AGH DRILLING, OIL, GAS • Vol. 34 • No. 1 • 2017
http://dx.doi.org/10.7494/drill.2017.34.1.141

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COMPARATIVE ANALYSIS OF USING BOREHOLE HEAT EXCHANGERS IN MACEDONIA AND IN POLAND

1. INTRODUCTION

Heating and cooling loads for a typical house in Skopje, Macedonia, and in Krakow, Poland, are compared in this paper. In Poland 90% of electricity comes from coal [2] and is of domestic production. While in Macedonia aproximatelly 50–55% of the energy comes from thermal plants from non-renewable energy sources-coal which is produced domestically. 15–20% from the energy is produced by renewable sources such as hidro-electric power plants. The share of geothermal energy in total energy final consumption is very low about 0.58%. Analising the momentary condition with available energy, Macedonia faces serious energetical problems. Macedonia has limited energy sources and has to import energy (petroleum, natural gas from Russia). Approximately 30% of the energy has to be imported [14].

As the energy from the borehole heat exchangers (BHE) is not consumed material it has a great potencial to be involved in the energy production. The other great advantage is that Is a nature friendly way which doesn't harm the environment.

The energy efficiency of a BHE depends mostly on the thermal conductivity of underground rock mass. Some other constructional parameters also influence the energy efficiency. There are various types of BHEs, the most typical being:

– single U-tube,
– multi U-tube,

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– coaxial [1, 10],
– deep BHE [5, 6],
– helical [12, 13],
– BHE in piles [4],
– BHE with direct evaporation system [7].

Most commonly used systems is heat pumps with a vertical single U-tube borehole heat exchangers. Scheme of heat pump is shown on the Figure 1.

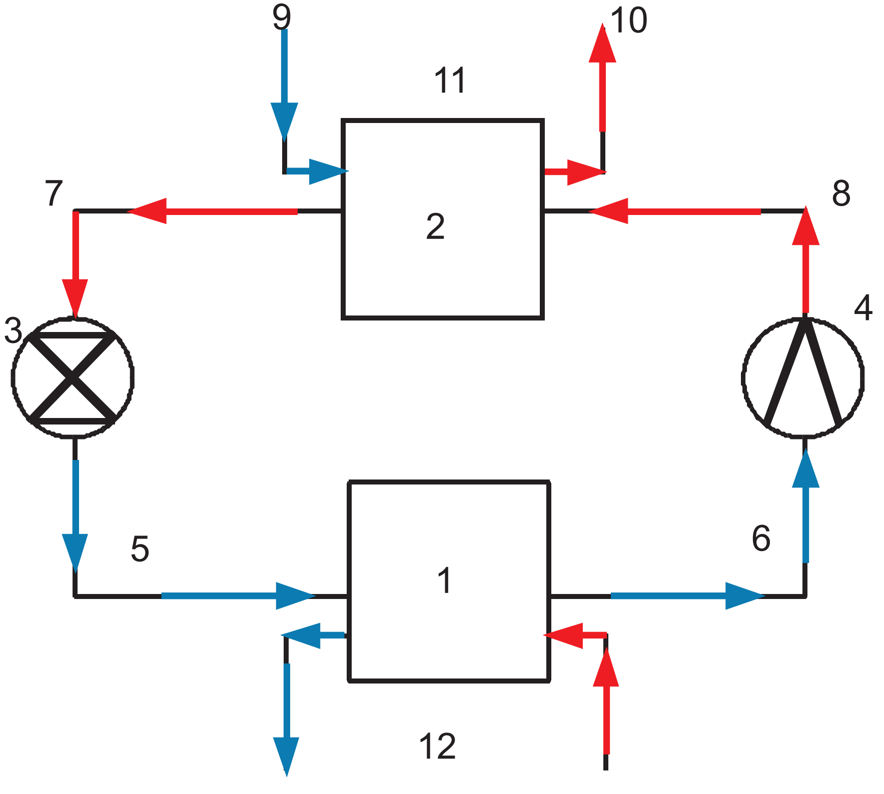

Fig. 1. Scheme of heat pump: 1 – Evaporator, 2 – Condenser, 3 – Expansion valve, 4 – Compressor, 5 – Temperature drop, 6 – Rise of temperature, 7 – Medium (liquid), 8 – Medium (gas), 9 – Return, 10 – Power, 11 – Carbon monoxide or hot top water, 12 – Air

The analysis was conducted because of the increasingly higher rate of air pollution. In large cities, it is important to limit the emissions of gas boilers and coal because of its large urban traffic, which is also a cause of poisoning the environment. Therefore, looking for new solutions limit the emissions to the environment. One solution is to replace the traditional heating system by a heat pump.

2. CLIMATIC CONDITIONS

The climate of Skopje is usually classified as continental sub-Mediterranean, while according to the other classification it has a humid subtropical climate. The summers are long, hot and humid. On average Skopje will see 88 days above 30°C each year, and 10.2 days above 35.0°C every year. Winters are short, relatively cold, and wet. Over the course of a year, the temperature typically varies from –4°C to 31°C and is rarely below – 11°C or above 36°C. The warm season lasts from May 31 to September 18 with an average daily high temperature above 26°C. The hottest day of the year is July 30, with an average high of 31°C and low of 17°C. The cold season lasts from November 23 to February 23 with an average daily high temperature below 9°C. The coldest day of the year is January 10, with an average low of –4°C and high of 4°C. In Krakow, the lowest monthly average air temperatures are recorded in January, the highest in July and August [17].

Table 1 shows the monthly air temperatures in Skopje, Macedonia and in Krakow, Poland. The average monthly air temperatures to both cities is shown on Figure 2.

Table 1

Monthly air temperature in Skopje and in Krakow [18]

Month	Average temperature over the years, °C					
	Maximum		Minimum		Average	
	Skopje	Krakow	Skopje	Krakow	Skopje	Krakow
Janurary	5	2	–4	–4	0.5	–1
February	9	4	–3	–3	3	0.5
March	15	9	2	0	8.5	4.5
April	19	15	5	4	12	9.5
May	24	20	10	9	17	14.5
June	29	23	10	12	19.5	17.5
July	32	25	16	14	24	19.5
August	32	25	16	13	24	19
September	26	19	12	9	19	14
October	20	14	7	5	13.5	9.5
November	12	7	2	1	7	4
December	5	3	–2	–3	1.5	0
Average	**19**	**13.8**	**5.9**	**4.8**	**12.5**	**9.3**

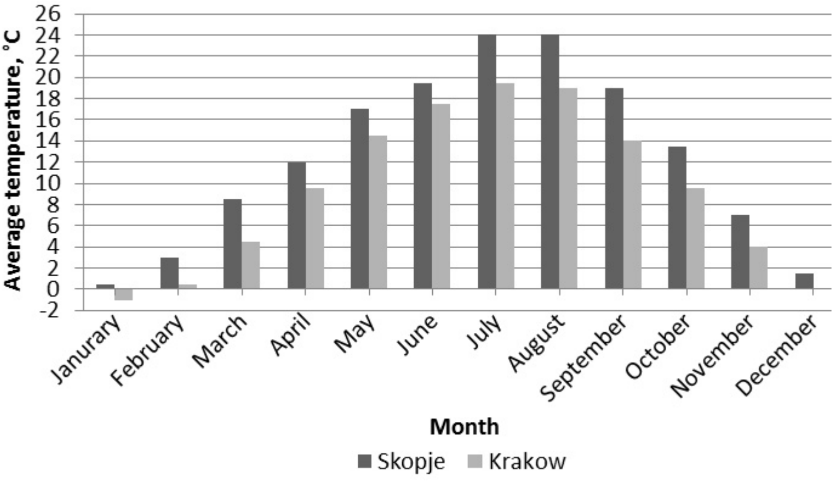

Fig. 2. Monthly average temperature in Skopje (black) and in Krakow (grey) [18]

3. ENERGY DEMAND FOR HEATING, AIR CONDITIONING AND HOT TAP WATER

This chapter presents the demand for heat, cold and hot tap water for Skopje and for Krakow. Heating and cooling loads were established based on the average monthly air temperature in these cities. The cost of energy will be discussed in the next section. It was assumed for both cities freestanding houses for four people on area of 140 m^2.

3.1. Heating load

Installation of heat pumps with a borehole heat exchangers is to obtain adequate heating power, able to heat the object. Installations always consist of multiple borehole heat exchangers located in the area in an appropriate placement and appropriately selected heat pumps for heating and cooling loads. The depth and location of the boreholes depends on the lithology of the area and the properties of the rock mass [9]. Assumed heating load for Skopje and for Krakow are presented in Table 2.

3.2. Cooling load

Heat pump systems can also be equipped with a cooling module. This solution is increasingly being used. This solution can be a cheaper way to cooling the room. In some installations, the cold collected and stored in the winter can be used to cooling the rooms in summer. In Skopje assumed period of refrigeration for 6 months, while in Krakow for 3 months. Assumed cooling load for Skopje and for Krakow are presented in the Table 3.

Table 2

Heating load in Skopje and in Krakow

Month	Heating load, kWh	
	Skopje	Krakow
Janurary	4 520.8	4 920.3
February	2 314.6	4 739.6
March	2 005.5	3 280.3
April	1 536.0	1 807.5
May	0.0	0.0
June	0.0	0.0
July	0.0	0.0
August	0.0	291.2
September	154.0	860.2
October	1 365.8	2 112.1
November	2 012.2	2 493.6
December	4 100.9	4 214.1
Total	**18 009.8**	**24 718.9**

Table 3

Cooling load in Skopje and in Krakow

Month	Cooling load, kWh	
	Skopje	Krakow
Janurary	0.0	0.0
February	0.0	0.0
March	0.0	0.0
April	25.2	0.0
May	55.2	0.0
June	358.2	338.0
July	831.3	831.1
August	662.2	462.7
September	35.1	0.0
October	0.0	0.0
November	0.0	0.0
December	0.0	0.0
Total	**1 967.2**	**1 631.8**

3.3. Hot tap water

To determine the energy needed for hot tap water for both climates, we assume the water to come in at 10°C and leave the heater at 60°C. We consider a daily consumption of hot tap water of 400 liters, assuming it is a house for a four-member family. Table 4 contains values of the parameters and calculation results. The energy demand for hot tap water can then be calculated as followed (1):

$$Q = \rho \cdot V \cdot c_w \cdot \Delta T \quad (1)$$

where:

- Q – energy demand for hot tap water, J,
- ρ – density of water, $kg \cdot m^{-3}$,
- V – daily consumption of hot tap water, m^3,
- c_w – specific heat of water, $J \cdot kg^{-1} \cdot K^{-1}$,
- ΔT – temperature difference, K.

Table 4

Parameters and calculation results for hot tap water

Parameter	Unit	Value
Density of water, ρ	$kg \cdot m^{-3}$	1000
Daily consumption of hot tap water, V	m^3	400
Annual consumption of hot tap water, V_a	m^3	146 000
Specific heat of water, c_w	$J \cdot kg^{-1} \cdot K^{-1}$	4200
Temperature of water before the heating	°C	10.00
Temperature of water before the heating	K	283.15
Temperature of water after the heating	°C	60
Temperature of water after the heating	K	333.15
Temperature difference, ΔT	K	50
Total energy demand for hot tap water, Q	J	$30.66 \cdot 10^{12}$
Total energy demand for hot tap water, Q	kWh	8 516.66

We assume that this energy demand is the same for both houses. The cost of this energy demand will be different for Skopje and Krakow because natural gas prices will not be equal.

4. COST OF HEATING, AIR-CONDITIONING AND HOT TAP WATER IN SKOPJE AND KRAKOW

To determine the cost of energy, we need to know the cost of electricity and the cost of natural gas, since heating in both countries is done by using natural gas.

Data from the institute that controls the energy price Energy Regulatory Commission of Republic of Macedonia shows that the consumers have one tariff payment or two tariff payment (low price at night and high price during the day) [15]

The average cost of electricity in Macedonia is 0.0904 $€\cdot kWh^{-1}$ [15] while cost of electricity in Poland is 0.1462 $€\cdot kWh^{-1}$ [8] The cost of natural gas in Macedonia is 0.2441 $€\cdot m^{-3}$ [15] while the cost in Poland is 0.4822 $€\cdot m^{-3}$ [8]. Furthermore, it was assumed that the calorific value of the natural gas is 10.5 $kWh\cdot m^{-3}$ and that the efficiency of the heating boiler is 0.8 for both cities. We can see the cost calculation for Skopje and Krakow in Tables 5, 6 and 7.

Table 5

Cost of heating for Skopje and Krakow

Month	Skopje			Krakow		
	Heating load, kWh	Gas, m^3	Euro	Heating load, kWh	Gas, m^3	Euro
Janurary	4 520.80	344.44	84.08	4 920.30	374.88	180.77
February	2 314.60	176.35	43.05	4 739.60	361.11	174.13
March	2 005.50	152.80	37.30	3 280.30	249.93	120.52
April	1 536.00	117.03	28.57	1 807.50	137.71	66.41
May	0.00	0.00	0.00	0.00	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	291.20	22.19	10.70
September	154.00	11.73	2.86	860.20	65.54	31.60
October	1 365.80	104.06	25.40	2 112.10	160.92	77.60
November	2 012.20	153.31	37.42	2 493.60	189.99	91.61
December	4 100.90	312.45	76.27	4 214.10	321.07	154.82
Total	**18 009.80**	**1 372.18**	**334.95**	**24 718.90**	**1 883.34**	**908.15**

Table 6

Cost of cooling for Skopje and Krakow

Month	Skopje		Krakow	
	Cooling load, kWh	Euro	Cooling load, kWh	Euro
Janurary	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00
March	0.00	0.00	0.00	0.00
April	25.20	2.28	0.00	0.00
May	55.20	4.99	0.00	0.00
June	358.20	32.38	338.00	49.41
July	831.30	75.15	831.10	121.49
August	662.20	59.86	462.70	67.64
September	35.10	3.17	0.00	0.00
October	0.00	0.00	0.00	0.00
November	0.00	0.00	0.00	0.00
December	0.00	0.00	0.00	0.00
Total	**1 967.20**	**177.83**	**1 631.80**	**238.54**

Table 7

Annual cost of hot tap water for Skopje and Krakow

Skopje			Krakow		
Heating load, kWh	Gas, m^3	Euro	Heating load, kWh	Gas, m^3	Euro
8 516.66	648.89	158.39	8 516.66	648.89	312.89

5. BOREHOLE HEAT EXCHANGERS

Design of borehole heat exchanger will be done by the Earth Energy Designer (EED) computer software. The required input for this program are the heating and cooling loads as presented above, the ground properties and the geometry, and the working fluid of the borehole heat exchanger. Ground properties was determined by the the geological profile. Soil profile for Skopje can be seen Table 8 and for Krakow in Table 9.

Table 8

Soil profile Skopje [3]

Top, m	Bottom, m	Thickness, m	Lithology	Thermal Conductivity, $W \cdot m^{-1} \cdot K^{-1}$	Specific Heat Capacity, $MJ \cdot m^{-3} \cdot K^{-1}$
0	60	60	Quaternary alluvial, prolluvial, limnic sediments	1.60	2.40
60	80	20	Conglomerate gravel and sandstone	2.00	2.00
Weighted average				1.80	2.20

Table 9

Soil profile Krakow [8]

Top, m	Bottom, m	Thickness, m	Lithology	Thermal Conductivity, $W \cdot m^{-1} \cdot K^{-1}$	Specific Heat Capacity, $MJ \cdot m^{-3} \cdot K^{-1}$
0	2.2	2.2	Clayed ground	1.60	2.00
2.2	2.6	0.4	Aggradate mud	1.60	2.20
2.6	4	1.4	Fine and dusty sand	1.00	2.00
4	6	2	Fine sand	1.20	2.50
6	15	9	All-in aggregate and gravel	1.80	2.40
15	30	15	Grey siltstone	2.20	2.30
30	78	48	Grey shaleclay	2.10	2.30
Weighted average				2.03	2.30

After analyzing the profile of the lithological decided in both cases, the drilling of the four holes with a depth of 75 m. It was decided to design a single U-tube. Diameter of borehole is 154.2 mm and diameter of borehole heat exchanger pipe 40 mm with thickness of pipe wall 3.7 mm. It was decided to traditional way to fill the boreholes with cement.

The calculated data with EED software can be found in Table 10. At the Figure 3 shows distribution of average temperature of heat carrier in 25th year of borehole operations in Krakow and Skopje. At the Figure 4 shows distribution of minimum and maximum temperature over 25 years of borehole operation in Krakow and Skopje.

Table 10

Data of borehole heat exchanger for Skopje and Krakow

Calculation data	Skopje	Krakow
Thermal Conductivity, $W \cdot m^{-1} \cdot K^{-1}$	1.8	2.03
Specific Heat Capacity, $MJ \cdot m^{-3} \cdot K^{-1}$	2.2	2.30
Type of borehole heat exchangers	Single U-pipe	
Distance between borehole heat exchangers, m	10	
Diameter of borehole, mm	154.2	
Diameter of BHE pipe, mm	40	
Thickness of BHE pipe wall, mm	3.7	
Shank spacing, mm	65	
Coefficient of thermal conductivity of borehole heat exchangers pipe material, $W \cdot m^{-1} \cdot K^{-1}$	0.42	
Heat transfer medium	33% glycol	
Number of BHE required	4	4
Required depth of BHE, m	75	75

Fig. 3. Distribution of average temperature of heat Cartier in 25th year of borehole operations in Krakow and Skopje

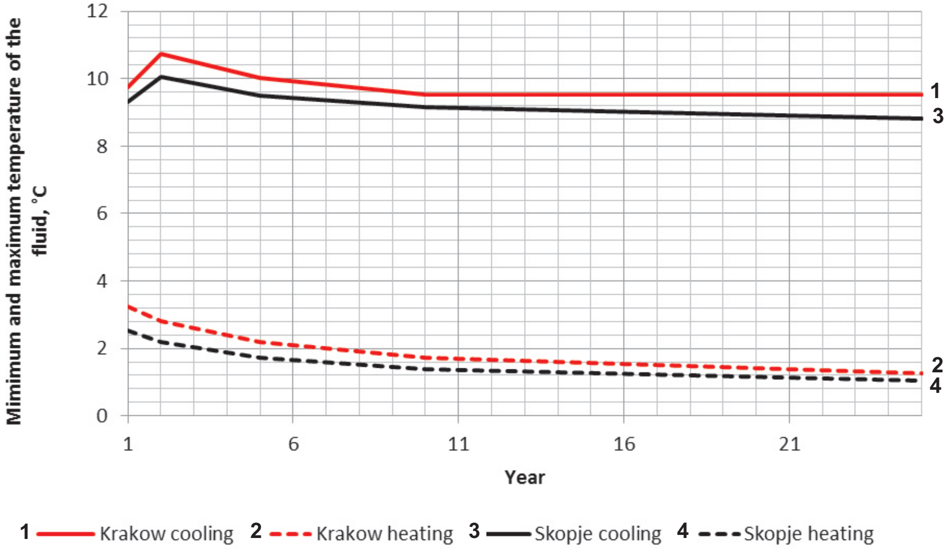

Fig. 4. Distribution of min. and max. temperature over 25 years of borehole operation in Krakow and Skopje

6. HEAT PUMP

Mass production of compressors was made that heat pumps became available to individuals and were used for producing heat during heating season, for air conditioning in summer and heating domestic hot water year-long. In recent years, the interest in these devices has been rising significantly in Poland and other countries. A heat pump facilitates an increase in the energetic state of such heat to a higher temperature so as to be useful to a given heat sink. A heat pump increases the temperature of the working agent, which facilitates heat transfer. Systems including heat pumps are systems which allow for the collection and use of dispersed, low-temperature thermal energy in users requiring the supply of heat of high temperature. A heat pump consists of four basic elements, which are heat exchangers – the evaporator and the condenser, the compressor and the expansion valve. The additional equipment is: a working agent tank, valves, sensors and elements of automated technology and sometimes recording systems. Many producers equip their heat pumps with circulating pumps in low-temperature source circulating systems and heat receiving systems [11].

Necessary to calculate coefficient of performance (COP) were temperatures which are calculated in Earth Energy Designer (EED) software. This coefficient allows for correct choice of heat pump.

We assume that the building will use planar heating (floor) parameters 35/50. Accordingly, the condensing temperature will be 38 degrees Celsius. Based on results from the average temperature on cooling, glycol passive cooling is assumed. The temperature of cooling on the input of the borehole heat exchangers is for Krakow 10.72°C, and for Skopje 10.06°C. Consequently, forcing circulation costs were omitted (costs of the circulation pump). Furthermore, the assumed efficiency of heating pump amounts to 0.6. This heat pump will be coupled with the borehole heat exchanger and will be working in both heating and cooling modes.

Coefficient of performance (COP_h) and total energy costs (T_{EC}) can be expressed by the equations (2) and (3):

$$COP_h = \varphi \frac{T_{cond}}{T_{cond} - T_{evap}} \quad (2)$$

where:

- φ – heat pump efficiency, –,
- T_{evap} – evaporation temperature, °C,
- T_{cond} – condensing temperature, °C.

$$T_{EC} = C_{HP} \cdot E_{Tot} \quad (3)$$

where:

- C_{HP} – cost energy heat pump, €·kWh^{-1},
- E_{Tot} – total energy heating and hot tap water, kWh.

Based on the calculations in the EED obtained evaporation temperature for Skopje –2.70°C and for Krakow –2.79°C Calculated on the basis of the above formulas coefficient of performance heating (COP_h) for Skopje 4.58 and for Krakow 4.57.

The size of the heat pump needs to be chosen accordingly to the peak loads that can occur during its lifetime. Prices pumps on the market were used [16].

7. COMPARISON OF HEATING, AIR-CONDITIONING AND HOT TAP WATER IN SKOPJE AND KRAKOW

Table 11 shows us the average temperature and energy need in Skopje and Krakow and the cost of energy when heating is done by using natural gas and a second way with using heat pump.

Table 11

Summarizing table for Skopje and Krakow

City	Skopje		Krakow	
Yearly average temperature, °C	12.5		9.3	
Heated surface, m^2	140		140	
Cost of electricity, €·kWh^{-1}	0.0904		0.1462	
Cost of natural gas, €·m^{-3}	0.2441		0.4822	
Heating	18 009.80 kWh·a^{-1}	334.95 €·a^{-1}	24 718.90 kWh·a^{-1}	908.15 €·a^{-1}
Cooling	1 967.20 kWh·a^{-1}	177.83 €·a^{-1}	1 631.80 kWh·a^{-1}	238.54 €·a^{-1}
Hot tap water	8 516.66 kWh·a^{-1}	158.39 €·a^{-1}	8 516.66 kWh·a^{-1}	312.89 €·a^{-1}
Traditional total energy and cost of heating, hot tap water and air conditioning	28 493.66 kWh·a^{-1}	671.17 €·a^{-1}	34 867.36 kWh·a^{-1}	1 459.58 €·a^{-1}
Traditional total unit quantities and cost of heating, hot tap water and air conditioning	203.53 kWh·$(a·m^2)^{-1}$	4.79 €·$(a·m^2)^{-1}$	249.05 kWh·$(a·m^2)^{-1}$	10.43 €·$(a·m^2)^{-1}$
Heat pump total energy and cost of heating and hot tap water	26 526.46 kWh·a^{-1}	868.63 €·a^{-1}	33 234.66 kWh·a^{-1}	1 119.68 €·a^{-1}
Heat pump total unit quantities and cost of heating and hot tap water	189.47 kWh·$(a·m^2)^{-1}$	6.18 €·$(a·m^2)^{-1}$	237.39 kWh·$(a·m^2)^{-1}$	7.99 €·$(a·m^2)^{-1}$

8. SIMPLE PAYBACK TIME

Besides environmental aspects important factor it is also the economic aspect. One of the methods of economic valuation of the investment is Simple Payback Time. Simple Payback Time must be as small as possible. The values for the two cities to be calculated and presented in Table 12. Simple Payback Time can be expressed by the equation (4):

$$\text{SPBT} = \frac{I_{HP} - I_{trad}}{C_{trad} - C_{HP}} \tag{4}$$

where:

SPBT – Simple Payback Time, year,
I_{HP} – heat pump and borehole heat exchangers investment cost, €,
I_{trad} – gas boiler investment cost, €,
C_{trad} – traditional heating, tap water and cooling cost, €·year^{-1},
C_{HP} – heat pump, heating, tap water cost, €·year^{-1}.

Table 12

Simple Payback Time

City	Skopje	Krakow
Heat pump and borehole heat exchangers investment cost, €	9 033.72	12 069.77
Gas boiler investment cost, €	1 511.63	1 798.84
Traditional heating, tap water and cooling cost, €·year^{-1}	1 329.50	2 074.07
Heat pump, heating, tap water cost, €·year^{-1}	863.63	1 119.68
Simple Payback Time, year	16.15	10.76

9. CONCLUSIONS

1. Krakow has better geological conditions. Higher thermal conductivity and higher specific heat capacity.
2. Average cost of electricity in Macedonia (0.0904 €·kWh^{-1}) is lower than in Poland (0.1462 €·kWh^{-1}). The price of natural gas is lower by half in Macedonia than in Poland.
3. Value of Coefficient of Performance in Krakow and in Skopje is approximately the same, in heating mode better in Macedonia, in cooling mode in Krakow.
4. Simple Payback Time in Poland is better than in Macedonia. In Krakow SPBT is 10.76 years, in Skopje is 16.15 years.
5. Referring to the above conclusions can be stated that due to the fact that the difference between the cost of traditional energy and the cost of renewable energy in Macedonia is small, therefore SPBT is bigger.

REFERENCES

[1] Beier R.A., Acuña J., Mogensen, P., Palm B.: *Borehole resistance and vertical temperature profiles in coaxial borehole heat exchangers*. Applied Energy, 102, 2013.

[2] Dubiński J., Turek M.: *Analiza bazy zasobowej węgla kamiennego w aspekcie dostaw dla polskiej elektroenergetyki do 2030 roku*. Scientific Conference „Clean coal engineering", Sosnowiec-Katowice 2008.

[3] Dumurdzanov N., Serafimovski T., Burchfiel B.C.: *Evolution of the Neogene--Pleistocene Basins of Macedonia*. The Geological Society of America, Digital Map and Chart Series, 1, 2004.

[4] Li M., Lai A.C.K.: *Heat-source solutions to heat conduction in anisotropic media with application to pile and borehole ground heat exchangers*. Applied Energy, 96, 2012.

[5] Sapinska-Sliwa A., Rosen M.A., Gonet A., Sliwa T.: *Deep borehole heat exchangers – a conceptual and comparative review*. International Journal of Air-Conditioning and Refrigeration, 24/1, 2016.

[6] Śliwa T.: *Techniczno-ekonomiczne problemy adaptacji wykorzystanych odwiertów na otworowe wymienniki ciepła* [The technical and economic issues of exploited wells adaptation for borehole heat exchangers], AGH University of Science and Technology in Krakow, Krakow, 2002 (PhD thesis).

[7] Śliwa T.: *System grzewczo-chłodniczy na bazie wymienników otworowych z bezpośrednim parowaniem czynnika roboczego w Centrum Pałecznicy, Efektywność energetyczna w gminach na przykładzie Pałecznicy*. Seminarium, Pałecznica 16 października 2014.

[8] Śliwa T., Decan G., Sapińska-Śliwa A., Bieda A., Kowalski T.: *Comparative analysis of borehole heat exchangers use in different climatic conditions*. AGH Drilling, Oil, Gas, vol. 33, No. 2, 2016, pp. 483–494.

[9] Śliwa T., Sapińska-Śliwa A., Wiśniowski R., Piechówka Z., Krzemień M., Pycha D., Jaszczur M.: *Influence of flow rate and heating power in effective thermal conductivity applied in borehole heat exchangers*. Journal of Physics: Conference Series, vol. 745, 2016, 8p.

[10] Śliwa T., Rosen M.A.: *Natural and artificial methods for regeneration of heat resources for borehole heat exchangers to enhance the sustainability of underground thermal storages: a review*. Sustainability, vol. 7, No. 10, 2015, pp. 13126–131441.

[11] Śliwa T., Sapińska-Śliwa A., Knez D., Bieda A., Kowalski T., Złotkowski A.: *Borehole heat exchangers: production and storage of heat in the rock mass*. Laboratory of Geoenergetics Book Series, vol. 2, Kraków 2016.

[12] Zarrella A., Capozza A., De Carli M.: *Analysis of short helical and double U-tube borehole heat exchangers: A simulation-based comparison*. Applied Energy, 112, 2013, pp. 358–370.
[13] Zarrella A., De Carli M.: *Heat transfer analysis of short helical borehole heat exchangers*. Applied Energy, 102, 2013.
[14] www.energetskaazbuka.mk
[15] www.erc.org.mk
[16] www.heatpumppriceguides.com
[17] www.weatherspark.com/averages/32456/Skopje-Ilinden-Macedonia
[18] www.worldweatheronline.com