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A control method for increasing the heat usage efficiency of nearly-zero-energy buildings with heat pumps

H. Pihlap[1,*], A. Annuk[1], M. Lehtonen[2], S. Muiste[1], A. Tooming[1] and A. Allik[1]

[1]Estonian University of Life Sciences, Institute of Technology, Chair of Energy Application Engineering, Kreutzwaldi 56, EE51006 Tartu, Estonia
[2]Aalto University, Department of Electrical Engineering and Automation, Maarintie 8, Espoo, Finland
[*]Correspondence: heino.pihlap@emu.ee

Abstract. In the retrofitting of older buildings with central heating into nearly zero-energy buildings more and more air to water heat pumps are used. These heat pumps are normally connected to heating systems, producing heat only on demand. The greatest demand for heat occurs when the outside temperature and therefore the COP of the pump is lowest. Outside temperature varies during the day, meaning it is possible to save energy by producing and storing heat in a situation where the COP is higher. To determine the periods with higher COP values weather forecast data and COP curves are used. The data enables to rank and select time periods for heat production. This in conjunction with the heat demand curve of the building enables to create an operation schedule for the heat pump. The aim of the study is to develop heat pump control methods for renovated buildings to comply with nearly zero energy building codes. Dependant on the heat pump and weather conditions, up to 10% of the electricity demand for heating can be decreased.

Key words: heat demand modelling, heat production scheduling, heating season, optimization, temperature fluctuations.

INTRODUCTION

The operation of heat pumps has been optimized in previous studies for different purposes, for example for the peaks shaving of renewable energy production (Vanhoudt et al., 2014) and voltage control (Mufaris et al., 2013) The coefficient of performance (COP) of the heat pump has been in the focus of few previous studies (Kazjonovs et al., 2014).

To plan the efficient use of an air-to-water heat pump (further described as heat pump), it is essential to know the coefficient of performance (COP) of the particular heat pump. Unfortunately, heat pump manufacturers only scarcely describe COP values, often only at 4–6 specific temperatures, which do not allow for sufficiently accurate predictions of COP values at other temperatures. Consequently, it is necessary to continuously refine the COP = f (temp) function that characterizes the air to water heat pump COP, using machine learning methods (Xu et al., 2019). Since the efficiency of the air to water heat pump is dependent on the outdoor temperature (t), the corresponding coefficient of performance is described as the outdoor temperature function COP = f (t)

(Di et al., 2011). To find the pump COP at various outdoor temperatures, it must be remembered that COP is the ratio of energy consumed to energy produced. $f(t) = g(t) / h(t)$, where $g(t)$ is the energy produced by the pump at the outside temperature (t) and h(t) is the energy consumed by the pump at the outside temperature (t) (Li et al., 2011). Because g (t) and h (t) are neither linear nor exponential functions, neither is COP linear or exponential. Depending on the type of air-to-water heat pump, the COP may also be different at the same outdoor temperature, since inverter-type heat pumps control the heat output according to the needs of the building being heated. The change the COP of a heat pump dependant on outside temperature is always one directional.

It is possible to plan the operation of the air to water heat pump (Zhao et al., 2020), by knowing the amount of energy required and the energy that the pump produces at a certain outside temperature and the weather forecast. If the heat pump's productivity is greater than the building's required energy, the excess energy can be stored in a water tank and used later if the heat pump's productivity is less than the building's required energy. The required size of the water tank is determined by the building's energy requirement, the amount of energy stored and the air-to-water heat pump heat capacity (Annuk et al., 2018; Kalder et al., 2018).

The hypothesis of the study is that it is possible to cover the demand by operating the heat pump only during the hours with the highest COP and lover the electricity consumption if the heat pump has a sufficient heating power to cover the buildings energy demand at every outside temperature in the working range of the pump.

Nearly zero energy buildings (NZEBs) have a heat demand limit defined by building codes. An NZEB is defined by an energy consumption per heated floor area and difference between inside and outside temperature lower than 0.75 W m^{-2}·K (Estonian Ministry of Economics and Communication, 2019). The current study uses this limit as an input for the calculations.

The novelty of the study includes the application of control methods in a new situation created by the widespread installation of heat pumps. Previous studies have mostly focused in the optimization of heat pump control on financial savings but the current study focuses on electricity and carbon emission savings.

Like the COP of the pump, it is also necessary to know the efficiency of the building to be heated (Bourdeau et al., 2019). Although NZEBs have limits on the energy consumption of a building, a similar function must be constructed for each individual building that characterizes the amount of thermal energy consumed by the building at a certain outdoor temperature. Unlike air-to-water heat pump COP, the building's COP is a linear function (Deb et al., 2017). However, the physical parameters of a building are not the only factors influencing the heat demand of the building. The number of residents in the building is also important.

The aim of the study is to develop heat pump control methods for retrofitted buildings to comply with nearly zero energy building codes.

MATERIALS AND METHODS

System Setup

The study used the following setup (Fig. 1). An internet connection is used to acquire weather forecasts for the scheduling of the operation of the heat pump. The heat pump supplies energy only to the buffer tank. The energy stored in the buffer tank is used by the heating contours regulated by the indoor controller. The indoor controller operates separately from the heat pump controller.

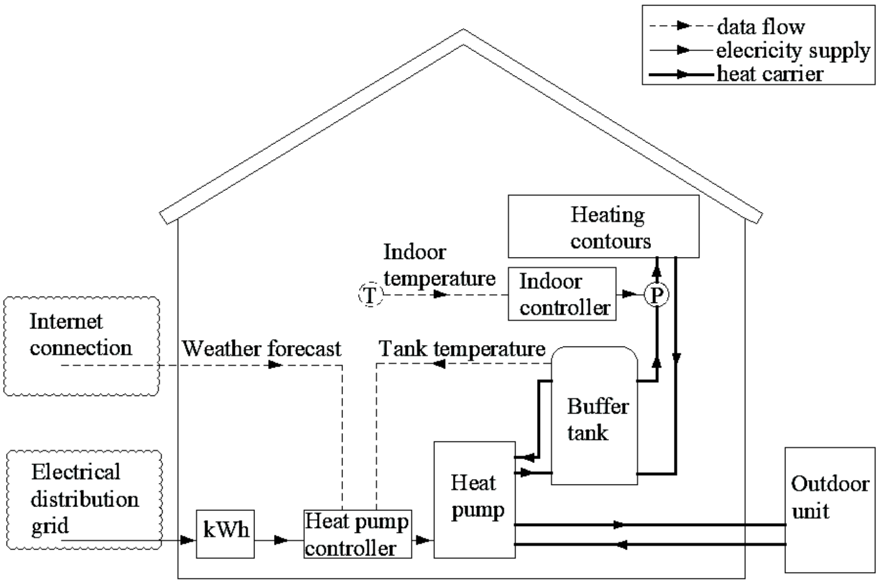

Figure 1. The analysed system.

Air to water heat pump and weather parameters

Air-water heat pumps nowadays have commonly inverter systems that follow the heating demand of the building directly. The lack of energy storage possibilities restricts the possibilities to optimize the energy use of heat pump. The addition of a thermal storage tank into the heating system of a building equipped with a heat pump enables to optimize the energy use of the heat pump. The optimization is made possible due to the COP change with the change of temperature.

While specific heat pump have different parameters, the COP is always dependant on the outside temperature.

The current study uses certified parameters from heat pump manufacturers (Table 1).

Table 1. Heat pump parameters (FSK Heat Pumps and Air Conditioners, 2019)

Temperature (C°)	-25	-20	-15	-7	2	7	15	20	25
Power (W)	3.85	4.95	4.88	4.28	3.4	2.51	2.18	1.98	1.88
COP	1.51	2	2.21	2.52	3.17	4.3	4.95	5.45	5.74

The real COP of an air-to-water heat pump is to a high degree of precision (R^2 = 0.999) described by a 6-degree polynomial (Fig. 2).

$$COP(t) = 0.0003t^6 - 0.0072t^5 + 0.0548t^4 - 0.1022t^3 - 0.3638t^2 + 1.6967t + 0.2289$$

Additionally to the COP, also the real power consumption at different temperatures and maximum heating power output is necessary for the modelling of the energy usage optimization strategies (Fig. 3).

$P_c(t) = -7E\text{-}05t^6 + 0.0015t^5 - 0.0158t^4 + 0.1607t^3 - 1.2367t^2 + 3.8598t + 1.0833$

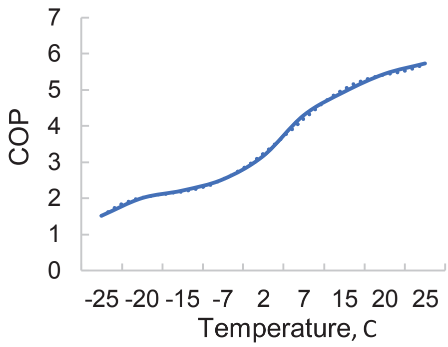

Figure 2. Relationship between temperature and COP.

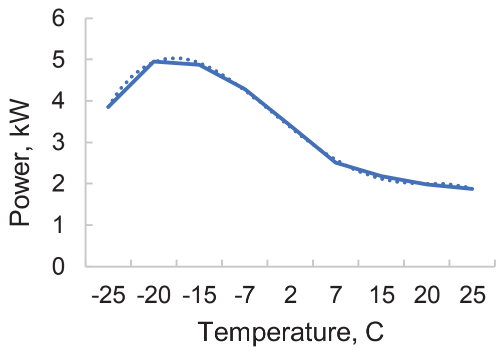

Figure 3. Relationship between temperature and power consumption at maximum power output.

On the basis of these relationships (Figs 2 and 3) the heat pumps maximal heating output can be calculated according to the following equation (Eq. 1).

$$P_h(t) = P_c(t) \cdot COP(t) \quad (1)$$

The most frequent temperature range was in 2019 between 0 and 6 C. Coincidently the change of the COP value is also the largest in this temperature range (Fig. 4). The statistical average temperature in Tartu (Estonia) throughout the heating period (1. October to 4. May) is -1.5 degrees (Estonian Ministry of Economics, 1997). Hourly average outdoor temperatures measured in Tartu are used.

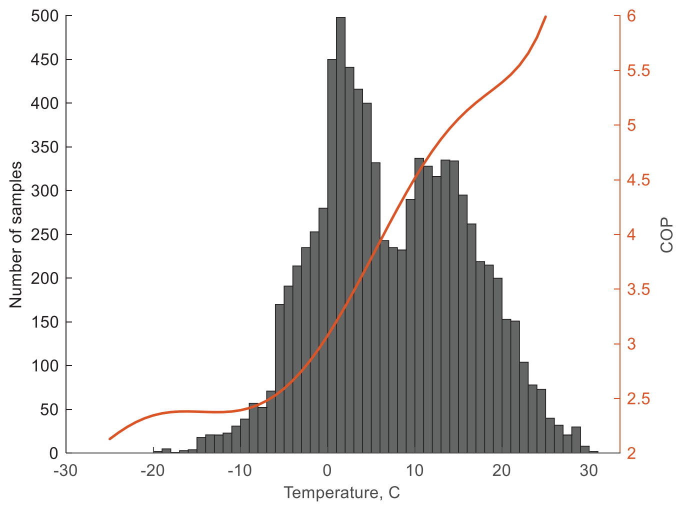

Figure 4. Temperature distribution 2019 and COP curve.

Building parameters

The current study focuses only on the heating demand of the building itself. Some previous has considered to cover separately the domestic hot water demand with heat pumps and ventilation heat exchangers (Torregrosa-Jaime et al., 2018; Yuan et al., 2019). The current study used specifically only the heating load of a building that has the following parameters:

1) Heated floor area, A = 100 m^2
2) Indoor temperature set point, t_b = 20 °C
3) Outside temperature, t
4) Heating load of the building according to the minimum requirements for nearly zero energy buildings, $Q_b = 0.75$ W $m^{-2}\cdot K$ (Estonian Ministry of Economics and Communication, 2019).

The function that determines the heating load of the building ($P_b(t)$) is characterized by the following equation:

$$P_b(t) = A \cdot (t_b - t) \cdot Q_b = 100 \cdot (20 - t) \cdot 0.75(W) \quad (2)$$

A time period was selected during which the energy expenditure is modelled when the different methods are applied (Fig. 5).

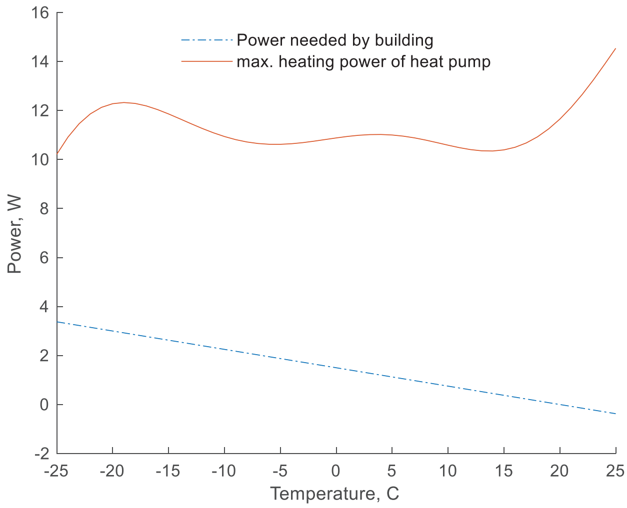

Figure 5. Heating demand and maximum heating power of the heat pump in relation to outside temperatuure.

The Estonian weather conditions may demand heating throughout the year, even in the summer. The changes of heat gains originating from the inhabitants and household equipment are not considered in this research. The heat losses from the heat storage are not considered separately because the tank is located in the building and the losses from the tank don't affect the total heat balance of the building.

Method I

It is presumed that the heat pump works at full power (on-off regime). Energy is not stored into an accumulation tank and the pump works according to demand. The figure above (Fig. 5) shows that the output of the heat pump is always higher than the heating demand of the house. This means that the daily consumed electrical energy (E_D) for the heat pump can be calculated by the following equation.

$$E_D = \sum_{i=1}^{24} \frac{P_b(t_i)}{COP(t_i)} \tag{3}$$

where E_D is the electrical energy consumed by the pump, kWh; $P_b(t_i)$ is the heating demand at the temperature t_i; $COP(t_i)$ is the coefficient of performance at the temperature t_i.

The yearly energy consumption (E_Y) is calculated by adding the daily energy amounts.

$$E_Y = \sum_{j=1}^{365} E_{D_j} \tag{4}$$

The logic of Eq. 4 is also used to calculate the monthly electrical energy demand (E_M).

Method II

A situation is modelled where the needed heat energy is produced with the highest possible COP values. A water tank is used as thermal storage for this purpose and the time frame during which the optimization is made is 24 hours. The presumption is made that the water tank has enough energy stored for the heating demand of the first day of the heating period and the capacity of the storage is large enough to accommodate all the energy needs that can occur during 24 h periods. The hours with the highest COP during a day are often not consecutive hours. The amount of head to cover the heating demand for each day can be calculated with the following equation:

$$Q_D = \sum_{i=1}^{24} P_b(t_i) \tag{5}$$

The presumption for the model is that algorithm acquires the weather forecasts of the outdoor temperatures for the next 24h at each midnight. On the basis of these forecasts and by using the COP and $P_b(t)$ values the hours that are most suitable for heat production are selected.

A software is created to calculate the amount of electrical energy that is used for the production of heat. The working principle of this algorithm is described on the following figure (Fig. 6). The software is used to calculate the daily and yearly amounts of electrical energy consumed when the house heating is controlled by Method II.

According to the described algorithm calculations were made with the MatLab programming language. Previous research has measured the effectiveness of heat pump control through the increase in seasonal COP (Pospíšil et al., 2019). The effectiveness of the method in this study was measured with the decrease of consumed energy in relation to the total electrical energy consumption.

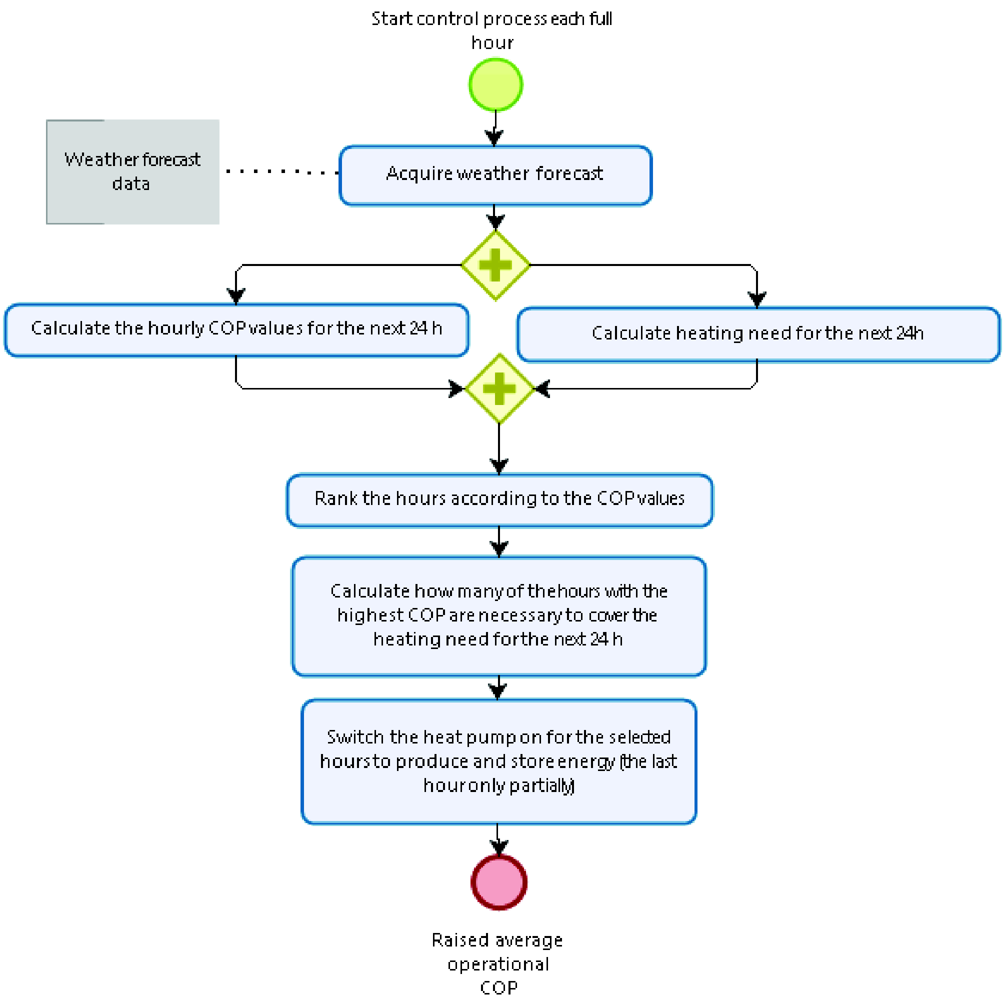

Figure 6. Flow chart of the second method.

RESULTS AND DISCUSSION

Method I

The modelling was made with the outdoor temperature data from the years 2018 and 2019. The yearly energy consumption of the air-to-water heat pump was calculated according to Eqs (3) and (4). The results are the following $E_{YI}(2018) = 2{,}870$ kWh and $E_{YI}(2019) = 2{,}600$ kWh.

Also the monthly electrical energy consumption values were calculated according to the logic given above. The modelling results on a monthly basis are given on the following figure (Fig. 7).

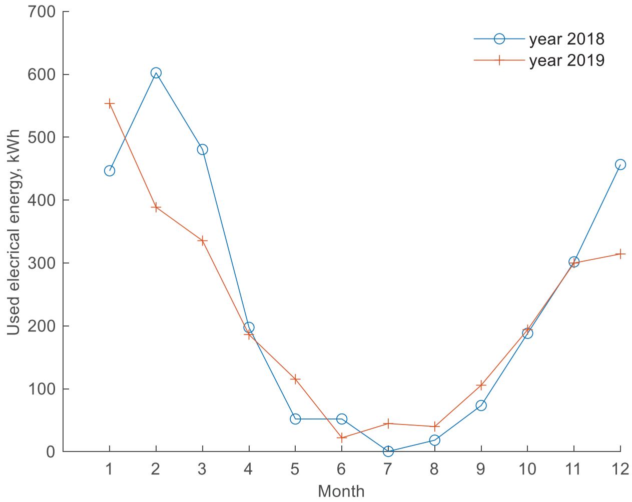

Figure 7. Modelled electrical energy usage with Method I.

Method II

The model used the same input data like Method I, with the outdoor temperature data from the years 2018 and 2019 and based on the Method II given in Fig. 5 the yearly energy consumption of the air-to-water heat pump was calculated. The results are the following $E_{YII}(2018) = 2{,}645.56$ kWh an $E_{YII}(2019) = 2{,}331.8$ kWh. The comparison of the results from the different methods, Method II (optimized energy usage) and Method I (non-optimized energy usage) are presented in the following figures (Figs 8 and 9).

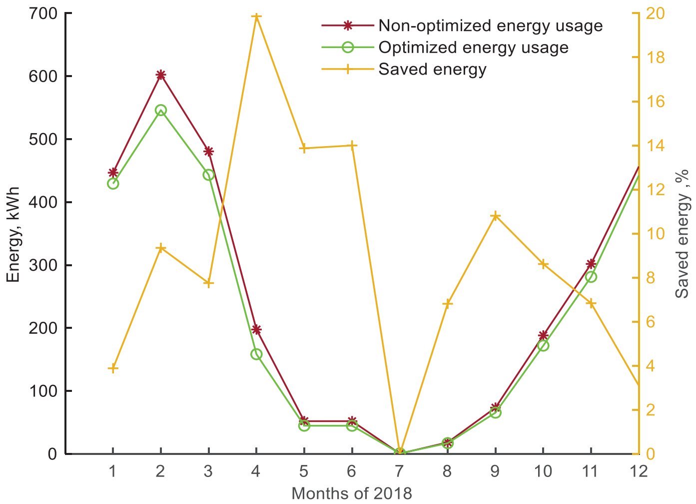

Figure 8. Comparison of non-optimized and optimized electrical energy usage and resulting Savings in 2018.

Energy savings (E_S) in the years 2018 and 2019 of Method II in comparison to Method I are the following: $E_S = E_{YI}(2018)\text{-}E_{YII}(2018) =$ 224,5kWh, which amounts to 7.82% of the non-optimized energy expenditure and $E_S = E_{YI}(2019)$-

$E_{YII}(2019) = 268.27$ kWh, which makes up 10.3% of the non-optimized electricity expenditure.

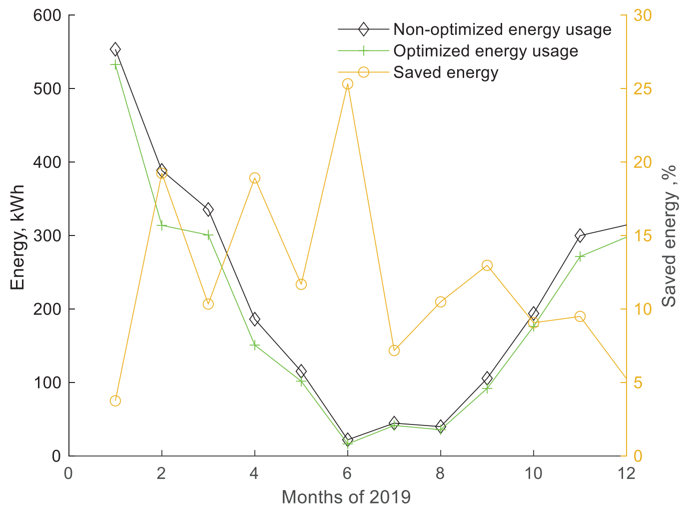

Figure 9. Comparison of non-optimized and optimized electrical energy usage and resulting Savings in 2019.

Since the COP is a function of the outdoor temperature, then the saved amount of energy is dependent on the speed and amplitude of the temperature changes. Larger changes enable larger energy savings when using the control methods described above.

The results (Fig. 9) show that the largest proportional savings can be achieved at the beginning and end of the heating period, when the largest changes in outdoor temperature occur between night and daytime.

The relative energy savings per month in 2018 and 2019 are given in the figure below (Fig. 10).

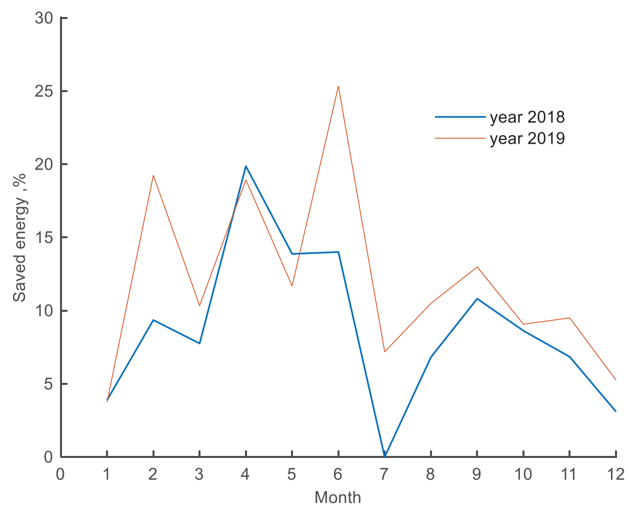

Figure 10. Comparison of relative energy saving per month during 2018 and 2019.

The theoretically achieved energy savings of 268.27 kWh per building during the year 2019 and the average CO_{2ekv} emissions in the Estonian Electricity consumption of 889 g kWh^{-1} (Tranberg et al., 2019) would enable the reduction of emissions by 238 kg CO_{2ekv} per year per building. The method has a significant potential for energy and CO_{2ekv} savings, for example, 164,000 households in Estonia still used wood fuels as a heating source for their living space, which most likely will be replaced in the future by heat pumps (Maasikmets et al., 2016).

The authors presume that the findings of this study can be generalized to all air to water heat pumps. While specific heat pump have different parameters, the COP is always dependant on the outside temperature.

Future research in this field will use more complex control models including the specified heat demand curve. Further research will also include the use of renewable energy produced on site for heat pumps.

CONCLUSIONS

The use of air-to-water heat pumps is increasing and the optimization of their operation enables significant energy savings and makes it possible to achieve European Union climate ambitions. Air to water heat pump installers should consider including more storage tanks into the heat pump systems. The main advice for heat pump manufacturers is to give out more information about the COP curves of their products and for the users to be more knowledgeable to ask for more information about the COP curves in the selection process. This enables the more effective design of heating systems with heat pumps.

The method requires as an input the total energy demand and weather forecast during a chosen period not the distribution of the demand inside the period. The main factor that determines the energy savings in practice is the precision of the weather forecasts. A more accurate weather forecast enables to the prognosis of the productivity of the heat pump and heating demand of the building at any given time. The continuous measurement and calculation of the COP of the heat pump would be necessary for the optimization of an air-to-water heat pump in real conditions.

By shifting the heat production inside a day to the hours with higher heat pump COP values, the electricity consumption can be significantly reduced, with this method by 7.82%. 10.3% dependant on the weather conditions. The described method enables energy savings regardless of the characteristic of the heating demand.

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