International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 824

ECONOMIC ASPECT OF HYBRID HEATING AND COOLING SYSTEMS IN A RESIDENTIAL BUILDING

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ABSTRACT

District heating is a well-established technology; however, the use of individual heat pumps has been expanding and is now the main competitor to district heating. The prices for both electricity and district heating often vary over time because of the variation of raw material prices in the marketplace. Consequently, for the building owner it would be cost effective if they had the possibility to integrate both district heating and heat pumps. Aiding in the flexibility to switch between the two systems in order to choose the one with the lowest operating cost throughout the year. In the presented work, the modeling and control of a detached house integrated with both district heating and a heat pump are developed. The operating costs of both systems are computed considering the marketplace prices and the coefficient of performance of the heat pump, related to the external temperature. The results show that heat pumps can be well exploited during the spring and fall to cover base loads, and in the summer can be used for ambient cooling.

Keywords: Dynamic modeling, control, District heating and cooling system, heat pump, financial analysis

NOMENCLATURE

Abbreviations	
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
HP	Heat pump
SEK	Swedish Krone

1. INTRODUCTION

District heating (DH) systems are a promising technology that are applied in all major urban areas in Sweden due to the economy of scope, economy of size, flexibility, local environmental impact and security of supply. Current national statistics lists about 500 systems, also including small district heating systems in small towns and villages. District heating is currently the market leader with a market share of about 55% during 2014 for all heat supplied to buildings [1]. However, despite the popularity of DH, the heat pump (HP) market has surpassed older technologies, i.e., electric, fuel oil, firewood and natural gas heating systems. During the last two decades, the use of individual HPs has been expanding and is now the main competitor to district heating with a market share of almost one quarter in 2014 [1]. About 46% of the detached houses in Sweden have some sort of HP installed [2]. The points made above clearly display the fact that both DH and HPs are promising solutions for ambient heating, and potentially cooling, in Sweden. Although DH is a well-established technology, statistical data shows that people are moving toward HP driven heating systems. Consequently, it may occur that in many buildings with an installed HP there is also, by historical reasons, a connection to DH. Furthermore, due to rising temperatures contributed to global warming, the cooling demand in residential building is also increasing. This trend is leading towards the utilization of cooling systems i.e., heat pumps during the summer even for northern countries like Sweden. It should be noted that both systems have different advantages and disadvantages according to different operating conditions. For example, the coefficient of performance (COP) of HPs varies significantly in relation to the external temperature and this makes HPs more convenient during some periods in comparison with other heating system. Moreover, the operating costs of both systems can vary significantly in different regions and at different times of the year. This is especially important when the price of electricity is concerned which can vary from hour to hour.

This study is motivated to understand how heat pumps and district heating can cooperate cost efficiently in order to provide a thermal comfort condition during different seasons of the year. In particular, a control strategy that can exploit the benefits of both systems and drive down the heating costs has been applied.

2. RESEARCH AIMS AND METHOD

The purpose of this study is to develop a dynamic model and a control strategy for the heating system of a building, where a residential building has been considered as the case of study. This building is indirectly attached to a DH network via a substation, and is simultaneously equipped with a HP. A cooling-system has been consider in order to cover the cooling demand during the summer. Subsequently, the HP is sized for the cooling load, and is therefore undersized in regards to the heating load. Therefore, both the HP and the DH system will supply the space heating demand, while the domestic hot water (DHW) has been integrated with the district heating system alone. The aim of the control strategy is to exploit the HP during the winter. In spite of the HP being under-sized for the winter, it can still be utilized to cover the base heating load, while DH is used to cover the peak demand. For this purpose, techno-economical considerations are achieved by a controller in order to determine if it is better to use only DH, or if both systems are to be initiated. Therefore, the controller has the ability to take into consideration the price variations for both DH and electricity. The model also takes into account for external disturbances, i.e., outdoor temperature, DHW consumption, and the variation of DH supply temperature, with the purpose of predicting the thermal losses from the building, and the consumption of hot water.

This study is performed by using the programming language Modelica and the software tool OpenModelica, which is an object-oriented, declarative, multi-domain modeling language capable of modeling complex systems. One of the most important aspect of Modelica is that instead of algorithms it computes equations. Because of this, Modelica is well suitable for modeling physical systems as it does not contain any prefixed causality.

2.1 Model Components

The main component of the proposed model in this study consists of a distribution network and transmission lines, substation, radiator and HP. In DH systems, there are many different ways in which a user can integrate into a heating network. In this study an indirectly connected user has been considered, and the implemented heat exchanger eliminates the influence of the network pressure on the static head due to high-rise buildings. The equation used to calculate the temperatures being supplied to the house from the substation follows the method proposed by Mota el al. [3], expressed as equation 1:

$$MCp\frac{dT_{out}}{dt} = \dot{m}Cp(T_{in} - T_{out}) + W \tag{1}$$

where M is the total mass of water (kg), $\dot{m}$ is the mass flow rate (kg s^{-1}), Cp is the specific heat (kJ kg^{-1} K^{-1}), W is the total heat transfer (kW), and T_{in} and T_{out} correspond to the temperature from the thermal network and the temperature to the house respectively. The model of the HP computes the COP in relationship to the ambient external temperature, equation 2:

$$COP = \frac{Q_c}{W_{comp}} \tag{2}$$

where Q_c (kW) is the heat leaving the condenser and W_{comp} (kW) is the power requested by the compressor. Therefore, for a given specific power input it is possible to calculate how much heat the pump provides. Work by Li et al. [4] provides a validated polynomial function to compute the COP of a heat pump for a residential building, equation 3:

$$COP = 2.79 + 0.036T_{amb} + 6.036 \times 10^{-4}T_{amb}^2 \tag{3}$$

where T_{amb} is the outdoor temperature.

A detached house with four inhabitants is used in this work to evaluate the performance of the proposed hybrid heating and cooling system. The case studied has a total area of 153m^2, and a total internal volume of 375m^3. The windows are triple glazed, with a total surface area of 36m^2, and an overall heat coefficient of

1.9 (W/m^{2}K), while the value for the envelope is 0.5 (W/m^{2}K). The building is connected with a DH supplied substation while equipped with a HP. The model developed for the building follows the work of Skruch [5]. Equation 4 shows the relationship between the heat being transferred to the room, or from it in the case of cooling, and the temperature of the air inside the room:

$$\frac{dT}{dt} = \frac{1}{Cp\rho V}(Q_{in} - Q_{out}) \quad (4)$$

where Cp is the specific heat (kJ kg^{-1} K^{-1}), ρ is the density of air (kg m^{-3}), V is the volume (m^3), and Q is the is the heat (kW) for the flows entering and leaving the room.

1.1 Model Overview

An overview of the whole system is illustrated in Fig. 1. Three external disturbance factors are considered in this study corresponding to the DHW consumption, ambient temperature and the energy price (i.e., electricity and district heating prices). According to Fuentes el al. [6], the daily average usage in a 100m^2 dwelling is about 100 L/day of hot water. Moreover, statistics show that there are two distinct heating peaks during the day, one in the morning and the other in the evening. Therefore, the proposed model uses a sinusoidal function in order to estimate the external disturbance of the heating peaks represented by equation 5:

$$u = 1.2 \times 10^{-6}\, sin\left(\frac{\pi}{21600}t + \frac{7\pi}{6}\right) + 1.2 \times 10^{-6} \quad (5)$$

Finally, the proposed DH costs are taken from the district heating provider Mälarenergi and the electricity prices are taken from Elspot, where taxes and distribution costs are considered, for 2018. The model of the DH network is comprised of two pipes, a supply and return line.

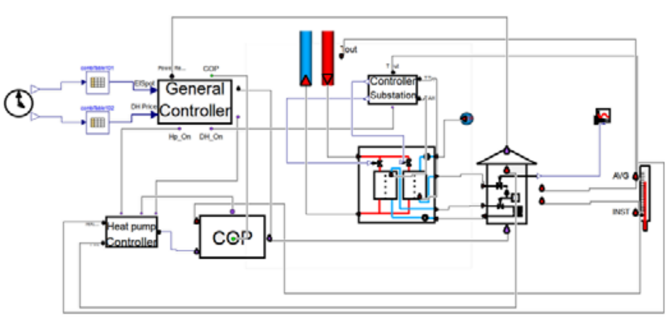

Fig. 1 Model overview in OpenModelica.

The DH supply temperature is taken from Gustafsson et al. [7], which is a function of outdoor temperature, and the model calculates the return temperature based on the end-user requirements.

1.2 Control

The indoor temperature and the DHW supply temperature are the control parameters of interest, illustrated in Fig. 2. The variables that can be controlled, using PID controllers, are the position of the two valves inside the substation (one for ambient heating and the other one for the tap water), the thermostatic valve upstream of the radiator and the power of the HP.

The indoor temperature is regulated to be 20 $\pm$2°C during the whole year due to the requirements of the end-users' thermal comfort. The temperature of the tap water must be keep at 50$\pm$2°C to avoid bacteria proliferation like legionella. Finally, the radiator supply-control temperature follows a variable set-point based on the outdoor temperature and is taken from [7]. The external controller computes the cost of heating and chooses the cheaper system for every time step (one hour sampling time). Therefore, the market prices of both district heating and electricity, as well as the COP of the HP are considered. If the controller decides that DH is cheaper, the HP is switched off since it will be able to cover the required heating demand. If the controller decides that electric-based heating is cheaper priority is given to the HP. However, since the heat pump is not sized to satisfy the whole building's heating demand, the controller is able to mitigate this difference and allows for DH to comprise the rest of the demand. If the power demand is less than the maximum power of the heat pump, the HP is switched on and the DH is switched off.

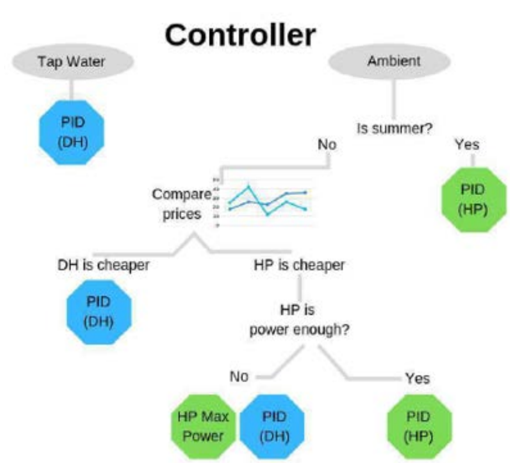

Fig. 2 Controller overview.

However, if the controller decides that the heat demand is greater than the HPs limits, then the HP is used at maximum power to cover only the basic request, while the DH cover the peaks demand.

2. RESULTS AND DISCUSSIONS

To evaluate the performance of the system under the performance of the identified control parameters. A simulation for one calendar year with DH prices and electricity prices, illustrated in Fig. 3, have been observed. The results are analyzed based on the operating costs and money saved, the running time of the systems, and the COP of the heat pump. The money saved is computed by using equation 6:

$$savedMoney = (DH_{price} - \frac{El_{price}}{COP}) \times HP_{power} \quad (6)$$

which assumes that if the user does not have an installed HP, they will pay the district heating price for the whole year.

Findings presented by Sköldberg and Rydén [8] shows that DH prices can greatly differ from one municipality to the next. Therefore, a sensitivity analysis has been performed in order to evaluate the system performance over three cases, and are defined as the base case, 30% case, and 60% case. The base case uses the DH cost set by Mälarenergi, in Västerås to demonstrate the applicability of the studied concept in the real engineering implementation. The 30% case, is the increase over the base case, and is taken to be the average value of DH prices in Sweden. An increase of 60% of the base case is used for the 60% case, and is associated with being the highest cost of DH in Sweden.

Illustrated in Fig. 4 are the results from the base case scenario, observed for one calendar year. It can be viewed that the main heating cost is associated with the cost of DH at 6000 SEK/year, and the cost of using a HP is 3800 SEK/year, for a total of 9800 SEK/year.

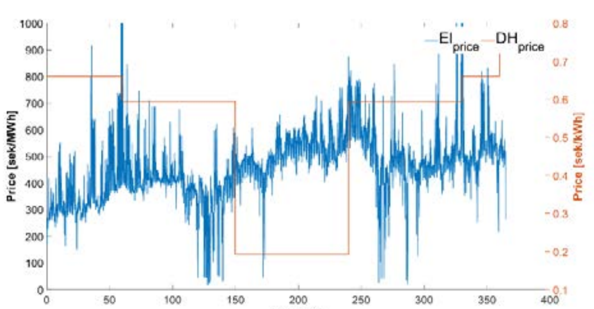

Fig. 3 Simulation using electricity prices (left) and DH prices (right).

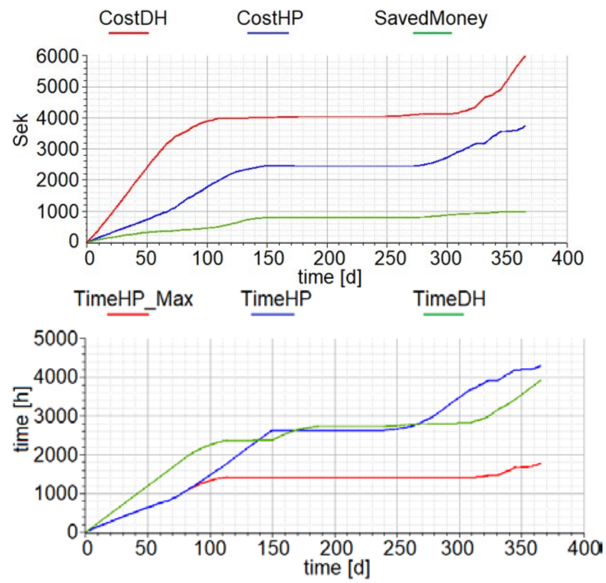

Fig. 4 Annual Operating costs and saved money (above) Operating time of both systems (bottom)

From equation 6, it is possible to calculate the potential savings for a hybrid system, and amounts to 1000 SEK/year, which is about 10% of the total cost. District heating is prominent during the coldest months of the year, and then around the 10th of April, 100 day mark, it is switched off because the heat pump provides enough heat by itself. The HP's COP generally varies between 2.5 when the outside temperature is low, to over 4 in summer. However, the result shows that during winter, when the temperature goes below -15°C the COP value drops to 1 because when this happen it is supposed that an electric heater is used instead of the heat pump.

2.1 *Sensitivity analysis*

The purpose of the sensitivity analysis is to establish if the proposed control strategy properly works with a variation in district heating prices. The 30% case shows that the total cost attributed to DH is 6200 SEK/year and HP cost of 5200 SEK/year. For a total of 11400 SEK/year, where the potential savings is calculated to be 2900 SEK/year (2.9 times more than the base case), and is 25% of the total cost. In the 60% case, the total cost attributed to DH is 7000 SEK/year and HP cost of 5700 SEK/year. For a total of 12700 SEK/year, where the total potential savings is calculated to be 4700 SEK/year (4.7 times more than the base case), which is about 35% of the total cost. Operating times for each case, based on the level of technology implemented, can be observed in table 1.

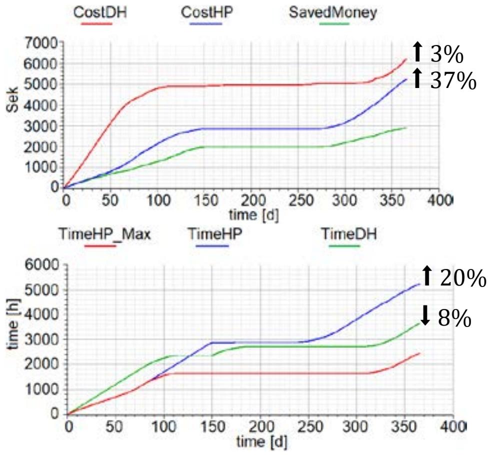

Fig. 5 Annual Operating costs and saved money (above) Operating time of both systems (bottom) with 30% increment in DH price

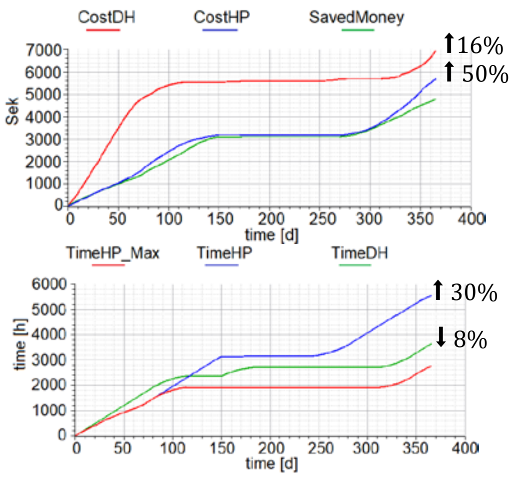

Fig. 6 Annual Operating costs and saved money (above) Operating time of both systems (bottom) with 60% increment in DH price

Table 1. sensitivity analysis on operating time for all cases

Type	Base DH price	30% increment	60% increment
Only DH	2100 hr/yr	1200 hr/yr	800 hr/yr
Only HP	2500 hr/yr	2800 hr/yr	2800 hr/yr
DH and HP	1800 hr/yr	2400 hr/yr	2800 r/yr

The results show that the number of hours using only a HP is the same for the second and third case , equal to 2800hr/yr. this could means that for a range of about 115 days, the HP can run by itself, but outside of that it requires a support system, i.e., electric heating, due to the higher heat demand. By considering a 30% increment in DH price, in comparison to the base case, DH implementation dropped by 8% while the use of HP grew by 20% (Fig. 5). The total cost of heating increased by 16% and the money saved is almost 3 times more than the base case. However, by applying a 60% increase in the DH price, DH implementation dropped by 8% while the use of HP grew of 30% (Fig.6). The total cost of heating increased by 30% and the saved money is almost 5 times more than base case.

3. CONCLUSION

The simulation shows that the HP is well exploited during the spring and fall to assist in ambient heating and with cooling in the summer. During the coldest season, because of the low COP, the HP is switched on intermittently, while DH prevails. The calculated savings amounts to 1000 SEK in the base case, which is about 10% of the total annual heating cost. A sensitivity analysis was done by considering different DH prices in order to establish if the proposed control strategy is useful in other cases. A second simulation considers an increase of 30% of the base DH price while the third case considers an increase of 60%. The second case shows a potential savings of 2900 SEK, 25% of the total heating cost, while the savings in the third case amounts to 4700 SEK, equal to 35% of the total heating cost. From the sensitivity analysis it can be concluded that the utilization of DH decreases as the price increases, where a significant percentage of the total annual heating cost can be saved. The sensitivity of the operating times for each case quantifies that the HP's COP can at times be too low to be economically beneficial.

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