	2.49	0

The future scope of this work involves assessing the flexibility based on different types of single-family residential building i.e., U-value and thermal mass, followed by the different types of heat pumps used. Furthermore, the heat pump technology i.e., with or without enhanced vapour injection, affects the flexibility result, as the heat delivering capability and COP would be high in the latter case. Also, considering the electric heating element used for complementing the heat pump of fixed type, greatly affects the result from flexibility studies focused on shorter time scales.

Acknowledgements

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