Total carbon dioxide emissions from ground source heat pump and groundwater one in Białystok

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Abstract. To limit greenhouse gases emissions caused by energy production European Union (EU) prompts heat pump as heat generator which should decrease CO₂ emissions to the atmosphere. Because of the climatic conditions and low efficiency of electrical energy production and transfer in Poland it could be possible a condensing gas boiler would emit less CO₂. The analysis includes ten-year temperature measurements in Białystok where is more severe climate in Poland. Due to relatively high seasonal coefficient of performance (SCOP) value heat pumps can emit less CO₂ than condensing gas boiler and can be applied as ecological heat generators.

1 Introduction

Temperature rise which has been observed on the land part of the Earth at the end of the second millennium, started a discussion its origin. By a common agreement of the majority of the states the greenhouse gases (methane, carbon dioxide, water vapour, ozone, nitrous oxide, halogenated hydrocarbons, etc.) emissions are blamed global warming. Isasmuch as, carbon dioxide concentration has been increasing from 316 ppm [1] at 1960 to 411.69 ppm on 1st April 2019 [2] the limitation of CO₂ emissions by minimum 20% of the 1990 content before 2020 year is a target of European Economic Area states [3]. Thus, EU prompts the exchange heating devices that combust fossil fuels for heat pumps [4].

Although heat pump emit no gases in its location, it uses up electrical energy which is generated in Poland from fossil fuels burning. Moreover, efficiency of electrical energy production in Poland $\eta_p = 37.6\%$, as stated by GUS [5], and efficiency of low voltage energy transfer $\eta_t = 79.2\%$ which was fixed by Ciura [6]. Overwhelming majority of electrical energy in Poland origins from bituminous coal and lignite combustion, see in Table 2. If we consider efficiency of electrical energy production and transfer, heat pump in Poland is energetically profitable if seasonal coefficient of performance SCOP > 3.5 (cf. Rubik [7], Gajewski et al. [8]). It means, a heat pump which SCOP equals 3.5, generates so much total (in situ plus distant) CO₂ emissions as a coal fuel boiler. Thus, it was possible the heat pump would cause

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more CO₂ emissions than a condensing gas boiler (cf. [8]), which is verified using an inequality derived in the paper [8].

$$\beta_a < \beta_g = \beta_{ng} \frac{SCOP}{\eta_b} \quad [kgCO_2 / GJ] \quad (1)$$

where:

β_a – average value of generation factor for electrical energy production [kgCO₂ /GJ],

β_g – green value of generation factor [kgCO₂ /GJ],

β_{ng} – generation factor for natural gas combustion [kgCO₂ /GJ],

η_b – efficiency of a condensing gas boiler.

Both β_a and β_{ng} include direct and indirect emissions. If inequality (1) is met then the heat pump is ecologically viable. Otherwise, the condensing gas boiler should be applied.

The aim of research is estimation of emitted CO₂ amount to atmosphere during ground to water heat pump (GSHP) and water to water heat pump (WSHP) operation. The first step is determination of seasonal coefficient of performance of GSHP and WSHP, which was done in the work [9]. The second stage which is total CO₂ emissions estimation, is presented in the paper.

2 Computations

Although an algorithm origins from European standard [10], because of buffer tank operation it must have been changed so as to accurately estimate the heat losses. As the buffer tank is dumped and unloaded, the computations start at midnight on the first day of a heating season and are continued in the consecutive hours until the end of the heating season, which is necessary modification of the standard's algorithm [10]. For that purpose, the mean values of external temperature are calculated in every hour (see in Fig. 1). The external temperature values for ten-year period (2003–2012) at Białystok weather station were received thanks to kindness of The Institute of Meteorology and Water Management-National Research Institute (IMGW-PIB).

Fig. 1. Mean values of external temperature along heating season.

The comparative calculations are done for a commercial building with total design heat load $Q_d = 92.73$ kW. The building is located in Białystok where the heating season starts on 21st September and ends on 10th May. Hence, including a leap day the heating seasons lasts

5592 hours. Inasmuch as, a leap year occur once per four years a bin hour on 29th Feb $h_j = 0.25$, on the other days $h_j = 1$.

There are two alternative heat generators: GSHP or WSHP which the most important data are written down in Table 1. If groundwater composition did not meet the manufacturer’s requiriements the WSHP circuit should be disjointed from groundwater by a separating heat exchanger (SHE). Thus three variants are taken into consideration: GSHP, WSHP and WSHP+SHE. In every variant heat pump have to be separated from a heating system with a buffer tank (cf. [11]) generating additional losses Q_j .

Table 1. Technical data of the sized ground and water heat pump units, an extract from a technical guide [11].

		Vitocal 300-G Pro type BW 302.B120	Vitocal 300-W Pro type WW 302.B125
Output data to EN 14511		B0/W35, 5 K spread	W10/W35, 5 K spread
Rated heating output	kW	117.2	112.1
Power consumption	kW	24.4	18.3
Coefficient of performance (COP)	-	4.8	6.1
Fluid in primary circuit		brine	water

The algorithm starts from part load for heating $P_h(t_j)$ determination applying a formula [10]:

$$P_h \left(t_j \right) = Q_d \frac{t_i - t_j}{t_i - t_e} \quad [kW] \tag{2}$$

where
 t_e is external design temperature,
 t_i is internal air temperature,
 t_j is bin temperature (external air temperature).

Electrical energy consumption is predicted using an expression that is extended from the equation in the standard [10] to preseneted hereafter formula that includes heat losses of buffer tank Q_j :

$$E_e = \sum_{j=1}^{5592} h_j \frac{[P_h(t_j) + Q_j]}{COP_{bin}(t_j)} \quad [GJ] \tag{3}$$

where $COP_{bin}(t_j)$ is obtained from the manufacturer data [11]. Whereas Q_j . is computed in every hour from a relation:

$$Q_j = [i_{k-1} - i(20^{\circ}C)] \rho_{k-1} V (1 - \eta_t) \quad [kJ] \tag{4}$$

where:
 i_{k-1} – specific enthalpy of water in the buffer tank in a previous hour [kJ/kg],
 $i(20^{\circ}C)$ – specific enthalpy of water in the buffer tank at room temperature [kJ/kg],
 ρ_{k-1} – water density at temperature in a previous hour [kg/m³],
 V – buffer tank volume [m³],
 η_t – heat storage efficiency of the buffer tank [-].

To correlate bin temperature t_j with temperature t_k in the buffer tank the latter is obtained from heating curve [11] which is approximated by quadratic polynomial shown in

Fig. 2.

Fig. 2. Heating curve which is assumed in the heating system and its approximated polynomial.

Carbon dioxide emissions ε_{CO_2} during generation electricity consumed by a heat pump is estimated as follows:

$$\varepsilon_{CO_2} = E_e \beta_a = E_e \frac{\sum \beta_i S_i}{\eta_p \eta_t} \left[\frac{kgCO_2}{a} \right] \tag{5}$$

where:
 β – generation factor of a fuel (cf. Table 2) [kgCO₂/GJ];
 S – share of the fuel in electrical energy generation (cf. Table 2).

Table 2. The characteristics of electrical energy production in Poland according to PGE-OBRÓT [12].

Fuel	Generation factor β [kgCO ₂ /GJ]	Share S
Bituminous coal	252.43	25.21%

Lignite	291.95	67.70%
Natural gas	108.28	2.95%
Hydropower	0.00	0.85%
Renewables	0.00	2.97%
Others	6.03	0.32%

3 The results and discussion

The results are affected by temperature of heat transfer medium. Since ground temperature is slightly lower than groundwater one, GSHP needs more work (electrical energy in the case) than WSHP to provide the same amount of heat. Hence, SCOP = 5.03 for GSHP is lower than SCOP = 6.12 for WSHP (cf. the paper [9]). Inasmuch as, SHE decreases brine temperature at 2°C in the WSHP circuit SCOP for WSHP+SHE is at 5.86 [9]. It is because each heat exchanger works at a temperature difference. After a substitution the above SCOP values the inequality (1) is verified. The results are plotted in Fig. 3. The relatively high magnitudes of SCOP causes each of analysed variant is ecologically viable as each heat pump would cause less CO₂ emissions than condensing gas boiler. It differs from the conclusions in the paper [8], which results from lower COP values in that case. An advantage of the present analysis is caused by the application of hourly measured temperature values.

Fig. 3. Unit carbon dioxide emissions for the three analysed variants.

Carbon dioxide emissions which are obtained from eq. (5) after a substitution the magnitudes from Table 2, are presented in Fig. 4. Because of the same reason the highest CO₂ amount is emitted during GSHP usage. 18% less CO₂ emissions are caused by WSHP usage. SHE instalation causes 3.7% higher CO₂ production.

Fig. 4. Annual carbon dioxide emissions for the three analysed variants.

4 Concluding remarks

Temperature value at a heating system depends on a heating curve and the weather conditions, which are the same in all the investigated variants. Thus, it does not affect the results of the comparison. As, ground temperature is lower than groundwater temperature in the location, WSHP needs less energy delivered as work. Hence, WSHP causes lesser emissions in a power plant. Although, SHE installation generates a drop in temperature, risen CO₂ emissions are lower than in the case of GSHP. After, a detailed analysis of carbon dioxide emissions in Białystok, we are allowed to conclude the ground-water or water-water heat pump can be applied as an ecological heat generator for the heating systems. Although, it is case study, the conclusions may be extended to less severe climatic zones in Poland. The particular decision which kind of heat pump should be applied, depends on a geological case and an economic analysis.

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