Sustainability **2015**, *7*, 13104-13125; doi:10.3390/su71013104

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Natural and Artificial Methods for Regeneration of Heat Resources for Borehole Heat Exchangers to Enhance the Sustainability of Underground Thermal Storages: A Review

Tomasz Sliwa [1,*] and Marc A. Rosen [2]

[1] Drilling and Geoengineering Department, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Cracow, Poland

[2] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, ON L1H 7K4, Canada; E-Mail: marc.rosen@uoit.ca

* Author to whom correspondence should be addressed; E-Mail: sliwa@agh.edu.pl; Tel.: +48-12-617-3784; Fax: +48-12-617-2206.

Academic Editor: Andrew Kusiak

Received: 22 June 2015 / Accepted: 18 September 2015 / Published: 25 September 2015

Abstract: The concept of borehole heat exchanger (BHE) field exploitation is described, along with problems regarding the sustainability of heat resources in rock masses. A BHE field sometimes has problems with the stability of the heat carrier temperature during long-term exploitation. The main reason for this is an insufficient heat stream with which to transfer heat by conduction in rock. Possibilities for the regeneration of heat in rock masses, based on experiences at the Geoenergetics Laboratory (Drilling, Oil and Gas Faculty, AGH University of Science and Technology), are described.

Keywords: borehole heat exchanger; geoenergetics; heat pump; underground thermal energy storage keyword

---

1. Introduction

Borehole thermal energy storages (BTESs) are increasing in interest and implementation, especially with systems for heating and/or cooling. The use of traditional fossil fuels alone to keep buildings at approximately 20 °C is wasteful, as there is a significant mismatch in the qualities of energy supply and demand. That is, fossil fuels are too valuable for use in heating/cooling. They can be used in more sophisticated systems and to meet higher quality energy needs. Heat pump technology is more efficient for heating and cooling, in part because it matches the quality of energy demand and supply better. Geothermal heat can also be extracted from non-geothermal waters, but for such processes it is necessary to locate appropriate geological layers and to solve problems regarding mineralization (Tomaszewska and Pająk 2012) [1].

One technology useful for helping to meet building heating and cooling demands is the borehole heat exchanger (BHE). This technology is often advantageous in most locations, and is independent of geological conditions. Shallow holes (to depths of about 200 m) are used for heat/cool storage and extraction. Deeper BHEs are generally only used for heating (Sapinska-Sliwa *et al.*, 2015) [2], also with use old oil and gas wells (Sliwa and Gonet, 2004) [3]. Typical constructions for BHEs are presented in Figure 1. The most popular construction is the U-tube design (a), while the least common is the coaxial type (c). Shown in Figure 1 are several key parts of the BHEs, including the borehole wall (1) and U-tube wall (4), the grout (2) and interior of the U-tube (3) and the annulus space (5), as well as the external column (8), the inner column (6) and the interior of inner column (7).

Generally the best heat transfer condition is observed for the coaxial system, but this depends on many factors, including good installation execution (workmanship).

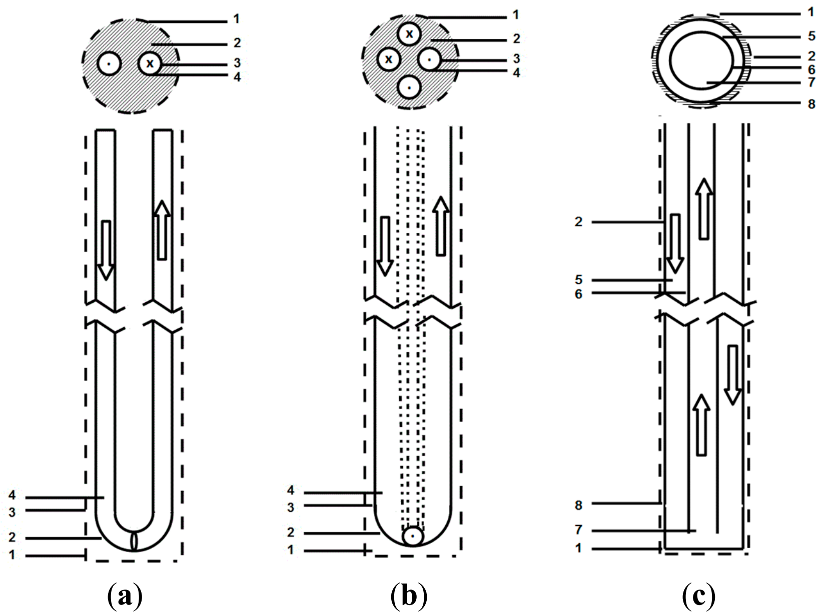


Figure 1. Borehole heat exchanger (BHE) constructions: (**a**) single U-tube; (**b**) double U-tube; (**c**) coaxial (Gonet *et al.* 2011) [4]. Legend: 1—borehole wall, 2—grout, 3—interior of U-tube, 4—U-tube wall, 5—annulus space, 6—inner column (pipe), 7—interior of inner column (pipe), 8—external column.

Borehole heat exchanger fields are in operation for heat extraction and cold extraction (heat injection); some reversing systems exist that provide heat and cool extraction. When the number of BHEs is low (one or few) there usually is no problem with heat carrier temperature during the long period of exploitation (often years or decades). When number of BHE is high there is the possibility for a systematic yearly increase or decrease in heat carrier temperature (Signorelli *et al.*, 2005) [5]. Such a continuous increase (or decrease) in BHE temperature is very much dependent on the main heat load type (heating or cooling), and not only on the number of BHEs. The effect of the number of boreholes is described below with examples of fields.

An example of the operating temperatures of a BHE field in which more heat is extracted than heat is input during the summer is shown in Figure 2. The calculations for that field accounts for 65 BHEs. The annual heat extraction is 534 MWh, and heat input is only 210 MWh. So an annual energy deficit of 324 MWh exists, which accounts for the systematic decrease in the temperature of the heat carrier. In Figure 2 are shown (1) the mean maximum temperatures during cooling mode (heat injection into the rock mass); and (2) the mean minimum temperatures during heating mode (heat extraction from the rock mass). The legend for this figure is the same as for Figures 3 and 4.

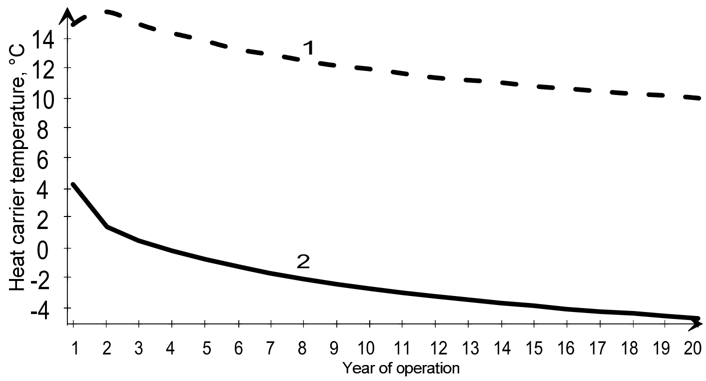


Figure 2. Variability of maximum and minimum heat carrier temperatures for a BHE field with 50 wells during 20 years of operation (Jaszczur and Sliwa, 2013) [6]. Legend: 1—maximum temperature during cooling mode (heat injected into rock mass), 2—minimum temperature during heating mode (heat extracted from rock mass).

The variability of the maximum and minimum temperatures during 25 years of operation for a BHE field with 50 wells is shown in Figure 3. The system serves a poultry hatchery. Only 585 MWh of heat is extracted from rock mass, while 830 MWh is injected. The ground temperatures thus increase every year. The calculations for example BHE fields have been made with EED3.16 software (Blomberg *et al.*, 2008) [7].

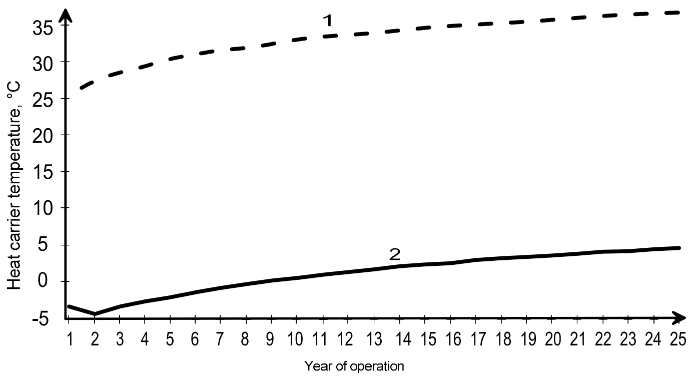


Figure 3. Variation of maximum and minimum temperatures of a heat carrier with load time for 25 years of system operation. Legend: 1—maximum temperature during cooling mode (heat injected into rock mass); 2—minimum temperature during heating mode (heat extracted from rock mass).

Figure 4 shows the behavior of the temperature of the heat carrier when approximately balancing the amount of heat produced and heat input to the rock mass. The maximum and minimum temperatures of the heat carrier seem to be stable during the long period of exploitation.

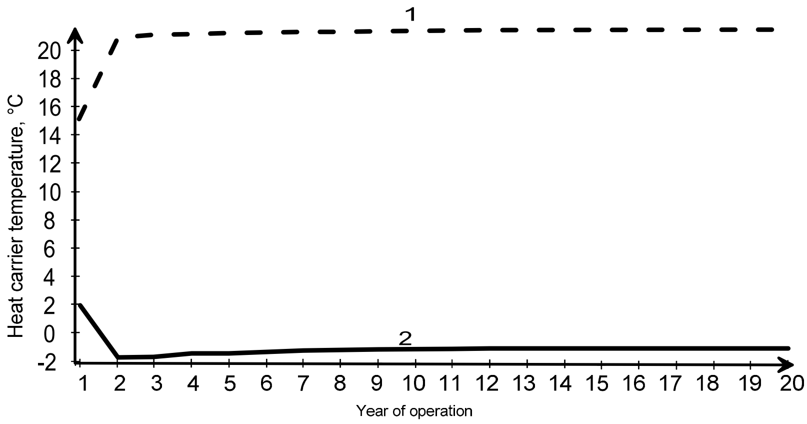


Figure 4. Minimum and maximum temperatures of a heat carrier for the operation of a near-balanced BHE field. Legend: 1—maximum temperature during cooling mode (heat injected into rock mass), 2—minimum temperature during heating mode (heat extracted from rock mass).

Research on BHE fields and heat storage in rock masses are in progress in many universities. The oldest work was carried out in Sweden. Luleå University of Technology, Luleå, Sweden had the first large-scale borehole heat store, constructed in 1982–1983 (Nordell, 1994) [8].

In addition to the work at AGH University of Science and Technology, studies are being conducted at the Technical University of Ostrava (VSB), Czech Republic among others. The BHE arrangement on this university campus is described by Bujok *et al.* (2012) [9]. The system at the University of Ontario Institute of Technology, Oshawa, Canada is described by Koohi-Fayegh and Rosen (2012) [10]. Systems with heat pumps and BHEs exist among others in Karlsruhe Institute of Technology, Polytechnic University of Turin, University of Western Ontario and, with a deep BHE, RWTH Aachen University.

Some of the most important experience and scientific output in the area of geothermal heat pumps has been done with BHEs in Europe (Sweden (Gehlin *et al.*, 2015) [11], Switzerland (Rybach and Eugster, 2010) [12] and Germany (Weber *et al.*, 2015) [13]); in the Americas (Canada (Raymond *et al.*, 2015) [14] and USA (Boyd *et al.*, 2015) [15]); and in Japan in Asia (Sasada, 2012) [16].

The largest installation of BHEs currently under construction is for Ball State University, Indiana, U.S., where 4100 vertical loops are being installed (Boyd *et al.*, 2015) [15]. That installation has BHE depths ranging from 122 to 152 m (Lund *et al.*, 2010) [17]. A general overview of that borehole thermal energy storage (BTES), along with discussions of the general procedures for design and construction, are to be found in Lee (2012) [18].

The main aim of the present article is to review and critically discuss the various geological and meteorological factors affecting the design, number, depth and distribution of BHEs. A BHE field project needs to take into consideration various technical options for heat exchange. Appropriate analysis and design can reduce the number of BHEs, and enable the construction of adequate BHE fields even when the field surface area is insufficient.

2. Approach and Methodology

The present research utilizes experimental data on borehole heat exchangers, so as to provide realistic results and interpretations.

2.1. Geoenergetics Laboratory

At the end of the 1990s the idea of converting existing, old boreholes to borehole heat exchangers (BHEs) was proposed at the Faculty of Drilling, Oil and Gas, AGH University of Science and Technology, Poland. After the research of Sliwa (2002) [19], work began on building a BHE research facility in the area of the university.

The Laboratory of Geoenergetics was inaugurated in 2007, when the first commercial Thermal Response Test (TRT) was performed in Poland (Gonet and Sliwa, 2008) [20]. The first equipment of the laboratory was a TRT set. The drilling of borehole heat exchangers began at AGH-UST in 2008. The Laboratory is based on five borehole heat exchangers of various designs. Additionally the types of grout and additive (Stryczek *et al.*, 2013) [21] influence the properties of cement. Research on the dependence of energy efficiency with construction and technology is important, and was therefore the first research task. The construction of the BHEs is described in Table 1. A schematic of the Laboratory of Geoenergetics installation is shown in Figure 5. The devices shown in that figure are designated as follows: 1—coaxial borehole heat exchanger, 2—single U-tube borehole heat exchanger filled with ordinary cement stone, 3—single U-tube borehole heat exchanger filled with cement stone of high thermal conductivity, 4—single U-tube borehole heat exchanger filled with gravel and sealed by clay in the interval of high permeability (*i.e.*, the interval 3–15 m deep), 5—double U-tube borehole heat exchanger, 6 - buffer tank for the heat transfer medium on the cold side (cold reservoir), 7—buffer tank for the heat transfer medium on the warm side (heat accumulator), 8—heat pump, 9—fan coil for heating or cooling the Laboratory room, 10—water heater/cooler (to dissipate excess electrical power), 11—water supply network to fill the system, 12—diaphragm expansion vessels, 13—plate heat exchanger for shifting heat between cold and heat storage tanks, 14—set of valves to change the direction of fluid flow in a coaxial borehole heat exchanger, 15—ventilation unit of the auditorium of the Faculty of Drilling, Oil and Gas at the Academy of Science and Technology which complements the heating or air conditioning equipment, 16—additional heat exchanger for heat exchange between BHEs and solar collectors directly (with no tanks), for direct heat regeneration of the rock mass, 17—additional heat exchanger—supporting heat exchanger in tanks—additional heat exchange surface to increase the efficiency, 18—stationary flat-plate solar collector, 19—stationary vacuum solar collector, 20—stationary collector “heat pipe”, 21—solartrack (mobile) flat collector, 22—solartrack (mobile) vacuum solar collector, 23—heating pipes installed in the parking lot for snow melting, 24—intake for extracting air from auditorium, 25—fresh air supply to auditorium, 26—discharge of exhaust air to the atmosphere, 27—intake for fresh atmospheric air, 28—recuperator, *i.e.*, a rotary heat exchanger (heat recovery ventilator), 29—peak heat source—heat from district heating.

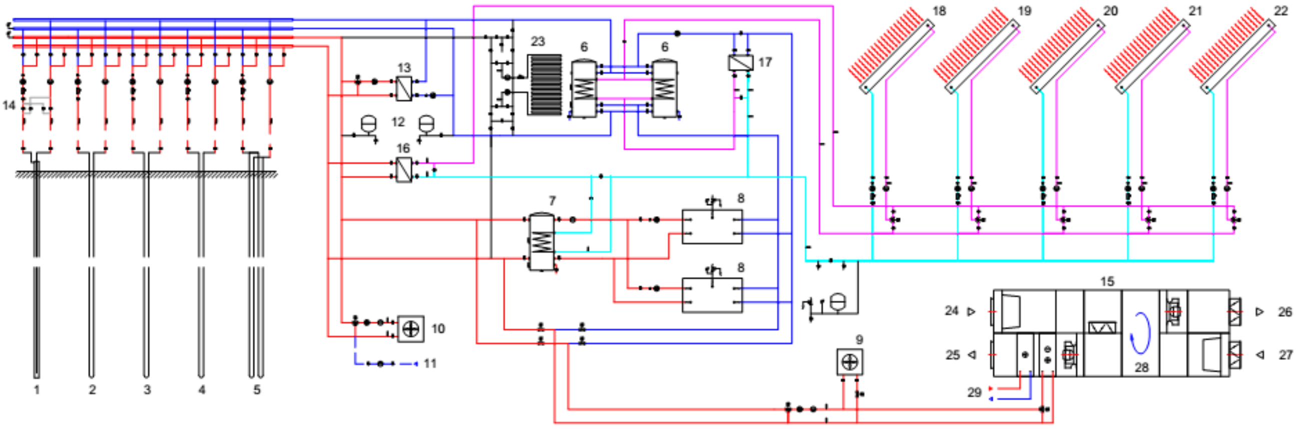


Figure 5. Schematic of Laboratory of Geoenergetics installation (Sliwa *et al.* 2015) [22]. Legend: 1—coaxial borehole heat exchanger, 2—single U-tube borehole heat exchanger filled with ordinary cement stone, 3—single U-tube borehole heat exchanger filled with cement stone of high thermal conductivity, 4—single U-tube borehole heat exchanger filled with gravel and sealed by clay in the interval of high permeability (*i.e.*, the interval 3–15 m deep), 5—double U-tube borehole heat exchanger, 6—buffer tank for the heat transfer medium on the cold side (cold reservoir), 7—buffer tank for the heat transfer medium on the warm side (heat accumulator), 8—heat pump, 9—fan coil for heating or cooling the Laboratory room, 10—water heater/cooler (to dissipate excess electrical power), 11—water supply network to fill the system, 12—diaphragm expansion vessels, 13—plate heat exchanger for shifting heat between cold and heat storage tanks, 14—set of valves to change the direction of fluid flow in a coaxial borehole heat exchanger, 15—ventilation unit of the auditorium of the Faculty of Drilling, Oil and Gas at the Academy of Science and Technology which complements the heating or air conditioning equipment, 16—additional heat exchanger for heat exchange between BHEs and solar collectors directly (with no tanks), for direct heat regeneration of the rock mass, 17—additional heat exchanger—supporting heat exchanger in tanks—additional heat exchange surface to increase the efficiency, 18—stationary flat-plate solar collector, 19—stationary vacuum solar collector, 20—stationary collector “heat pipe”, 21—solartrack (mobile) flat collector, 22—solartrack (mobile) vacuum solar collector, 23—heating pipes installed in the parking lot for snow melting, 24—intake for extracting air from auditorium, 25—fresh air supply to auditorium, 26—discharge of exhaust air to the atmosphere, 27—intake for fresh atmospheric air, 28—recuperator, *i.e.*, a rotary heat exchanger (heat recovery ventilator), 29—peak heat source—heat from district heating.

Table 1. Detailed parameters of BHEs of Laboratory of Geoenergetics (Gonet *et al.*, 2011) [4].

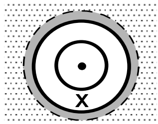
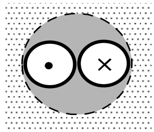
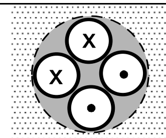
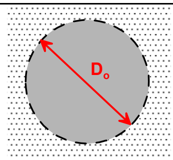
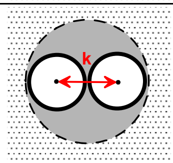
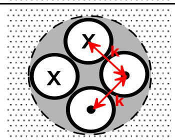
No.	Parameter	Pictorial Configuration	Value				
			LG 1 (BHE 1)	LG 2 (BHE 2)	LG 3 (BHE 3)	LG 4 (BHE 4)	LG 5 (BHE 5)
1	Depth of borehole	-	78 m	82 m	78 m	78 m	78 m
2	Depth at which exchanger's tubes are seated				78 m		
3	Design of borehole heat exchanger	-	 coaxial		 single U-tube		 double U-tube
4	Borehole diameter D_o (drill tool diameter)				143 mm		
5	Distance between tubes in heat exchanger, k		n/a		80 mm		n/a
5`	Distance between tubes in heat exchanger, k		n/a		n/a		70 mm

Table 1. *Cont.*

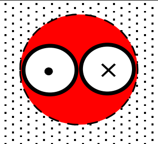
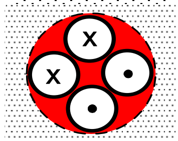
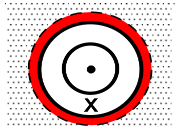
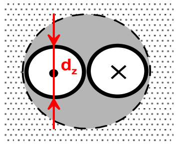
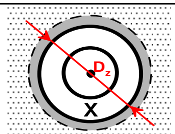
No.	Parameter	Pictorial Configuration	Value				
			LG 1 (BHE 1)	LG 2 (BHE 2)	LG 3 (BHE 3)	LG 4 (BHE 4)	LG 5 (BHE 5)
6	Material used for sealing heat exchanger (grout)	  	cement, $\lambda = 1.2$ $Wm^{-1}\cdot K^{-1}$	cement, $\lambda = 1.2$ $Wm^{-1}\cdot K^{-1}$	Thermocem, increased thermal conductivity cement, $\lambda = 2.0$ $Wm^{-1}\cdot K^{-1}$	Gravel 8–16 mm of grain and clayey plugs, $\lambda = 1.8$ $Wm^{-1}\cdot K^{-1}$	cement, $\lambda = 1.2$ $Wm^{-1}\cdot K^{-1}$
7	Outer diameter of tubes in heat exchanger		n/a		40 mm		32 mm
7`	Outer diameter of outer tubes in heat exchanger		90 mm			n/a	

Table 1. *Cont.*

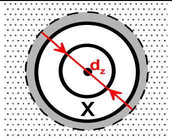
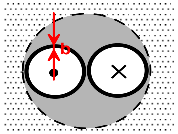
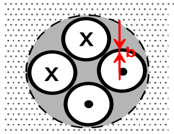
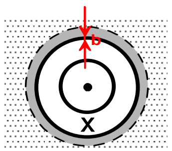
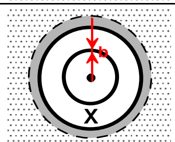
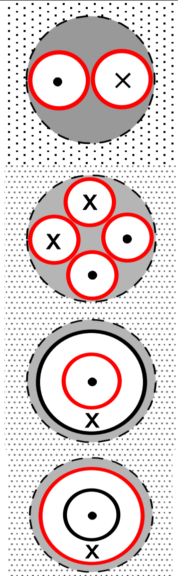
No.	Parameter	Pictorial Configuration	Value				
			LG 1 (BHE 1)	LG 2 (BHE 2)	LG 3 (BHE 3)	LG 4 (BHE 4)	LG 5 (BHE 5)
7``	Outer diameter of inner tubes in heat exchanger		40 mm		n/a		
8	Thickness of tube wall in heat exchanger	 	n/a		2.4 mm		2.4 mm
8`	Thickness of outer tube wall in heat exchanger		5.4 mm		n/a		
8``	Thickness of inner tube wall in heat exchanger		2.4 mm		n/a		

Table 1. *Cont.*

No.	**Parameter**	**Pictorial Configuration**	**Value**				
			LG 1 (BHE 1)	**LG 2 (BHE 2)**	**LG 3 (BHE 3)**	**LG 4 (BHE 4)**	**LG 5 (BHE 5)**
9	Material of tubes in heat exchanger		Polyethylene, $\lambda = 0.42\ \mathrm{Wm^{-1}{\cdot}K^{-1}}$				

2.2. Ground Characteristics at Test Site

The lithological-stratigraphic profile under the Lab is presented in Table 2. The thermal conductivity of rocks and the volumetric specific heat are included. At a depth of 3–4 m, a highly permeable layer begins. Its bottom is at a depth of 15 m. In this layer, underground water flows (Figure 6).

Table 2. Lithological and stratigraphic profile of BHE 2 (AGH LG-2 well) with thermal parameters of rocks (Gonet *et al.*, 2011) [4].

No.	Top, m	Bottom, m	Thickness, m	Lithology	Stratigraphy	Thermal Conductivity, λ, $W·m^{-1}·K^{-1}$	Volumetric Specific Heat, c_v, $MJ·m^{-3}·K^{-1}$
1	0.0	2.2	2.2	Anthropogenic ground (dark grey fill with debris)	Quaternary (Pleistocene, Holocene)	1.600	2.000
2	2.2	2.6	0.4	Aggregate mud (grey ground)		1.600	2.200
3	2.6	4.0	1.4	Fine, dusty and slightly clayey sand		1.000	2.000
4	4.0	6.0	2.0	Fine sand		1.200	2.500
5	6.0	15.0	9.0	Sand and slag mix, slag		1.800	2.400
6	15.0	30.0	15.0	Grey clay	Tertiary (Miocene)	2.200	2.300
7	30.0	78.0	48.0	Gray clay slate		2.100	2.300
				Weighted average		**2.039**	**2.309**

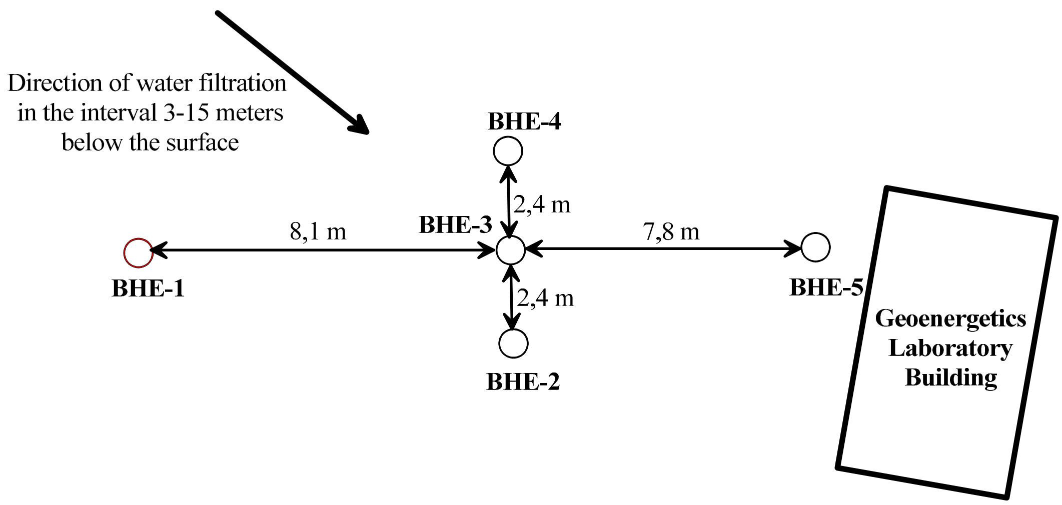


Figure 6. Location of borehole exchangers of Laboratory of Geoenergetics and direction of underground water flow.

2.3. Experimental Capability and Measurable Quantities

The Laboratory of Geoenergetics, after drilling and constructing the BHEs, was built on the surface. The installation is equipped with (Sliwa *et al.*, 2015) [22]:

(1) A heating-cooling system for the Faculty Auditorium, which has a seating capacity of 160
(2) Solar collectors for regeneration of heat in the rock mass, with individual measurement sensors
(3) A system for snow melting of the parking lot in front of the Laboratory
(4) A fan for heating and cooling glycol using atmospheric air

Heat transfers in the Laboratory are listed in Table 3 and shown in Figure 7, where arrows indicate the possible direction of heat flow. The installation has many possibilities for heat regeneration in the rock mass, or heat rejection (when necessary).

Table 3. Natural and artificial heat sources for regeneration of energy resources in BHE field of Geoenergetics Laboratory.

No.	Natural Heat Sources for Regeneration BHE of Field	Artificial Heat Sources for Regeneration BHE of Field
1	Underground water flow	Heating-air-conditioning system of Auditorium
2	Sun operation on surface (also wind and frost)	Solar collectors
3	Heat transfer from the sides of the BHE space	Snow melting installation
4	Heat transfer from the bottom of the BHE space	Fan (heater/cooler)

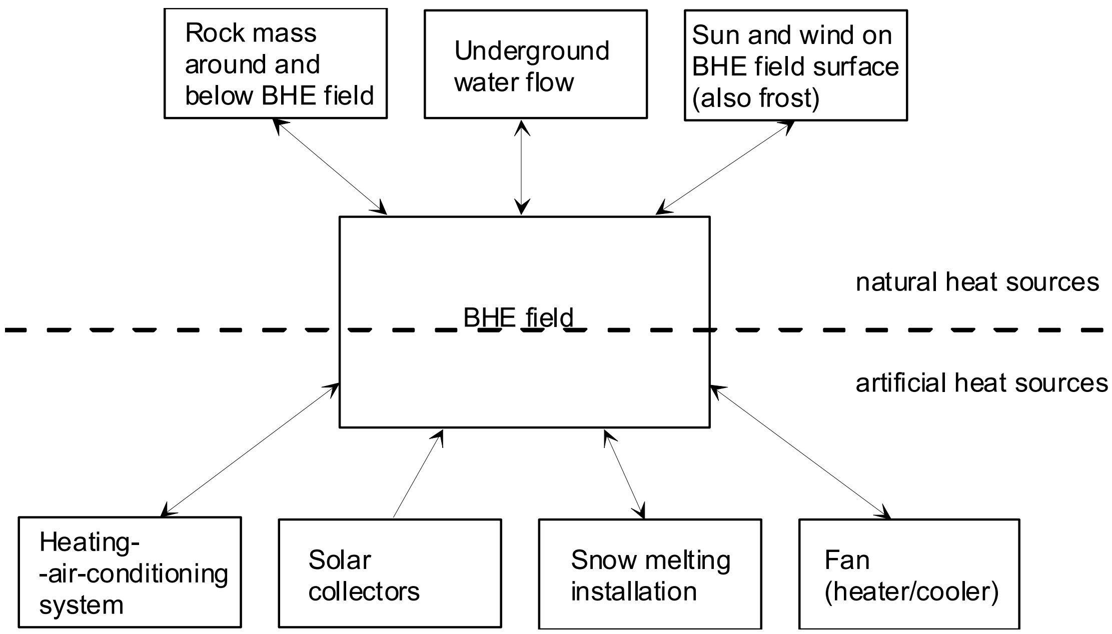


Figure 7. Schematic of directions of heat flows for various devices of the Geoenergetics Laboratory and by natural heat transfer. Note that only the solar collectors have one-way heat transfer.

3. Natural Heat Resources Regeneration

Solar radiation on the ground surface and warm ambient air/wind are two significant sources of heat for BHE fields. These sources are especially important when the depth of wells is not great. Temperatures profiles for the ground down to a 30 m depth are shown in Figure 8 for a borehole not using a BHE. This well was made especially for temperature measurement. In a typical direct evaporation BHE field, the distance of this well from active BHEs (*i.e.*, exploited ones) is about 5 m.

Notable changes in temperature are observed to a depth of about 15 m. No inflow of heat from exploited BHEs is observed in the field.

In deep BHEs, heat regeneration from solar radiation and ambient air is not as significant, and the importance declines as well depth increases. For BHEs in former oil wells (Sliwa *et al.*, 2014) [23] or other deep BHEs (Sapinska-Sliwa *et al.*, 2015) [2], including directional wells (Knez, 2014) [24], it can be assumed for modeling that ground surface temperature is constant at the average annual ambient air temperature. The relation between heat extraction rate and temperature of the heat carrier fluid, under various conditions, is described by Eskilson (1987) [25]. Eskilson's research was used as the basis for the software EED, which is in use around the world by designers.

Hellström (1991) [26] describes formulas for the ground thermal resistance for several types of borehole heat exchangers. The resistance has a big impact on the heat transfer between the heat carrier and the rock mass. The impact of temperature distribution and geothermal gradient is described by Kurevija *et al.* (2011) [27].

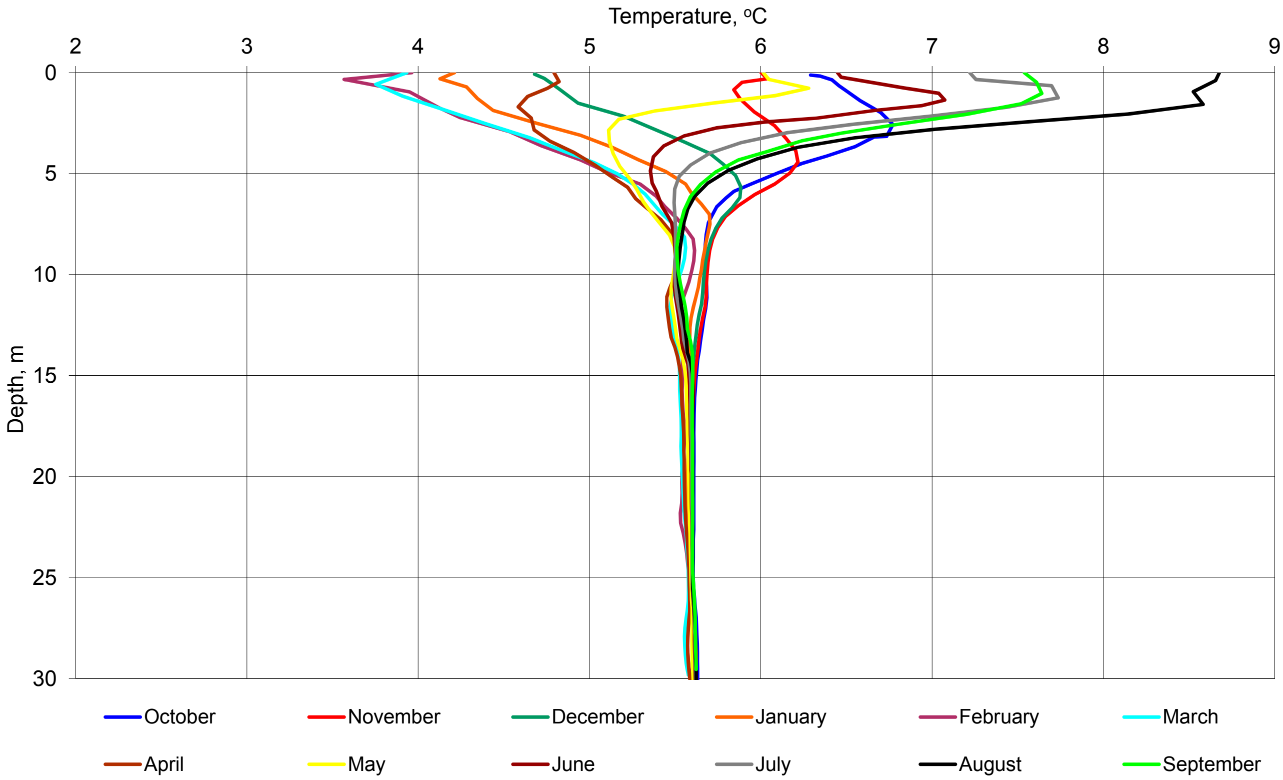


Figure 8. Mean ground temperatures in a well not using an active BHE near Krakow (in the village of Pałecznica, 50 km northeast) broken down by month for the period October 2013 to September 2014.

The second group of heat sources for resource regeneration is geothermic heat from around and under the BHE field. When a geothermal source heat pump (GSHP) system is the only regeneration heat source, heat conduction from rocks alone may not be sufficient, and the temperature of the BHE field may drop every year, as shown in Figure 2. The renewability of heat in such BHEs fields is not complete (Cataldi, 2001, Signorelli *et al.*, 2004) [28,29]. After a few years of temperature drop, the temperature takes on a low value at which point heat from surrounding rocks can conduct adequately to the field. Then the temperature of the BHE field reaches a value at which the extracted heat has the same value as heat conducted from surrounding rocks for regeneration.

The third group of natural heat sources for regeneration is convection. The sensitivity of the loop outlet temperatures and heat exchange rates to hydrogeological, system and meteorological factors was analyzed over 6-month and 25-year operation periods by Dehkordi and Schincariol (2014) [30]. Long-term exploitation of BTES (10 years) is also evaluated by Chiasson *et al.* (2000) [31]. Other researchers have analyzed the effect of waterflow in geological layers on heat transfer efficiency and heat loss (Diao *et al.*, 2004; Fujii *et al.*, 2005; Hecht-Méndez *et al.*, 2013; Molina-Giraldo *et al.*, 2011; Fan *et al.*, 2007) [32–36].

In the case where underground water flow is present, heat transfer can accompany the mass flow. In Figure 9 the results are shown of a numerical simulation of a deep BHE with a permeability layer (Sliwa and Gonet, 2005) [37]. At depths of 300–400 m, the isotherm curves are clearly disturbed.

In Figure 10, the temperature distribution is shown around the five BHEs of the Geoenergetics Laboratory. In the interval 3–15 m deep is a moist layer with water flow (as shown in Figure 6). A cross-section at a depth of 9 m (inside the underground water layer) is shown in Figure 11. The increased heat convection is visible according to the direction of the flow of water.

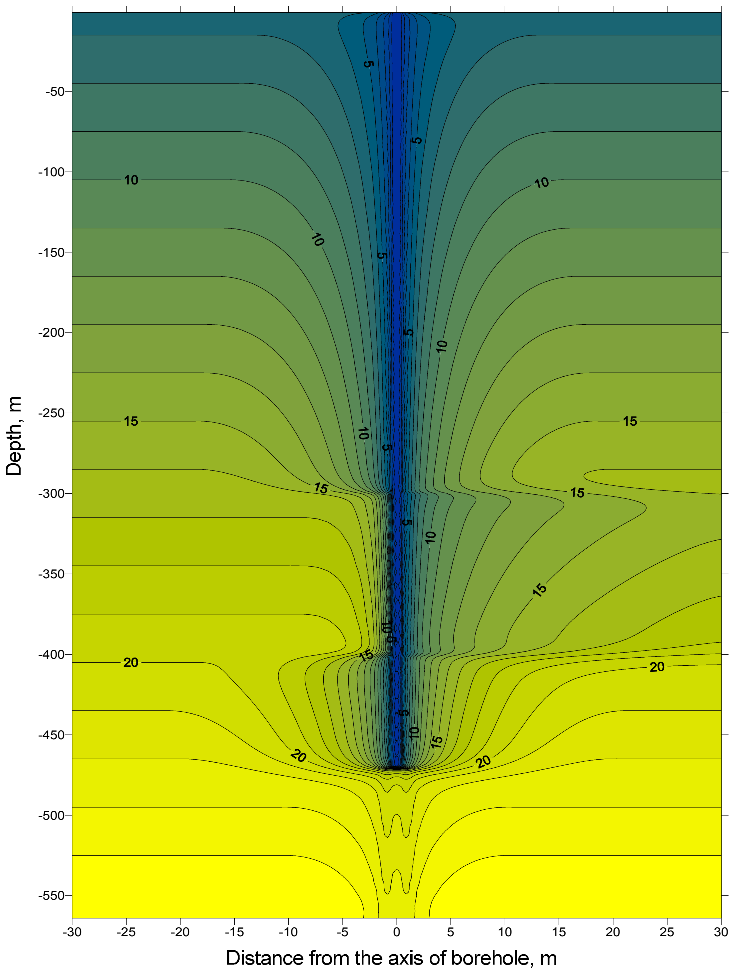


Figure 9. Isotherms (in °C) for a cross-section through a deep BHE (Sliwa, 2002) [19]; example of underground water flow impact to rock mass temperature distribution.

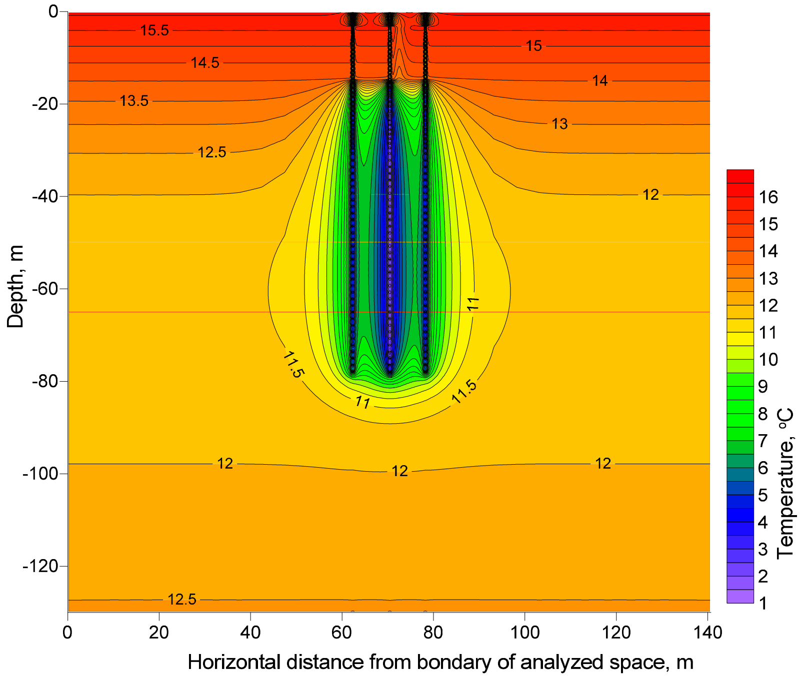


Figure 10. Vertical cross-section through the BHEs of Laboratory of Geoenergetics (wells No. 1, 3 and 5, as shown in Figure 6) showing isotherms (in °C) from numerical simulation (Gonet *et al.*, 2011) [4]; interval between −3 and −15 m with water filtration gives just natural temperature distribution.

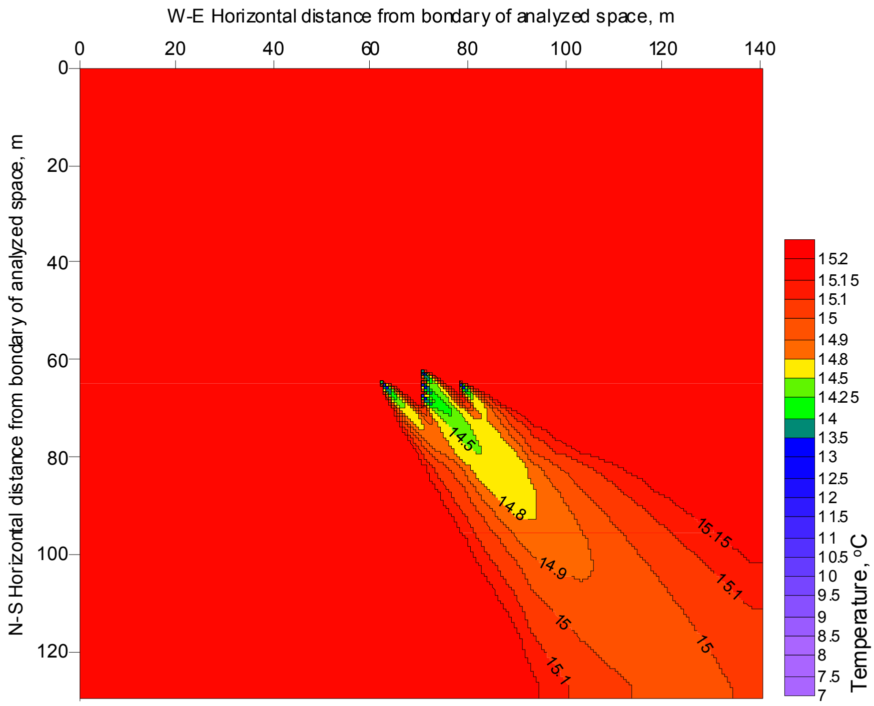


Figure 11. Horizontal cross-section at a level 9 m below the ground surface showing isotherms (in °C) based on simulation for exploited BHEs at the Geoenergetics Laboratory (Gonet *et al.*, 2011) [4].

Natural ways of heat regeneration can result in full or only partial temperature regeneration. When full temperature renewability is not achieved due to supplemental heat resources, it is necessary to use artificial sources of heat.

4. Artificial Heat Resources Regeneration

The only sources of heat existing in the Geoenergetics Laboratory are described here. In real projects, it is necessary to take into consideration all possible options.

4.1. Heating/Air-Conditioning System of the Auditorium

BHE fields typically work by injecting heat into the surrounding rock mass. Hotels, office buildings, commercial facilities, university buildings, and private residences can use BHEs for heating and air-conditioning. The simple payback time for investment costs of such installations can be fewer than 10 years. Air-conditioning processes of the auditorium in AGH University of Science and Technology. Drilling, Oil and Gas Faculty correspond to heat injection into BHEs. The origin of the heat is the sun in addition to electrical energy for the compressor. So, cooling of building interiors with use of heat pumps and BHEs fields is indirectly a process of solar heat storage. If the amount of the total heat from air-conditioning is lower than the total energy extracted from rocks in winter time, what has occurred can be termed a regeneration of heat resources.

Using heat pumps can avoid the need for separate heating and cooling equipment. Also operational costs of heating and cooling are often lower than traditional methods. In countries with temperate climates, the amount of energy from air-conditioning injected into rock masses in summer is usually lower than the heat extracted from ground in winter time.

4.2. Solar Collectors

Five solar collectors have been investigated in terms of heat recovery performance. The best results regarding efficiency is achieved for a collector “heat pipe,” while the lowest efficiency is observed for a stationary flat-plate collector. Much better efficiency is observed when the temperature of the working fluid of the heat pipe, glycol, is low. In typical heating systems, for domestic hot water heating for example, the efficiency of solar collectors is about 60%–70%. In case that involve circulating the heat carrier from BHEs at low temperatures, the efficiency can be higher than 80%. In the Laboratory of Geoenergetics, the heating stream was also observed at night. That observation occurred in summer, when the ambient air temperature was high. About 0.5 kW heating power can be attained with five solar collectors, using low-temperature glycol to transfer heat into rock masses.

4.3. Snow Melting Installation

In the laboratory testing facility, a heating rate of over 33 kW was possible. Over a minimum duration of 32 min, it was possible to attain 58.5 MJ of heat transfer from the parking area, which was 1880 m^2. The system’s working fluid is a glycol solution. The time to raise the temperature of 1.50 m^3 glycol from 0 to 10 °C was observed.

The snow melting installation works like a solar collector in summer. It receives heat from solar radiation and warm air on the surface. The unit heating rate observed is 17.5 W/m^2 when the maximum solar energy (900–1000 W/m^2) is received from the collectors. The unit heat extracted from the parking area is 31.1 kJ/m^2 over a period of 32 min.

Research was also undertaken by partially shading the parking area. It is necessary to prepare long term observations (at least one year) to determine seasonal effects and outputs.

The installation for snow melting can be used in summer not only for heat extraction, but also for cooling the surface of road to protect against ruts (Heliasz and Ostaficzuk, 2002) [38].

4.4. Fan (Heater/Cooler)

In the Geoenergetics Laboratory, research was undertaken involving the heating of 1.0 m^3 of glycol solution. For the snow melting installation, the initial temperature of the heat carrier was 0 °C, and the final temperature was 10 °C. Poniedziałek and Sliwa (2013) [39] demonstrate that it is possible to obtain examples of research. Various air temperatures with time of heating have been measured. For the average air temperature (18.1 °C), the average heating time was 233 min, leading to an average heating power of 4.18 kW.

Using the fan is probably the most inexpensive way for heating, considering investments and operational costs. The fan can heat the working medium when the air temperature is higher than the temperature of the glycol solution, and also in warmer winter days.

Many examples of use of waste heat for regeneration of underground resources can be cited. Some examples are described by Hellström and Gehlin (1997), Andersson *et al.* (2009) and, for waste cold, Andersson *et al.* (2003) [40–42].

4.5. Further Discussion

The paper addresses the medium/long- term sustainability of BHE fields, which is important since an unbalanced load between winter and summer operations can lead to a failure of the ground-coupled heat pump system. This result is consistent with other studies, but the results are more quantified for the Laboratory of Geoenergetics in Poland.

Details relating to the results demonstrated with regard to the Laboratory of Geoenergetics are presented in brief for this paper to allow it to focus on the general concepts raised. Specific details like measurement equipment used, error analysis and numerical models are presented in many of the references already cited, and work is ongoing to prepare a detailed article on these engineering and scientific details.

5. Conclusions

The following conclusions are drawn from the review and analysis, based on the Laboratory of Geoenergetics:

(1) Natural ways of heat regeneration can permit full or partial temperature restoration. For supplemented heat resources, when natural full renewability is not possible but necessary (or advantageous), artificial sources of heat can be used.

(2) In real projects, it is necessary to take into consideration all possible options for obtaining heat. Sometimes it is possible to obtain a low-temperature heat flux from other sources, such as waste heat.
(3) Nowadays designers should analyze all energetic aspects of buildings and other structures as well as the neighborhood of designed projects.
(4) BHE fields can be effectively used for energy storage. This is particularly important for renewable energy sources, which are often characterized by intermittency (like wind energy for example). Energy storage also enables greater use of distributed energy sources.
(5) Natural heat regeneration options for BHEs storages are sun, wind, surrounding rocks and underground water. Artificial options that can be used include solar heat using, for example, air-conditioning installations, solar collectors, fans, snow melting installations working in reverse mode and waste heat from industry.

Natural and artificial heat sources for regeneration of the energy resources in a BHE field, based findings from the Laboratory of Geoenergetics, are summarized in Table 4.

Table 4. Natural and artificial heat sources for regeneration of the energy resources in a BHE field.

No.	Heat Source	Origin	Comments
1	Underground water flow	Natural	Positive in the case of heating and cooling systems with deficit of heat or cool. Negative when storing heat or cool.
2	Solar energy incidence on surface (wind and frost also)	Natural	Heat gain positive when heat deficit/storage. Heat loss positive when cold deficit/storage.
3	Heat transfer from the sides of the BHE space	Natural	Positive when heat deficit. Negative when cold storage.
4	Heat transfer from the bottom of the BHE space	Natural	Positive when heat deficit. Negative when cold storage.
5	Heating-air-conditioning system of Auditorium	Artificial, need extra installation	Should be used in both directions of heat transfer when possible.
6	Solar collectors	Artificial, need extra installation	Can be used only for heat recovery when heat deficit in annual balance or for heat storage.
7	Snow melting installation	Artificial, need extra installation	In reverse mode can be used as a heat source when there is a deficit of heat.
8	Fan (heater/cooler)	Artificial, need extra installation	Can be used in the case of deficit of heat or cool in annual balance. Can be used for heat or cool storage.

Acknowledgments

The paper was founded in Statutory Research carried out at the Drilling, Oil and Gas Faculty, AGH University of Science and Technology, funded by the Polish Ministry of Science and Higher Education (No. 11.11.190.555). The authors thank Zbigniew Jezuit and Anna Bieda from AGH-UST and Agnieszka Pycia and Tomasz Nowosiad from the Student Scientific Association GEOWIERT AGH-UST DOGF for help in preparing of some pictures.

Author Contributions

Tomasz Sliwa and Marc A. Rosen equally contributed to the paper. Tomasz Sliwa designed the sites of in situ measurements and did the modeling, and performed the experiments and analyzed the data. Marc A. Rosen formulated and depicted the innovative proposals within the paper. He also collected the research resources and systematized the content, analyzed the accuracy and reliability of the method, and participated in the editing of the paper. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Tomaszewska, B.; Pająk, L. Geothermal water resources management-economic aspects of their treatment. *Miner. Resour. Manag. (Gospodarka Surowcami Mineralnymi*) **2012**, *28*, 59–70. Available online: https://www.min-pan.krakow.pl/Wydawnictwa/GSM284/tomaszewska-pajak.pdf (accessed on 24 August 2015).
2. Sapinska-Sliwa, A.; Rosen, M.A.; Gonet, A.; Sliwa, T. Deep Borehole Heat Exchangers: A Conceptual Review. In Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015; pp. 1–11. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/28045.pdf? (accessed on 24 August 2015).
3. Sliwa, T.; Gonet, A. The closing wells as heat source. *Acta Montan. Slovaca* **2004**, *9*, 300–302. Available online: http://actamont.tuke.sk/pdf/2004/n3/37sliwa.pdf (accessed on 24 August 2015).
4. Gonet, A.; Sliwa, 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 Borehole Heat Exchangers)*; AGH University of Science and Technology Press: Krakow, Poland, 2011; p. 439. (In Polish)
5. Signorelli, S.; Kohl, T.; Rybach, L. Sustainability of Production from Borehole Heat Exchanger Fields. In Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 26–28 January 2005; pp. 1–6. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/1450.pdf? (accessed on 8 September 2015).
6. Jaszczur, M.; Śliwa, T. The analysis of long-term borehole heat exchanger system exploitation. *CAMES* **2013**, *20*, 227–235. Available online: http://cames.ippt.gov.pl/pdf/CAMES_20_3_6.pdf (accessed on 24 August 2015).
7. Blomberg, T.; Claesson, J.; Eskilson, P.; Hellström, G.; Sanner, B. Earth Energy Designer (EED 3.16), Software within Building Physics and Ground Heat Storage. Available online: http://www.buildingphysics.com/manuals/EED3.pdf (accessed on 24 August 2015).

8. Nordell, B. Borehole Heat Store Design Optimization. Ph.D. Thesis, Division of Water Resources Engineering, Luleå University of Technology, Luleå, Sweden, 1994; p. 217. Available online: http://www.ltu.se/cms_fs/1.5013!/file/FINAL_NORDELL_PHD_red.pdf (accessed on 24 August 2015).
9. Bujok, P.; Klempa, M.; Koziorek, J.; Rado, R.; Porzer, M. Ocena Wpływu Warunków Klimatycznych na Bilans Energetyczny Górotworu na Obszarze Poligonu Badawczego VSB—TU Ostrava. Available online: http://journals.bg.agh.edu.pl/DRILLING/2012-01/W_2012_1_07.pdf (accessed on 22 September 2015). (In Polish)
10. Koohi-Fayegh, S.; Rosen, M.A. Examination of thermal interaction of multiple vertical ground heat exchangers. *Appl. Energy* **2012**, *97*, 962–969.
11. Gehlin, S.; Andersson, O.; Bjelm, L.; Alm, P.G.; Rosberg, J.E. Country Update for Sweden. In Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015. Available online: https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01021.pdf (accessed on 8 September 2015).
12. Rybach, L.; Eugster, W.J. Sustainability aspects of geothermal heat pump operation, with experience from Switzerland. *Geothermics* **2010**, *39*, 365–369.
13. Weber, J.; Ganz, B.; Schellschmidt, R.; Sanner, B.; Schulz, R. Geothermal Energy Use in Germany. In Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015 Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/01045.pdf? (accessed on 24 August 2015).
14. Raymond, J.; Malo, M.; Tanguay, D.; Grasby, S.; Bakhteyar, F. Direct Utilization of Geothermal Energy from Coast to Coast: A Review of Current Applications and Research in Canada. In Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/28041.pdf? (accessed on 24 August 2015).
15. Boyd, T.L.; Sifford, A.; Lund, J.W. The United States of America Country Update 2015. In Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015; pp. 1–12. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/01009.pdf? (accessed on 24 August 2015).
16. Sasada, M. Geothermal Heat Pumps in Japan. Japan International Geothermal Symposium, Geothermal Research Society of Japan, Japan, 2012. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/Japan/2012/p17-Masakatsu_Sasada(Eng-Jpn).pdf? (accessed on 8 September 2015).
17. Lund, J.W.; Gawell, K.; Boyd, T.L.; Jennejohn, D. The United States of America Country Update 2010. In Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010; pp. 1–18. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0102.pdf? (accessed on 24 August 2015).
18. Lee, K.S. *Underground Thermal Energy Storage*; Springer Science & Business Media: Heidelberg, Germany, 2012; p. 152.

19. Sliwa, T. Techniczno-ekonomiczne problemy adaptacji wykorzystanych odwiertów na otworowe wymienniki ciepła (Technical and Economic Problems of Adaptation of Used Wells into Borehole Heat Exchangers). Ph.D. Thesis, AGH University of Science and Technology in Krakow, Krakow, Poland, 2002; p. 128.
20. Gonet, A.; Sliwa, T. Thermal Response Test on the Example of Borehole Heat Exchangers in Ecological Park Of Education and Amusement "OSSA". *Transport. Logist.* **2008**, *6*, 42–47.
21. Stryczek, S.; Wiśniowski, R.; Gonet, A.; Złotkowski, A.; Ziaja, J. Influence of polycarboxylate superplasticizers on rheological properties of cement slurries used in drilling technologies. *Arch. Min. Sci.* **2013**, *58*, 719–728. Available online: http://mining.archives.pl/index.php/index.php?option=com_remository&Itemid=0&func=fileinfo&id=645&lang=pl (accessed on 24 August 2015).
22. Sliwa, T.; Knez, D.; Gonet, A.; Sapinska-Sliwa, A.; Szłapa, B. Research and Teaching Capacities of the Geoenergetics Laboratory at Drilling, Oil and Gas Faculty AGH University of Science and Technology in Kraków (Poland). In Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015; pp. 1–14. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/09012.pdf? (accessed on 24 August 2015).
23. Sliwa, T.; Rosen, M.A.; Jezuit, Z. Use of oil boreholes in the Carpathians in geoenergetics systems historical and conceptual review. *Res. J. Environ. Sci.* **2014**, *8*, 231–242. Available online: http://scialert.net/qredirect.php?doi=rjes.2014.231.242&linkid=pdf (accessed on 24 August 2015).
24. Knez, D. Stress state analysis in aspect of wellbore drilling direction. *Arch. Min. Sci.* **2014**, *59*, 71–76.
25. Eskilson, P. Thermal Analyses of Heat Extraction Boreholes. Ph.D. Thesis, Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden, 1987. Available online: http://www.buildingphysics.com/Eskilson1987.pdf (accessed on 8 September 2015).
26. Hellström, G. Ground Heat Storage, Thermal Analyses of Duct Storage Systems. Ph.D. Thesis, Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden, 24 May 1991.
27. Kurevija, T.; Vulin, D.; Krapec, V. Influence of Undisturbed Ground Temperature and Geothermal Gradient on the Sizing of Borehole Heat Exchangers. In Proceedings of the World Renewable Energy Congress 2011, Linköping, Sweden, 8–13 May 2011; pp. 1360–1367. Available online: http://www.ep.liu.se/ecp/057/vol5/017/ecp57vol5_017.pdf (accessed on 8 September 2015).
28. Cataldi, R. Sustainability and Renewability of Geothermal Energy. In Proceedings of the International Scientific Conference on Geothermal Energy in Underground Mines, Ustron, Poland, 21–23 November 2001. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/Poland/2001/a4.pdf? (accessed on 24 August 2015).
29. Signorelli, S.; Kohl, T.; Rybach, L. Sustainability of Production from Borehole Heat Exchanger Fields. In Proceedings of the Twenty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA, 2004; pp. 1–6. Available online: http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2004/Signorelli.pdf? (accessed on 24 August 2015).

30. Dehkordi, E.; Schincariol, R.A. Effect of thermal-hydrogeological and borehole heat exchanger properties on performance and impact of vertical closed-loop geothermal heat pump systems. *Hydrogeol. J.* **2014**, *22*, 189–203.
31. Chiasson, A.C.; Rees, S.J.; Spitler, J.D. A preliminary assessment of the effects of ground-water flow on closed-loop ground-source heat pump systems. *ASHRAE Trans.* **2000**, *106*, 380–393.
32. Diao, N.; Li, Q.; Fang, Z. Heat transfer in ground heat exchangers with groundwater advection. *Int. J. Therm. Sci.* **2004**, *43*, 1203–1211.
33. Fujii, H.; Itoi, R.; Fujii, J.; Uchida, Y. Optimizing the design of large-scale ground-coupled heat pump systems using groundwater and heat transport modelling. *Geothermics* **2005**, *34*, 347–364.
34. Hecht-Méndez, J.; de Paly, M.; Beck, M.; Bayer, P. Optimization of energy extraction for vertical closed-loop geothermal systems considering groundwater flow. *Energy Convers. Manag.* **2013**, *66*, 1–10.
35. Molina-Giraldo, N.; Blum, P.; Zhu, K.; Bayer, P.; Fang, Z. A moving finite line source model to simulate borehole heat exchangers with groundwater advection. *Int. J. Therm. Sci.* **2011**, *50*, 2506–2513.
36. Fan, R.; Jiang, Y.Q.; Yao, Y.; Shiming, D.; Ma, Z.L. A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection. *Energy* **2007**, *32*, 2199–2209.
37. Sliwa, T.; Gonet, A. Theoretical model of borehole heat exchanger. *J. Energy Res. Technol.* **2005**, *127*, 142–148.
38. Heliasz, Z.; Ostaficzuk, S. Możliwości i sposoby wykorzystania w Polsce ciepła odpadowego i energii geotermalnej do odśnieżania i odladzania—koncepcje i problemy (Possibilities and ways to use in Poland the waste heat and geothermal energy for snow melting and de-icing—Concepts and problems). *Prace Wydz. Nauk Ziemi Uniw. Śląskiego* **2002**, *17*, 243–256. (In Polish)
39. Poniedziałek, M.; Sliwa, T. The Use of a Heater and Borehole Heat Exchangers for Regeneration of Heat Resources in the Rock Mass on the Example of the Geoenergetics Laboratory. *AGH Drill. Oil Gas* **2013**, *30*, 353–359. Available online: http://journals.bg.agh.edu.pl/DRILLING/2013.30.2/drill.2013.30.2.353.pdf (accessed on 24 August 2015).
40. Hellström, G.; Gehlin, S. Direct Cooling of Telephone Switching Stations Using a Borehole Heat Exchanger. In Proceedings of the 7th International Conference on Thermal Energy Storage, Megastock'97, 1997, Sapporo, Japan, 18–21 June 1997; pp. 509–514.
41. Andersson, O.; Rydell, L.; Algotsson, T. Efficient usage of waste heat by applying a seasonal energy storage (BTES) at ITT Water & Wastewater AB, Emmaboda, Sweden. Available online: http://intraweb.stockton.edu/eyos/energy_studies/content/docs/effstock09/Session_11_1_Case%20studies_Overviews/101.pdf (accessed on 8 September 2015).
42. Andersson, O.; Hellström, G.; Nordell, B. Heating and Cooling with UTES in Sweden—Current Situation and Potential Market Development. Available online: https://pure.ltu.se/portal/files/350717/artikel.pdf (accessed on 8 September 2015).