Eligibility of a Heat Pump Based on the Primary Energy Factor

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Abstract

This paper presents the method for the determination of the eligibility of a heat pump (HP) based on the primary energy factor (PEF) analysis. To calculate the PEFs of air, water and ground source HPs, the seasonal performance factor of each HP was determined by using a simulation tool TRNSYS. For the purpose of the analysis the residential house with the fixed geometric data and energy labels from A to E has been considered. The calculation of PEFs for HPs heating systems was performed by considering different cases for use of the electricity from various sources: electricity energy mix from the EU grid, renewable energy sources, and the nuclear power plant. The results show that all three HPs, if they utilize electricity from the EU mix, are more primary energy efficient compared to 6 individual heating systems, which are based on oil, natural gas, biomass and LPG propane. Besides, when using electricity from the renewable sources, HPs are more primary energy efficient compared to a district heating, based on the coal fired cogeneration units if the temperatures of the district heating (DH) network system are higher than 90 °C. In case of the temperature levels of the DH network system of 70/50 °C the water and ground source HPs are comparable at appropriate ratios of extracted steam and appropriate energy efficiency of electricity generation.

Keywords: heat pump, energy efficiency, primary energy factor, district heating, renewable energy sources

1. Introduction

Heat pumps (HPs) are one of the most effective ways to use renewable- (air, water or ground), waste-energy resources and district heat at a suitable temperature level [1]. HPs can be found in many applications, since they are suitable for heating and cooling of living and working spaces, as well as for the sanitary water heating. Higher performance of HPs can be established by utilizing the renewable resources [2]. Also, in combination with, for instance, low temperature floor heating systems, relatively higher values of COP are achievable. Usually HPs are driven by electric power, however, there are also some other types of HPs, for instance sorption/adsorption, hybrid and gas engine heat pumps [3-5].

HPs are often considered as not only as the economically competitive technology, but also the exergetically efficient heating technology with relatively high primary energy factor (PEF) [6]. However, the economic and energetic performances of HPs strongly depend on several different factors. Therefore, there exist limiting conditions or parameters, at which the HPs are not thermo-economically effective and PEF efficient compared to

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other heating systems. Hence, in public, as well as in the scientific community different opinions regarding the eligibility of their application often appear [7]. One of strong impacts can be considered by the energy market and its prices, which are often a result of political actions and not so clear market rules or conditions.

Another strong impact regards the limiting parameters or conditions which are directly related to the seasonal performance factor (SPF) of the heat pump. This depends strongly on the heat source and heat sink variable conditions, ambient conditions, the components and other devices that form the heat pump system or the internal heating system, the characteristics of the building, and finally, the user's behavior [8]. Many HP manufacturers list the measured COP according to the European standard EN 14511, which was often also a subject of different critical debates. The main concern about using this standard is that the COP measurements are performed at ideal laboratory conditions. In March 2016 in Slovenia, the Slovenian Government replaced the standard EN 1451 with the new and stricter terms for HPs accreditation for heating purposes. According to new terms, the HPs must achieve the minimum statutory seasonal performance factor for heating purposes, prescribed in [9]. Those terms are in accordance with the Commission Regulation (EU) No. 811/2013 and Commission Regulation (EU) No. 813/2013 [10, 11].

The aim of this paper is to present the results of a comprehensive comparative analysis on 10 different heating systems. For this purpose, the primary energy factor (PEF) of the HP was defined by using different simulation-based SPFs for the air, water, and ground source HPs respectively, by considering a single-family residential house with energy labels from A to E for the heat source conditions, which correspond to Slovenia. Moreover, different sources for the electricity supplied to the HP have been considered: the electric energy mix from the grid (EU mix), electricity generated from various renewable sources, and the electricity from nuclear energy. The first part of the PEF analysis was dedicated to the comparison between the HP heating systems and the heating systems based on the oil, natural gas, biomass (firewood, pellets, wood chips) and the LPG propane. The second part of the PEF analysis compared HP heating systems with the district heating from the coal fired cogeneration unit. Different potential temperature levels of a district heating network system were considered for the PEF analysis. In all cases, the comparison with various types of heat pumps was performed for a broad number of SPFs.

Nomenclature

Variables:

h	[kJ/kg]	enthalpy
$\dot{m}$	[kg/s]	mass flow
P	[W]	electric power
PEF	[/]	primary energy factor
Q	[J]	heat
$\dot{Q}$	[W]	heat flow
SPF	[/]	seasonal performance factor
W	[J]	electric energy
x	[/]	ratio between the energy efficiency of the electricity generation in a cogeneration system and the energy efficiency of the electricity generation when operation is related only to the production of electricity

Subscripts:

chp	combined heat and power
dn	district heating network

el		electric
hp		heat pump
hs		heating system
st		steam

Greek letters:

η	[/]	energy efficiency

2. Seasonal performance factor of heat pumps

In order to determine the primary energy factor (PEF) of a heat pump (HP), the seasonal performance factor (SPF) of each type of the HP was determined by using the simulation tool TRNSYS. With that tool, the one-year simulations for the energy used for heating and hot sanitary hot water in the one-family residential house were performed for each type of the HP (air, water, and ground source heat pump, respectively). The following characteristics for the residential house were considered in the simulation:

- considered location: Ljubljana → the test reference year of Ljubljana was used in the simulation [12]
- net heating area: 180 m2
- dimensions of the sides of the residential house: 8×12 m

All the technical performance data of all three considered HPs were based on the manufacturers' data [13-15]. The nominal heating power for all HPs was taken to be 8 kW.

The SPF of the HP heating system is the ratio between the annual produced heat - Q_{HP} and the annual used electric energy of the HP system - W_{el}. The SPF for each type of the HPs was calculated by the well-known equation:

$$SPF = \frac{Q_{hp}}{W_{el}} \tag{1}$$

The one-year-average SPF considered the produced heat and used electric energy for heating and domestic hot water. The temperatures of the air, water, and ground source HPs respectively were defined by taking into account hourly values of an external air temperature (provided by the TRY Ljubljana), average temperature of ground water of 10 °C and the temperature of the ground in the range of 2.2-22.2 °C, respectively (Fig. 1).

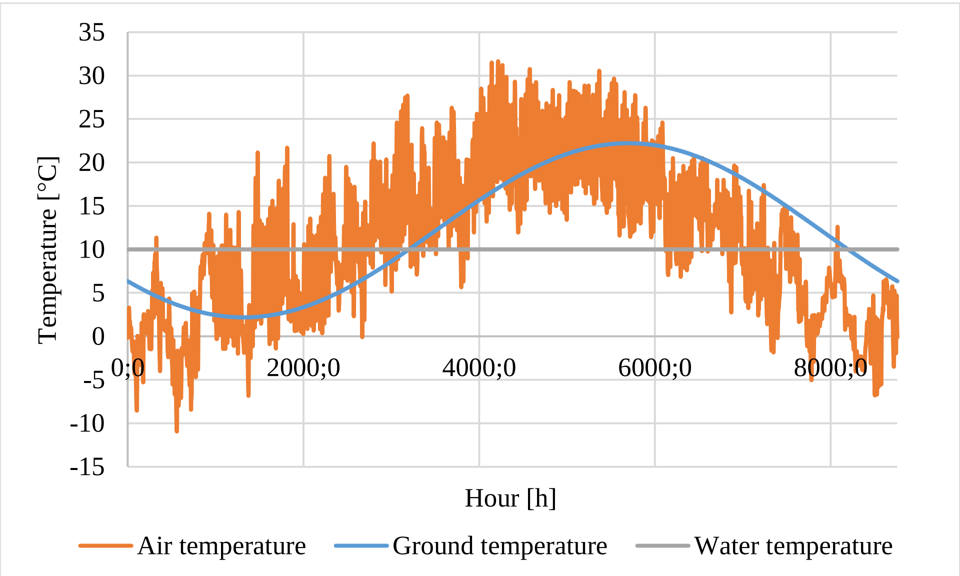

Fig. 1. The annual temperature variation of air, ground and ground sources

Other important factors used in the simulation were the following:

- Air-to-water (A-W) HP: frost formation on the evaporator coils was not considered in the simulation
- Water-to-water (W-W) HP: depth of the well was considered to be 18 m. The pumping of water was provided by the pump with the nominal power of 800 W.
- Ground-to-water (G-W) HP: depth of the collector field was considered to be 1.5 m. The pumping of water was provided by the pump with the nominal power of 75 W.
- Design temperature regimes were chosen according to the energy label of the residential house and the project temperature, which for Ljubljana is -13 °C. The inlet temperature of the radiator or floor heating system was variating with the external air temperature. The correlation between those two temperatures are shown in the Fig. 2.

The SPFs were calculated for the following cases:

- Residential house with fixed geometric data, but with different energy use. Hence, the residential house considered in simulations had energy labels from A to E (Table 1).
- Air, water, and ground source HPs
- Residential house with different combinations of heating systems, which are shown in the Table 1.

The heating temperature levels for labels with the higher energy consumption were taken to be higher that for the case of the well-insulated house.

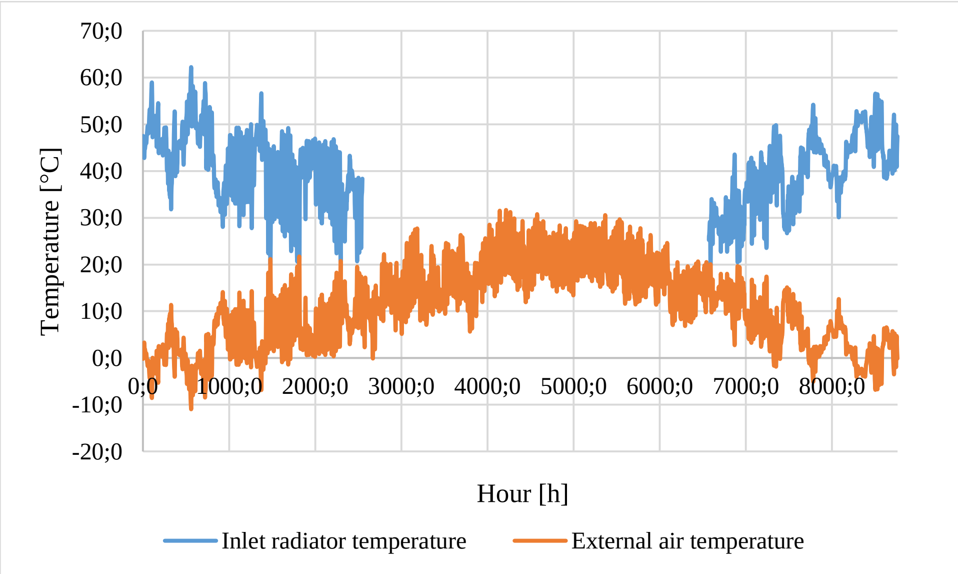

Fig. 2. An example shows the external air temperature and the inlet radiator temperature for the water-to-water heat pump in the case of the residential house with the energy label E and design temperature regimes 65/55 °C, which correspond to the maximum heating load

Table 1. All considered cases and related data used in simulations

Energy label of the residential house	A	B	C	D	E
Design temperature regime [°C]	35/30	35/30	45/35	55/45	65/55
Annual energy consumption [kWh/m^{2}a]	0-15	15-35	35-60	60-105	105-150
Heating system	Floor heating	Floor heating	Floor and radiator heating	Radiator heating	Radiator heating
Sanitary hot water heating	YES	YES	YES	YES	YES

The simulation-based SPFs for each type of HP, used in residential house with labels from A to E are shown in the Fig. 3. Based on the data, shown in the Fig. 3, one can see that the SPF are increasing gradually from the residential house with energy label from E to D. However, between the energy labels C and A the SPF decreases. The main reason for this is due to bigger ratio between the energy used for hot sanitary water heating and energy used of the residential house heating. Sanitary hot water heating requires input water temperatures in of at least 55 °C, while the residential house with the energy label from C to A requires much lower temperatures for heating purposes (45/35 °C and 35/30 °C). Also, if we compare the water-to-water (W-W) and ground-to-water (G-W) HPs, one can see that between the energy label D and E there is a shift in the SPF values, where G-W HP has higher values of SPF until energy label A. The main cause of this shift is due to constant temperature of the water at 10 °C in comparison to the temperature of the ground, which varies between 2.2 – 22.2 °C.

The biggest discrepancy between all three types of the HPs can be seen for the energy labels between E to C. The differences between the HPs is also smaller in case of energy labels A and B due to the higher ratio of the hot sanitary water preparation. Of course, if for the same label different temperature levels are compared, the highest SPF will be obtained for the lowest temperature level.

Fig. 3. Simulation-based SPFs for each type of HP, used in residential house with energy labels from A to E. Note: A-W: air-to-water heat pump; W-W: water-to-water heat pump; G-W: ground-to-water heat pump; SPF: seasonal performance factor

3. Analysis of the primary energy factors

The primary energy factor (PEF) analysis is a well-established method to determine the quantity of the primary energy used for the heat production. The determination of PEFs is based on the calculation of all primary energy inputs for extraction, conversion, transport and usage of energy source for electricity and heat production [16]. In the following chapters (3.1 – 3.3), methods for the calculation of PEFs for air, water, and ground source HPs, heating systems based on oil, natural gas, biomass, LPG propane, as well as district heating using coal fired cogeneration unit are presented.

3.1. PEFs of air, water, and ground source HPs

PEFs for heat production in case of air, water, and ground source HPs heating systems were calculated using the equation:

$$PEF_{hp} = \frac{PEF_{el}}{SPF} \tag{2}$$

where PEF_{el} denotes primary energy factor of the electricity, SPF denotes the seasonal performance factor of the heat pump. Primary energy factors of the electricity from various sources were considered:

- the electricity energy mix from the grid [17, 18]: PEF = 2.49
- electricity generated with photovoltaics [17, 18]: PEF = 1.14
- hydroelectricity [17, 18]: PEF = 1.08
- electricity generated with wind power [17, 18]: PEF = 1.03

- electricity generated with nuclear power [17, 18]: PEF = 3.50

All the calculated PEFs for all combinations of the simulation-based SPFs and the PEFs in case of the EU mix as well as average PEF of electricity, generated from various renewable sources are presented in the Table 2. The range of the PEFs for all three HPs in case of electricity used from the EU mix is from 0.64 to 1.10, while in case of electricity used from renewable sources is in average from 0.28 to 0.48. All the presented PEFs values are compared with the PEFs of the heating system in the following chapters (3.2 and 3.3).

Table 2: Simulation-based SPF and calculated PEF for air, water, and ground source HPs in case of using electricity from the EU mix and in case of using electricity produced from renewable sources

Energy label of the residential house	SPF			PEF					
				EU mix			Renewables average		
	A-W	W-W	G-W	A-W	W-W	G-W	A-W	W-W	G-W
E	2.45	3.39	3.23	1.12	0.73	0.77	0.44	0.32	0.33
D	2.83	3.69	3.80	0.88	0.67	0.66	0.38	0.29	0.28
C	2.95	3.66	3.92	0.84	0.68	0.64	0.37	0.30	0.28
B	2.82	3.28	3.65	0.88	0.76	0.68	0.38	0.33	0.30
A	2.69	2.92	3.32	0.93	0.85	0.75	0.4	0.37	0.33

Note: A-W: air-to-water heat pump; W-W: water-to-water heat pump; G-W: ground-to-water heat pump

3.2 PEFs of oil, natural gas, biomass and LPG propane heating systems

PEFs for heat production in case of oil, natural gas, biomass and LPG propane heating systems were calculated using the equation:

$$PEF_{hp} = \frac{PEF_{hs}}{\eta_{hs}} \qquad (3)$$

where PEF_{hs} denotes primary energy factor of heat source, η_{hs} denotes the efficiency of the heating system. PEF_{hs} values were found in [17, 18]. All the PEFs for heat production in case of oil, natural gas, biomass and LPG propane heating systems are presented in Table 3.

Table 3. Primary energy factor analysis for 6 different heating systems under consideration

Heating system		PEF of heat source [/]	Heating system efficiency [%]	PEF for heat production [/]
Oil	CB	1.10	90	1.22
Natural gas	CB	1.22	95	1.28
Biomass	Firewood	1.26	75	1.68
	Pellets	1.26	84	1.50
	Wood chips	1.12	79	1.42
LPG propane	CB	1.09	95	1.15

Note: CB: condensing boiler

If we compare the PEFs of all HPs under consideration with the PEFs of 6 heating systems based on oil, natural gas, biomass and LPG propane one can see that there is a point at which the eligibility of HPs is achieved. This can be seen in the Fig. 4 by intersection of the horizontal curves, which represent the PEFs of all 6 heating systems with the curves that represent the HP PEFs values. The blue, yellow and red transparent squares in the Fig. 4 represent the range of HP SPFs for residential house with energy label from A to E, determined with the simulation for the air, water, and ground source HPs.

The first thing to be noticed is that the PEF of all HPs within the operational range of SPFs is significantly lower compared to the PEF in case of heating system based on electric resistance heater.

If we consider the limiting points at which the use of HPs under consideration is eligible, the limiting SPFs of all such heat pumps are presented in the Table 4. That means, when considering the HP, that particular HP must be able to achieve the SPF above the limiting point. In case of the heating system based on LPG propane and using electricity from the EU mix, that system has the highest limiting SPF - 2.30. According to the Table 2, which presents the simulation-based SPFs and calculated PEFs of all HPs under consideration, all three HPs are eligible in case of residential house with the energy labels of from A to E versus the heating systems based on oil, natural gas, biomass and LPG propane.

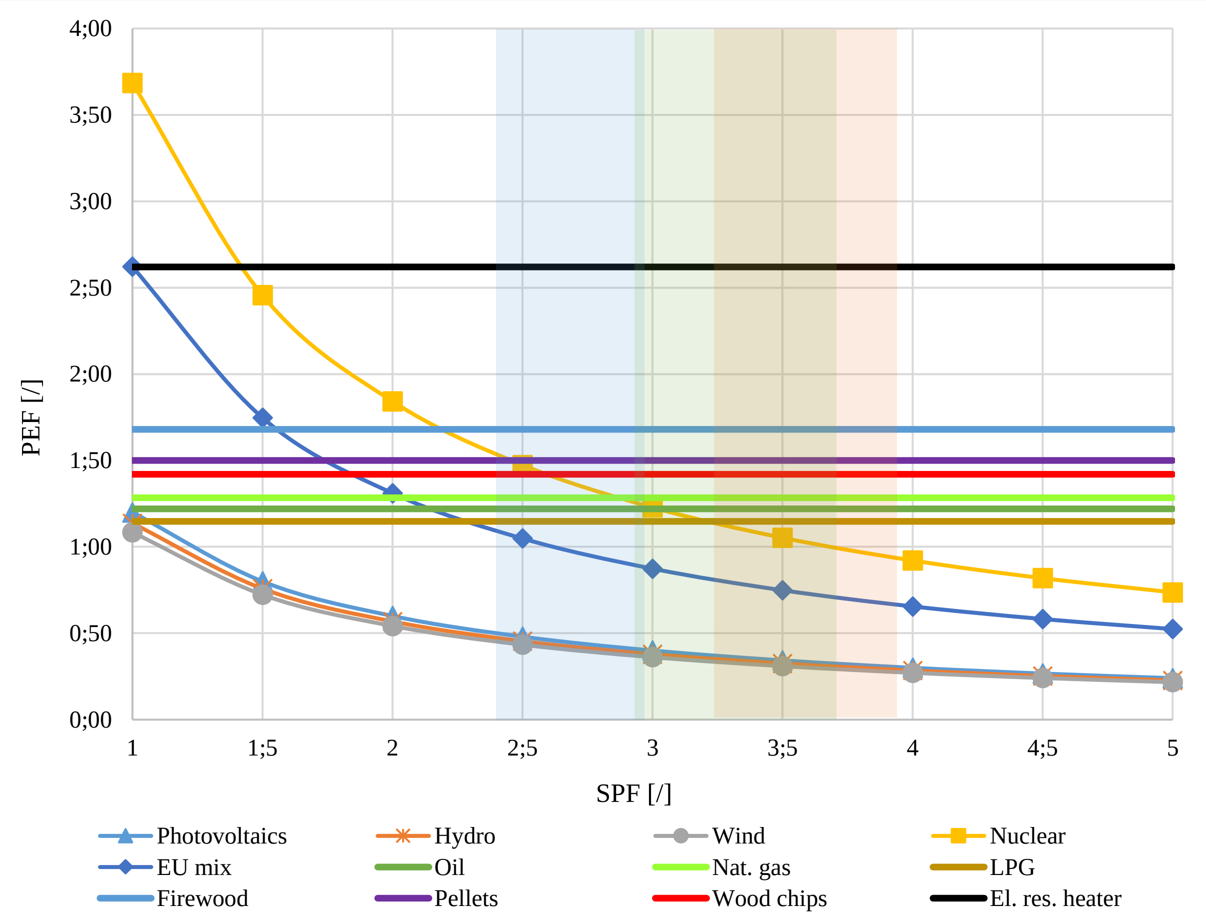

Fig. 4. PEFs of a HP (variable SPF given to evaluate the limits) when using electricity from EU mix, renewable sources and nuclear power plant compared to PEFs of heating systems based on oil, natural gas, biomass and LPG propane

If we use electricity from the nuclear power plant, the eligibility of the HP is achieved if the SPF of the HPs is above 3.20 when compared to the LPG propane heating system. Only the G-W HP is fully eligible when compared to all 6 heating systems and for residential house with energy labels from A to E. The other two HPs, A-W and W-W, are eligible in the proper combination of heating system and residential house with appropriate energy label.

The last thing to be noticed is that the PEFs of all the HPs under consideration in case of using the electricity from various renewable sources are noticeably lower compared to the PEFs of all 6 heating systems. That means, compared to the all 6 heating systems all three HPs are fully eligible in case of residential house with the energy labels of from A to E.

Table 4. Limiting SPFs in comparison with the 6 heating systems when using the HP with the electricity from the EU mix and nuclear

	EU mix	Nuclear
Firewood	1.55	2.20
Pellets	1.75	2.45
Wood chips	1.85	2.60
Natural gas	2.05	2.85
Oil	2.15	3.00
LPG	2.30	3.20

3.3 PEFs of DH using coal fired cogeneration unit

The primary energy factor of a steam turbine in a CHP unit using coal as a heat source, is calculated using the equation:

$$PEF_{st,chp} = \frac{PEF_{coal}(1-x)}{\eta_{dn}\left(\eta_{coal,chp} - \eta_{el,chp}\right)} \quad (4)$$

where PEF_{coal} denotes the primary energy factor of coal, η_{dn} denotes the energy efficiency of a district heating network system, $\eta_{coal,chp}$ denotes the energy efficiency of a CHP unit according to the coal, $\eta_{el,chp}$ denotes the energy efficiency of electricity generation of a steam turbine in a cogeneration system, x denotes the ratio between the energy efficiency of the electricity generation in a cogeneration system - $\eta_{el,chp}$ and the energy efficiency of the electricity generation when operation is related only to the production of electricity - η_{el}. It is calculated by:

$$x = \frac{\eta_{el,chp}}{\eta_{el}} \quad (5)$$

The calculation of the x is made by the following derivation: according to the Fig. 5 a) the energy flow inside the extraction-condensing (heat and power production) and condensing turbines (power production) are equal to:

$$\dot{Q}_{in} = \frac{P_{el}}{\eta_{el}} = \frac{P_{el,chp}}{\eta_{el,chp}} \quad (6)$$

The power of the condensing and extraction-condensing turbines is calculated as (see Fig. 5 b):

$$P_{el} = \dot{m}_{st}(h_1 - h_2) \quad (7)$$

$$P_{el,chp} = \dot{m}_{st}(h_1 - h_3) + \left(\dot{m}_{st} - \dot{m}_{st,dn}\right)(h_3 - h_2)$$

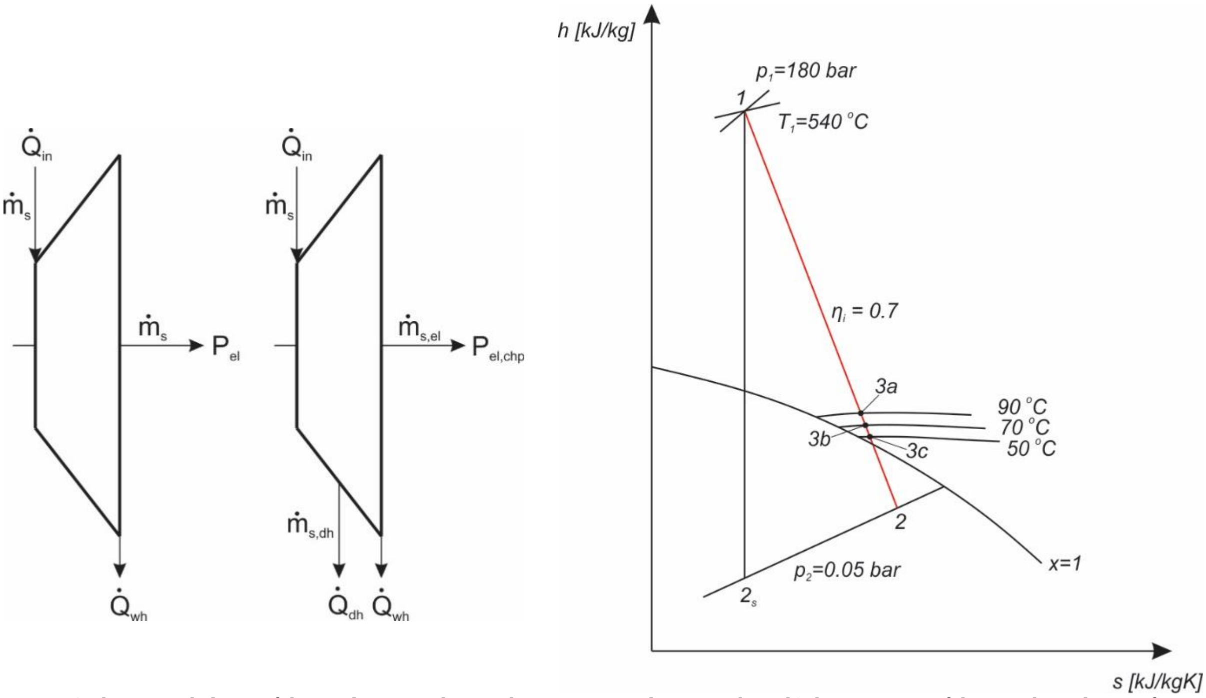

Fig. 5. a) The energy balance of the condensing turbine and extraction-condensing turbine. b) the expansion of the superheated steam for one inner energy efficiency of the steam turbine

It is known that:

$$\dot{m}_{st} = \dot{m}_{st,dn} + \dot{m}_{st,el} \tag{8}$$

and

$$y = \frac{\dot{m}_{st,dn}}{\dot{m}_{st}} \tag{9}$$

Therefore:

$$x = \frac{\eta_{el,chp}}{\eta_{el}} = \frac{P_{el,chp}}{P_{el}} = \frac{(h_1 - h_3) + (1 - y)(h_3 - h_2)}{(h_1 - h_2)} \tag{10}$$

In order to calculate the ratio x for an inner energy efficiency of 0.7, we have chosen the input parameters of a steam turbine, found in the Table 5. We also selected the energy efficiency of the electricity generation in a thermal power plant when operation is related only to the production of electricity, which is: $\eta_{el} = 0.35$.

The PEF_{ST} of a steam turbine in a CHP unit using coal were calculated according the Eq. 10 with the data, provided in the Table 6. Also, the PEF_{ST} were calculated for different energy efficiencies of electricity generation which varied from 0.2 – 0.45 in case of coal CHP unit.

Table 5. Input parameters of a steam turbine for the calculation of the ratio x

$\eta_i = 0.7$	
h_1 (540 °C, 180 bar) [kJ/kg]	3059.5
h_{2s} (0.05 bar) [kJ/kg]	1850
h_2 (0.05 bar, η_i) [kJ/kg]	2212.9
h_{3a} (90 °C) [kJ/kg]	2400
h_{3b} (70 °C) [kJ/kg]	2300
h_{3c} (50 °C) [kJ/kg]	2220

Table 6. Input parameters for the calculation of the PEFs of district heating network system using coal cogeneration unit

PEF_{coal}	1.3

$\eta_{chp,coal}$	0.88
η_{dh} at 90/70 °C	0.9
η_{dh} at 70/50 °C	0.929
η_{dh} at 50/30 °C	0.957

The PEFs in case of steam turbine in the coal fired cogeneration unit for the case of three different ratio of extracted steam: 20%, 50% and 100% are presented in the Figs. 6-8. If we compare PEFs in case of steam turbine with the PEFs of the HPs under consideration, one can see that in case of using the electricity from the EU mix the HPs are not eligible. However, the PEFs of the HPs in case of using the electricity from the renewable sources, one can see that those PEF values could be compared to the PEFs of the steam turbine. In the Figs. 6-8 the blue, yellow and red transparent squares represent the range of PEFs for residential house with energy label from A to E, determined with the simulation for the air, water, and ground source HPs, in case of using electricity from renewable sources.

In case of 20% of extracted steam for district heating network system, the PEFs of all HPs are considerably higher compared to the PEFs of the heat, generated in the coal fired cogeneration unit (Fig. 6).
If the ratio of the extracted steam is 50%, the PEFs of the cogeneration unit and the PEFs for the water and ground-source HPs in case of higher value of energy efficiency of electricity generation are comparable just in case of the district heating network with the temperatures of 90/70 °C (Fig. 7).

In the last case, with 100% of extracted steam (Fig. 8), the PEFs of the cogeneration unit are higher than the PEFs of all three HPs for the whole range of energy efficiency of electricity generation for district heating network with the temperatures of 90/70 °C. If the temperature of the district heating network system is lower - 70/50 °C, the PEFs of the water and ground source HPs are comparable with the PEF of heat, generated in the coal fired cogeneration unit.

Based on the data, found in the Figs. 6-8, all HPs under consideration are fully eligible in case of district heating network systems with higher temperatures (90/70 °C and above) with higher ratios of the extracted steam. For temperatures of 70/50 °C the eligibility can be achieved just in case of water and ground-source HPs, with higher ratios of the extracted steam and with higher energy efficiencies of the electricity production.

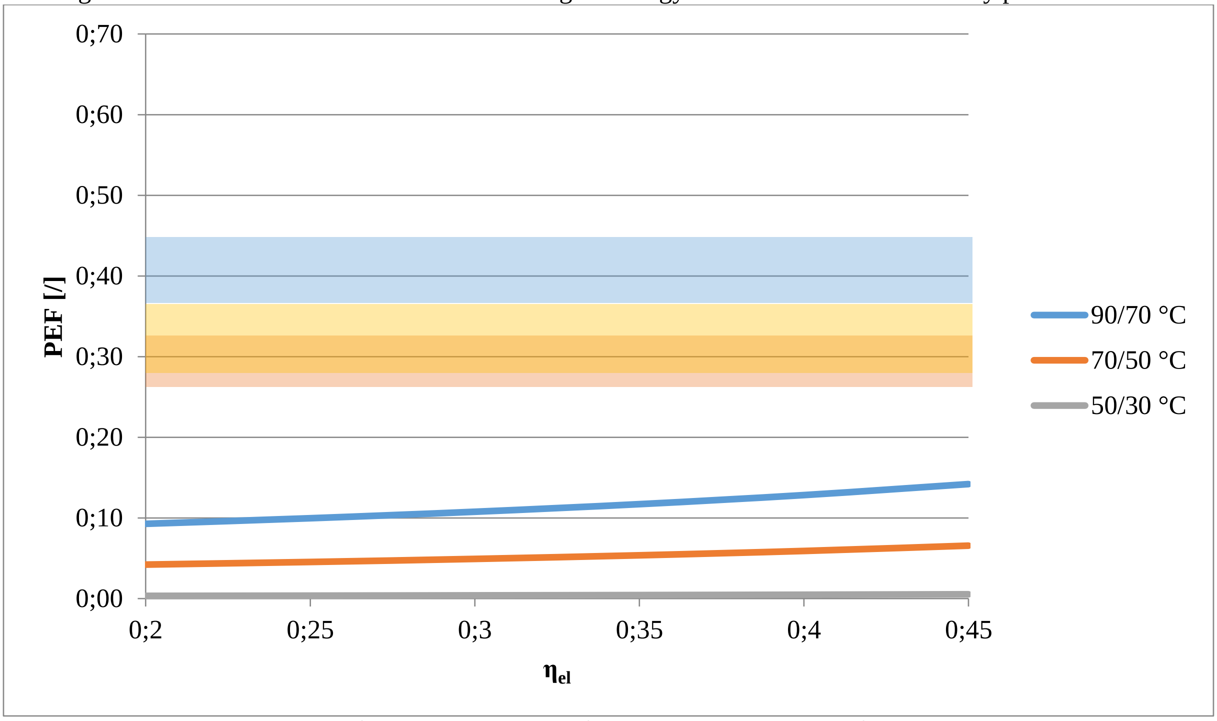

Figure 6: PEFs of a steam turbine in a coal fired cogeneration unit at 20% of extracted steam

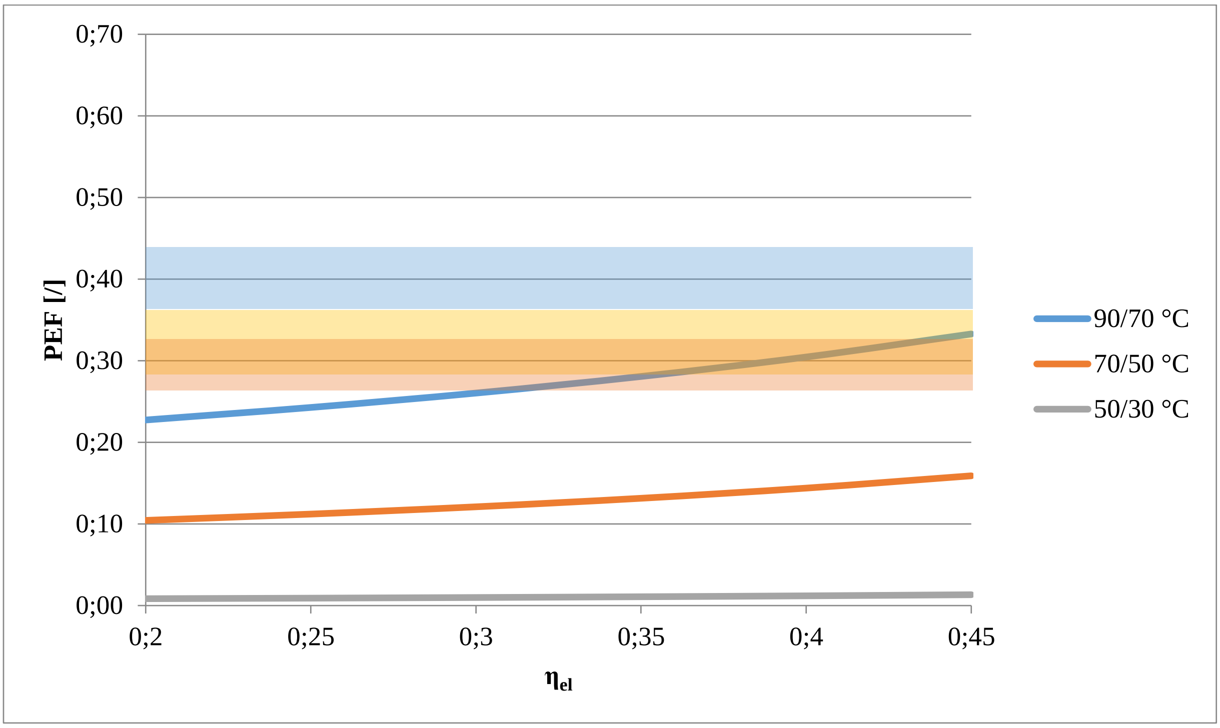

Figure 7: PEFs of a steam turbine in a coal fired cogeneration unit at 50% of extracted steam

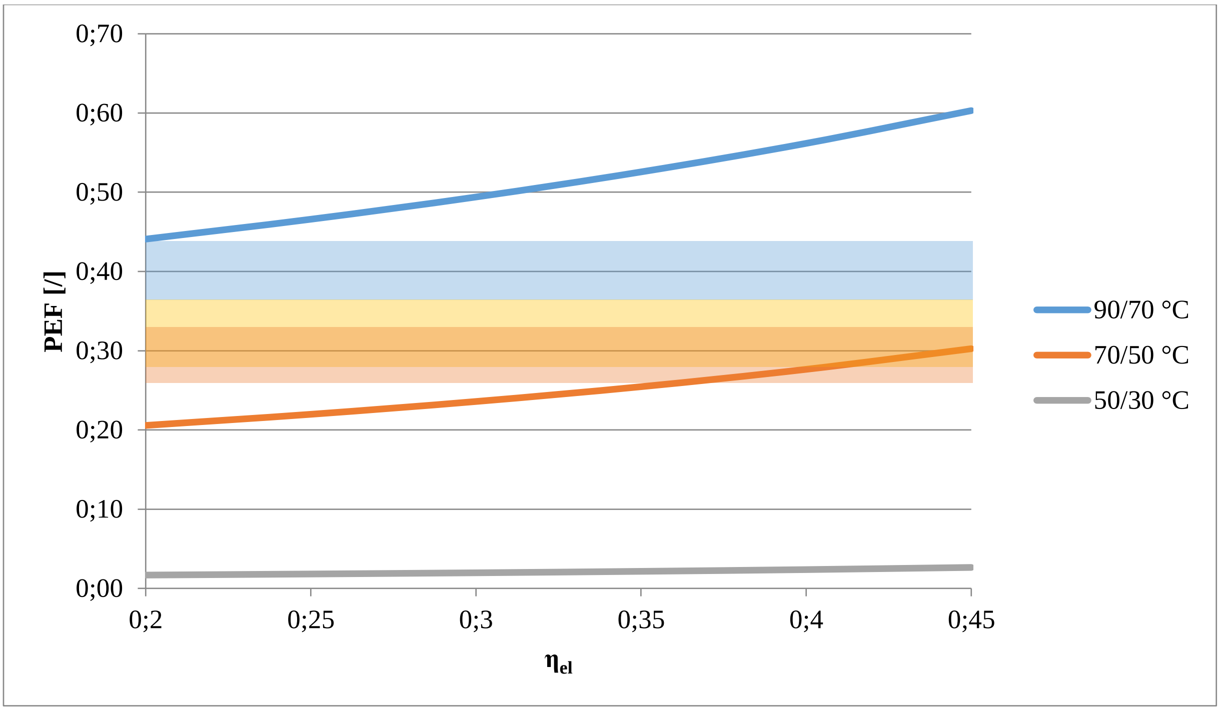

Figure 8: PEFs of a steam turbine in a coal fired cogeneration unit at 100% of extracted steam

4. Conclusions

In this paper, we present the method for determination of eligibility of a heat pump (HP) based on the primary energy factor (PEF) analysis. For this purpose, the comparison the PEFs of an air, water, and ground source HPs with the PEFs of the heating systems based on the oil, natural gas, biomass (firewood, pellets, wood chips), LPG propane and the district heating has been performed.

In order to calculate the PEFs of all three types of the HPs, the seasonal performance factor of each HP was determined by using a simulation tool TRNSYS. This simulation was done for the residential house with fixed geometric data, but with different energy losses. Hence, the residential house used energy labels from A to E and with two different evaluated heating systems: floor and radiator heating, respectively. Besides, the hot sanitary water heating was also considered.

The calculation of PEFs for heat production in case of an air, water and ground source HP heating systems was considered to be performed by use of the electricity from various sources: electricity energy mix from the EU grid, hydroelectricity, electricity generated with wind power, photovoltaics and nuclear power plant.

When comparing the PEFs of all considered HPs with the PEFs of heating systems based on oil, natural gas, biomass and LPG propane, the limiting SPFs, above which the heat generation with HPs is eligible, were identified for both, the electricity from the EU mix and the nuclear power plant. In the case of using the HP with the electricity from the EU mix, the SPFs should be above 1.55 and 2.30 in order for the HP to be competitive to the heating system based on firewood and LPG propane, respectively. In case of using the HP with the electricity from the nuclear power plant, the SPFs should be above 2.20 and 3.20 when comparing to the heating system based on firewood and LPG propane, respectively.

When considering the district heat from the coal fired cogeneration units, the PEFs of such units are much lower compared to the PEFs of HP using electricity from the EU mix and nuclear power plant. If HPs are using the electricity from the renewable sources, the PEFs of considered HPs are lower compared to the PEFs of cogeneration units for the temperature levels of the district heating systems above 90/70 °C in case of 100% extracted steam. In case the temperature levels of the district heating systems at 70/50 °C the PEFs of water and ground-source HPs are comparable in case of higher efficiencies of the electricity production. At 50% extracted steam the PEFs of water and ground-source HPs are comparable with the PEFs of the cogeneration unit in case of higher efficiencies of the electricity production.

The final highlights of the presented paper are:

- Heat should not be directly converted from the electricity by using electric resistance heaters. This namely should not be used for solving the problems of the surplus heat from nuclear power or some renewable energy sources (e.g. wind). It is namely avoiding the well-established knowledge on the second law of the thermodynamics and such practice should be strictly prohibited in the EU. If not, then the heat from the direct conversion from the electricity should be taxed and should win a carbon footprint, related to the whole chain of the technology production (e.g. nuclear, wind, etc).
- HPs are more primary energy efficient compared to 6 individual heating systems based on oil, natural gas, biomass and LPG propane when considering residential house with the energy labels from A to E and when considering the electricity from the EU mix. When considering the electricity from the nuclear power plant, only the ground source HP is fully eligible compared to all other 6 heating systems for residential house with energy labels from A to E. The air and water source HPs are eligible in the proper combination of heating system and residential house with appropriate energy label.
- HPs are more primary energy efficient compared to district heating, based on coal fired cogeneration units if the temperatures of the DH network system are high (90 °C and above). In the case of the temperature levels of the DH network system the water and ground source HPs are comparable at appropriate ratios of extracted steam and appropriate energy efficiency of the electricity generation.
- Heat should not be generated by heating plants, using coal, gas, biomass, etc. The heat production must be achieved by the cogeneration units in combination with the newer generation of the district heating network systems (also for these kinds of systems, one should not avoid the well-established knowledge on the second law of the thermodynamics and such practice should also be considered to be prohibited in the future of the EU).
- Heat pumps are suitable source of heat when combined with the district heating systems of 4. generation and in case of using the electricity from renewable sources.

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