AGH DRILLING, OIL, GAS • Vol. 33 • No. 2 • 2016

http://dx.doi.org/10.7494/drill.2016.33.2.483

Tomasz Śliwa*, Gilles Decan, Aneta Sapińska-Śliwa*, Anna Bieda*, Tomasz Kowalski***

COMPARATIVE ANALYSIS OF BOREHOLE HEAT EXCHANGER USE IN DIFFERENT CLIMATIC CONDITIONS***

1. INTRODUCTION

Nowadays the problem of global warming is omnipresent and all kinds of solutions are suggested to counteract this problem. One of them is the use of a heat pump, coupled with a borehole heat exchanger for heating and cooling of a house. In this article, a comparison is made between the heating and cooling load for a typical house in Ghent, Belgium and Krakow, Poland. The cost of heating and cooling is examined together with the cost of hot tap water. Then a study of a borehole heat exchanger with a heat pump is conducted. In this way, heating and cooling can be done in a cheaper and more environmental friendly way.

2. CLIMATIC CONDITIONS

First of all, to be able to determine heating and cooling loads, the climate for both cities needs to be examined. Monthly average temperatures as well as the total average temperature were determined, together with the heating degree days and cooling degree days (HDD, CDD). Figure 1 is a schematic representation of the average temperatures in both cities [12].

* AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

** Faculty of Mechanical Energy Engineering (Flow, Heat and Combustion) at Ghent University, Ghent, Belgium

*** The work was realised within the Statute Studies at the Faculty of Drilling, Oil and Gas at AGH UST, contract no. AGH 11.11.190.555

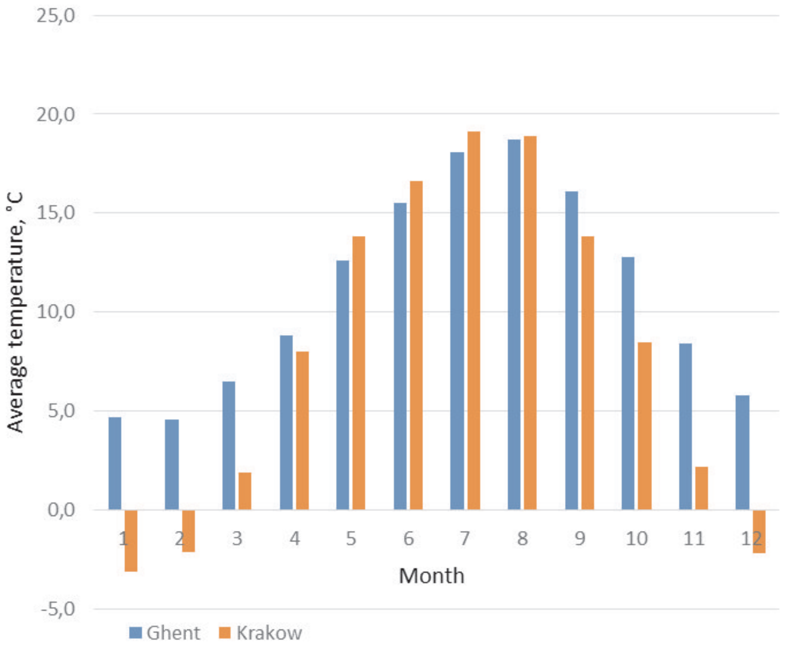

Fig. 1. Monthly average temperature Ghent (blue) and Krakow (orange)

We can see that temperature averages in summer between the two cities are similar, which means that the cooling loads for both cities will be almost the same. This is also visible in the small differences in cooling degree days. In contrast, the winter average temperatures are very different for each city, which will result in a bigger difference in heating load, as also represented by the big difference in heating degree days.

3. HEATING AND COOLING LOAD

To determine the heating and cooling load for a typical house in the city of Ghent, we use the Belgian software *EPB Vlaanderen*. In this software you can implement the complete design and orientation of your house and then the software will do the load calculations. We implement a house in Ghent, with a ground surface of 150 m^2 and with its orientation towards the south. Further design parameters are:

- Walls consisting of different layers with a total k-value of 0.20 W/(m^2·K).
- Insulated roof with a k-value of 0.19 W/(m^2·K).
- Insulated floor with a k-value of 0.35 W/(m^2·K).
- Aluminum door with window with a total k-value of 1.23 W/(m^2·K).
- Double glazed windows with aluminum frame with a total k-value of 1.50 W/(m^2·K).

For an average house in Krakow considering a house with a total ground surface of 150 m^2 [8].

We can see the total heating and cooling loads for both cities in Figures 2 and 3 [3, 8, 16].

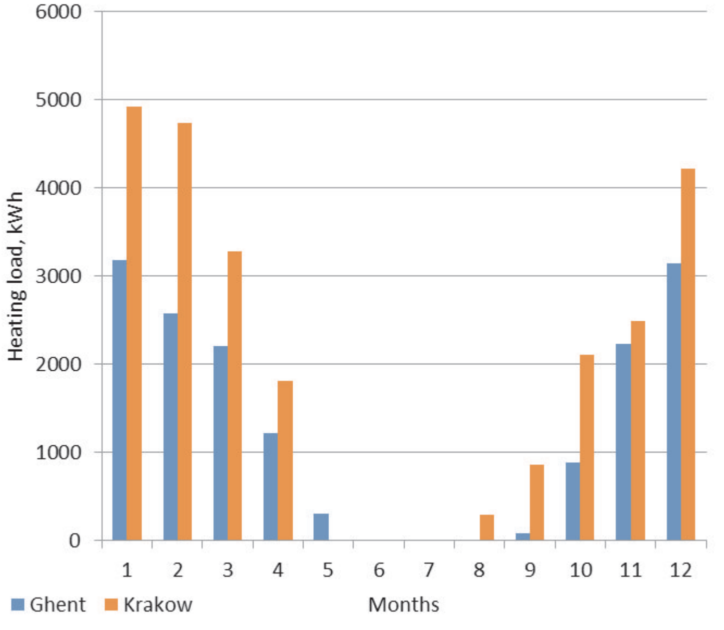

Fig. 2. Heating load Ghent (blue) and Krakow (orange)

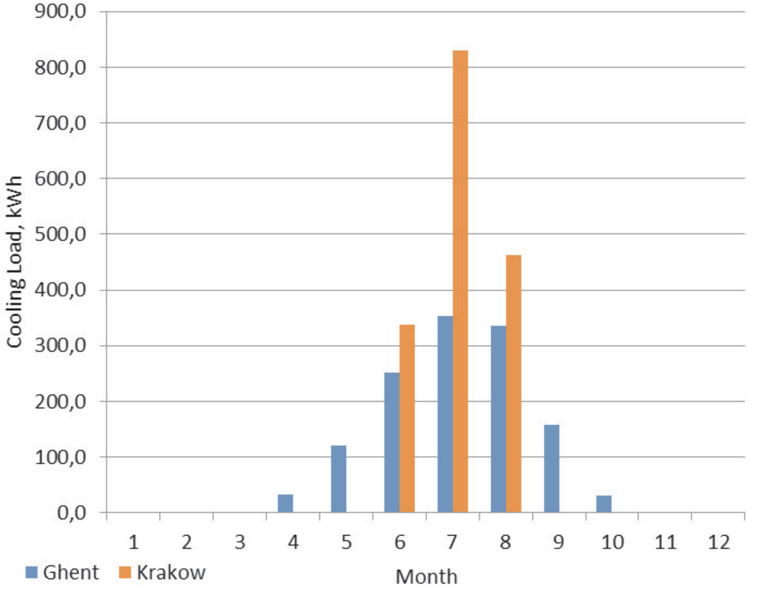

Fig. 3. Cooling load Ghent (blue) and Krakow (orange)

4. 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. The energy demand for hot tap water can then be calculated as followed:

$$Q = \rho V c_w \Delta T = 3.056 \cdot 10^{10} \text{ J} = 8490 \text{ kWh}$$

This energy demand is the same for both houses, since both families need the same amount of water and the water temperatures are supposed to be the same. Of course the cost of this energy demand will be different for Ghent and Krakow because natural gas prices will not be equal. The cost of energy will be discussed in the next section.

5. COST OF HEATING, COOLING AND HOT TAP WATER

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. The cost of electricity in Belgium is 0.22576 €/kWh while cost of electricity in Poland is 0.14618 €/kWh. The cost of natural gas in Belgium is 0.59044 €/m^3 while the cost in Poland is 0.4822 €/m^3. Because of the high gas prices in Belgium, we can already predict the benefits of borehole heat exchangers for heating.

Furthermore, it was assumed that the calorific value of the natural gas is 10.5 kWh/m^3 and that the efficiency of the heating boiler is 0.85 for both cities.

We can see the cost calculation for Ghent and Krakow in Tables 1, 2 and 3.

Table 1

Cost of heating for Ghent and Krakow [7, 11]

Month	Ghent			Krakow		
	Heating load, kWh	Gas, m^3	Euro	Heating load, kWh	Gas, m^3	Euro
January	3180.6	257.5	152.0	4920.3	398.3	192.1
February	2580.3	208.9	123.3	4739.6	383.7	185.0
March	2205	178.5	105.4	3280.3	265.5	128.0
April	1215	98.4	58.1	1807.5	146.3	70.6
May	307.2	24.9	14.7	0	0.0	0.0
June	0	0.0	0.0	0	0.0	0.0
July	0	0.0	0.0	0	0.0	0.0
August	0	0.0	0.0	291.2	23.6	11.4
September	77.2	6.2	3.7	860.2	69.6	33.6
October	888.1	71.9	42.4	2112.1	171.0	82.4
November	2231.7	180.7	106.7	2493.6	201.9	97.3
December	3143.3	254.5	150.2	4214.1	341.1	164.5
Total	**15828.4**	**1281.3**	**756.6**	**24718.9**	**2001.1**	**964.9**

Table 2

Cost of cooling for Ghent and Krakow [7, 11]

Month	Ghent		Krakow	
	Cooling load, kWh	Euro	Cooling load, kWh	Euro
January	0	0.0	0	0.0
February	0	0.0	0	0.0
March	0	0.0	0	0.0
April	32.2	3.6	0	0.0
May	121	13.7	0	0.0
June	250.9	28.3	338	24.7
July	353.9	39.9	831.1	60.7
August	334.7	37.8	462.7	33.8
September	157.3	17.8	0	0.0
October	30	3.4	0	0.0
November	0	0.0	0	0.0
December	0	0.0	0	0.0
Total	**1280.0**	**144.5**	**1631.8**	**119.3**

Table 3

Cost of hot tap water for Ghent and Krakow [11]

	Ghent			Krakow		
	Hot tap water	Gas, m^3	Euro	Hot tap water	Gas, m^3	Euro
Total	8490.3	687.31	405.8	8490.3	687.31	331.4

The results of the calculations confirm the high cost for heating. The option of a borehole heat exchanger could be a worthy alternative and will be evaluated next, after the final comparison of energy need and cost.

6. BOREHOLE HEAT EXCHANGER

The design of the required 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 calculated above, the ground properties and the geometry, and the working fluid of the borehole heat exchanger.

The ground properties are determined by the soil profile of the cities of Ghent and Krakow. Soil profile for Ghent can be seen in Table 4 (on the basis of the profile city Knokke in [2]).

Table 4
Soil profile Ghent [2]

Top, m	Bottom, m	Thickness, m	Lithology	Thermal Cond, W/(m·K)	Vol Spec Heat, MJ/(m^3·K)
0	30	30	Sand	1.00	2.00
30	37	7	Clay	2.00	2.40
37	63	26	Gray clay	2.20	2.30
63	80	17	Fine sand	2.20	2.30
Weighted average				1.73	2.20

Table 5
Soil profile Krakow [1]

Top, m	Bottom, m	Thickness, m	Lithology	Thermal Cond, W/(m·K)	Vol Spec Heat, MJ/(m^3·K)
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 shale clay	2.10	2.30
Weighted average				2.03	2.30

For the borehole heat exchanger, a single U-pipe is chosen, where multiple boreholes are placed ten meters away from each other. The setup is shown in Figure 4 (the same construction for both cities). In Figure 5 temperature of the fluid per year for both cities is given. Figure 6 present minimum and maximum temperatures of the fluid per year for both cities. The calculated data with EED software can be found in Table 6.

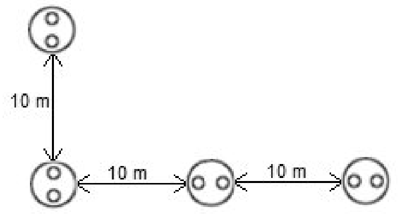

Fig. 4. Setup of the borehole heat exchangers [1]

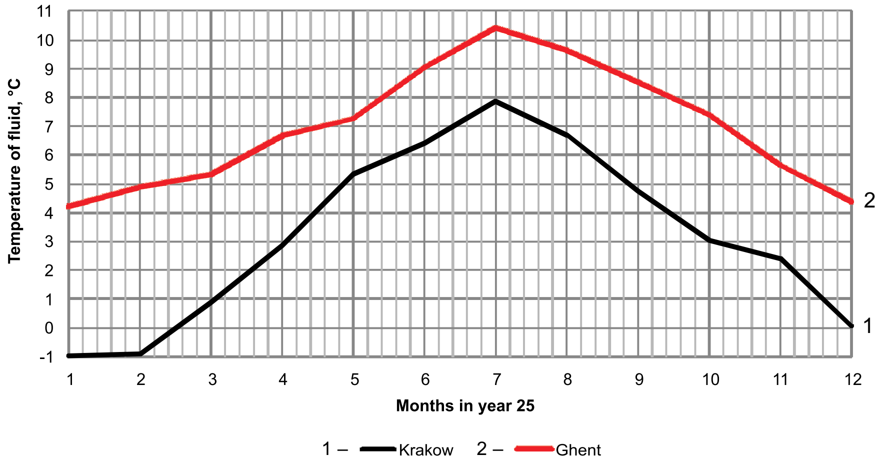

Fig. 5. Distribution of average temperature of heat carrier in 25th year of borehole operation in Krakow and Ghent

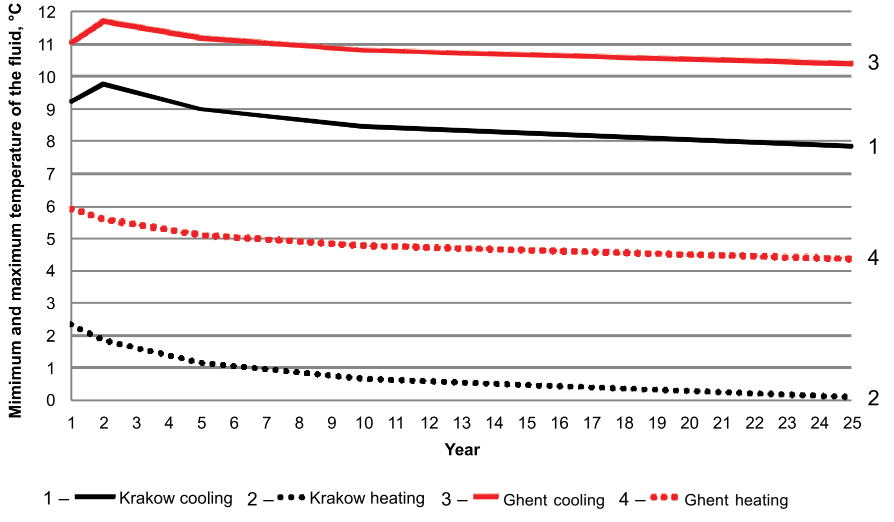

Fig. 6. Distribution of min. and max. temperature over 25 years of borehole operation in Krakow and Ghent

Table 6

Data of borehole heat exchanger for Ghent and Krakow [1]

Calculation Data	Ghent	Krakow
Thermal conductivity, W/(m·K)	1.73	2.30
Volume specific heat, MJ/(m^3·K)	2.2	2.03
Type of BHE	Single U-pipe	
Distance between BHE, m	10	
Diameter of borehole, mm	149	
Diameter of BHE pipe, mm	40	
Thickness of BHE pipe wall, mm	3.7	
Shank spacing, mm	65	
Coefficient of thermal conductivity of BHE pipe material, W/(m·K)	0.42	
Heat carrier	33% glycole	
Number of BHE required	4	4
Required depth of BHE	80	80

7. HEAT PUMP AND CALCULATION

With the temperatures calculated by the Earth Energy Designer software, it is possible to calculate the necessary coefficient of performance of the needed heat pump. This heat pump will be coupled with the borehole heat exchanger and will be working in both heating modes.

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 9.35°C., and for Ghent 11.92°C. Consequently, forcing circulation costs were omitted (costs of the circulation pump). Furthermore, the assumed efficiency of heating pump amounts to 0.6.

7.1. Heat pump efficiency and energy costs in Krakow

$$\mathrm{COP}_h = \varphi \frac{T_{cond}}{T_{cond} - T_{evap}}$$

$$T_{evap} = -5.49°C$$

$$T_{cond} = 38°C$$

$$COP_h = 4.29$$

$$Cost\ energy\ heat\ pump = \frac{Cost\ energy}{COP_h} = 0.034\ €/kWh$$

$$Total\ cost\ energy\ Heat\ Pump =$$
$$= Cost\ energy\ Heat\ Pump \cdot Total\ energy\ heating\ and\ hot\ tap\ water =$$
$$= 1129.11\ €$$

7.2. Heat pump efficiency and energy costs in Ghent

$$T_{evap} = -0.28°C$$

$$T_{cond} = 38°C$$

$$COP_h = 4.87$$

$$Cost\ energy\ Heat\ Pump = \frac{Cost\ energy}{COP_h} = 0.046 \frac{€}{kWh}$$

$$Total\ cost\ energy\ Heat\ Pump =$$
$$= Cost\ energy\ Heat\ Pump \cdot Total\ energy\ heating\ and\ hot\ tap\ water =$$
$$= 1118.66\ €$$

Based on the calculations in the EED obtained evaporation temperature for Krakow –5.49°C., and for Ghent –0.28°C. It gives coefficient of performance (COP_h) for Krakow 4.29 and for Ghent 4.87.

The size of the heat pump needs to be chosen accordingly to the peak loads that can occur during its lifetime.

8. COMPARISON OF CLIMATE, ENERGY NEED AND ENERGY COST

Before examining the option of a borehole heat exchanger, the last summarizing table between the two cities is given. Table 7 shows us the average temperature and energy need in Ghent and Krakow and the cost of energy when heating is done by using natural gas and a second way with using heat pump.

Table 7

Summarizing table of Ghent and Krakow [7, 8, 11, 12, 16]

City	Ghent		Krakow	
Yearly average temperature, °C	11.1		8.0	
Heated surface, m^2	150		150	
Cost of electricity, €/kWh	0.22576		0.14618	
Cost of natural gas, €/m^3	0.59044		0.4822	
Heating	15828.3 kWh/a	756.56 €/a	24718.9 kWh/a	964.91 €/a
Hot tap water	8490.3 kWh/a	405.80 €/a	8490.3 kWh/a	331.40 €/a
Cooling	1280.0 kWh/a	144.50 €/a	1631.8 kWh/a	119.25 €/a
Traditional total energy and cost of heating, hot tap water and air conditioning	25598.6 kWh/a	1306.86 €/a	34841.0 kWh/a	1415.56 €/a
Traditional total unit quantities and cost of heating, hot tap water and air conditioning	170.7 kWh/(a·m^2)	8.71 €/(a·m^2)	232.3 kWh/(a·m^2)	9.44 €/(a·m^2)
Heat pump total energy and cost of heating and hot tap water	24318.6 kWh/a	1118.66 €/a	33209.2 kWh/a	1129.11 €/a
Heat pump total unit quantities and cost of heating and hot tap water	162.12 kWh/(a·m^2)	7.46 €/(a·m^2)	221.39 kWh/(a·m^2)	7.53 €/(a·m^2)

This table again shows us the high cost of heating and of hot tap water in Belgium. This is due to the cost of natural gas in Belgium, which is higher than the cost of natural gas in Poland. The use of a heat pump together with a borehole heat exchanger can lower this natural gas cost and can hold great advantages and will thus be examined next.

9. PAYBACK PERIOD

To assess if geothermal system for heating and cooling is achievable, it is important to recognize the different economic resources implicated. Also it is necessary to make a comparison between traditional fuels and this clean method. Payback period is the time involved to recover all the investment made at the start of the project. It is and acceptable payback period for up to 10 years for houses. The values were adopted on the basis of [9, 10, 13, 14, 15]:

$$\mathrm{SPBT} = \frac{I_{HP} - I_{trad}}{C_{trad} - C_{HP}}$$

where:

- SPBT – Simple Payback Time,
- 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,
- C_{HP} – heat pump, heating, tap water cost.

SPBT for Krakow amounts:

$$\mathrm{SPBT} = \frac{8909.51 - 1794.66}{2073.96 - 1193.79} = 8.08 \text{ years}$$

SPBT for Ghent amounts:

$$\mathrm{SPBT} = \frac{12986.89 - 2320.19}{3149.76 - 2028.53} = 9.51 \text{ years}$$

10. CONCLUSIONS

1. The moderate climate in Belgium and Poland is really beneficial towards the use of heat pumps and borehole heat exchangers for heating and cooling.
2. Simple payback time in Poland is better than in Belgium. In Krakow it amounts to 8.08, but in Ghent 9.51 years. Although value of COP is higher in Ghent (4.87) than in Krakow (4.29). The reason is that costs of investments and operational costs are different.
3. Krakow has better geological conditions (higher value of rock mass heat conductivity). But higher temperature of the heat carrier is calculated for Ghent. The reason is higher value of heating load in Krakow.

REFERENCES

[1] Gonet A., Śliwa T., Stryczek S., Sapinska-Sliwa A., Jaszczur M., Pająk L., Złotkowski A.: *Metodyka identyfikacji potencjału cieplnego górotworu wraz z technologią wykonywania i eksploatacji otworowych wymienników ciepła [Methodology for the identification of potential heat of the rock mass along with technology implementation and operation of the borehole heat exchangers]*. Wydawnictwa AGH, Kraków 2011, p. 438.

[2] Laga P., Vandenberghe N.: *A geological profile along the Belgian coast*. In: Henriet J.-P. et al. (Ed.), The Quaternary and Tertiary geology of the Southern Bight, North Sea, 1989, pp. 5–8, In: Henriet J.-P.; De Moor G.; De Batist M. (Eds),The Quaternary and Tertiary geology of the Southern Bight, North Sea ,1989. Ministry of Economic Affairs. Belgian Geological Survey, Brussel 1989, p. 241.

[3] Sliwa T., Freidenberger C.: *Comparative analysis of borehole heat exchanger use in different climatic conditions*. Proceeding World Geothermal Conference 2015, Melbourne 2015, pp 1–14.

[4] Sliwa T., Gonet A.: *Analysis of Borehole Heat Exchangers Design in View of Stream of Heat Exchanged Maximization with the Rock Mass*. Proceeding World Geothermal Conference 2010, Bali, 2010, pp 1–7.

[5] Sliwa T., Gonet A.: *Otworowe wymieniki ciepla jako źródło ciepła lub chłodu na przykładzie Laboratorium Geoenergetyki WWNiG AGH*. Wiertnictwo Nafta Gaz, vol. 28, 2011.

[6] Sliwa T, Sakellariou K.: Comparison Analysis of Use BHE in Different Climatic Conditions, Proceeding World Geothermal Conference 2010, Bali, 2010, pp 1–8.

[7] https://www.electrabel.nl/producten-en-tarieven/driejaarvast (access 02.08.2015).

[8] https://eosweb.larc.nasa.gov/sse/RETScreen/ (access 27.07.2015).

[9] http://kursy-walut.mybank.pl/ (access 27.02.2016).

[10] http://oferta.pgnig.pl/dla-domu/gaz/cennik-uslug-przylaczeniowych (access 7.02.2016).

[11] http://www.unitrove.com/engineering/tools/gas/natural-gas-calorific-value (access 02.08.2015).

[12] http://www.weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine, ghent,Belgium (access 27.07.2015).

[13] http://www.viessmann.com/web/poland/ofertowanie.nsf/www (access 27.02.2016).

[14] http://vikersonn.eu/kalkulator?area=150&habitants=4 (access 27.02.2016).

[15] http://vikersonn.eu/oferta/parametry-specyfikacja-techniczna-vikersonn (access 27.02.2016).

[16] http://www.yr.no/place/Belgium/Flanders/Ghent/statistics.html (access 27.07.2015).