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SIMULTANEOUS PRODUCTION AND INJECTION OF TWO WATER-BEARING LAYERS IN THE SAME WELL

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ABSTRACT

Technical and basic economical analyses regarding simultaneous production and injection of two water-bearing layers by one well are presented in this paper. Calculations were done based on geological, hydro-geological and economical data from the southern part of Poland. To estimate reservoir working parameters, i.e. temperature and pressure distribution, the numerical simulator TOUGH2 was used. To estimate temperature drop because of heat losses to surrounding rocks and because of heat exchange processes connected with system characteristics, a semi-empirical solution was used. The results of the calculations confirm the possibility of utilising the system over a long period of time.

The design of a geothermal heating station based on compression heat pumps has been proposed. After heat demand specification for a certain location, two types of geothermal heating stations were considered, with, and without additional heat sources operating during the lowest temperature period of the year. Energy production and consumption based on calculated load factor for those installations were estimated. Then economical analyses were carried out taking into account running and investment costs. Based on the analyses, the prices of the energy produced with different financing scenarios were calculated and compared with other popular energy sources. Even when investment costs increased because of additional heat sources, the real costs of energy production were lower than for the case with heat pumps only. The paper discusses positive environmental effects of geothermal utilisation connected with a reduction of emission impurities to the atmosphere. Taxes connected with emission impurities were taken into account.

1. INTRODUCTION

The utilisation of renewable energy sources is usually connected with high investment costs and low operating costs. Accurate economical analyses must take into account the investment costs of a venture. Usually during the first few exploitation-years, expenditures have to be paid off and most profits are destined for that.

Geothermal energy utilisations usually require high investment costs. A substantial expense is the underground part of an installation - especially when we include the price of geothermal surveys, which precede well localisation. These costs increase when geothermal fluid is not of good enough quality and cannot be used as drinking water, or pumped away as sewage. A high value of the total dissolved solids factor (TDS) usually causes this situation. Investment and exploitation costs increase because of the need for an additional well for reinjection; additional energy to drive pumps may also be needed. The use of existing wells, when possible, should give good results. In some places in the world where many fossil fuel wells have been drilled, some of them could be used as geothermal wells (Bujakowski, 2000). An additional advantage is that there may exist information about water-bearing layers found. Often reinjection is connected with environmental protection aspects (it helps to avoid ground surface subsidence) and keeps constant water pressure inside a reservoir. Even when investment outlays are high, the operating costs connected with geothermal energy utilisation are relatively low. It helps to keep economical equilibrium for these kinds of solutions. In some situations non-conventional exploitation methods can also be taken into account, as shown in the presented paper. The discussed subject can reduce investment costs.

Geothermal energy and other renewable energy sources are important because they do not cause strong pollution, and provide alternatives to fossil fuel sources. When it is possible to reduce fossil fuel consumption, renewable energy sources help to preserve it and to improve environmental quality. In the Polish energy sector, 70% of the primary energy consumption is based on fossil fuels. The share of all renewable energy sources, including geothermal, is officially projected to increase several percentages in the years 2015-2020 according to the ALTENER Programme. Poland has large low-enthalpy resources connected with sedimentary basins (Kepinska et al., 2000). Because of its chemical composition, geothermal fluid in Poland often has to be reinjected after cooling.

The following report is structured as follows:

- In Chapter 2 the reservoir working parameters are estimated;
- Chapter 3 contains a design of a geothermal heating station based on the reservoir parameters and other parameters with the well localization connected. Thermal energy production according to the load factor is estimated there also;
- Chapter 4 presents estimations of the energy unit production price in different financial scenarios, taking into account total investment costs. Environmental effects with connected emission reduction is also estimated;
- In Chapter 5, general conclusions connected with the presented solution are gathered.

2. UTILISATION OF THE GEOTHERMAL RESERVOIR

2.1 General information

The presented paper describes a non-conventional method for geothermal reservoir exploitation that involves simultaneous production and injection of two water-bearing layers by the same well. Presented calculations are based on geological and hydrogeological data from Rzezawa town in the southern part of Poland (Figure 1). The population of the town is 2525. The existing well on which the presented solution is based is located 800 m away from the town. About 1000 m away from the well is another town - Lazy, with 1036 inhabitants (see Figure 1).

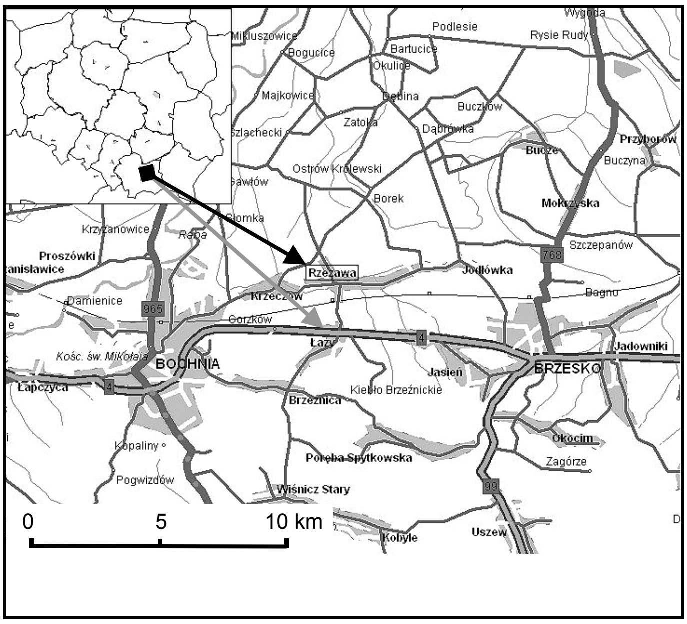

FIGURE 1: Locations of Rzezawa and Lazy towns

2.2 The system description

The system consists of three coaxial tubes of different diameters (Figure 2). The outside tube is a direct part of the existing well casing. Between the outside tube and the tube with middle diameter, a channel (annulus) for geothermal water flow is created. Two internal tubes create insulation for water with different temperatures. The tube with the smallest diameter also creates a flowing channel for the geothermal water. The well intersects two permeable water-bearing layers separated by near-impermeable formations. Information about hydrogeological and thermal properties of the geological layers is given in Table 1.

The outside tube is perforated by a high water-bearing horizon. It allows water to flow inside the channel between the outside pipe and the pipe with the middle diameter. Deep in the well, a packer closes this flowing channel. The packer is located a little higher than the upper ceiling of the lower water-bearing layer. Geothermal fluid can flow only to the upper part of the installation and at the top of the well it has temperature t_{out}. Below the packer (in the lower water-bearing layer level), all three tubes are perforated. By using the pipe with the smallest diameter, a possibility for reinjection of water into this layer was created. Thus, the system can be used for simultaneous exploitation of two water-bearing layers. Hotter water is explored from an upper reservoir. It flows to the surface where it is cooled down and then reinjected into the lower reservoir.

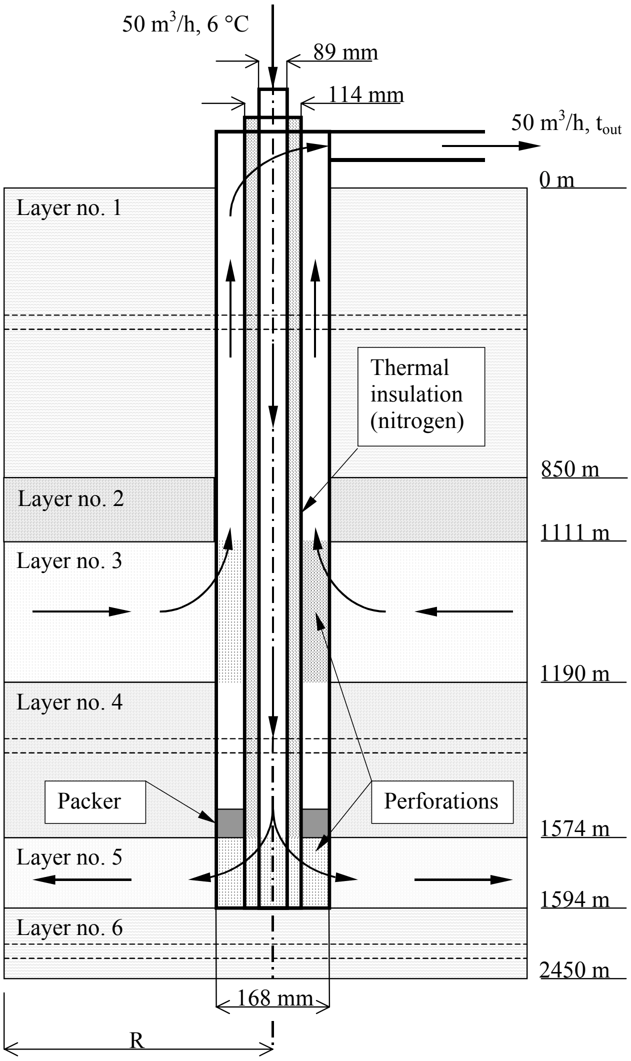

FIGURE 2: Scheme of the system for simultaneous exploitation of two water-bearing layers by one well

TABLE 1: Hydrogeological and thermal properties of geological layers (the vertical permeability is the horizontal one divided by 100)

Layer no.	Depth from surface [m]	Lithostratigraphy	Thermal cond.coeff. [W/mK]	Specific heat [J/kgK]	Density [kg/m³]	Porosity [%]	Permea -bility [mD]
1	0-850	Miocene, Quaternary sediments (sands, sandstones, loams, pudding stones)	2.5	1500	2400	5	40
2	850-1111	Upper Cretaceous	3.0	1200	2450	1	10^{-4}
3	1111-1190	Cenomanian (sands, pudding stones)	2.0	1800	2550	25	3000
4	1190-1574	Upper Jurassic	3.2	840	2600	1	10^{-4}
5	1574-1594	Dogger	2.5	800	2400	10	400
6	1594-1885	Precambrian, Silurian	3.5	950	2600	1	37167

Usually during exploitation we can assume that fluid flow through a geothermal well from a reservoir to the ground surface is isenthalpic. This assumption is reasonable in standard geothermal well exploitation, where geological formations surrounding a well are heated up approximately to the reservoir temperature. It can happen that the considered case does not fit this behaviour. The heat exchange process between hotter and colder water can cause the mentioned situation. This process decreases the efficiency of the system; hot water is cooled down by reinjected colder water. The scheme of the system is similar to the most efficient scheme of a heat exchanger, the counterflow heat exchanger (Shvets et al., 1975). To avoid heat exchange between hotter and colder water, a thermal insulation between the fluid streams must be used. A compressed nitrogen layer creates the thermal insulation. It fills the free space between the tubes with the smallest and medium diameters. Usage of nitrogen helps to avoid damages due to corrosive processes. Nitrogen is also relatively cheap and has good thermal insulating properties. Thermal conductivity of nitrogen under atmospheric pressure at 27°C equals 0.0262 W/mK (Holman, 1989).

Because of a lack of space for well pump installation inside the well, there are some problems with reservoir exploitation. This type of utilisation is possible when there is artesian flow from one of the layers. In the described well, free (artesian) water flow in both water-bearing layers during well tests was noticed with: 66 m^3/h - for the upper layer and 2 m^3/h for the lower layer. It should avoid problems connected with fluid pumping. Measured water temperature is much higher in the lower water-bearing layer, about 50°C, than in the upper layer, about 39°C.

Geothermal fluid in the lower water layer has high enough temperature to be used directly for central heating and domestic usage. According to the following calculations, assuming backwater temperature to be 30°C, it is possible to receive 47 kW_{th}.

$$\dot{Q}_s = 2\ [m^3/h] \times 1/3600\ [h/s] \times 997.4\ [kg/m^3] \times 4.2\ [kJ/kg^\circ C] \times (50 - 30)\ [^\circ C] \approx 47\ kW_{th}$$

Water temperature in the upper layer is much lower and cannot be used directly in heating installations. Because of higher flow rate, it contains more energy. It can be exploited by heat pumps, assuming cooling down to 6°C. The following calculations show, it is possible to receive 1920 kW_{th}.

$$\dot{Q}_s = 50\ [m^3/h] \times 1/3600\ [h/s] \times 997.4\ [kg/m^3] \times 4.2\ [kJ/kg^\circ C] \times (39 - 6)\ [^\circ C] \approx 1920\ kW_{th}$$

The first aforementioned solution is obviously connected with the smallest investment costs, but taking into account well location (800 m away from the town) and the number of potential consumers, the second solution should be reasonable because of economical and environmental aspects (geothermal energy utilisation helps to decrease pollution caused by fossil fuel combustion).

2.3 Calculation of reservoir parameters

Pressure and temperature distribution under the ground surface have been calculated by using the numerical simulator TOUGH2 (Pruess et al., 1999). It handles non-isothermal flows of multicomponent and multiphase fluids through porous and fractured media.

2.3.1 Basic assumptions

A conceptual model of the described system is based on the following basic assumptions:

- Rock formations in the whole space surrounding the well are assumed to be a porous (without cracks) and isotropic body (see properties of geological layers in Table 1);

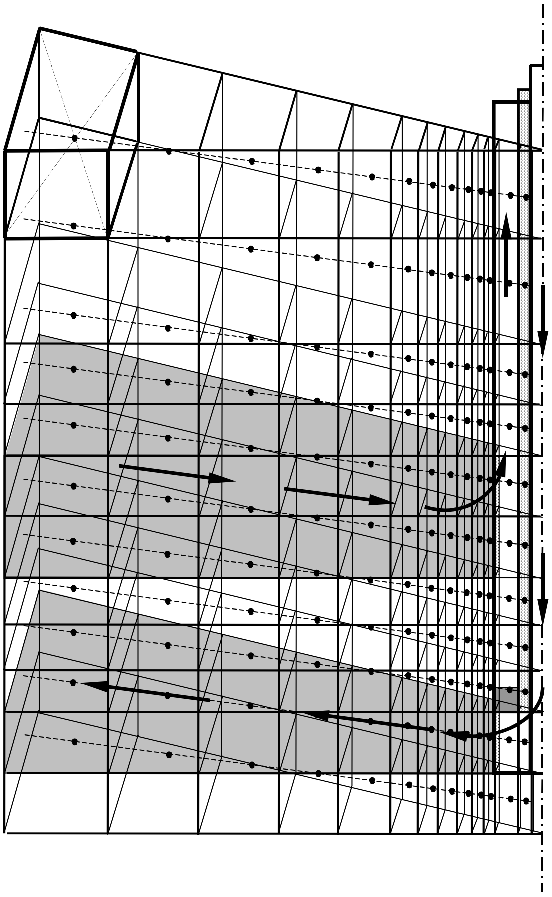

FIGURE 3: The radially symmetric grid used in the reservoir calculations

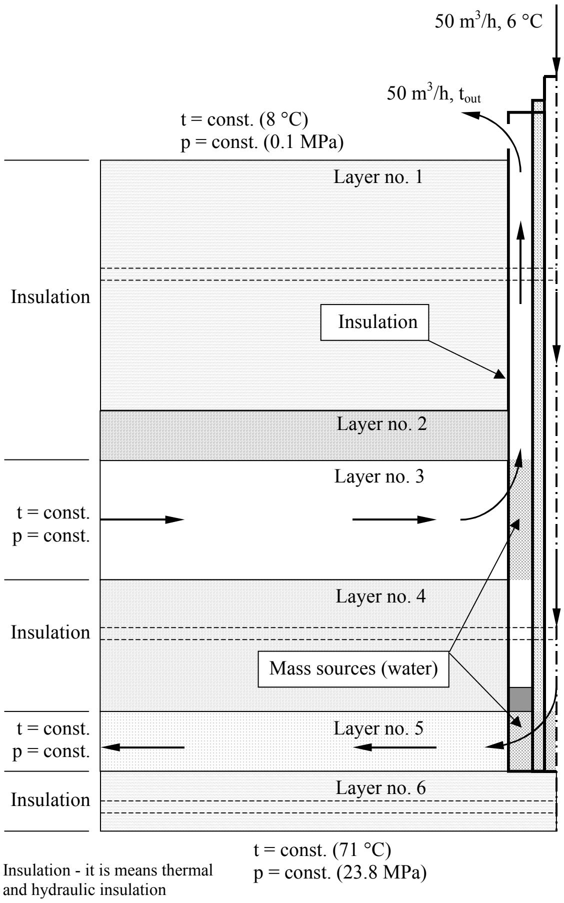

FIGURE 4: Boundary conditions used in the reservoir calculations connected with the exploitation mode

- Thermal and hydraulic parameters are described in two dimensions (the depth and distance from the well; see the grid schematic in Figure 3);
- Both water-bearing layers are connected to open reservoirs (different infinite reservoirs for each water-bearing layer), and the constant pressure, and temperature are used as boundary conditions in the calculations connected with exploitation. The values of pressure and temperature in reservoirs with radius R = 10 km away from the well casing (Figure 4) are equal to the reservoirs' pressure and temperature in the steady-state solution;
- Yearly changes in atmospheric conditions are negligible. This assumption is reasonable in the presented situation because the influence of changes in atmospheric conditions in Poland can reach from 7.7 m up to 27.1 m under the ground surface (Plewa, 1984). Furthermore, this influence decreases as the surrounding formations are heated by the well;
- The outlet hot water is cooled by a heat pump system to 7˚C and the water is reinjected at this temperature. These are the working conditions of the system throughout the modelling.

2.3.2 Boundary conditions

Figure 4 shows how boundary conditions are fixed during exploitation. The boundary conditions at the bottom part of the reservoir are temperature 71˚C, pressure 23.8 MPa; the upper surface has temperature 8˚C and pressure 0.1 MPa. Temperature and pressure in the reservoirs connected with the upper and lower water-bearing layers are set according to the steady-state solution.

2.3.3 Initial conditions

Correct initial temperature and pressure distribution in the reservoir area greatly influence the accuracy of calculations. To estimate proper initial conditions, calculations were made in two steps:

- The first was connected with the steady-state description - initial conditions (temperature and pressure distributions) in this step were set according to natural gradient conditions as Figure 5 shows. It was allowed to change temperature and pressure in the reservoir - except the upper and the bottom parts. For them, the constant working conditions were described with the same values as in the exploitation mode. The steady-state conditions are shown in Figure 6;
- The results of the steady-state calculations were used as initial conditions in the exploitation model.

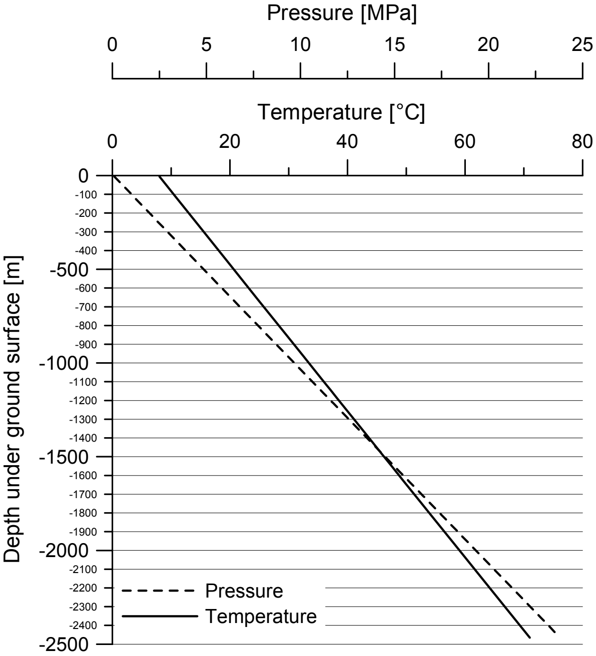

FIGURE 5: Initial conditions for the steady state solution

Parameter distribution for temperature and pressure according to the natural gradient (average values) was as follows :

Upper water-bearing layer: 37.3˚C and 11.13 MPa;
Lower water-bearing layer: 48.4˚C and 15.31 MPa;

The average values for temperature and pressure in steady-state conditions were:

Upper water-bearing layer: 41.3˚C and 11.41 MPa;
Lower water-bearing layer: 52˚C and 15.47 MPa.

Because the pressure under steady-state conditions is higher than the pressure under natural gradient conditions in both layers, the free flow of water can be expected as has been confirmed by measurements.

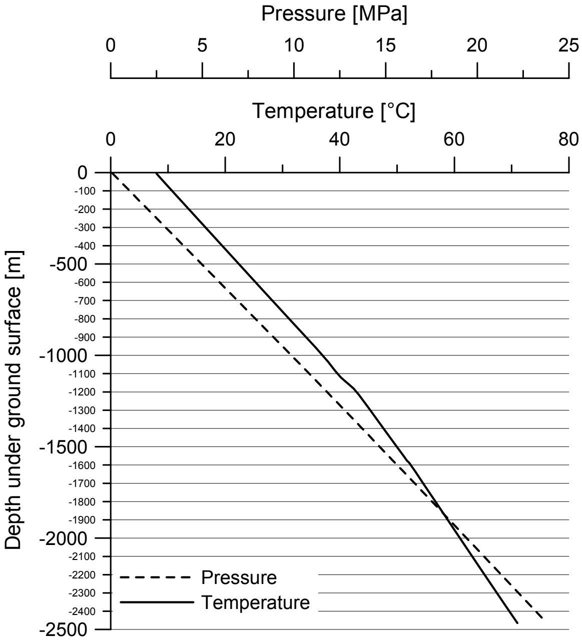

FIGURE 6: Steady state temperature and pressure distribution

2.3.4 Reservoir exploitation

Because the working parameters in the system change with time, it was assumed that the calculations should be run over some time length when the parameter values change slowly. This time length should also be limited to a reasonable operating period for the installation. By output data analyses, the time length chosen was 100 years.

To describe exploitation conditions in the system, numerical and analytical methods were used. Heat and mass exchange processes in the reservoir were calculated by using the numerical simulator TOUGH2. Heat exchange processes between hotter water in the space between inner and casing pipes, and reinjected (colder) water that flows through the inner pipe, and heat losses from the well to rocks formations have been described by using semi-empirical solutions.

2.4 Calculations of the interaction between the two water-bearing layers

2.4.1 Heat losses to surrounding rock formations

Heat losses to surrounding rock formation are described by Equation 1 when $at/r_w^2 >> 1$ (Carslaw and Jaeger, 1948). Nomenclature is given at the end of the report.

$$Q_l = 4\lambda_{rock}\Pi(t' - t_\infty)\left[\ln\left(\frac{4a\tau}{r_w^2} - 2\gamma\right)\right]^{-1} \tag{1}$$

Values of Q_l vs. time are presented in Figure 7 assuming the following parameters:

λ_{rock} = 2.5 W/mK (see Table 1);
t' = 41.3°C – 1°C = 40.3°C, assuming 2°C temperature drop for the hotter water (Figure 6); accuracy of this will be checked later;
t_∞ = (8 + 41.3)/2 [°C] ≈ 25°C (Figure 6);
a = 2.5 [W/mK] / (2400 [kg/m^3] × 1500 [J/kgK]) ≈ 6.94×10^{-7} m^2/s (Table 1);
r_w = 0.084 m (Figure 2).

Because of heat losses, outlet water temperature from the well will be lower than water temperature in the exploited water-bearing layer. The temperature drop can be estimated by Equation 2:

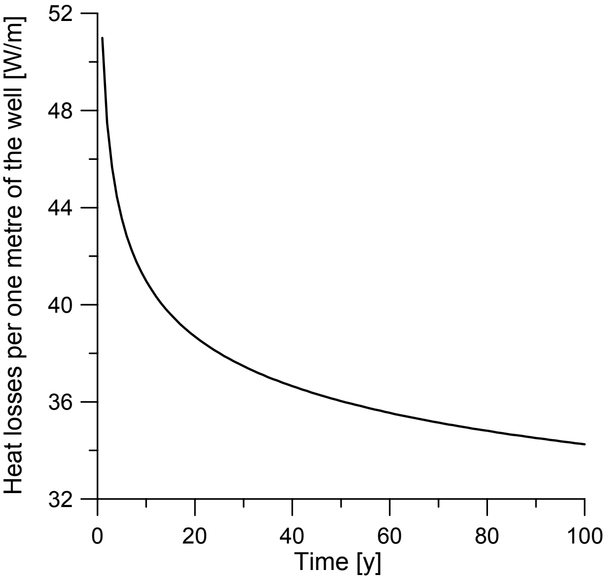

FIGURE 8: Heat losses from the well to the rock formations vs. time

$$\Delta t_l = \frac{3600 \cdot Q_l}{\dot{V} \cdot \rho_w \cdot c_w} \cdot H \tag{2}$$

The highest value of water temperature drop is at the beginning of exploitation, after that the value decreases. Based on Equation 2 the temperature drops are as follows:

After 1 year -1.043°C; after 10 years -0.838°C; after 100 years -0.701°C.

From this we can see that it can be assumed that the water temperature drop due to heat losses to surrounding rocks equals about 1°C in the presented case.

2.4.2 Heat exchange between hotter and colder water

As mentioned earlier the system closed in the well space is similar to a counterflow heat exchanger. Equation 3 describes the energy balance for this heat exchanger assuming that the heat exchange process is adiabatic; reinjected water temperature does not change from upper to lower water-bearing layer; the flow of hotter and colder water is the same; and values for water heat capacity and density are constant.

$$(t_r' - t_{out}) = (t_{rei}'' - t_{rei}) \tag{3}$$

Heat exchange from hotter to colder water can be described by Equation 4

$$\frac{\dot{V}\cdot\rho_w\cdot c_w\left(t_r'-t_{out}\right)}{3600} = K\cdot\Delta t_m \tag{4}$$

where Δt_m is the logarithmic mean temperature difference between the hotter and the colder water described by Equation 4a.

$$\Delta t_m = \frac{\left(t_r'-t_{rei}''\right)-\left(t_{out}-t_{rei}\right)}{\ln\left(\dfrac{t_r'-t_{rei}''}{t_{out}-t_{rei}}\right)} \tag{4a}$$

and K is defined by

$$K = \frac{2\Pi H}{\dfrac{2}{\alpha_{in}d_{2w}}+\dfrac{\ln\dfrac{d_{2z}}{d_{2w}}}{\lambda_{steel}}+\dfrac{\ln\dfrac{d_{1w}}{d_{2z}}}{\lambda_{nitr}}+\dfrac{\ln\dfrac{d_{1z}}{d_{1w}}}{\lambda_{steel}}+\dfrac{2}{\alpha_{out}d_{1z}}} \tag{4b}$$

To estimate convective heat transfer coefficients, empirical equations checked before in a similar solution (Pajak, 2000) have been used. Depending on the fluid flow type the convective heat transfer coefficient, α [W/m^{2}K] can be calculated as described in Equations 4c - 4e (Senkara, 1983):

Laminar flow, Re < 2000:

$$\alpha = \Omega\,\frac{\left(\rho_w w\right)^{0.2}}{d_h^{\;0.5}}\Delta t_{ws}^{\;0.1} \tag{4c}$$

Mixed flow, 2000 ≤ Re ≤ 10000:

$$\alpha = \frac{\left[\Psi\,\mathrm{Pr}^{0.4}\left(\dfrac{\mathrm{Pr}}{\mathrm{Pr}_s}\right)^{0.25}\right]\lambda_w}{d_h} \tag{4d}$$

Turbulent flow, Re > 10000:

$$\alpha = \Phi\,\frac{\left(\rho_w w\right)^{0.8}}{d_h^{\;0.2}} \tag{4e}$$

Equations 3 and 4 create a system of equations where the unknown values are t_{out} and t_{rei}”. The solutions give the following temperature values of t_{out} and t_{rei}”, respectively, 40.461°C and 7.839°C. Presented calculations help to assume that exploitation water will be cooled down from 41 to 39°C when reinjection water is heated up from 7 to 8°C. According to this the accuracy of the assumption in the previous chapter regarding exploitation water temperature drop is satisfactory.

Calculations of the outlet water temperature and reinjected water temperature as described above are based on the assumption that the cooling effect (connected with cold water reinjection) has not reached the exploitation water-bearing layer. When the cooling front passes through the insulation layer (layer number 4 in Figure 2), then the temperature in the upper water-bearing layer will change in time and should be much lower than assumed here.

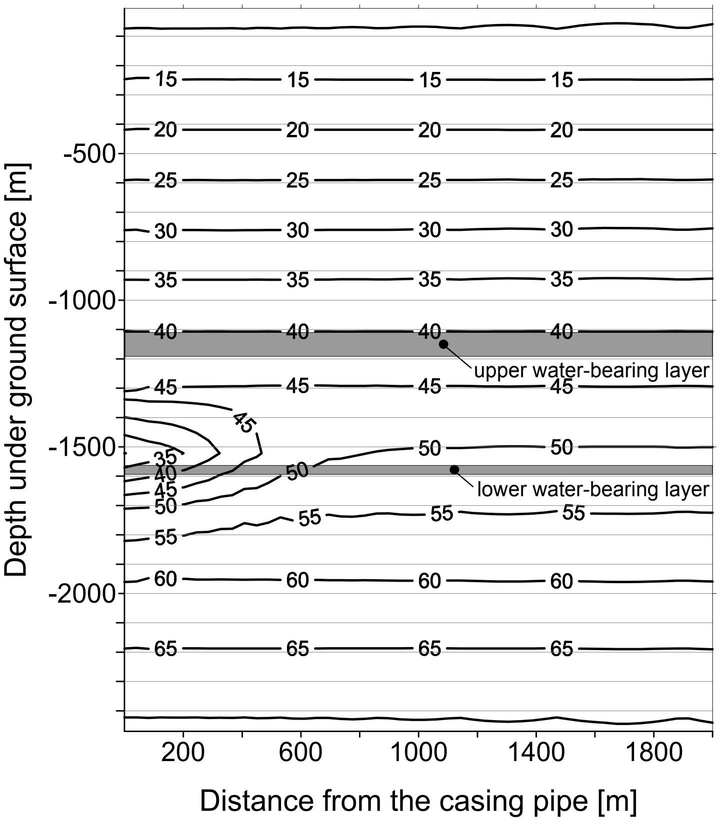

FIGURE 8: Temperature distribution in surrounding rock formations [˚C] after one hundred years of exploitation

The temperature distribution in the exploitation mode has been calculated by using the TOUGH2 numerical simulator. Results of the calculations after one hundred years of exploitation are shown in Figure 8. Data analysis from Figure 8 confirm the correctness of the assumption regarding exploited water temperature, i.e. temperature changes after one hundred years of exploitation reach up to a depth of 1300 m, or about 110 m below the lower part of the upper water-bearing layer.

Another important parameter for further consideration has been estimated during the calculations, pressure changes in the water-bearing layers. This parameter is important in both layers. Pressure drop in the exploitation layer tells if it is possible to utilize as much fluid as assumed. Pressure in this layer has to be high enough to cause artesian free flow of fluid (as mentioned, technical problems with pumping water are associated with disappearing artesian flow). Pressure growth in the reinjected layer helps to estimate energy consumption by a reinjection pump. Data analyses from Figure 9 confirm free flow from the exploitation water-bearing layer as there exists 0.1 MPa artesian hypertension compared to natural gradient conditions.

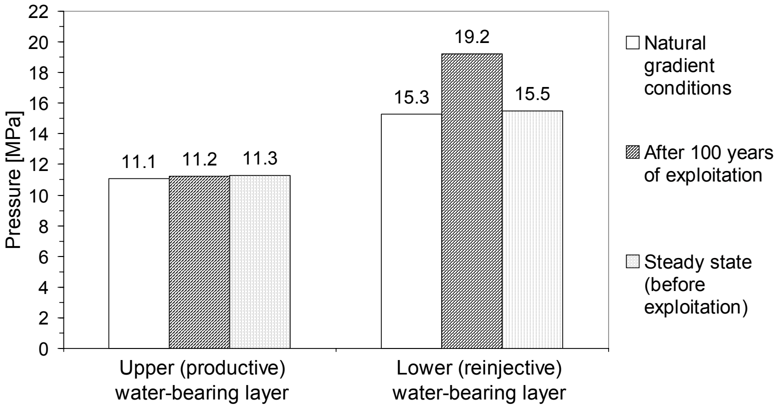

FIGURE 9: Comparison of pressure values [MPa] in the water-bearing layers near to the liners

3. HEAT PUMP INSTALLATION DESIGN

Heat demand estimations for Rzezawa town can be calculated by using Equation 5, i.e.

$$\dot{Q}_d = q_{sa} \cdot f \cdot n \tag{5}$$

According to statistical data for 1999, the average floor space for one person in Poland equals 18.7 m^2 (Statistic yearbook, 1999) and heat demand for houses can be assumed to be 100 W/m^2 (Recknagel et al., 1994). Thus, an approximate value for heat demands for Rzezawa town equals 4.7 MW_{th}.

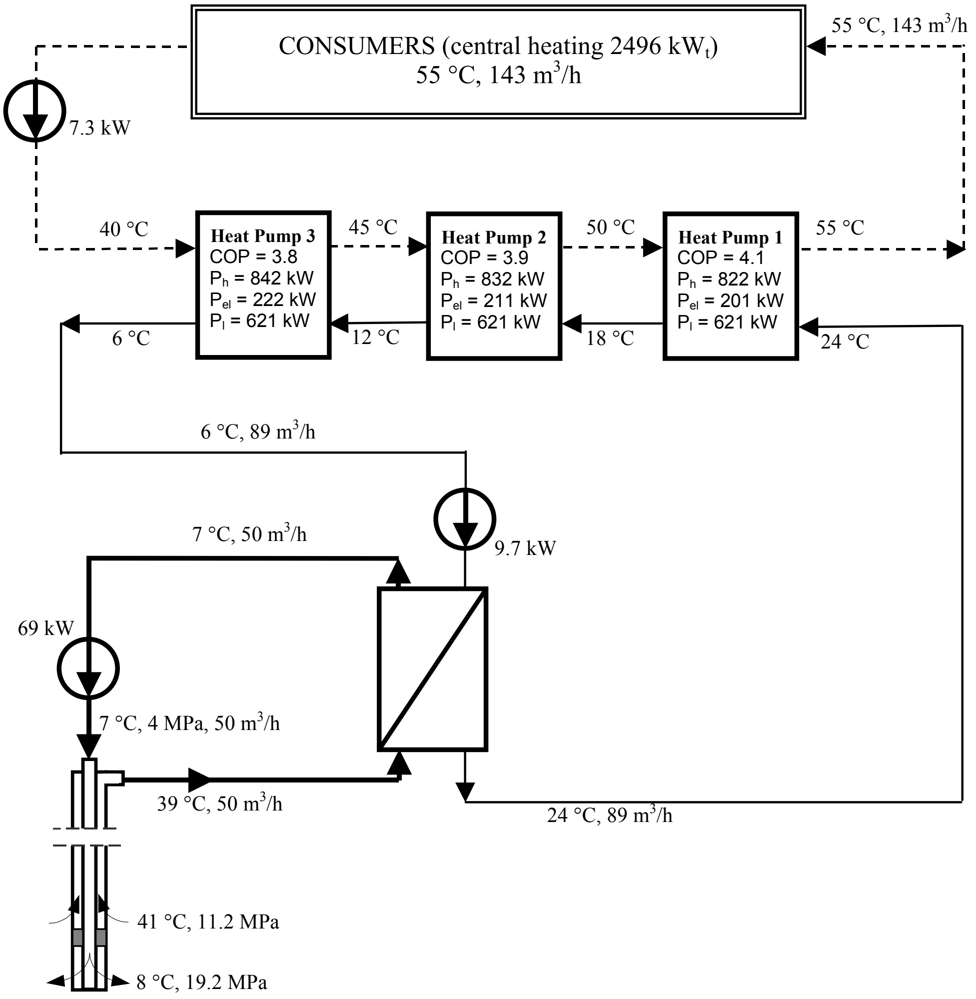

FIGURE 10: The surface installation design. Case A - heat pumps only

Exploitation water has high enough temperature for direct use in floor-heating installations (usually the working fluid temperature in this type of solution is not higher than 35˚C). Due to the fact that the well is located near existing houses that are not equipped with floor-heating installations, it is assumed that space heating is provided with radiators. In this work, a solution based on compression heat pumps is presented. The general scheme of the surface installation is shown in Figure 10.

The most popular pumps for Polish conditions are compression heat pumps based on the R22 refrigerant with an electricity-driven compressor. For this type of unit, the highest save value for a low-temperature heat source is 25˚C (this value is connected with the life time of a heat pump unit). It means that water from the reservoir has too high temperature to be passed directly through heat pumps. A reasonable solution is to transform energy contained by using a heat exchanger. After the heat exchange, the working fluid goes through three heat pump units where it is cooled down. The water heated in the heat pumps' upper heat sources is used for central heating.

The number of heat pumps was decided taking into account economical and technical aspects. According to the economical aspect, the best solution would be using one heat pump unit with a high thermal capacity. Usually, the price for an installed thermal energy unit (e.g. kW) in that case is lower - it means that the total investment cost for the whole installation decreases also. As an example of this situation, the following data can be presented:

- The cost for the compression heat pump unit HIBERNATUS-W6W3Q with thermal power 16 kW_{th} is 4,190 USD (Hibernatus, 1999), it gives 262 USD/kW_{th};
- A bigger unit with thermal power 78 kW_{th} HIBERNATUS -W29W3 costs 9,477 USD (Hibernatus, 1999), it gives 122 USD/kW_{th};
- Finally a compression heat pump with thermal power 1,870 kW_{th} produced by GRAM Company costs 146,336 USD* (Árnason, 1997). It gives 78 USD/kW_{th}.

However, the comparison between prices is not easy - especially for heat pumps with high thermal capacity. This type of equipment is usually designed to order by a client and depends on the producer as well.

One of the important parameters characterizing heat pumps is the Coefficient of Performance (COP). In heating mode, it describes the ratio of the heating capacity to the input driving power consumption. An approximate value of the COP for a real heat pump can be found by using Equation 6.

$$\mathrm{COP} = \chi \cdot \mathrm{COP_C} = \chi \cdot \frac{T_h}{T_h - T_l} \tag{6}$$

For a real heat pump unit, the χ value equals 0.5-0.6 (Rubik, 1996). The value of χ is not constant and changes with working conditions and heat pump construction (refrigerant, compressor type, etc.). For modern heat pumps χ has high values - near to the upper mentioned limit. Consequently, the χ value of 0.6 is assumed in further calculations. Evaporation and condensation temperatures, respectively, for a refrigerant can be calculated according to Equations 7 and 8 (Rubik, 1996).

$$t_l = t_{lh}' - \frac{\Delta t_{lh}}{1 - e^{-\frac{\Delta t_{lh}}{\Delta t_{lh} + \Delta t_E}}} \tag{7}$$

$$t_h = t_h' + \frac{\Delta t_h}{1 - e^{-\frac{\Delta t_h}{\Delta t_h + \Delta t_C}}} \tag{8}$$

The values for Δt_E and Δt_C for heat pumps, based on water as both heat sources, can be assumed as 3-4°C (Rubik, 1996). By combining Equations 6 (for $\chi = 1$), 7 and 8, Equation 9 is derived. It describes the $\mathrm{COP_C}$ value as a function of heat source, temperatures, and temperature differences.

$$\mathrm{COP_C} = \frac{t_h' + \dfrac{\Delta t_h}{1 - e^{-\frac{\Delta t_h}{\Delta t_h + \Delta t_C}}} + 273\,\mathrm{K}}{\left(t_h' + \dfrac{\Delta t_h}{1 - e^{-\frac{\Delta t_h}{\Delta t_h + \Delta t_C}}} \right) - \left(t_{lh}' - \dfrac{\Delta t_{lh}}{1 - e^{-\frac{\Delta t_{lh}}{\Delta t_{lh} + \Delta t_E}}} \right)} \tag{9}$$

The shape of the $\mathrm{COP_C}$ function versus heat sources' temperature changes is presented in Figure 11 (assuming $\Delta t_E = \Delta t_C = 3$°C). The $\mathrm{COP_C}$ has higher values when temperature differences Δt_h and Δt_l are small. According to Equation 6 this conclusion is true for real heat pumps also. Because of that, it can be said that COP for heat pumps increases when temperature differences decrease. The value of χ is not constant but the correlation shown in Figure 11 is general. Further calculations of $\mathrm{COP_C}$ by Equation 9 are described assuming $\Delta t_E = \Delta t_C = 3$°C.

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* The original price (Árnason, 1997) was in ISK. The price in UDS was calculated according to the exchange rate of 11 October 2000 which was 1 USD = 85.42 ISK.

Taking into account the described aspects and the working parameters for the underground part of the installation, it was decided to use three heat pump units. In one heat pump, water for central heating is heated by 5˚C, while on the other side water connected with the geothermal loop is cooled down by 6˚C.

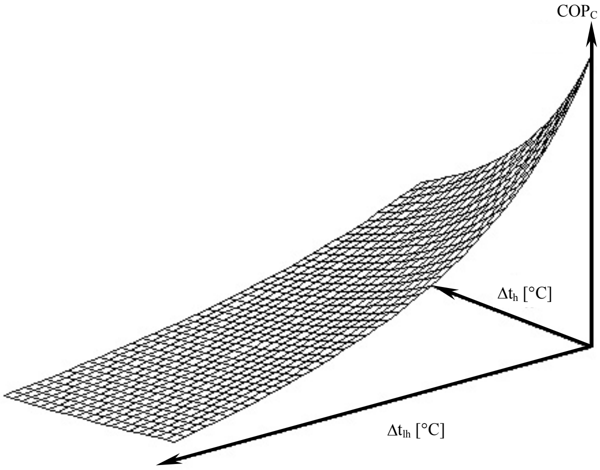


FIGURE 11: COP$_C$ for a heat pump as a function of the temperature changes of the upper and lower heat sources

3.1 Energy production and consumption for the installation based on heat pumps only - without additional heat sources

The total thermal power for the installation presented in Figure 10 is estimated as 2496 kW$_{th}$ and the total electric energy consumption is 721 kW$_e$ (including heat pumps, the pump for reinjection and circulation pumps for water). Because the total demand for Rzezawa town is higher than possible energy production, the entire amount of energy will be utilized.

Yearly energy production and consumption for the presented solution can be calculated based on average yearly thermal power demands. Thermal energy demands per cubic metre of a building for a whole year, supposing a minimum value for the outdoor temperature, can be described by Equation 10 (86400 = seconds/day):

$$Q_{max} = q_b \cdot n_{dt} \cdot (t_{ind} - t_{outd}) \cdot 86400 \qquad (10)$$

Such a situation does not actually exist in Poland. The heating season starts in October and stops in April, thus, its duration is 7 months. There are only a few days with minimum outdoor temperature, according to meteorological data, on average only 22 days with temperatures lower than -10˚C per year in Poland (Markowicz, 2000). Rzezawa town can be described by average Polish parameters because of its location. In reality, annual energy demands per cubic metre of a building located in this area can be described by Equation 11.

$$Q_{av} = q_b \cdot n_{dh} \cdot (t_{ind} - t_{hs}) \cdot 86400 \qquad (11)$$

Average values for monthly outdoor temperature in Poland are presented in Figure 12. An average outdoor temperature value for the whole heating season is described by Equation 12.

$$t_{hs} = \frac{\sum_{i=1}^{4} t_{mi} + \sum_{i=10}^{12} t_{mi}}{7} \qquad (12)$$

According to Equation 12 the average outdoor temperature during the heating season equals 2˚C. By dividing the average thermal energy consumption of the heating season by thermal energy consumption, supposing minimal outdoor temperature through the whole year, the load factor can be found as described in Equation 13.

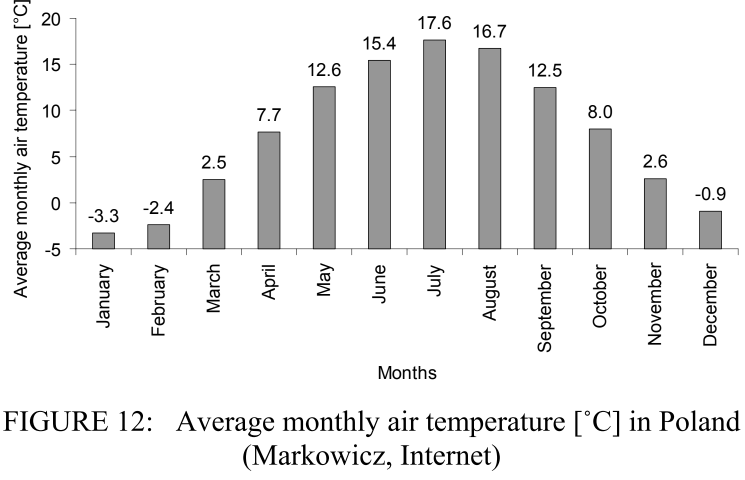


FIGURE 12: Average monthly air temperature [˚C] in Poland (Markowicz, Internet)

$$q_Y = \frac{Q_{av}}{Q_{max}} = \frac{212 \cdot (t_{ind} - t_{hs})}{365 \cdot (t_{ind} - t_{outd})} = 0.276 \tag{13}$$

Yearly energy production and electrical consumption of the described installation can be calculated from Equations 14 and 15.

$$Q_Y = 8.76 \cdot q_Y \cdot \dot{Q}_s = 6035 \ \text{MWh}_{th} / y \tag{14}$$

$$Q_{YE} = 8.76 \cdot q_Y \cdot \dot{Q}_{el} = 1744 \ \text{MWh}_{th} / y \tag{15}$$

3.2 Energy production and consumption for the installation with additional heat sources

The same heat pumps can be utilised with higher efficiency (produce more energy yearly) when they are operated together with an additional heat source, e.g. a boiler based on natural gas as shown in Figure 13.

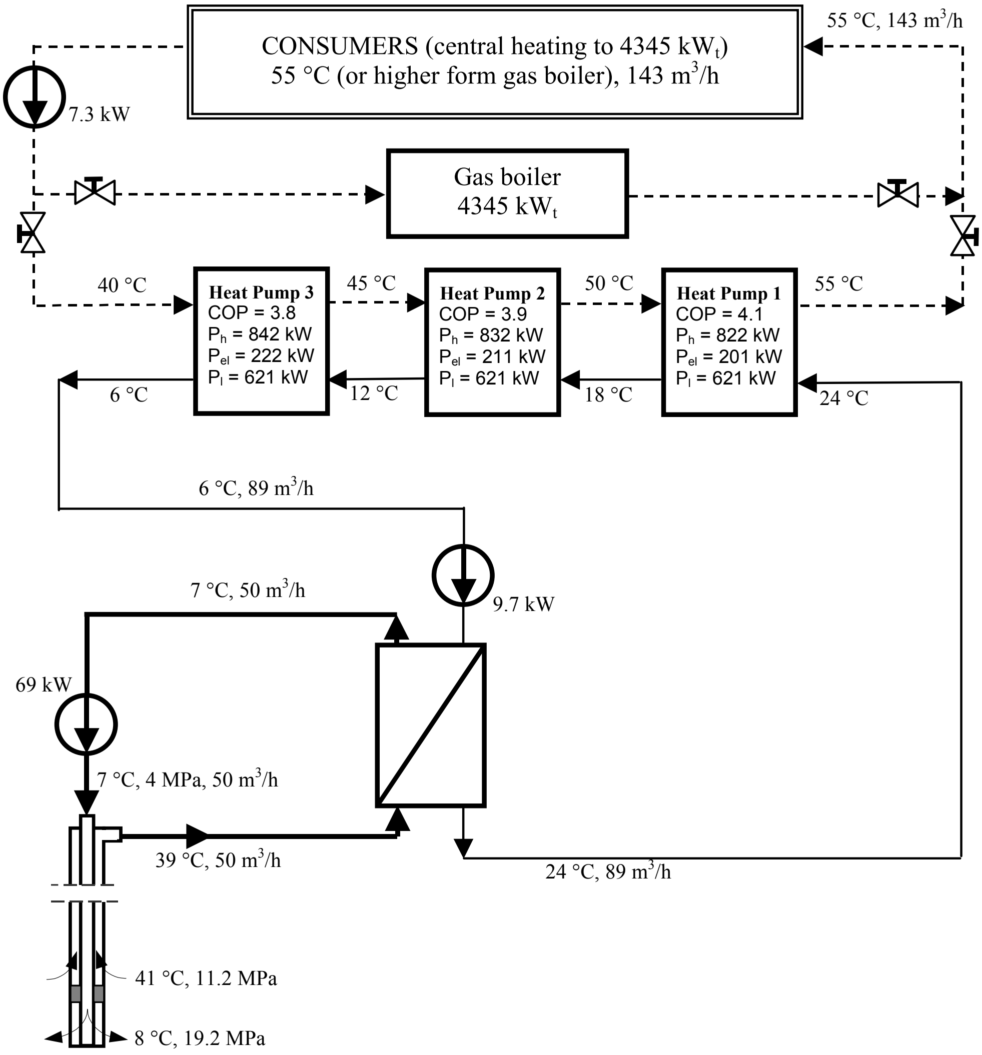


FIGURE 13: The surface installation design; Case B - with additional heat sources

Assume that the heat pumps are able to supply the consumers with the thermal energy needed to -5°C outdoor temperature and after that they are turned off and the boiler used instead. The reason for not using the heat pumps in co-operation with the gas boiler is that too high return water temperature from the consumers' loop is expected. Because there is no district heating system in Rzezawa town, the heat is supplied by local heat sources at the houses. When creating the installation, a reasonable solution is to keep this local heat source and let the consumers decide if they want to use the district heating system or a private source of heat (e.g. if it is too cold). This solution helps to decrease investment costs because the boiler should not be bought. Of course, according to the environmental aspects, the better solution is to supply consumers with heat from the central gas boiler, but investment costs increase with it and this device works only for few dozen days per year.

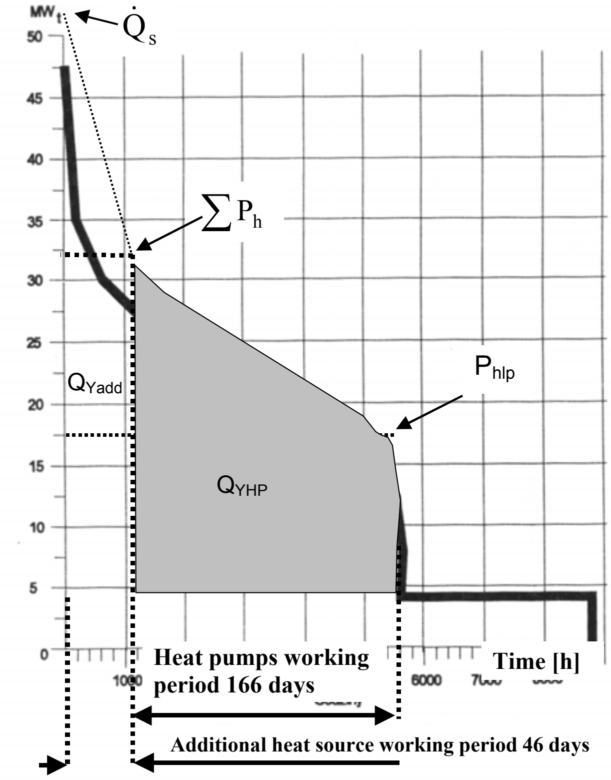


FIGURE 14: The heat demand curve for Zakopane town (Houe & Olsen, 1996) with additional notices

The choice of the temperature limit when an additional heat source starts to work and heat pumps are turned off depends on buildings' thermal characteristics q_b, but from the author's observations, -5°C is reasonable under Polish conditions. The number of days with temperatures lower than -5°C in Poland is 46 per year (Markowicz, 2000). Finally, it is assumed that the total length of the heating season equals 5,088 h/y (212 day/y); the additional heat source will be working 1,104 h/y (46 day/y). It means that the heat pumps' working period equals 3,984 h/y (166 day/y).

Because the heat demand curve for Rzezawa is not available, a similar curve for Zakopane town will be used. Following calculations are based on the geometrical similarity theory, which helps to estimate unknown values. Figure 14 shows the heat demand curve for Zakopane town (Houe & Olsen, 1996).

Because of its location, Zakopane's heating season is longer than in Rzezawa and equals about 5600 h/y. Outside the heating season, heat consumption is relative to use of hot tab water. Energy production in this period is not taken into account in further considerations. The length of the heating season in Zakopane town is not used in mentioned calculations but the assumed value is used. It is only the general curve shape that is important.

According to data from Figure 14 the thermal power for the additional heat sources can be found as described by Equation 16.

$$Q_{add} = \frac{47}{27} \cdot \sum P_h = 1.74 \cdot \sum P_h = 4345\,\mathrm{kW_{th}} \tag{16}$$

Calculated maximum thermal power for the installation is lower than thermal energy demands for Rzezawa town, wich means that the installed thermal power can be fully utilized. To make further calculations clearer, the additional variable P_{hlp} connected with heat pump thermal power was added. Its value is described by Equation 17.

$$P_{hlp} = \frac{13}{27} \cdot \sum P_h = 1151 kW_{th} \tag{17}$$

Thermal energy production per year can be calculated according to Figure 14 as the surface under the energy consumption curve, shown in Equations 18 and 19.

$$Q_{Yadd} = \frac{\left(\dot{Q}_s - \sum P_h\right) \cdot 1104}{2} + \sum P_h \cdot 1104 \tag{18}$$

$$Q_{YHP} = \frac{\left(\sum P_h - P_{hlp}\right) \cdot 3984}{2} + P_{hlp} \cdot 3984 \tag{19}$$

Energy production can, thus, be found as follows. For an additional heat source of 3,776 MWh_{th}/y, and for heat pumps 7,366 MWh_{th}/y, the total energy production is 11,142 MWh_{th}/y. Energy consumption can also be calculated assuming fuel used in an additional heat source and based on average COP values for the heat pump system. Assume that the fuel is natural gas with a lower caloric number 35,000 kJ/m^3; efficiency of the burning process h is 95%; the average value for COP is 3.94; and the pump for reinjection and the running pump for the lower heat sources work only when the heat pumps work.

To produce 11,142 MWh_{th}/y of heat, the necessary consumption of natural gas is described by Equation 20 and the corresponding electricity consumption by Equation 21.

$$V_{Yg} = \frac{3.6 \cdot 10^6 \cdot Q_{Yadd}}{Q_w \cdot \eta} = 408830 \ m^3/y \tag{20}$$

$$Q_{YE} = \frac{Q_{YHP}}{\sum P_h} \cdot \left(\frac{\sum P_h}{COP} + P_{o1} + P_{rei} \right) + \frac{Q_Y}{\dot{Q}_s} \cdot P_{o2} = 2113 \ MWh_e/y \tag{21}$$

By analysing the results of the calculations above, we can see that by increasing investment costs of the installation by adding a gas boiler or even keeping the cost the same if there exist additional heat sources, one can almost double the heat production. This fact is important when considering the economical feasibility of the project.

When calculating energy production from the installation with an additional heat source in the same way as the calculations for the installation without it, we have yearly thermal energy production of 10,512 kWh_{th}/y. That is 5.7% lower than the value received by the calculation based on the heat demands curve. It can be said that the two ways of calculating the yearly energy production for heating installations give similar results.

4. ECONOMICAL AND ENVIROMENTAL ASPECTS

The calculations presented below take into account running costs and investments costs for the installations shown in Figures 10 and 13.

The price of electricity p_{el} used in the calculations equals 0.0594 USD/kWh_e (one scale of charges) and for natural gas p_{ng} is 0.202 USD/m^3. Equation 22 shows how energy costs are estimated.

$$p_{eu} = \frac{10^3 \cdot Q_{YE} \cdot p_{el} + V_{Yg} \cdot p_{ng}}{Q_Y} \tag{22}$$

However, the calculations describing investment costs based on real prices should be taken as estimates only. Prices of some included components can differ from the assumed values because they are hard to estimate without accurate technical analysis which is beyond the scope of this work (e.g. well reconstruction, building construction, connection of the gas boiler to the gas network, pipeline). The others depend on equipment producers (e.g. there can be some discounts and different prices for the same kind of equipment).

In Table 2, investment costs for the ventures are given, based on recent projects worked out at the Geothermal Laboratory - Polish Academy of Sciences. To make further considerations as clear as possible it was decided to call the case of installation without additional heat sources (Figure 10) case A, and the solution with an additional gas boiler (Figure 13) case B.

TABLE 2: Calculation of the investment costs for case A (heat pumps only - Figure 10) and case B (with additional heat sources - Figure 13)

No.	**Name of component**	**The price of one unit**	**Number of units**		**Investment costs USD**	
			Case A	**Case B**	**Case A**	**Case B**
1	Underground part of the installation	12 USD/m	1594 m	1594 m	18705	18705
2	Plate heat exchanger	14 USD/kW	1863 kW	1863 kW	26644	26644
3	Reinjection pump	191 USD/kW	69 kW	69 kW	13208	13208
4	Running pumps	220 USD/kW	17 kW	17 kW	3740	3740
5	Heat pumps	100 USD/kW	2496 kW	2496 kW	249600	249600
6	Gas boiler	20 USD/kW	0	4345 kW	0	86040
7	Thermal station building	42 USD/m^3	2000 m^3	2000 m^3	83608	83608
8	Measurements and controls equipment	30 % of positions from 2 to 6	1	1	87958	113769
9	Connection to the electrical network	40484 USD/connection	1	1	40484	40484
10	Connection to gas network	22002 USD/connection	0	1	0	22002
11	Pipe line from the well to the town	220 USD/m	800 m	800 m	176018	176018
12	Designs and managements	15% of total from 1-11	1	1	104995	125073
	TOTAL				**804960**	**958891**

To estimate the final energy price, other parameters were taken into account as follows:

- Annual maintenance costs as 1% of the total investment costs;
- Annual insurance as 1% of the total investment costs;
- Annual taxes as 1% of the total investment costs;
- Repayment time for the investment costs, including credit as 15 years is assumed;
- Taxes connected with impurities emissions - depending on solution;
- A subsidy value from the government - depending on finance scenarios;
- Credit from banks were considered as a special type of credit connected with low interest rates because of the pro-ecological character of the solution;
- An interest rate to an Investor that gives the rest of the money after taking into account the subsidy and credits.

Monthly payment rates for credit and Investor interests are assumed. The value of the monthly payment connected with the aforementioned is described by Equation 23 (Lund et al., 1998).

$$PC_m = W \cdot \left(\frac{i \cdot (1+i)^{nm}}{(1+i)^{nm} - 1} \right) \tag{23}$$

Yearly payments connected with the system operation are described by Equation 24.

$$R_Y = (PC_{mcr} + PC_{minv}) \cdot 12 + (Oc + In + Tx) \cdot P_{invest} + F_p + Q_Y \cdot p_{eu} \tag{24}$$

The real price for energy production, including every mentioned cost, is described by Equation 25.

$$p_{tc} = \frac{R_Y}{Q_Y} \tag{25}$$

To compare prices of the thermal energy production, different financing scenarios were considered. They are described in Table 3. It is assumed that money connected with the Investor and bank credit is paid back monthly.

TABLE 3: Financing scenarios description

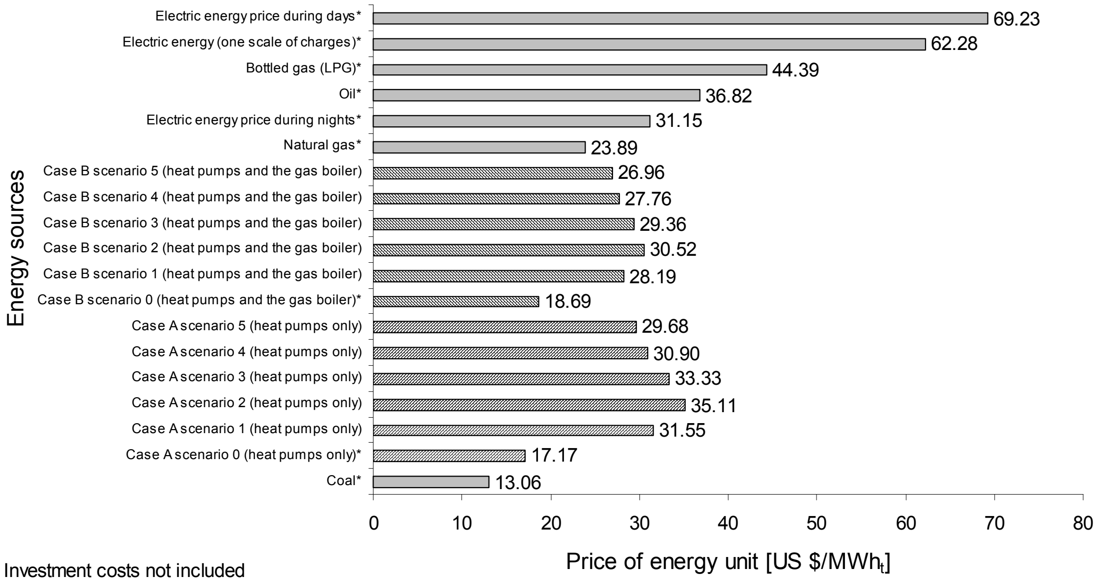
Scenario	Financed by the Investor			Financed by bank credits			Financed by government subsidy
	% of total investment	% annual interest rate	Repayment time [y]	% of total investment	% annual interest rate	Repayment time [y]	% of total investment
SC0*	-	-	-	-	-	-	-
SC1	100	4	15	0	0	0	0
SC2	0	0	0	100	8	15	0
SC3	50	4	15	50	8	15	0
SC4	30	4	15	50	8	15	20
SC5	20	4	15	50	8	15	30

* Investment costs are excluded

Table 4 presents the energy prices for cases A and B in each scenario. A comparison of these energy prices with prices of different energy sources (USGDC, 2000) is shown in Figure 15.

TABLE 4: Total costs of energy production for different scenarios of investment costs covered

Scenario	Energy production costs for Case A [USD/MWh$_{th}$]	Energy production costs for Case B [USD/MWh$_{th}$]
SC0	17.17	18.69
SC1	31.55	28.19
SC2	35.11	30.52
SC3	33.33	29.36
SC4	30.90	27.76
SC5	29.68	26.96



* Investment costs not included

FIGURE 15: Unit energy price comparison based on different energy sources (USGDC, 2000)

Prices of thermal energy produced by the described schemes without investment costs are relatively low, and according to Figure 15 only thermal energy produced by coal burning is cheaper. Because of the relatively low price of coal, it is one of the most popular energy sources in Poland. Regarding environmental effects, unfortunately, it is one of the most harmful. In places where a district heating system does not exist (e.g. Rzezawa town) it is very common to burn coal in small boilers (for one house) but in bigger installations also. The following considerations show the ecological effect when the geothermal heating station reduces local coal consumption:

TABLE 5: Impurities emissions during fuel burner processes (*based on material printed by Polish Environmental Protection Ministry) and prices for substances emissions to the atmosphere (**Ministry Council of Poland - Law Act) - main substances only

No.	**Name of substance**	**Emission from fuel burners processes***		**Price for causing the pollution** [USD/kg]**
		Coal [kg/Mg]	**Natural gas [kg/m^3]**	
1	Benzo(a)piren	0.014	0	50.83
2	Soot	0.9	0	0.2
3	Dust	36	1.45×10^{-5}	0.05
4	Carbon dioxide	2000	1.964	3.74×10^{-5}
5	Carbon oxide	45	2.7×10^{-4}	0.02
6	Nitrogen oxides calculated to nitrogen dioxide	1	19.2×10^{-4}	0.07
7	Sulphur dioxide	12.8	2×10^{-6}	0.07
8	Aliphatic hydrocarbons	5	8.96×10^{-5}	0.02
9	Aromatic hydrocarbons	5	3.84×10^{-5}	0.19

* Lower caloric value of coal Q_w=25 MJ/kg, ash content 18%, sulphur content 0.8%, combus-tion process efficiency η=70%, dust extractor efficiency 0%, burnable fraction in dust 25%;
Lower caloric value of natural gas Q_w=35 MJ/m^3, sulphur content 1 mg/m^3, combustion process efficiency η=95%, dust extractor efficiency 0%, burnable fraction in dust 0%.
** Exchange ratio for USD: 4.545 zl/USD (25.09.2000)

The situation regarding an energy unit price (Figure 15) looks better for geothermal energy profit when we additionally take into account taxes, which have to be paid when the same amount of energy is produced by burning coal. The taxes according to Polish law for causing impurities emissions are shown in Table 5. Based on data from Table 5, the amount of taxes connected with impurities emission to the atmosphere was calculated. The results are presented in Table 6.

TABLE 6: Impurities emission for fuel burners and taxes for impurities emission to atmospheric air (emission with coal burning connected as eliminated should be understood) – based on Table 5

No.	**Name of substance**	**Emission from the fuel burners process [Mg/y]**			**Fine for causing the pollution [USD/y]**		
		Case A coal*	**Case B coal***	**Case B nat. gas**	**Case A coal***	**Case B coal***	**Case B nat. gas**
1	Benzo(a)piren	0.017	0.030	0	884.52	1540.00	0
2	Soot	1.119	1.948	0	221.54	385.66	0
3	Dust	44.751	77.903	0.593	2166.00	3771.00	0.29
4	Carbon dioxide	2486	4328	802.942	92.99	161.88	30.03
5	Carbon oxide	55.939	97.378	0.110	1108.00	1928.00	2.19
6	Nitrogen oxides calculated to nitrogen dioxide	1.243	2.164	0.785	90.268	157.12	56.99
7	Sulphur dioxide	15.912	27.699	0.818	1155.00	2011.00	0.06
8	Aliphatic hydrocarbons	6.215	10.820	0.037	123.08	214.25	0.73
9	Aromatic hydrocarbons	6.215	10.820	0.016	1203.00	2095.00	3.04
10	**TOTAL**	**2617.411**	**4556.762**	**805.301**	**7044.40**	**12263.91**	**93.33**

* Comparatives values for production of the same amount of thermal energy by using coal (which is possible to reduce)

Emissions connected with coal can be eliminated when the geothermal heating station starts to operate. The emissions for natural gas (Tables 5 and 6) are bound to the gas boiler working in the installation shown in Figure 13. As we can see, the emissions from the gas boiler are low, as are the taxes connected with it.

Finally, by including additional money which has to be spent to pay taxes, the price for an energy unit for a coal-based heating station increases by about 1.2 USD/MWh$_{th}$ and equals about 14.26 USD/MWh$_{th}$. The described ecological effect is important locally (in the place where the installation is located) - but because electrical energy production in Poland is based on fossil fuel, even the geothermal closed system operations cause some pollution. Average efficiency when converting the chemical energy content in coal to electricity for most Polish power stations equals about 0.3, including distribution losses (Kubski, 1997). Equation 26 helps to estimate real global coal saving effects and directly connect it with the environmental effects when comparing the described solution (driven by electricity produced in power stations) and a heating station with coal burners. Equation 26 was derived assuming the same quality of coal and the same running time for the installations.

$$\Delta M_c = \frac{M_{c0}-M_{cg}}{M_{c0}}\cdot 100\,\% = \frac{\dfrac{\dot{Q}_s}{Q_w\eta}\cdot\tau - \dfrac{\dot{Q}_{el}}{Q_w\varepsilon}\cdot\tau}{\dfrac{\dot{Q}_s}{Q_w\eta}\cdot\tau}\cdot 100\,\% = \left(1-\frac{\eta\cdot\dot{Q}_{el}}{\varepsilon\cdot\dot{Q}_s}\right)\cdot 100\,\% \qquad (26)$$

It is assumed that $\varepsilon = 0.3$ and $\eta = 0.7$ (Table 5). When taking into account only the time period when heat pumps supply consumers with thermal energy (up to 2,496 kW$_{th}$), the total savings of coal on a global scale, comparing the geothermal station to the conventional coal-based system, equals 33%. Of course when the gas boiler works in case B, some volume of fossil fuel is used, and some pollution is caused.

The environmental saving effect has a positive value because impurities emissions drop approximately 33% (emission is proportional to fuel usage and, in case B, emissions from the gas boiler are low as mentioned above). Described situations should look even better because professional power stations use better purifying exhaust installations than local heating stations.

5. CONCLUSIONS

- Calculations of thermal energy demands for Rzezawa town and the possibilities of energy production show that it is more profitable to explore water from the Cenomanian water-bearing horizon than from the Dogger water-bearing horizon (Table 1). The thermal power demands are estimated as 4.7 MW_{th} and, by using a heat pump installation with additional heat sources, 93% of the demand can be met.

- Results of the calculations performed confirm the technical possibility of long time reservoir exploitation by the way proposed. During 100 years of exploitation, no changes in temperature in the upper water-bearing layer can be found, which means that the system can operate without thermal efficiency losses. Pressure distribution in the exploitive layer is favourable for this kind of geothermal energy utilisation because hypertension in the layer does not disappear.

- When channels for hotter and colder water are well insulated, the heat exchange process between the fluid streams does not influence system efficiency very much. This heat exchange causes only about 1˚C temperature drop in the water flow. A similar situation is found with heat losses to the surrounding rock formations; system efficiency does not decrease very much and the importance of heat loss over time decreases. Total temperature drop in the underground part of the installation was estimated as 2˚C.

- Calculations of the total annual energy production based on meteorological data and the thermal energy demands curve give similar results.

- When running costs are taken into account, only in scenario SC0 the price of the energy unit produced in the presented solution is comparable to the cheapest energy source in Poland, coal. When total costs of energy production are taken into account (including investment costs), only coal and natural gas are cheaper; electricity during nights is cheaper for some financing scenarios.

- The thermal installation design has a big influence on the energy production cost. Utilising an additional heat source is important for the described geothermal energy utilisation. It helps to produce almost twice as much energy, while the investment cost increases only by 16%. Thus, even when investment costs increase, the price for the energy unit is lower for the case with an additional heat source than in the case without it in the same financial scenario.

- Replacement of coal-based boilers by the environmental friendly geothermal energy source helps to improve environmental conditions also. The described effect is noticeable even when the electricity used to drive the heat pumps is produced by coal burning processes.

- Results of the presented calculations show that simultaneous exploitation of two water-bearing layers is ecological and can be economically profitable under Polish conditions.

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NOMENCLATURE

Symbols

$\dot{V}$ = Water flow rate [m^3/h];
A = Thermal diffusivity of rock [m^2/s];
COP = Coefficient of performance for a heat pump;
F = Average value of floor space per person [m^2/person];
H = The heat exchange length between the exploitation layer and ground surface (in presented situation 1111 m) [m];
i = Yearly interest rate recalculated for one month [%/month];
In = Annual insurance costs as percentage of the total investment costs [%/y];
K = Heat exchange coefficient from hotter water (filling space between casing and inner pipes) and colder water (reinjected) for whole heat exchange surface; this coefficient takes into account convection and conduction heat transfer [W/˚C];
N = Population [person];
Nm = Number of months after which money should be paid back [month];
Oc = Annual maintenance costs as percentage of the total investment costs [%/y];
Pr = Prandtl number;
R = The modulated space radius (distance from casing to the constant reservoir conditions) [m];
Re = Reynolds number;
t' = Average fluid temperature in the space between casing and inner pipe [˚C];
Tx = Annual taxes as percentage of the total investment costs [%/y];
w = Velocity [m/s];
W = The amount of money connected with credit or investor financing [USD].

Greek symbols

Ω, Φ, Ψ = Coefficients - the values are presented in Senkara (1983);
χ = Coefficient that compares a real heat pump COP to the ideal heat pump COP_C working in Carnot's circle at the same working conditions $g = COP/COP_C$;
α = Heat transfer coefficient [W/m^{2}K]
ε = Transformation coefficient of chemical energy content in fuel to electricity;
γ = Euler's number, 0.577216…
η = Transformation coefficient of chemical energy content in fuel to thermal energy;
τ = Time [s].

Symbols with subscripts

$\dot{Q}_d$ = Heat demands [kW_{th}];

$\dot{Q}_s$ = System thermal power [kW_{th}];

Q_{el} = Electricity consumption [kW_e];

COP_C = Coefficient of performance for a heat pump working with the Carnot's circle;

c_w = Heat capacity of water [J/kgK];

d_{1w} = Inside diameter of the middle pipe (0.102 m) [m];

d_{1z} = Outside diameter of the middle pipe (0.114 m) [m];

d_{2w} = Inside diameter of the smallest pipe (0.078 m) [m];

d_{2z} = Outside diameter of the smallest pipe (0.089 m) [m];

d_h = Hydraulic diameter [m];

F_p = Annual taxes connected with impurities emissions to the atmosphere [USD/y];

M_{c0} = Coal mass used by a heating station based on coal burning to produce certain amount of thermal energy [kg/s];

M_{cg} = Coal mass used by a power station to produce and distribute electricity used by a geothermal heating station which produces certain amount of thermal energy [kg/s];

n_{dh} = Number of days in the heating season [day];

n_{dt} = Number of days in one year [day];

PC_m = The value of monthly payment connected with credit and Investor interests [USD/month];

PC_{mcr} = Monthly payment connected with credit repayment including bank interest [USD/month];

PC_{minv} = Monthly payment connected with Investor repayment including interests [USD/month];

p_{el} = The price for electricity [USD/MWh_e];

p_{eu} = Energy price estimate for the installation taking into account only prices for running energy sources, i.e. electricity and natural gas [USD/MWh_{th}];

P_h = The upper heat source, thermal power for a heat pump [W_{th}];

P_{hlp} = Fictitious thermal power for the heat pumps installation used to estimate energy production by heat pumps [kW_{th}];

P_{invest} = Total investment costs [USD];

P_l = Thermal power of the lower-heat source for a heat pump [W_{th}];

p_{ng} = Price for the natural gas [USD/m^3];

P_{o1} = Power of the running pump in the heat pumps lower heat sources loop [kW_e];

P_{o2} = Power of the running pump in the consumers loop [kW_e];

P_{rei} = Power of the running pump to reinjection [kW_e];

Pr_s = Prandtl number for fluid at a wall temperature;

p_{tc} = The real price for energy production including total costs, i.e. running and investment costs [USD/MWh_{th}];

p_{eu} = Energy unit price in presented solution when taking into account only energy sources consumption [USD/MWh_{th}];

Q_{av} = Average thermal energy consumption per cubic meter of a building assuming average value of the outdoor temperature at the building locations during a calculated time period [J/m^3];

q_b = A building thermal characteristic [W_{th}/m^3K];

Q_{YE} = Yearly electricity consumption [MWh/y];

Q_l = Heat losses per metre of a well [W/m];

Q_{max} = Thermal energy consumption per cubic metre of a building assuming the lowest value of the outdoor temperature through whole year (for Rzeawa town –20°C) [J/m^3];

q_{sa} = Heat demands per floor unit [W_{th}/m^2];

Q_w = Lower caloric value for fuels: coal [kJ/kg], gas [kJ/m^3];

Q_Y = Yearly thermal energy production [MWh_{th}/y];

q_Y = Load factor;

Q_{Yadd} = Yearly thermal energy production by an additional heat source [MWh_{th}/y];

Q_{YHP} = Yearly thermal energy production by heat pumps [MWh_{th}/y];

r_w = A well radius [m];

R_Y = Total annual costs connected with the system operation [USD/y];
t_∞ = Initial rock temperature (or rock temperature at a distance from a casing pipe where thermal influence of the well is negligible) [˚C];
T_h, t_h = Condensation temperature for refrigerant in a heat pump [K], [˚C];
t_h' = Inlet temperature of an upper heat source substance into a heat pump unit [˚C];
t_{hs} = Average outdoor temperature during heating season [˚C];
t_{ind} = Indoor temperature (22˚C) [˚C];
T_l, t_l = Evaporation temperature for refrigerant in a heat pump [K], [˚C];
t_{lh}' = Inlet temperature of a lower heat source substance into a heat pump unit [˚C];
t_m = Average monthly air temperature [˚C];
t_{out} = Outlet water temperature from the well [˚C];
t_{outd} = The lowest value of outdoor temperature for which the heating system of a building at a certain location has to be calculated (for Rzezawa town area –20˚C) [˚C];
t_r' = Average temperature in the upper water-bearing layer [˚C];
t_{rei} = Reinjected water temperature at the top of the well (7˚C) [˚C];
t_{rei}'' = Reinjected water temperature in the lower water-bearing layer [˚C];
V_{Yg} = Yearly consumption of natural gas [m^3/y];
ΔM_c = Global effect of coal saving [kg/s];
Δt_l = Water temperature drop because of heat losses to surrounding rocks [˚C];
Δt_C = Temperature difference between the refrigerant condensation temperature and the outlet upper heat source substance’ temperature [˚C];
Δt_E = Temperature difference between the refrigerant evaporation temperature and the outlet lower heat source substance’ temperature [˚C];
Δt_h = Heat source substance’ temperature growth in the upper heat source [˚C];
Δt_{lh} = Heat source substance’ temperature drop in the lower heat source [˚C];
Δt_m = The logarithmic temperature difference [˚C];
Δt_{ws} = Temperature difference between water and a wall surface [˚C];
α_{in} = Convection heat exchange coefficient between reinjected water and the pipe surface with the smallest diameter [W/m^2K];
α_{out} = Convection heat exchange coefficient between exploitation water and the pipe surface with the middle diameter [W/m^2K];
λ_{nitr} = Heat conduction coefficient of nitrogen (0.0262 W/mK) [W/mK];
λ_{rock} = Thermal conductivity of rocks [W/mK];
λ_{steel} = Heat conduction coefficient of steel (43 W/mK) [W/mK];
λ_w = Heat conduction coefficient of water (0.604 W/mK) [W/mK];
ρ_w = Density of water [kg/m^3].

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