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Hydrogeothermal Cascade Heat Pump – Economic and Ecologic Appropriacy

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Abstract. The article considers economy of exploiting heat from low-temperature geothermal sources for high-temperature heating of buildings using a heat pump. For the exploitation of low-temperature geothermal sources, a two stage heat pump with a heat transmitter was planned. The pump consists of two single stage heat pumps which use different refrigerants at each stage. At stage one, the calculation of the heat pump is conducted with refrigerant
R407c; at stage two of the heat pump, the refrigerant R600a is used. The main operational characteristics of a two stage heat pump are presented in the form of diagrams. For the exploitation of heat from geothermal water with a temperature of 45°C, a profitability evaluation of the investment in the heat pump was carried out, using the method of the net present value. In the research, also the coefficient of profitability and the period of time in which the investment is going to return itself were established.

Key words

Geothermal energy, heat pump, coefficient of performance, refrigerant, economy

1. Introduction

Due to the use of fossil fuels, the amount of greenhouse gases emitted into the atmosphere is increasing considerably, which leads to climate changes. Therefore it is expected of people to reduce the use of fossil fuels as a source of energy. This initiated the search and exploitation of renewable energy sources which are environment friendly and at the same time also cheaper. One of renewable energy sources is also geothermal energy, whose exploitation is becoming more and more competitive, as the prices of fossil fuels rise.

Geothermal energy presents the heat of the earth's interior. It consists of three components:

- the energy flow through the earth's crust in the form of substance transfer,
- the heat flow due to the heat conductivity of rocks, and
- the energy stored in rocks and fluids of the earth's crust.

Geothermal energy is primarily used for heating buildings, greenhouses, fish-farms, in balneology and in industry.

The decision regarding the exploitation of geothermal energy was also made in the town of Lendava, where a geothermal well Le-2g was drilled.
The geothermal well yield is 20 kg/s at pressure $3 \cdot 10^5$ Pa and at a temperature of 62°C.

Geothermal water is to be used for district heating of buildings in the Lendava town centre.

The current heating plan includes only the exploitation of heat from geothermal water for the
needs of district heating of buildings. Through a heat transmitter, the heat from the primary geothermal circuit is transmitted to the water of the secondary system of the district heating with a temperature regime 40°C/60°C. Figure 1 illustrates the current district heating system.

The temperature of the used geothermal water is 42°C, which is still enough for the water to be used for high-temperature heating of buildings using a heat pump. The objective of the research is to evaluate the profitability of the use of a heat pump in a district heating system, where the heat source is low-temperature geothermal water. In this way, the energy of the geothermal water could be exploited to the maximum before it is returned back into the earth through a reinjection well. With reinjection also an ecological problem is solved, as geothermal water must not be released into local water courses. With reinjection the used geothermal water is reheated in deep geological layers. Therefore geothermal water is a renewable energy source.

The majority of buildings in the Lendava town centre are old, with a poor thermal insulation. For their heating, a high-temperature radiator system is used. Only a few of the new buildings have a low-temperature floor warming systems. Because of the required high temperature of the secondary heat carrier, two stage heat pumps would be needed for the heating of buildings. The heat source would be used geothermal water with a temperature of 42°C.

2. Geothermal water in Slovenia and Serbia

Geologic and tectonic structure of Slovenia is rather complex, because its territory happens to belong to five different geological structural units: Panonnian Basin, Eastern Alps, Southern Alps, borderline between Eastern and Southern Alps, and outer Dinarides. Since Slovenia lies in the region where Alps, Dinarides and Panonian Basin connect, fold and oppose, what followed collision of the African and European plates, created deep cracks (tectonic zones), that enables deeper circulation of water.

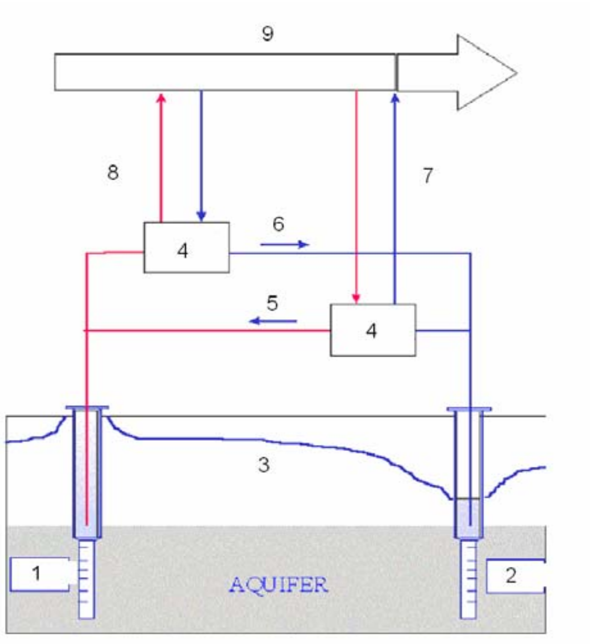

Figure 1 – Scheme of AQUIFER (1-hot well, 2-cold well, 3-soil temperature, 4-heat exchanger, 5-summer regime, 6-winter regime, 7-cooling, 8-heating, 9-ventilation)

For transport of water to the surface, quantity of top significance is the Earth crust thickness. It is maximal in western Slovenia, about 50 km. The layer gets thinner towards the east, so in Prekmurje it is only about 30 km.

In Slovenia there are 27 locations [6] available where geothermal water emerges from a well, of total installed thermal power 42 MW_t (53% of it is in use). 750 TJ of heat comes from this well, per annum. It is estimated that in Slovenia there are 50.000 PJ theoretically, 12.000 PJ of which can be used, heat only in geothermal aquifers.

Search for sources of thermal water in tertiar layers of Panonnian basin tells that somewhat more significant quantities of thermal water can be found only in Plyocene layers of Mura formation and that this geothermal aquifer (that is low-enthalpy geothermal system), never exceeds 100 m, supplies water to about all balneology-recreation centres (spa) of north-east Slovenia.

Aquifers are used for accumulation and exploitation of geothermal energy in conjunction with heat pumps. Such a system consists of two wells, as in Figure 1. In the heating mode, water from the hot well is fed into a heat exchanger where it releases heat, and then fed in the cold well. In the cooling mode, all is completely opposite.

Upon our knowledge, in Slovenia exists single high-enthalpy geothermal system, in tertiare based layers, that is not that deep in its north part (less than 2000 m), where temperature of geothermal water doesnt exceed 100°C. In the south part of the region, between cities Ptuj, Ormož, Ljutomer i Lendava, one can find thicker layers (4000 to even above 5000 m), and there geothermal water surely reaches temperatures above 200°C.

In territory of Serbia outside the Panonnian basin are over 160 natural wells of thermal water with temperature above 20 ^{o}C. The highest temperatures have been noted in thermal water of wells in Vranjska banja /spa/ (96 ^{o}C), then in Jošanička banja (78 ^{o}C), Sijarinska banja (72 ^{o}C), Kuršumliska banja (68 ^{o}C), Novopazarska Banja (54 ^{o}C), etc. Total production of all natural wells is about 4000 l/s. Most of thermal wells is located in Dinarides, then in Karpato-Balkanides and in Serbia-Macedonian massive. With respect to altitude, the largest number of thermal wells is located between 200-300 m, i.e. below +600 m is situated >90 % of all the thermal wells. Taking in account degree of investigation and extensivity of use, the leading locality of geothermal energy in Serbia is presently in Vranjska banja where it is used in balneo-therapy and for heating a complex of greenhouses. Recorded temperature of thermal waters in the borehole VG-2 is 112 ^{o}C. Total production is 80 l/s. Based upon research, most prospective habitat of geothermal energy is located in the region Mačva and is an energy ressource that could significantly substitute our need for oil import and coal. Total production of drilled research boreholes is 170 l/s of self-yield with average temperature of thermal waters at 70 ^{o}C. Geothermal energy is clean and recoverable. In Serbia it is found in different forms: as thermal energy stored in aquifers, i.e natural reservoirs of underground thermal waters with temperature of 10-90 ^{o}C; as thermal energy stored in hot aquifer waters with / without steam at temperature above 80 ^{o}C (80-200 ^{o}C); as thermal energy stored in warm and hot dry rocks.

Exploitation of geothermal energy for heating and other power purposes is in the initial phase and very humble as compared with the potentiality and ressources. In the hydro-geothermal system of the Panonnian basin used are thermal waters at 23 locations predominantly for balneology purposes and sporadically in power purposes. Outside the Panonnian basin thermal waters are used for heating at several locations i.e. at spas (Vranjska, Niška, Kuršumlijska, Sijarinska spa etc.). Total installed thermal power at places where it is directly used is 74 MWt, and with heat pumps 86 MW_t [1] Foreseen minimal reserves of thermal energy in thermal waters in Serbia are equal to thermal equivalent about 420 milions tons of crude oil, i.e. same quantity of heat can be obtained by combusting that quantity of oil. Adding the geothermal potentials of provinces Vojvodina & Kosovo, total equivalent foreseen minimal reserves rise to over 550 milions tons of oil.

3. Heat pump

For heating purposes three basic types of heat pumps are used:

- a single stage heat pump,
- a two stage heat pump with a flash vessel, and
- a two stage h. pump with a heat transmitter [1,4].

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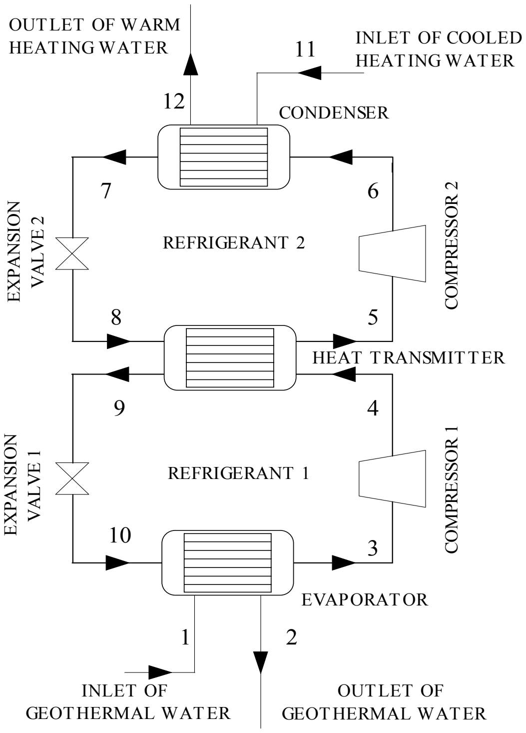

Figure 2: Scheme of two stage h.p. with a heat transmitter

Using a single stage heat pump for heating buildings, the temperature of the secondary carrier can reach 55°C at the maximum, which is considerably too little for the heating of buildings with a radiator heating system

Therefore, single stage heat pumps are primarily used for low-temperature heating systems, with the temperature of the secondary carrier up to 45°C. In high-temperature heating systems, the temperature of the secondary carrier must be higher than 60°C.

A two stage heat pump with a flash vessel could – with an appropriate refrigerant – be used for high-temperature heating systems. The problem lies in the fact that it is difficult to find a refrigerant with which we could exploit the temperature of geothermal water by cooling it to 10°C and at the same time reach a high temperature in the condenser of the second stage in the heat pump.

Because of this problem the research was based on a two stage heat pump with a heat transmitter (heat exchanger), schematically shown in figure 2. The heat pump consists of two single stage heat pumps which are connected by a heat transmitter. The advantage of such a heat pump is that according to their physical-chemical characteristics different refrigerants can be used at each stage. The heat transmitter between the two stages represents a condenser for the first stage and an evaporator for the second.

The use of two stage heat pumps with a heat transmitter is suggested in the existing district heating system of buildings. The heat source for the heat pumps would be the used geothermal water (T_{gm} = 42°C). The principle of exploiting heat from geothermal water in an individual facility is shown in figure 3. With such a system it would be possible to exploit the heat of geothermal water to the temperature 10°C [5,6].

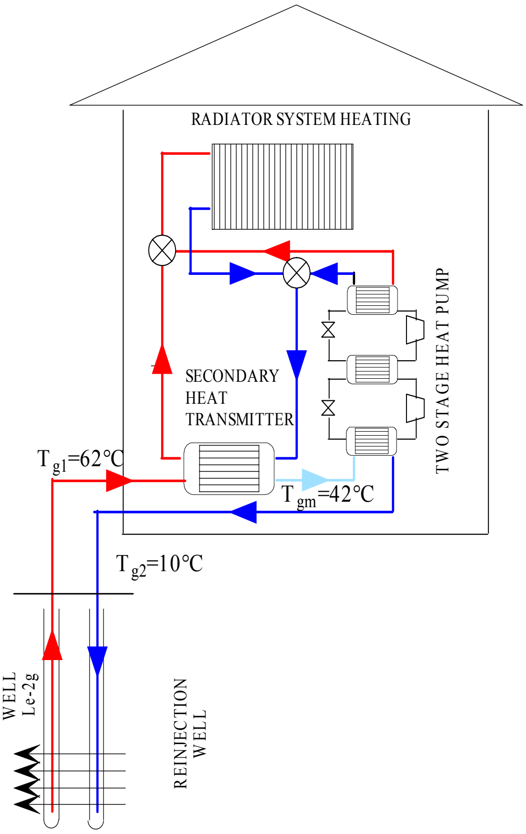

Figure 3: Heating of buildings by a two stage heat pump.

Table 1: Physical characteristics of refrigerants

Refrig.	Chemical formula	Mol. mass (g/mol)	Temp. of condens. (°C)	Enthalpy of evaporation (kJ/kg)
R 125	C_2HF_5	120	-48.9	159.7
R 32	CH_2F_2	52.02	-52.0	382.5
R 134a	$C_2H_2F_4$	102.0	-26.4	216.1
R 600a	i-C_4H_{10}	58.1	-12.3	355.4

4. Calculation of a two stage heat pump

With combining refrigerants in the first and second stages of a heat pump, the best operational characteristics are achieved with the combination of refrigerant R407c in the first stage and refrigerant R600a in the second. In choosing the refrigerant a lot of attention was paid to the physical-chemical characteristics of the refrigerant, ecological acceptability, and to the trends of using refrigerants of well-known heat pump manufacturers. Refrigerant R407c is a mixture of the following refrigerants: 23% R32, 25% R125 and 52% R134a [1,3]. Some of the physical-chemical characteristics of these refrigerants are presented in table 1

As the source of heat, energetically partly exploited geothermal water with a temperature of 42°C is used.

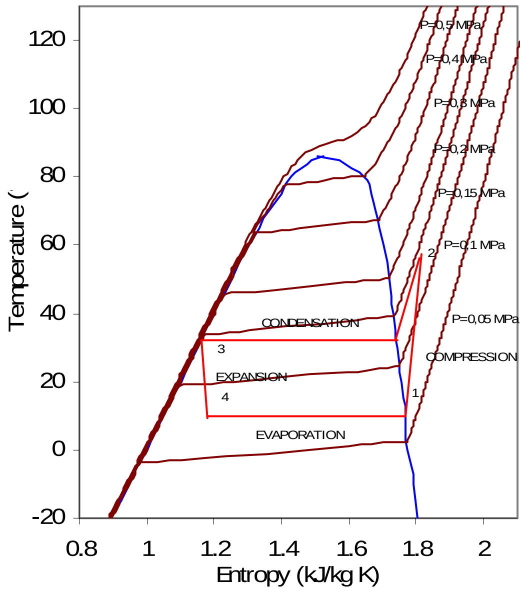

Figure 4: T, s – diagram of operation of the first stage of a heat pump with refrigerant R407c

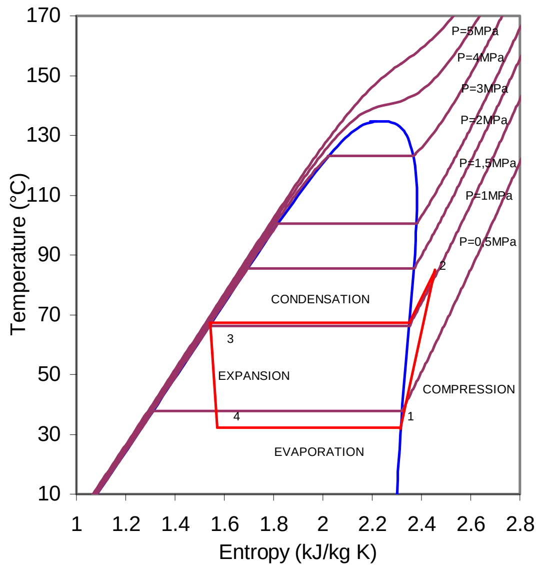

Figure 5: T, s – diagram of operation of the second stage of a heat pump with refrigerant R600a.

The thermodynamic course of operation for each stage of a heat pump is shown in figures 4 and 5. The results of the calculation of a heat pump are presented in the form of diagrams in figures 6 and 7, where the dependence of the heat flows of the evaporator and the condenser is shown, and the consumption of power of the compressor depending on the outlet temperature of geothermal water is also shown.

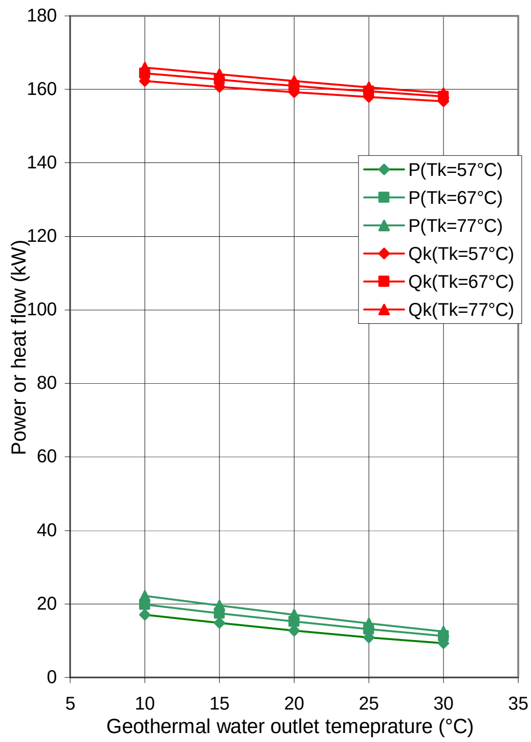

Figure 6: Heat flow in the first stage of a two stage heat pump and the power needed by the compressor

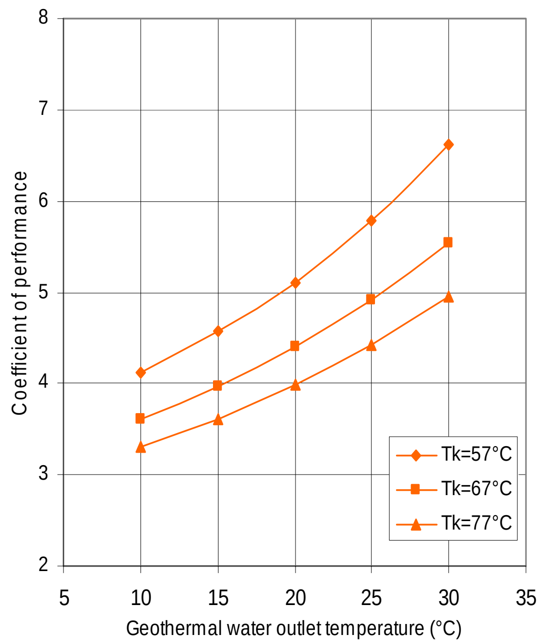

Figure 7: Coefficient of performance of a two stage heat pump using refrigerants R407c and R600a.

It is evident from the diagrams that the power needed for the running of the compressor is relatively small in regard to the extracted heat flow in the condenser of the second stage of the heat pump. The coefficient of performance of the heat pump is shown in figure 7. When the outlet temperature of geothermal water is 10°C and the temperature of water needed for heating is 77°C, the value is 3.5.

5. Profitability evaluation of exploiting geothermal energy using a heat pump

Any economic analysis is based on 2 presumptions:

- the investment which represents the amount of money needed for the realization of a project, and
- the surplus (the difference between incomes and operating expenses).

The net present value is very commonly used in preparing investment projects in later phases of project development, when a sufficient amount of data is available. The net present value is the sum of present value of all cash flows. The rule when deciding about a certain investment based on the NPV is that the investment is accepted when the NPV is larger than zero, and rejected when the NPV is negative.

The costs of the investment can be covered with one's own funds, bank loans, or the combination of both. The present value of investment costs C_{INV} is determined with discounting annual installments according to eq'n:

$$C_{INV} = C_0 + \sum_{j=0}^{N} \frac{a_n \cdot C_{TČ}}{(1+r)^j} \tag{7}$$

The annual installment factor - a_n is determined with the equation:

$$a_n = \frac{r_a \cdot (1+r_a)^{n_1}}{(1+r_a)^{n_1} - 1} \tag{8}$$

The maintenance costs of a heat pump C_S are estimated at 2% of the purchase price. The NPV of the costs, while taking into consideration inflation, is determined with the equation:

$$C_S = \sum_{j=0}^{N} \frac{0.02 \cdot C_{TČ} \cdot (1+r_j)^j}{(1+r_j+r)^j} \tag{9}$$

The NPV of the electricity costs for the running of a compressor C_{PS} is determined with the equation:

$$C_{PS} = \sum_{j=0}^{N} \frac{C_E \cdot P_E \cdot t_1 \cdot t_2 \cdot (1+r_j)^j}{(1+r_j+r)^j} \tag{10}$$

The NPV of the incomes from the extracted heat C_P, w. taking into consideration inflation and the discounting of annual installments, is determined with the equation:

$$C_P = \sum_{j=0}^{N} \frac{Q_k \cdot C_T \cdot t_1 \cdot t_2 \cdot (1+r_j)^j}{(1+r_j+r)^j} \tag{11}$$

The NPV of the income from the extracted heat, while taking into consideration the costs of the investment, maintenance, and electricity needed for the running of a compressor, is determined with the equation:

$$C = C_P - (C_{INV} + C_S + C_{PS}) \tag{12}$$

The successfulness of an investment is determined with the coefficient of profitability:

$$K = \frac{C_P}{C_{INV} + C_S + C_{PS}} \tag{13}$$

The coefficient of profitability K represents the ratio between the NPV of incomes from the sale of heat, and the sum of all NPV expenses.

The other criterion for the successfulness of the investment is the period of time in which the investment is going to return itself [7,8].

An example for evaluating profitability of a two stage heat pump for heating buildings. The data needed for an economic analysis of a two stage heat pump with refrigerants R407c and R600a is shown in table 2.

The results of calculating the NPV of a heat pump, which is using cool geothermal water to 10°C, are shown in table 3. On basis of NPV we calculated the coefficient of profitability and the period of time in which the investment is going to return itself. The coefficient of profitability is 1.19, and the investment is going to return in 3.2 years. Figure 10 shows the relation between NPV and the outlet temperature of used geothermal water.

The diagram can be used to determine at which outlet temperature of geothermal water the heat pump investment is still economically suitable.

Table 3: Net present values (NPV)

N (years)	Cinv EUR/year	Cs EUR/year	Cps EUR/year	Cp EUR/year	NPV EUR/year
0	8000.0	0.0	0.0	0.0	-8000.0
1	2661.0	523.8	7324.0	12300.0	1791.2
2	2487.0	489.9	6850.0	11500.0	1673.1
3	2324.0	458.2	6407.0	10760.0	1570.8
4	2172.0	428.6	5993.0	10060.0	1466.5
5	2030.0	400.8	5605.0	9411.0	1375.2
6	1897.0	374.9	5242.0	8802.0	1288.1
7	1773.0	350.6	4903.0	8233.0	1206.4
8	1657.0	328.0	4586.0	7700.0	1129.0
9	1549.0	306.7	4289.0	7202.0	1057.3
10	1448.0	286.9	4012.0	6736.0	989.1
11	0.0	268.3	3752.0	6300.0	2279.7
12	0.0	251.0	3509.0	5893.0	2133.0
13	0.0	234.7	3282.0	5511.0	1994.3
14	0.0	219.6	3070.0	5155.0	1865.5
15	0.0	205.3	2871.0	4821.0	1744.7
16	0.0	192.1	2686.0	4509.0	1630.9
17	0.0	179.6	2512.0	4218.0	1526.4
18	0.0	168.0	2349.0	3945.0	1428.0
19	0.0	157.1	2197.0	3690.0	1335.9
20	0.0	147.0	2055.0	3451.0	1249.0
NPV	27998.0	5971.1	83494	140197.0	22733.9

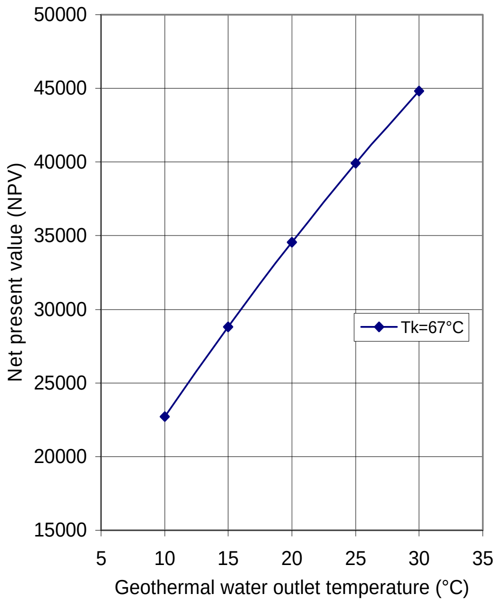

Figure 10: NPV vs. outlet temperature of geothermal water.

6. Conclusion

The presented economic calculation shows that it is suitable to exploit low-temperature geothermal energy for district heating of buildings. The use of a heat pump is justifiable in every individual facility, where the heat of geothermal water is already partly extracted in the secondary transmitter.

Due to a high-temperature radiator system heating, the majority of buildings require a high temperature of a heat carrier in the heating system. It is not possible to achieve such high temperatures using a single stage heat pump; therefore a two stage heat pump with a heat transmitter must be installed. Such a heat pump enables the use of two different refrigerants in each stage of compressing. It was established with calculations of a heat pump that the best results are obtained with the combination of refrigerant R407c in the first stage, and refrigerant R600a in the second.

The coefficient of performance COP of a heat pump is between 3.5 and 4.4, at an outlet temperature of geothermal water 10°C. An economic analysis of the investment was also carried out. In evaluating the profitability of the investment the method of the net present value (NPV) was used. The economic calculation shows that the investment into a heat pump is suitable, as the money investment returns itself in a time period of just a few years.

Nomenclature:

a_n	- annual installment factor
C	- profit (EUR/year)
C_0	- investor's own resources (EUR)
C_E	- price of electricity (EUR/kWh)
C_T	- price of heat (EUR/kWh)
$C_{TČ}$	- price of heat pump (EUR)
C_S	- expenses (EUR/year)
c_p	- specific heat capacity (kJ/kgK)
h	- specific enthalpy (kJ/kg)
h^0_{298}	- standard specific enthalpy (kJ/kg)
h_2	- specific enthalpy pressure side compressor (kJ/kg)
h_3	- specific enthalpy of refriger. in condenser (kJ/kg)
K	- coefficient of profitability
N	- operational life of a heat pump (years)
p_0	- atmospheric pressure (Pa)
p_T	- pressure on the pressure side of a compressor (Pa)
p_S	- pressure on the sucking side of a compressor (Pa)
p_{R407c}	- steam pressure of the refrigerant R407c
p_{R600a}	- steam pressure of the refrigerant R600a (Pa)
P	- power of a compressor (W)
r	- discount rate
r_a	- discount rate of annual installments
n_1	- time of paying off annual installments (years)
r_j	- inflation rate
t_1	- operational time of a heat pump (h/day)
t_2	- operational time of a heat pump (days/year)
T_k	- condensation temperature (K)
T_{g1}	- inlet temperature of geothermal water (K)
T_{g2}	- outlet temperature of geothermal water (K)
T_0	- temperature at standard conditions (K)
T	- temperature (K)
β_K	- utilization rate of a compressor
ε_c	- coefficient of performance
η	- utilization rate of a compressor
Φ_R	- input heat flow in a evaporator (W)
Φ_C	- output heat flow in a condenser (W)

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