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Comparison Analysis of Use BHE in Different Climatic Conditions

Tomasz Śliwa, Kyriaki Sakellariou

Drilling, Oil and Gas Faculty AGH University of Science and Technology, Aristotle University of Thessaloniki

sliwa@agh.edu.pl, kyrsakel@yahoo.gr

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ABSTRACT

The ways in which borehole heat exchangers are used in various climatic conditions are analyzed and compared in this paper. The heating and cooling modes of heat pumps were considered. The analysis was based on economic and energy operation of a heat pump system for a typical family house. The costs of running borehole heat exchangers in Poland and Greece were compared.

1. INTRODUCTION

Economic and energy conditions of heating and cooling a typical family house were analyzed for Poland (Cracow region) and Greece (Thessaloniki region). This energy is necessary for heating (domestic heating, and tap water heating) and cooling (air-conditioning).

In Poland 90% of electricity comes from coal (Dubiński and Turek 2008) and is of domestic production. According to European Commission (2007), the primary energy supply in Greece was estimated at 33 ktoe in 2004. About 30% of the energy supply is produced domestically. The energy balance in Greece heavily relies on two fossil fuels: (a) lignite dominates domestic production, with an 84% share, and it is used primarily for electricity generation (representing 60% of total generation), mainly in Western Macedonia; (b) imported oil as the most important fuel source, accounting for approximately 60% of total energy consumption. In addition, imported oil is the fuel that is used for power generation in the islands (Andritsos 2007).

2. CLIMATIC CONDITIONS

The average monthly air temperatures in Thessaloniki over the year are presented in table 1 as average maximum and minimum daily temperature (BBC-Weather Center). The yearly mean temperature in Thessaloniki according to the chart (table 1) is about 16ºC.

Table 1. Average monthly air temperature in Thessaloniki.

Month	Average Temperature, ºC		
	Maximum	Minimum	Monthly
January	9	2	5.5
February	12	3	7.5
March	14	5	9.5
April	20	10	15
May	25	14	19.5
June	29	18	23.5
July	32	21	26.5
August	32	21	26.5
September	28	17	22.5
October	22	13	17.5
November	16	9	12.5
December	11	4	7.5

The mean monthly air temperatures in Cracow are presented in Table 2. The average long-term annual temperature in Cracow is 8.5°C (Statistical yearbook 2004).

Table 2. Average monthly air temperatures from meteorological station in Cracow, °C.

Months	Average of years 1991-2000	2005	2006	Average of years 1991-2006
January	-1.4	0.0	-8.3	-1.9
February	-0.2	-3.2	-3.1	-0.7
March	3.2	1.3	0.1	2.8
April	8.8	9.7	9.2	8.9
May	13.9	14.3	13.2	13.9
June	17.1	16.9	17.4	17.1
July	18.7	19.7	21.6	19.0
August	18.4	17.5	17.0	18.2
September	13.5	14.3	15.5	13.7
October	8.6	8.7	10.3	8.8
November	2.8	1.9	5.2	2.9
December	-1.2	-0.9	2.4	-0.9

Figure 1 presents average monthly temperatures in Thessaloniki and Cracow. Figure 2 shows load (energy demand) of heating and air-conditioning.

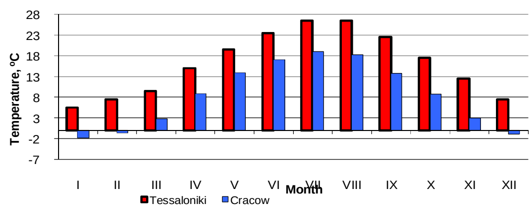

Figure 1: Average monthly temperatures in Thessaloniki and Cracow.

3. COST AND ENERGY DEMAND FOR HEATING AND AIR-CONDITIONING IN GREECE

According to data found from the national electricity organisation of Greece (www.dei.gr), low voltage (220 V) energy is used for a house's needs. A typical family house consumes about 400 kWh per month (4800 kWh per year) of electricity and the cost of electricity is 0.08761 euros/kWh.

As we can see from Figure 2, according to the temperatures in Thessaloniki, heating is used during 5 months (from

November to March). The fuels used for heating are basically oil and natural gas.

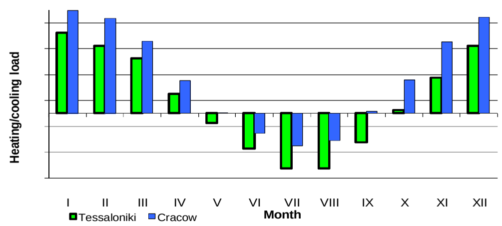

Figure 2: Energy consumption for heating and air-conditioning.

Data from the Ministry of Development of Greece (Ministry of Development of Greece, 2009) show that oil for heating costs 0.656 euro/L during the year 2008. Additionally, the lower thermogenic power of oil is 11.92 kWh/kg and the density is 0.86kg/L. So the cost of oil for heating leads to be 0.064 euros/kWh.

The natural gas available on the Greek market is 20% cheaper than oil, which means that the price of natural gas of 2008 is approximately 0.044 euros/kWh.

Statistical data show that a typical family house consumes about 1000 L of oil per year and 1000-1200 m^3 natural gas, giving 8-12 hours of heating a day.

Table 1 shows that the temperature is very high over 4 months (from June to September). The kind of cooling used during this season of the year is air-conditioning consuming electrical energy. Cooling of a typical family house requires using air-conditioning machines 12000 kcal each (36000 kcal = 41.934 kWh). The daily cooling time in the city of Thessaloniki is about 6 hours.

The study of annual demand of heating and cooling in a typical house in Greece was conducted referring to a typical 85 m^2 house in Thessaloniki, which was constructed in 2008.

3.1 Heating

The fuel used for heating is oil. The lower thermogenic power and density of oil are B=11.92 kWh/kg and ρ=0.86 kg/dm^3, respectively. According to the heat balance, an 85 m^2 apartment consumes Q=2.036 MWh of energy for heating per month. If we consider that the output of the boiler is η=80%, then the amount of oil consumed within a month is:

$$V = \frac{Q}{B \cdot \rho \cdot \eta} = 248\, dm^3$$

Therefore, considering that the heating is used 7 months per year, the annual oil consumption of an 85 m^2 apartment for heating is 1736 dm^3. The average cost of oil used for heating in the years 2008-2009 is $C_{un\text{-}oil}$=0.55 €/dm^3. Accordingly, the annual cost of oil for heating is C_{oil}=956 €/a.

3.2 Hot Water Supply and Costs

Hot water can be obtained by using fuel (oil or physical gas), electrical energy and solar energy. The total amount of electrical energy used by a house is Q_{el}=2000 kWh per year and the cost of a 1 kWh of electrical energy is $C_{un\text{-}el}$=0.09€ *(www.cres.gr)*.

<u>3.2.1 Fuel & Electrical Energy</u>

In the case where the hot water is provided by an electrical heater, the total cost of heating and hot water supply is:

$$\boldsymbol{C_{el} = C_{un-el} \cdot Q_{el} = 180} \text{ €/a}$$

$$\boldsymbol{C_{total} = C_{el} + C_{oil} = 1136} \text{ €/a}$$

<u>3.2.2 Fuel & Boiler</u>

As mentioned above, heating is used for 7 months per year and the oil combustion can provide the house with hot water. So for the remaining 5 months hot water can be supplied by a boiler. The electrical energy consumed within 5 months is Q_{el}=831 kWh (electrical energy per month amounts to 2000/12 = 167 kWh, i.e. 167*7 = 1169 kWh for 7 months).

$$\boldsymbol{C_{el} = C_{un-el} \cdot Q_{el} = 75} \text{ €/a}$$

$$\boldsymbol{C_{total} = C_{el} + C_{oil} = 1031} \text{ €/a}$$

<u>3.2.3 Fuel & Solar Energy & Electrical Energy</u>

When solar energy is used for hot water supply, it can cover up to 70% of the annual electrical energy (which is equal to 1400 kWh) consumed by a 4-member-family. Therefore, the electrical energy charge is Q_{el} = 600 kWh.

$$\boldsymbol{C_{el} = C_{un-el} \cdot Q_{el} = 54} \text{ €/a}$$

$$C_{total} = C_{el} + C_{oil} = 1010 \text{ €/a}$$

3.3 Cooling

An 85 m^2 apartment demands three air conditioners for its cooling during the summer months, one of 12000 Btu (3.51 kWh) and two of 9000 Btu (2.64 kWh) each. Considering that the air conditioners work for 4 months per year (120 days), 4 hours per day, the electrical energy consumed is Q_{el}=6328.8 kWh/a and its cost is:

$$C_{el} = C_{un-el} \cdot Q_{el} = 569.6 \text{ €/a}$$

4. COST AND ENERGY DEMAND FOR HEATING AND AIR-CONDITIONING IN POLAND

The heat demand Poland for heating houses has changed over the years. The changes in the construction law necessitated introduction of thermal insulation of buildings (table 3).

4.1 Parameters of a Reference House

As an example a one-floor building of the following parameters was assumed:

- surface of building (outer house dimensions), A_z=195 m^2,
- heated useful surface of the house, A_f = 180 m^2,
- cooled useful surface of the house, $A_{f,c}$ = 180 m^2,
- height of the heated rooms, h= 2.7 m,

- cubature of the heated part of the building, except for arcades, balconies, galleries etc. (outer house dimensions) $V_e = 513\ m^3$,
- total surface of all walls in the building separating the heated part from the outer air, ground and adjacent unheated parts (outer house dimensions) $A = 541.2\ m^2$,
- surface of outer walls of the building (outer house dimensions) $A_{w,e} = 151.2\ m^2$.

Table 3. Energy standard of buildings constructed over the years and now.

Description of groups of buildings	Index of season heat demand, kWh/m^2a
poor energy quality buildings (large-panel and traditional built in 1970-1984)	180 < E < 250
average energy quality buildings (large-panel and traditional built after 1984)	140 < E < 180
good poor energy quality detached and semi detached buildings built from1993 onwards	70 < E < 140
low-energy buildings - built presently	15 < E < 70

4.2 Energy Demand for Heating, Cooling, Air Conditioning and Hot Tap Water Purposes

The maximum yearly calculation index of non-renewable primary energy demand for heating, air conditioning and hot tap water purposes depends on the building's shape factor. Depending on the value of this coefficient A/V_e, the demand indices are calculated following the regulation of the Minister of Infrastructure of 6 November 2008 about technical conditions to be met by buildings and their site.

4.2.1 For Heating, Air Conditioning and Hot Tap Water

Depending on the shape factor which for the analyzed building equals to:

$$A/V_e = 541.2/513 = 1.055$$

the following condition is met $A/V_e \geq 1.05$, for which:

$$EP_{H+W} = 149.5 + \Delta EP\ kWh/(m^2 \cdot year)$$

where:

$\Delta EP = \Delta EP_W$ – addition for unit demand for non-renewable primary energy for hot tap water over a year.

This addition is calculated from the formula:

$$\Delta EP_W = 7800/(300 + 0.1 \cdot A_f)\ kWh/(m^2 \cdot year)$$

The following is obtained in the analyzed case:

$$\Delta EP_W = 7800/(300 + 0.1 \cdot 180) = 24.5\ kWh/(m^2 \cdot year)$$

After recalculating for the useful space of the building we obtain annual energy consumption for hot tap water (HTW) equal to 4410 kWh.

For comparison's sake, if the daily HTW demand equals to 45 dm^3/person, water temperature $T_c = 60^oC$, temperature of water before heating $T_z = 10^oC$ and number of persons n = 5, the energy spent on heating HTW may be calculated from the relation:

$$Q = m \cdot c_w \cdot \Delta T$$

After substituting we get:

$$Q = 45 \cdot 5 \cdot 365 \cdot 4187 \cdot (60-10) = 17193\ MJ = 4776\ kWh/a$$

Annual unit energy consumption for heating, air conditioning and HTW can be calculated from the equation:

$$EP_{H+W} = 149.5 + 24.5 = 174\ kWh/(m^2 \cdot year)$$

After multiplying it by the useful space of the building we get the annual energy consumption for heating, air conditioning and HTW as 31320 kWh/a.

4.3 Energy for Air Conditioning

Energy for consumption for heating, air conditioning and HTW is determined from the formula:

$$EP_{HC+W} = EP_{H+W} + (5 + 15 \cdot A_{w,e}/A_f) \cdot (1 - 0.2 \cdot A/V_e) \cdot A_{f,c}/A_f\ kWh/(m^2 \cdot a)$$

After substituting we get:

$$EP_{HC+W} = 174 + (5 + 15 \cdot 151.2/180) \cdot (1 - 0.2 \cdot 1.055) \cdot 1 = 187.9\ kWh/(m^2 \cdot a)$$

Hence the energy demand for cooling:

$$EPC = 13.89\ kWh/(m^2 \cdot a)$$

4.4 Prices of Energy Carriers

Variable tariffs of Enion operator (valid from 01.03.2009) were assumed for the daily tariff (G11) equal to 0.1731 €/kWh. The assumed exchange rate was 1 EUR=4.35 PLN. The assumed oil cost was the average of the last 5 years which was 2.92 PLN/dm^3. The calorific value of oil was 42.9 MJ/kg. The efficiency of oil boiler was assumed to be 95%. Density of oil was assumed to be 0,96kg/dm^3.

5. COMPARISON OF HEATING AND CLIMATIC CONDITIONS IN POLAND AND GREECE

The heating and climatic conditions in Polish and Greek households are listed in table 4.

Table 4. Heating data for Poland and Greece.

Parameter	Poland (Cracow)		Greece (Thessaloniki)	
Yearly average temperature of atmospheric air	8.5°C		16°C	
Heated surface	180 m^2		85 m^2	
Cost of electricity	0.1731 €/kWh		0.09 €/kWh	
Heating + air conditioning	26910 kWh/a	128€/a (oil)	14252 kWh/a	956 €/a (oil)
Hot tap water	4410 kWh/a	21€/a (oil)	2000 kWh/a	1010 €/a (boiler and sun)
Air-conditioning	2500 kWh/a	433 €/a (el.)	4219.2 kWh/a	379.73 €/a(el.)
Total energy and costs of heating and air conditioning	33820 kWh/a	582€/a	20471.2 kWh/a	2345.73 €/a
Total unit quantities and costs of heating and air conditioning	187.9 kWh/a/m^2	3.23€/a/m^2	240 kWh/a/m^2	27.60 €/a/m^2

The prices of electrical energy for Cracow were assumed according to tariffs G11, accounting for all the variable components depending on electrical energy consumption.

The analysis of the table reveals that higher unit energy consumption is observed for Thessaloniki. This is connected with the fact that the loading of the heating/cooling system is bigger in the summer months. The plots of loading are presented in Fig. 3 and Fig. 4 for Thessaloniki and Cracow, respectively. For simplicity's sake, uniform monthly loading for heating and air conditioning was assumed.

6. BOREHOLE HEAT EXCHANGERS

The economic analysis of heat pumps use for heating and air conditioning purposes was based on several assumptions. The total energy was assumed to be delivered from a heat pump cooperating borehole heat exchangers. The number and distribution of borehole heat exchangers were so selected as to maintain the temperature of the energy carrier ≥ 0^{o}C after 10 years of circulation.

Geologic and geothermal data for Cracow were assumed on the basis of performed borehole heat exchangers (Śliwa & Gonet 2010). They are presented in Table 5. For Thessaloniki the data were assumed on the basis of the literature (Hatziyannis 2007; Andritsos et al. 2007; Kolios1, N. et al. 2007; Kolios N. et al., 2005; Karydaki G., et al. 2005).

The design of the borehole heat exchanger is presented in Fig. 5, and the most important information about the analyzed borehole heat exchangers in Table 6. Identical lithological conditions were assumed, therefore the specific heat of rocks and thermal conductivity coefficient values were equal.

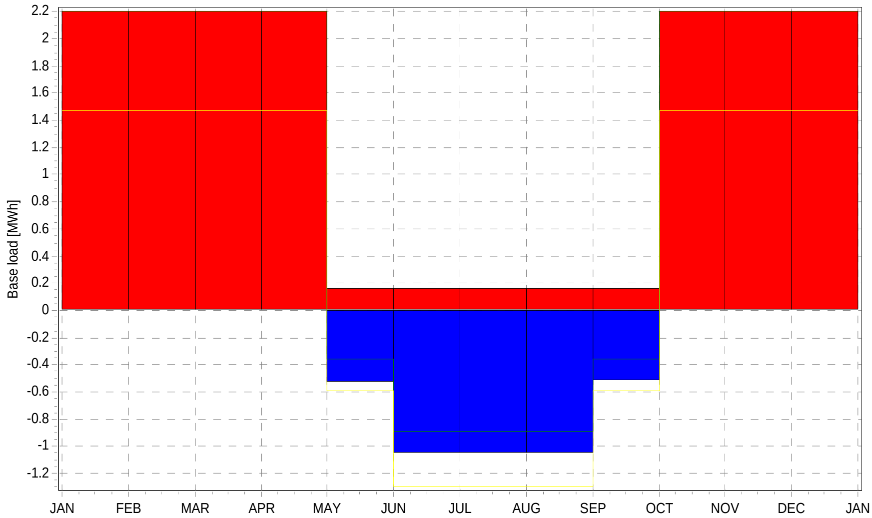

Figure 3: Heating-cooling load for an object in Thessaloniki. Red – heating; blue – air conditioning, yellow line – loading of rock mass.

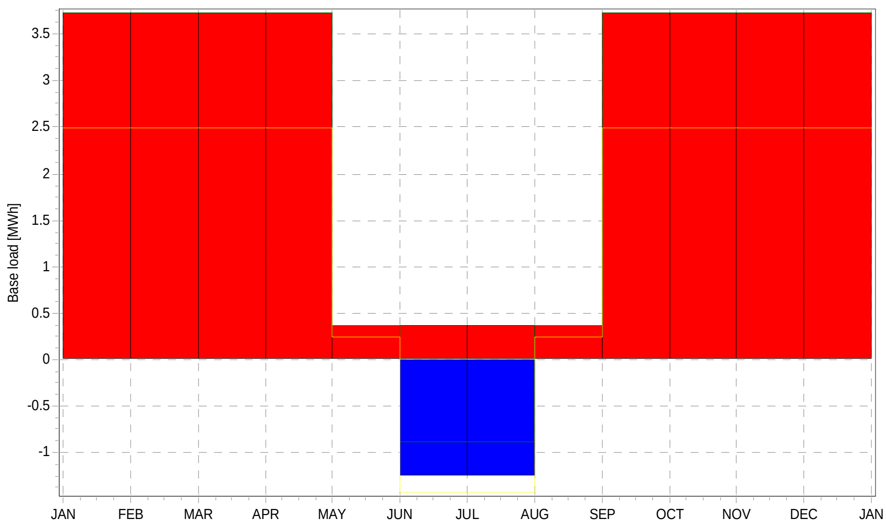

Figure 4: Heating-cooling load for an object in Cracow. Red – heating; blue – air conditioning, yellow line – loading of rock mass.

Table 5. Lithological profile of a borehole heat exchanger in Cracow (Śliwa and Gonet 2010).

Top	Botto m	Thickness of bed, m	Lithology	Coefficient of thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$	Volume specific heat, $MJ{\cdot}m^{-3}{\cdot}K^{-1}$
1.8	2.2	0.4	Clayey ground	1.5	2
2.2	2.6	0.4	Aggregate mud	1.5	2.2
2.6	4.0	1.4	Fine and dusty sand	2	2
4.0	6.0	2	Fine sand	2.2	2.5
6.0	15.0	9	All-in aggregate and gravel	1.8	2.4
15. 0	30.0	15	Grey siltstone	2	2.3
30. 0	78.0	48	Grey shale clay	2.1	2.3
Weighted average				2.039	2.309

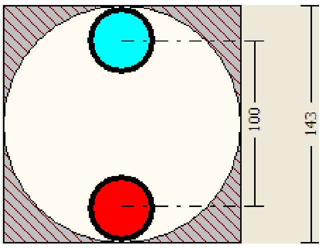

Figure 5: U-pipe in a borehole.

Table 6. Data of the analyzed borehole heat exchangers.

Calculation data	Poland (Cracow)	Greece (Thessaloniki)
Thermal conductivity of rocks, $Wm^{-1}K^{-1}$	2.039	
Bulk heat capacity, $Jm^{-3}K^{-1}$	2.309	
Heat steam, Wm^{-2}	0.060	0.090
Type of BHE	single u-pipe	
Distance between BHE, m	10	
Diameter of borehole, m	0.143	
Diameter of BHE pipe, m	0.04	
Thickness of BHE pipe wall, m	0.0024	
Coefficient of thermal conductivity of BHE pipe material, $Wm^{-1}K^{-1}$	0.42	
Heat carrier	33% propylenglycole	

The spatial system of borehole heat exchanger is presented in a horizontal projection (Fig. 6).

The calculations were made with the use of a computer program Earth Energy Designer (EED). The depth of borehole heat exchangers was analyzed for their continuous 10-year operation. Figs. 7 and 8 represent temperature distribution in the 10th year of exploitation of borehole heat exchangers in Thessaloniki and Cracow.

For comparison's sake, similar calculations were made for a situation when the heat pump and borehole heat exchangers were used only in the heating mode. The variability of temperature of the heat carrier in the 10th year of exploitation in Thessaloniki and Cracow is presented in Figs. 10 and 11, respectively. A course of temperature changes over the 10-year exploitation of borehole heat exchangers used only for recovering the heat of the rock mass for Thessaloniki and Cracow is plotted in Figs. 12 and 13, respectively.

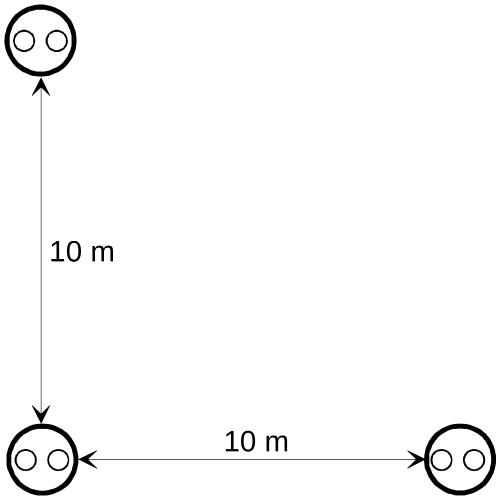

Figure 6: Distribution of BHE.

The results of calculations are listed in Table 7. The depth and exploitation parameters of borehole heat exchangers are given provided the average temperature of heat carrier does not drop down below 0°C over the 10-year exploitation.

7. CONCLUSIONS

1. Heating with the use of heat pumps and borehole heat exchangers for heating purposes in Greece requires employing less total depth. This results from the assumptions regarding maximum cooling of heat carrier. In Cracow the heat carrier reaches zero faster as the initial temperature is lower owing to the average temperature of atmospheric air. Moreover, a thermal anomaly is observed in the Thessaloniki area, therefore a higher stream of Earth heat was assumed.

2. The aggregate depth of borehole heat exchangers is higher when one-direction heat flow is involved.

3. Higher heat flows in a borehole heat exchanger can be achieved in the south Europe conditions. This is related with higher cooling demand for air conditioning purposes.

4. In the Polish conditions (Cracow) the rock mass after a long exploitation cools down more intensely than in Greece (Thessaloniki). Higher stability of average temperature results from the higher quantity of heat pumped in during air conditioning. In the Greek conditions the average temperatures of heat carrier vary more significantly over the year.

5. Heat pumps cooperating with borehole heat exchangers should be commonly applied in countries of moderate climate. Their applicability to heating and air conditioning results in reduction of primary fuel consumption.

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Table 7. Depth and exploitation coefficients of borehole heat exchangers, provided that the average temperature does not drop down below 0°C after 10-year exploitation

City	10-year operation in heating-cooling mode		10-year operation in heating mode	
	Depth of BHE, m	Aggregate length of BHE, m	Depth of BHE, m	Aggregate length of BHE, m
Thessaloniki	20.77	62.30	22.27	66.82
Cracow	72.58	217.75	75.15	225.44
City	Index of unit load for total bi-direction useful heat flow, kWh/m	Range of variability of average temperature of heat carrier over a year, °C	Index of unit load for total bi-direction useful heat flow, kWh/m	Range of variability of average temperature of heat carrier over a year, °C
Thessaloniki	20471.2/62.3=328.6	28.26	16252/66.82=243.2	13.18
Cracow	33820/217.75=155	11.43	31320/225.44=138.9	6.48

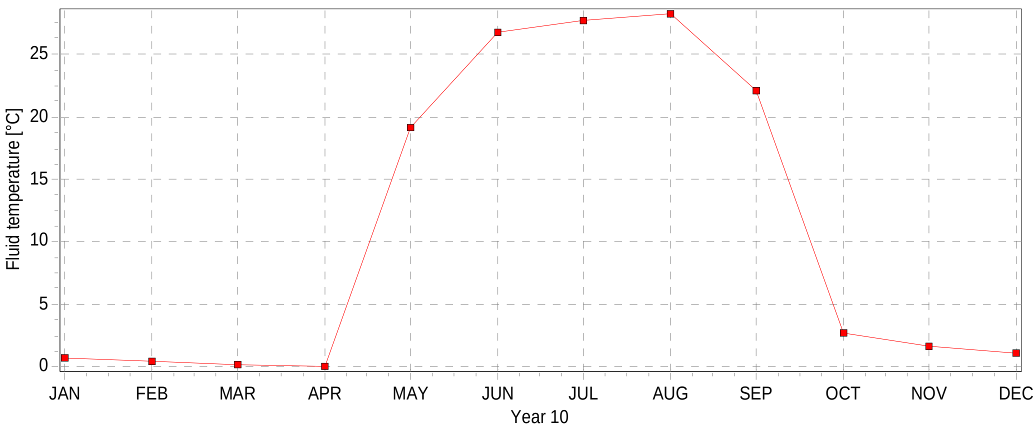

Figure 7: Distribution of average temperature of heat carrier in the 10th year of BHE operation with loading as in Figure 3.

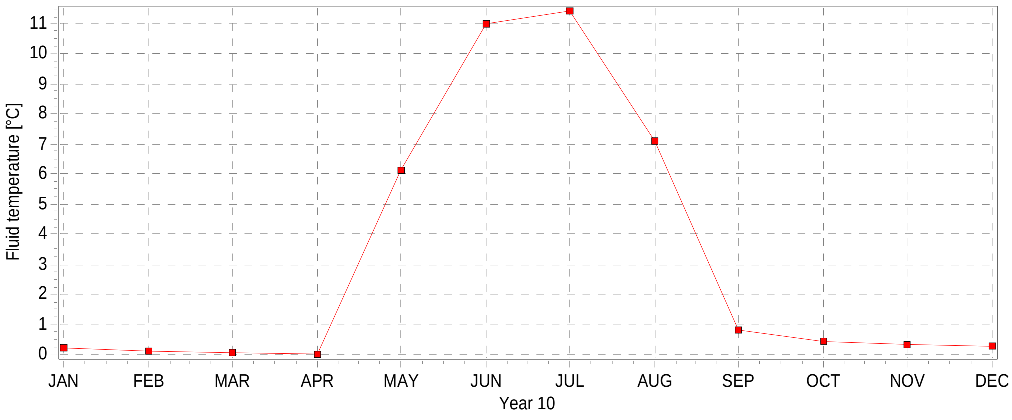

Figure 8: Distribution of average temperature of heat carrier in the 10th year of BHE operation with loading as in Figure 4.

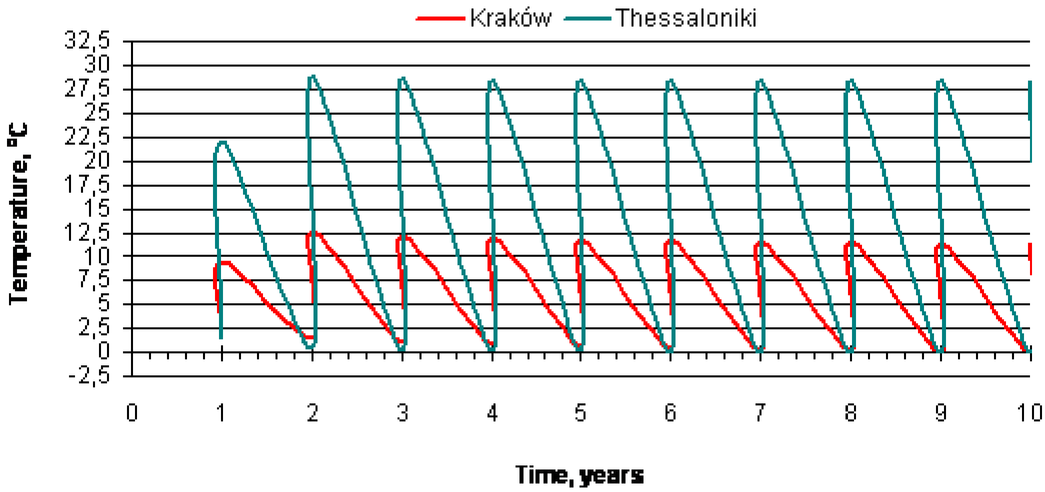

Figure 9: Distribution of average temperature of heat carrier in the 10th year of BHE operation with loading as in Figs. 3 and 4.

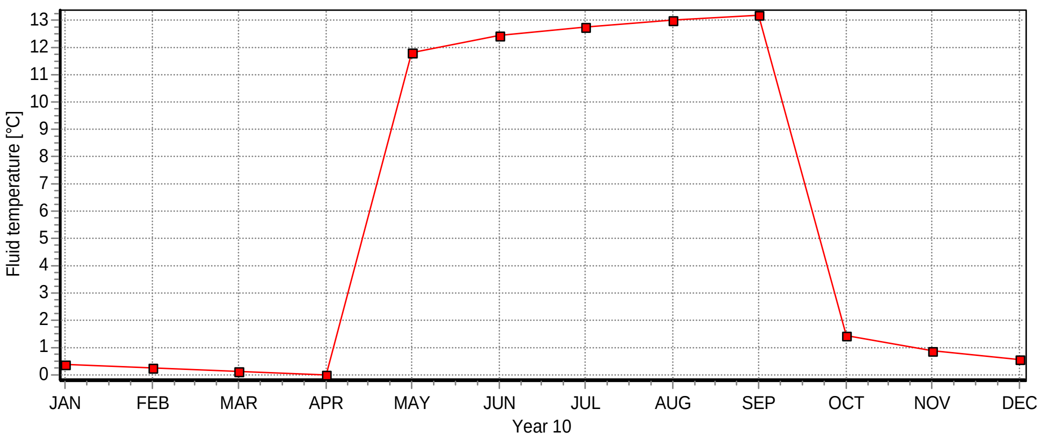

Figure 10: Distribution of average temperature of heat carrier in the 10th year of BHE operation only in the heating mode (for Thessaloniki).

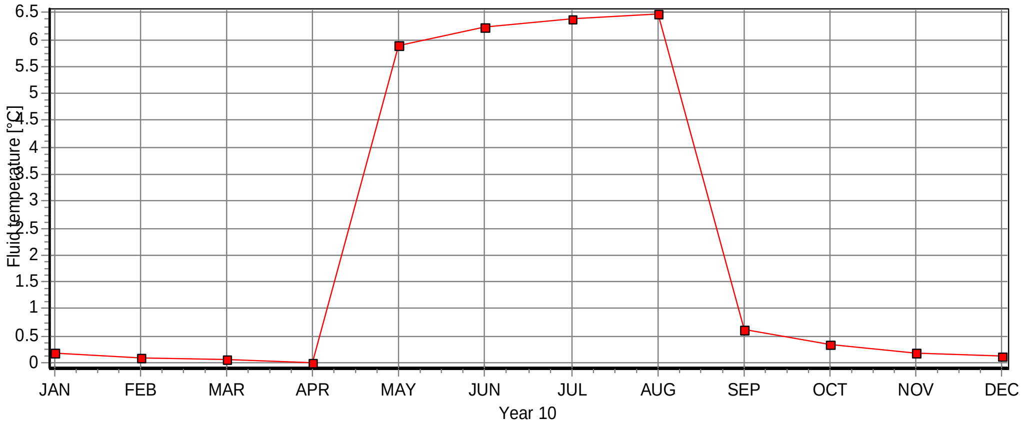

Fig. 11: Distribution of average temperature of heat carrier in the 10th year of BHE operation only in the heating mode (for Cracow).

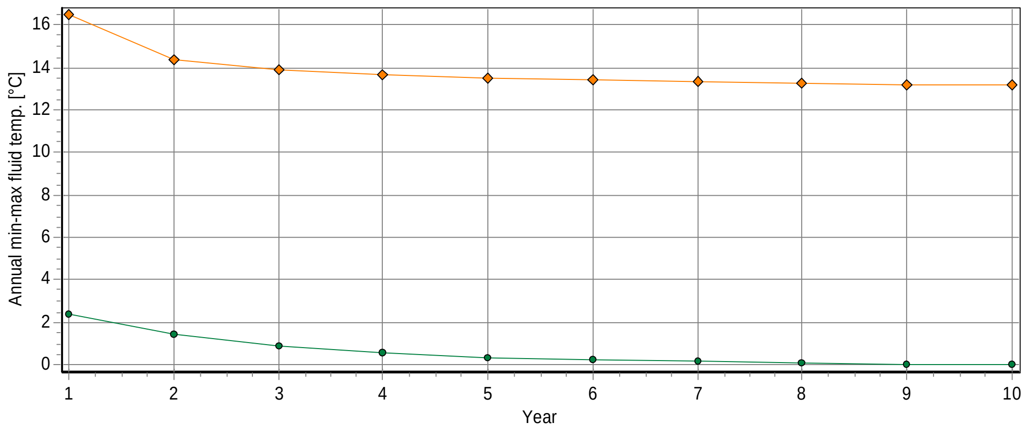

Fig. 12: Distribution of maximum (red line) and minimum (dashed green line) temperature of heat carrier over 10-year BHE operation with heating load for Thessaloniki.

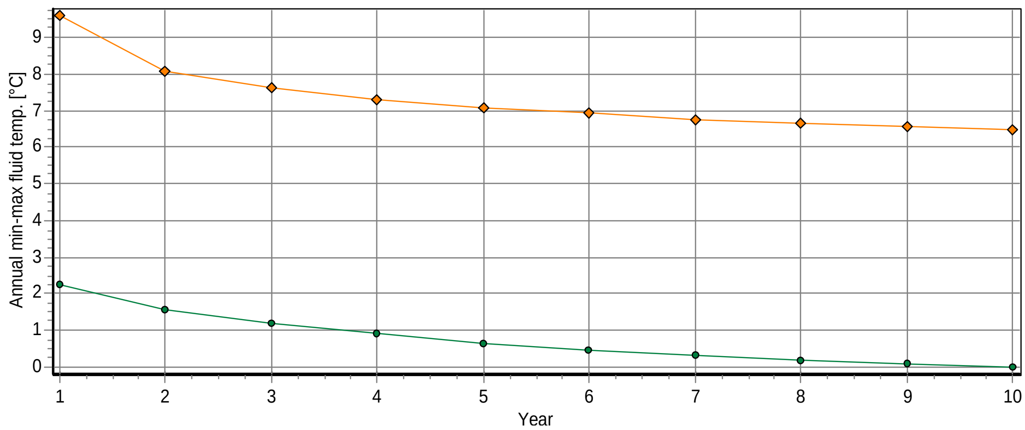

Fig. 13: Distribution of maximum (red line) and minimum (dashed green line) temperature of heat carrier over 10-year BHE operation with heating load for Cracow.