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Article

Geothermal Boreholes in Poland—Overview of the Current State of Knowledge

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Abstract: Geothermal energy can be useful after extraction from geothermal wells, borehole heat exchangers and/or natural sources. Types of geothermal boreholes are geothermal wells (for geothermal water production and injection) and borehole heat exchangers (for heat exchange with the ground without mass transfer). The purpose of geothermal production wells is to harvest the geothermal water present in the aquifer. They often involve a pumping chamber. Geothermal injection wells are used for injecting back the produced geothermal water into the aquifer, having harvested the energy contained within. The paper presents the parameters of geothermal boreholes in Poland (geothermal wells and borehole heat exchangers). The definitions of geothermal boreholes, geothermal wells and borehole heat exchangers were ordered. The dates of construction, depth, purposes, spatial orientation, materials used in the construction of geothermal boreholes for casing pipes, method of water production and type of closure for the boreholes are presented. Additionally, production boreholes are presented along with their efficiency and the temperature of produced water measured at the head. Borehole heat exchangers of different designs are presented in the paper. Only 19 boreholes were created at the Laboratory of Geoenergetics at the Faculty of Drilling, Oil and Gas, AGH University of Science and Technology in Krakow; however, it is a globally unique collection of borehole heat exchangers, each of which has a different design for identical geological conditions: heat exchanger pipe configuration, seal/filling and shank spacing are variable. Using these boreholes, the operating parameters for different designs are tested. The laboratory system is also used to provide heat and cold for two university buildings. Two coefficients, which separately characterize geothermal boreholes (wells and borehole heat exchangers) are described in the paper.

Keywords: geothermal wells; borehole heat exchangers; geothermal boreholes; geothermal waters; geothermal energy; geoenergetics

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1. Introduction

Renewable energy sources are increasingly used around the world. These include geothermal energy, which is exploited by geothermal boreholes. Two types of boreholes are used: geothermal wells (production and injection) and borehole heat exchangers (BHE).

A geothermal well is a borehole that allows production or injection of geothermal waters from both deep and shallow aquifers. The deep layers are used for production and injection of geothermal waters, whereas the shallow layers are mostly used as low-temperature waters for geothermal heat pumps.

Geothermal boreholes may be vertical, inclined or directional. They can also (earlier) fulfill an exploratory role. As a rule, the construction of the first geothermal borehole must take into account detailed specialist tests, including geophysical and hydrogeological research of the aquifer with geothermal water or thermal response tests in the case of BHEs [1]. In addition, the heat accumulated in the greater depths of the rock mass (mostly between 3000 and 6000 m [2]) can be exploited using HDR and EGS systems [3,4]. Hydraulic fracturing is a procedure for greater consumption of geothermal energy from such significant depths [2]. An increasing amount of EGS research demonstrates its development [5–8].

(Very) low-temperature heat can be used by shallow geothermal boreholes known as borehole heat exchangers (BHEs). Borehole heat exchangers are becoming more and more popular. They are used in heating systems or heating and cooling installations with heat pumps [9]. Exploiting the heat of the shallow layers, besides geothermal heat in the Earth, also includes solar heat, which is accumulated in the surface layers as a result of solar radiation and higher temperatures of atmospheric air. The system's basic parameter is the obtainable heating power. This parameter is affected mainly by the depth, the number and the location of borehole heat exchangers, exploiting parameters and construction of the BHE [10]. The topic of borehole heat exchangers design is also considered by Aresti et al. 2018 [11]. It is also necessary to mention the so-called ground-coupled heat exchangers (GSHE) or hybrid systems for space heating/cooling [12] with heat/cold storage in the rock mass. In addition, there is a growing interest regarding the geothermal resources available at shallow depths beneath urban areas [13]. Computer modeling and simulations [14–16] are used to properly design the installations of borehole heat exchangers.

One of the most important tests performed to understand the properties of rocks, and simultaneously the appropriate selection of borehole heat exchanger's design is the Thermal Response Test—TRT [17,18]. The main parameters which can be determined using TRT are effective thermal conductivity and borehole resistance [19]. Currently, Thermal Response Tests are being conducted in an increasingly advanced form [20,21].

New ideas for using geothermal boreholes have been described in the last few years. Examples include the geothermal energy-assisted natural gas hydrate recovery method, which can simultaneously exploit geothermal energy and natural gas hydrates by injecting water into a geothermal heat exchange well, proposed by Liu et al. [22]. Dai et al. described a deep geothermal well with a downhole coaxial open-loop design [23]. Multilateral wells can be also used for heat extraction in enhanced geothermal systems [24].

Every year more papers describe the use of abandoned oil and gas wells. Advanced geothermal utilizations have been described by Nian and Cheng [25]. The utilization of closed mines is also mentioned in the scientific articles [26,27]. Recently, many publications have also been made regarding the use of new heat carriers in geothermal systems, for instance using CO_2, as indicated by Esteves et al. [28] and Shi et al. [29]. Various organic fluids were analyzed by Cheng et al. [30] and Van Erdeweghe [31].

Currently in Poland hydrogeothermal resources are utilized, for which the energy carrier is hot groundwater extracted from the geothermal wells [32] with various economic benefits [33]. Additionally, the number of geothermal heat pumps based on borehole heat exchangers grows every year. The Laboratory of Geoenergetics conducts research on the effectiveness of various borehole solutions for very low-temperature heat extraction. Under similar geological and hydrogeological conditions, 19 BHEs were drilled. Each of them has a different design. Thermal Response Tests are ongoing to identify the most energy-efficient design and the optimal operating parameters, primarily the flow rate of the heat carrier [19]. An energy pile was also studied in the Laboratory. The combination of the load-bearing pile with the borehole heat exchanger gives double the benefit—it increases the load capacity of the rock mass and provides a source of heat/cold [34].

Development in the field of geothermal wells is stimulated by the oil and gas industry. New solutions in drilling and borehole engineering can often be adapted to suit geothermal solutions.Examples include drilling using pads (shale gas/oil), and horizontal drilling, which are becoming some of the most influential innovations in the oil and gas industry of recent years. Those methods have become the standard for increasingly efficient exploitation, and it is expected that they will become more widespread. In addition, previously exploited oil wells can be adapted for geothermal purposes, e.g., as deep borehole heat exchangers.

2. Materials and Methods

Effective exploration and sharing of geothermal water resources is possible across modern technology for drilling. At present, the rotary method with the right circulation of the mud is used [1].

2.1. Materials Used in Geothermal Wells

The casing pipes are usually made of steel, and therefore are susceptible to corrosion. While selecting the type of steel used for casing pipes, one should avoid carbon steel and low-alloy steel, because they are highly vulnerable to corrosion. In many cases non-alloyed steel with high strength, such as J-55 (Pyrzyce GT-4) and N-80 (LidzbarkWarmiński GT–1), is used [35].

In recent years, lining the inside of steel pipes with plastic has found wide application. Fiberglass pipes are also used. An example of steel pipes with an inner coating are Pyrzyce GT–2 and Pyrzyce GT–4 boreholes [36], as well as Toruń TG-1 where fiberglass pipes were used in the construction [37]. Such applications are used in order to reduce unfavorable processes in geothermal wells, such as corrosion [35,38].

There are many methods limiting processes and results of corrosion, as well as precipitation of secondary mineral substances in geothermal installations. They aim to recover production parameters in geothermal systems. These methods include: application of inhibitors, soft acidizing treatments and processes using non-organic and organic acid solutions [39].

In geothermal wells, Class G cement slurries with various additives and admixtures are most commonly used [40–42]. Most often silica flour is added in a quantity varying from 20 to even 100% BWOC (by weight of cement) together with additives and admixtures depending on the need to achieve the appropriate parameters of fresh cement slurry. Additives and admixtures include bentonite, carboxymethylcellulose or lime [40,41]. Another type of cement used in geothermal drilling is Class A cement [43]. The literature also includes the use of Class F and Class J cements in geothermal systems [41].

2.2. List of Geothermal Wells with Theirparameters in Poland

This subsection presents a list of geothermal borehole parameters in Poland (Table 1). Presented parameters such as: borehole name, year of construction, depth, production or injection rate, aquifer opening, geothermal water temperature at the head, borehole type, borehole purpose, spatial orientation, construction material, borehole bottom.

In Poland new boreholes are most often drilled for geothermal wells. In Table 1, those are specified as type “New”. Boreholes drilled for other purposes, or geothermal wells made much earlier, in which reconstruction and adaptation works are necessary for the needs of obtaining geothermal water, are specified as type “Archival” in Table 1.

Table 1 does not include boreholes in: Dębica GT-1, Lądek Zdrój LZT-1, Sękowa GT-1 and others due to the lack of data in available publications.

Table 1. Collective data on geothermal borehole parameters in Poland (based on [37–39,44–86]).

Borehole Name	Year of Implementation	Depth H, m	Production (Injection) Rate $\dot{V}(\dot{V}_i)$, m^3/h	Aquifer	Geothermal Water Temperature at the Wellhead T_{wh}, °C	Potential Theoretical Heat Flow—Heating Power (by Cooling to 0 °C) P, MW (Average Density, Average Spec. Heat Capacity—for Distilled Water in $T_{wh}/2$)	Borehole Type	Borehole Purpose	Spatial Orientation	Construction Material: Technical Column/Pumping Column	Borehole Bottom	Comments
Bańska IG-1	1979/81 [39,58,67]	5261 [39,51,52,58,59,67] 5263 [58]	120 [39,49,50,58–60,68]	Namulite limestone (middle Eocene) and limestone and dolomite (middle Triasic) [59]	At the beginning 60, after the intensification 82 [51,52] 82 [39,49,50,56,58,59,68,69] 86 [59]	11.33 (991.9; 4179)	Archival *****	Production [39,68]	Vertical	Steel/-	Perforated in borehole	Depth 5261 m in [58] at site 73, depth 5263 m w in [58] at site 71; Temperature on the outflow 82 °C in [59] in Table 4, and 86 °C in [59] in Table 1 Depth of the water level 2565–3345 m [39]
Bańska PGP-1	1997 [39,72]	3242 [39,59]	550 [39,49,50,59,60,68]	Marly limestones (middle Eocene) and limestones and dolomites (middle Triassic) [59]	85 [56] 86 [49,50,59,68] 87 [39,58]	53.78 (991.1; 4179)	New ***	Production ** [39,68]	Vertical	Steel/-	Perforated on surface, 3032–3242 m uncased [72]	Depth of the water level 2709–3242 m [39]; Perforated on surface 2772–3032 m uncased [39]
Bańska PGP-3k	2012/2013	3500 MD [73] 3519 MD [70] 3380.7 TVD [73] 3400 TVD [70]	290 [68,70]	Middle Triassic	82.4 to 85.8 [61] 85 [56,68,70]	28.36 (991.1; 4179)	New *** [38]	Production ** [68]	Directional [38]	Steel/-	Filtred [38] Perforated [71]	-
BiałkaTatrzańska GT-1	2007 [75]	2500 [75]	32 [50] 38 [49]	-	72 [75] 73 [49,50,56]	2.66 (993.7; 4178)	New ****	Production	Vertical	-	-	-
BiałyDunajec PAN-1	1989 [39,53]	2394 [39,53,59]	270 [59] (200) [39,49,50,58,60,68]	Conglomerates (middle Eocene) and limestones and dolomites (middle Triassic) [59]	82 [49,50,56] 86 [59]	25.49 (991.9; 4179)	New ****	Injection ** [39,68]	Vertical	Steel/-	Perforated, 2117–2132 uncased [39]	Depth of water level 2113–2394 m [39]; closed 11.09.2003; reconstruction in 2011 [39]; partly repaired in 2011; in 2014, the well was directionally deepened and restored to operation [46]
BiałyDunajec PGP-2	1996/97 [39,72]	2450 [39,59]	175 [59] (400) [39,49,50,58,60] (500) [68]	Limestones and dolomites (middle Triassic) [59]	85 [56] 86 [49,50,59]	17.11 (991.1; 4179)	New ****	Injection ** [39,68]	Vertical	Steel/-	Perforated on surface [39]	Depth of water level 2048–2450 m [39]
BukowinaTatrzańska PIG/PNiG-1	1992 [59]	3780 [51,59]	40 [49] 48 [50] 70 [59]	Marly limestones (lower Jurassic, upper Cretaceous) [59]	64.5 [49] 67 [50,56,59]	3.09 (994.4; 4178)	New ****	Production	Vertical	-	-	-
Celejów GT-1	2014 [75] 2013–2015 [65]	3500 [75] 3504 [65]	-	-	-		New ****	-	-	-	-	-
Celejów GT-2	2014 [75] 2013–2015 [65]	1234 [75]	-	-	-		New ****	-	-	-	-	-
Chochołów PIG-1	1989/90 [76]	3572 [51,59,76]	120 [49,50] 190 [59]	Dolomites and limestones (middle Eocene)—(depth 3218–3572 m) [59]	82 [49,50,56,59]	11.33 (991.9; 4179)	New ****	Production **	Vertical	-	-	-
CiepliceZdrój C-1	1997 [79]	2002 [78]	50 [79]		87.5 [79]	5.03 (990.6; 4179)						
CiepliceZdrój C-2		750 [78,79]	28 [79]		63 [79]	2.04 (995.09; 4178)						
CzarnyPotok GT-1	2011 [75]	2853 [75]	-	-	-		New ****	-	-	-	-	-
DusznikiZdrój GT-1	2002 [79]	1695 [86]	30 ** [79]		35 [79]	1.4183)						
Furmanowa PIG-1	1989/90 [76]	2324 [51,59,76]	60 [59] 90 [49,50,59]	Conglomerates (middle Eocene) and sandstones (Jurassic) and limestones (Jurassic and Cretaceous)—(depth 2003–2324 m) [59]	60.5 [49,50,56,59]	6.29 (995.7; 4178)	New **** [76]	Inactive (unemployed) **	-	-	-	Flow rate 60 m^3/h in [59] in Table 4, and 90 m^3/h in [59] in Table 1
Gostynin GT-1	2007 [47] 2008 [75] 2007/08 [37,38,64]	2734 [63,64,75]	120 [63,64]	Lower Jurassic [37,38,47,64]	82 [63,64,75]	11.33 (991.9; 4179)	New ****	Production [37,38]	Vertical	Steel/steel [37,38]	Widened, bare foot [37,38]	-
Jachranka GT-1	2019 [75]	1780 [75]	180 [75]	Lower Jurasic [75]	44 [75]	9.18 (997.9; 4181)						
Jaworze IG-1	1981	1525 [77,85]	0.9 [77,85]		23 [77,85]	0.02 (999.58; 4189)						
Jaworze IG-2	1981	1650 [77,85]	4 [77,85]		32 [77,85]	0.15 (999.03; 4185)						
Karpniki KT-1		1997 [74]	44 [74]		54 [74]	2.75 (996.59; 4179)					Bare foot [78]	
KazimierzaWielka GT-1	2015 [81]	750	200–300	-	-		-	-	Vertical	-	-	-

Table 1. *Cont.*

Borehole Name	Year of Implementation	Depth H, m	Production (Injection) Rate $\dot{V}(\dot{V}_i)$, m^3/h	Aquifer	Geothermal Water Temperature at the Wellhead T_{wh}, °C	Potential Theoretical Heat Flow—Heating Power (by Cooling to 0 °C) P, MW (Average Density, Average Spec. Heat Capacity—for Distilled Water in T_{wh}/2)	Borehole Type	Borehole Purpose	Spatial Orientation	Construction Material: Technical Column/Pumping Column	Borehole Bottom	Comments
Kleszczów GT-1	2009 [37,38,55,64,75]	1620 [55,63,64,75]	200 [63,75] 150 resulting from the pumping [64] 202.6 on the temperature 52.2 resulting from the pumping [55]	Lower Jurassic [37,38,47,64]	52 [63,64] 52.2 [55,75]	12.03 (996.9; 4179)	New ****	Production [37,38]	Vertical	Steel/steel [37,38]	Non-widened, bare foot [38]	52.2 with Flow rate 202.6 during measuring pumping [55]
Kleszczów GT-2	2010/11 [37,38]	1725 [55]	240.6 [55]	Lower Jurassic [37,38]	45.9 [55]	12.79 (997.6; 4180)	New ****	Injection [37,38]	Vertical	Fiberglass/- [37]	Widened, filtered [37,38]	Flow rate 240.6 m^3/h. The temperature recorded at the outlet from the borehole (45.9 °C) is lower than borehole Kleszczów GT-1 (52.2 °C) although greater depth (Kleszczów GT-1—1620 m, Kleszczów GT-2—1725 m).
Koło GT-1	2018 [75]	3905 [75]	260 [75]		86 [75]	25.72 (991.1; 4179)						
Konin GT-1	2014 [75]	2660 [75]	130–150 [80,84]	-	95 [75] 97.5 [80,84]	14.17 (988.5; 4180)	New ****	-	-	-	-	-
LidzbarkWarmiński GT-1	2011 [37,38,64,75]	1030 [75] 1200 [64]	120 [64]	Lower Jurassic [37,38,63,64]	24 [64]	3.35 (999.6; 4189)	New **** [75]	Production [37,38]	Vertical	Steel/steel [37,38]	Widened, filtered [37,38]	-
Mszczonów IG-1	1976 [38,44] 1977 [51,52]	1700 [63] 1793 [46] 4119 [51,52]	55 [63] 60 after reconstruction [44] 60 [63]	Lower Cretaceous [44,51,52,63] Lower Jurassic [38]	40 [51,52,63] 42 after reconstuction [44] 42 with reservoir 55 $m^3 \cdot h^{-1}$ [63]	2.92 (998.3; 4181)	Not for geothermal purposes [44] Archival [37]	Production [37,38]	Vertical [37,38]	Steel/steel [37,38]	Perforated pipes [37,38]	Flow rate 60 m^3/h in [63] in Table 2, and 55 m^3/h in [63] on the site 135. Temperature 40 °C [63] in Table 2 and 42 °C in [63] on site 135.
Odra 5-I\Lech w Grabinie		545 [86]			31 [86]							
Piaseczno GT-1	2011/12 [37,38,64]	1892 [64]	120 [63,64]	Lower Jurassic [37,38,63,64]	45 [63,64]	6.26 (997.9; 4180)	New ****	Production [37,38]	Vertical [38]	Steel/steel [37,38]	Widened, filtered [37,38]	-
PorębaWielka IG-1	1973/75 [48]	2002.4 [48]	12.1 [48,51,52]	Upper Cretaceous [48]	42 [48,51,52]	0.59 (998.3; 4181)	Archival	Production	Vertical	Steel/-	Filtered [48]	Reservoir 12.1 m^3/his the initial documented resource [51,52], also referred to as the outflow of a year 1976 [48]
Poddębice GT-2	2009/10 [37,38,64] 2010 [75]	2100 [63] 2101 [64,75]	115 [63,64]	Lower Cretaceous [37,38,64]	72 [63,64]	9.55 (993.7; 4178)	New ****	Production [37,38]	Vertical [38]	Steel/steel [38]	Widened, filtered [38]	-
Poronin PAN-1	1988/89 [54]	3003 [54,59]	70 [49,50] 90 [59]	Limestones and dolomites (middle Triassic)—(depth 1768–1855 m) [59]	63 [49,50,59]	5.09 (995.1; 4178)	New [59]	Inactive	Vertical	Steel/-	-	-
Pyrzyce GT-1	1992 [38]	1632 [45]	170 [39,63]	Lower Jurassic [38]	61–63 [39]	11.98 (995.4; 4178)	New [37]	Production [37,38]	Vertical [37,38]	Steel/steel [37,38]	Widened, filtered [37,38]	Total flow rate from Pyrzyce GT-1 and GT-3 340 m^3/h [39,63] At the turn of 2008/09 the geothermal heating plant in Pyrzyce GT-2 and GT-4 have installed HDPE—High Density Poly Ethylene lining [37,63]
Pyrzyce GT-2	1992/93 [38]	1523 [45] 152.1 [72]	-	Lower Jurassic [38]	-		New [37]	Injection [37,38]	Vertical [37,38]	Steel/- [37,38]	Widened, filtered [37,38]	
Pyrzyce GT-3	1992/93 [38]	1632 [45]	170 [39,63]	Lower Jurassic [38]	61–63 [39]	11.98 (995.4; 4178)	New [37]	Production [37,38]	Vertical [37,38]	Steel/steel [37,38]	Widened, filtered [37,38]	
Pyrzyce GT-4	1992/93 [38]	1523 [45] 1523.1 [72] 1630 [75]	-	Lower Jurassic [38]	-		New [37]	Injection [37,38]	Vertical [37,38]	Steel/- [37] Steel/steel [38]	Widened, filtered [37,38]	
Pyrzyce GT-1 bis	2017 [75]	1645 [80]	200 [75]	-	65 [75]	15.01 (994.8; 4178)	New ***	-	Directional [75]	-	-	-
Rabka IG-1		1215 [77]	4,5 [77]		28 [77]	0.15 (999.33; 4187)						
Sieradz GT-1	2018	1505 [75,82]	249 250 [75]	Lower Jurassic	51.8 50 [75]	14.98 (996.8; 4179)	New	Research and Production	Vertical	-	-	-

Table 1. *Cont.*

Borehole Name	Year of Implementation	Depth H, m	Production (Injection) Rate $\dot{V}(\dot{V}_i)$, m^3/h	Aquifer	Geothermal Water Temperature at the Wellhead T_{wh}, °C	Potential Theoretical Heat Flow—Heating Power (by Cooling to 0 °C) P, MW (Average Density, Average Spec. Heat Capacity—for Distilled Water in $T_{wh}/2$)	Borehole Type	Borehole Purpose	Spatial Orientation	Construction Material: Technical Column/Pumping Column	Borehole Bottom	Comments
SiwaWoda IG-1	1972/73 [76]	856 [51,59]	4 [49,50,59]	conglomerates (middle Eocene) and sandstones (Jurassic) and limestones (Jurassic and Cretaceous)—(depth 2003–2324 m) [59]	20 [49,50,59]	0.09 (999.8; 4192)	Archival ******	Inactive (unemployed) ** [49]	-	-	-	-
Skierniewice GT-1	1990/91 [39]	3001 [39]	70 [39] (13) [39]	Sandstones, siltstones, claystones (Lower Jurassic) depth 2875–2941 m [39] Lower Jurassic [72]	69.2 [39]	5.59 (994.1; 4178)	New **** [39]	Inactive	Vertical	-	Filtered [39]	The exploitation reservoirs are 70 m^3/according to hydrogeological surveys from 1990/91, and from 1997 the final borehole flow rate 13 m^3/h [39] Temperature of geothermal water was 69.2 °C in 1990/91 [39]
Skierniewice GT-2	1996/97 [39]	2900 [39]	86.6 [39]	Lower Jurassic depth 2771–2886 m [39] Lower Jurassic [72]	57.5 [39]	5.76 (996.0; 4179)	New **** [39]	Inactive	Vertical	-	Widened, filtered [39]	Flow rate: 86.6 m^3/h with temperature 57.5 °C [39]
Sochaczew GT-1	2018	1540 [75]	Min. 180	44 [75]	-	9.18 (997.9; 4181)	New	-	-	-	-	-
Staniszów ST-1		1501 [74]	20.5 [74]		37.3 [74]	0.89 (998.49; 4182)					Filtered [78]	Temperature and flow rate in 2014
StargardSzczeciński GT-1	2001 [38,72]	Planned depth 2670 [72] 2672 [58] 2750 [75]	200 [63]	Lower Jurassic [38,63]	87 [63]	20.01 (990.6; 4179)	New [37]	Production [37,38]	Vertical [37,38]	Steel/steel [37,38]	Widened, filtered [37,38]	in 2008 the role of geothermal boreholes was changed [37]
Stargard Szczeciński GT-2k	2003 [38,72] 2005 [46]	Planned depth 3300 [72] Final depth 3080 [72,75] 2450 TVD [58] 2960 MD [58]	-	Lower Jurassic [38]	-		New [37]	Injection [37,38]	Directional [37,38,72]	Steel/steel [37,38]	Widened, bare foot [37,38]	In 2008 the role of geothermal boreholes was changed [37] Depth of the start directional 450 m, azimuth 17°, maximum angle 39° [72]
Stargard GT-3	2016 [75]	2665 [75]	-	-	-		-	Injection [75]	-	-	-	-
Swarzędz IGH-1	1982 [62]	1306 [62]	33.84 to 73.36 [62]	Lower Jurassic [62]	36.6 to 42.2 [62]	1.44 (998.7; 4183)	-	-	-	-	Filtered876,6 to 1306 m, with perforation in 138,06 m [62]	The temperature of sodium-chloride water was 39.6–42.2 °C and depended on flow rate 33.84 do 73.36 m^3/h [62]
Szymoszkowa GT-1	2006 [75,76]	1737 [75,76]	70 [50] 80 [49]	-	27 [49,50]	2.20 (999.3; 4187)	New **** [75]	Production	Vertical	-	-	-
TarnowoPodgórne GT-1	2010 [37,38] 2011 [64,75]	1200 [63,64,75]	220 [63,64]	Lower Jurassic [37,38,64]	44 [63,64]	11.23 (998.9; 4181)	New **** [75]	Production [37,38]	Vertical [38]	Steel/steel [37,38]	Widened, filtered [37,38]	-
Tomaszów Mazowiecki GT-1		2090 m (+/− 20%) [83]					New **** [83]					
Toruń GT-1 [38] Toruń TG-1 [37,63,64,72]	2008 [72] 2008/09 [37,38,64]	Planned depth 2970 [72] Final depth 2925 [64,72]	350 [63,64]	Lower Jurassic [37,38,64] Lower Jurassic and middle Triassic [63]	64 [63,64]	25.87 (995.1; 4178)	New [38]	Production [37,38]	Vertical [38]	Steel/fiberglass [37,38]	Widened, filtered [37,38]	Flow rate 350 m^3/h [63]
Toruń GT-2 [38] Toruń TG-2 [37,63,64,72]	2009 [37,38]	2353 [38]	-	Lower Jurassic [37,38]	-		New [38]	Injection [37,38]	Vertical [38]	Fiberglassl/- [37,38]	Widened, filtered [37,38]	-
Trzęsacz GT-1	2012 [37,38,64]	1200 [64] 1224.5 [75]	180 [64]	Lower Jurassic [37,38,63,64,75]	27 [64]	5.65 (999.3; 4187)	New ****	Production [37,38]	Vertical [38]	Steel/steel [37,38]	Widened, filtered [37,38]	-
Uniejów IGH-1	1978 [38,39,66]	2245 [39] 2254 [66,72]	55 [66] 65 [66] 65.4 [66] (54.9) [66]	Lower Cretaceous [39,57,66]	68 [66]	4.32 (994.4; 4178)	Archival ******	Injection [37–39,66]	Vertical [37,38]	Steel/- [37,38]	Perforated pipes [37–39]	Flow rates: [66]: −65,4 m^3/h test production in 1991, 65 m^3/h in 1978, 55 m^3/h in 1981.
Uniejów PIG/AGH-1	1990/91 [38,57,66]	2065 [39,66,72]	90.14 [66] (80.5) [66]	Lower Cretaceous [38,39,57,66]	-		Archival [38] New [37]	Injection [37–39,66]	Vertical [37,38]	Steel/- [37,38]	Perforated pipes [37–39]	Flow rate 90.14 m^3/h [66]

Table 1. *Cont.*

Borehole Name	Year of Implementation	Depth H, m	Production (Injection) Rate $\dot{V}(\dot{V}_i)$, m^3/h	Aquifer	Geothermal Water Temperature at the Wellhead T_{wh}, °C	Potential Theoretical Heat Flow—Heating Power (by Cooling to 0 °C) P, MW (Average Density, Average Spec. Heat Capacity—for Distilled Water in $T_{wh}/2$)	Borehole Type	Borehole Purpose	Spatial Orientation	Construction Material: Technical Column/Pumping Column	Borehole Bottom	Comments
Uniejów PIG/AGH-2	1990/91 [38,66]	2031 [66,72] 2042 [39]	120 [66]	Lower Cretaceous [38,39,57,66]	69.2 [66] 68 [63]	9.58 (994.1; 4178)	Archival [38] New [37]	Production [38,39,66]	Vertical [37,38]	Steel/steel [37,38]	Perforated pipes [37–39]	Flow rate 120 m^3/h and temperature 69.2 °C in 2005 [66]
Ustroń IG-3		1837.5 [77]		6 [77]	21 [77] 32—brine [52]	0.15 (999.77; 4191)						
Wręcza GT-1	2018 [75]	1688 [75]	150 [75]	Kredadolna [75]	~40 [75]	6.96 (998.3; 4182)						
Zakopane IG-1	1961/63 [76] 1963 [58]	3072.2 [51,52] 3073 [58] 3073.2 [59,76]	50 [49,50,59]	Marl and limestones (lower Jurassic) [59]	36 [58] 37 [49,50,59]	2.09 (998.7; 4183)	Archival	-	Vertical	-	-	-
Zakopane 2	1973 [58] 1975 [76]	1113 [59,76]	80 [49,50,58,59] 90 [59]	Namulite limestones (middle Eocene) and limestones and dolomites (middle Triassic) [59]	26 [49,50,59] 26.6 [58]	2.42 (999.5; 4188)	Archival	-	-	-	-	Flow rate 90 m^3/h [59] and 80 m^3/h [59] in Table 1.
Zazadnia IG-1	1985/86 [76]	680 [51,59]	25 [49,50] 25.1 [59]	Namulite limestones (middle Eocene) and limestones and dolomites (middle Triassic) [59]	22 [49,50,59]	0.64 (999.8; 4191)	Archival	-	-	-	-	-
Total		12,8236.1	6257,18			735.4						

* temperatures are variable with the actual flow rate and with the production time, ** self-outflow (head pressure by natural temperature profile in the well), *** the geothermal wells for direct use, **** the geothermal wells exploratory or research, ***** the exploratory wells (but not for geothermal exploration), ****** the hydrogeological wells.

Geothermal waters in Poland are most often used for recreational, heating and health purposes. Geothermal waters are used in heating plants in Stargard, Pyrzyce, Uniejów, Mszczonów, Poddębice and in Podhale [87]. Often, boreholes in Poland, as well as in other countries, are located in poorly urbanized areas. The distribution of geothermal installations in Poland is shown in Figure 1.

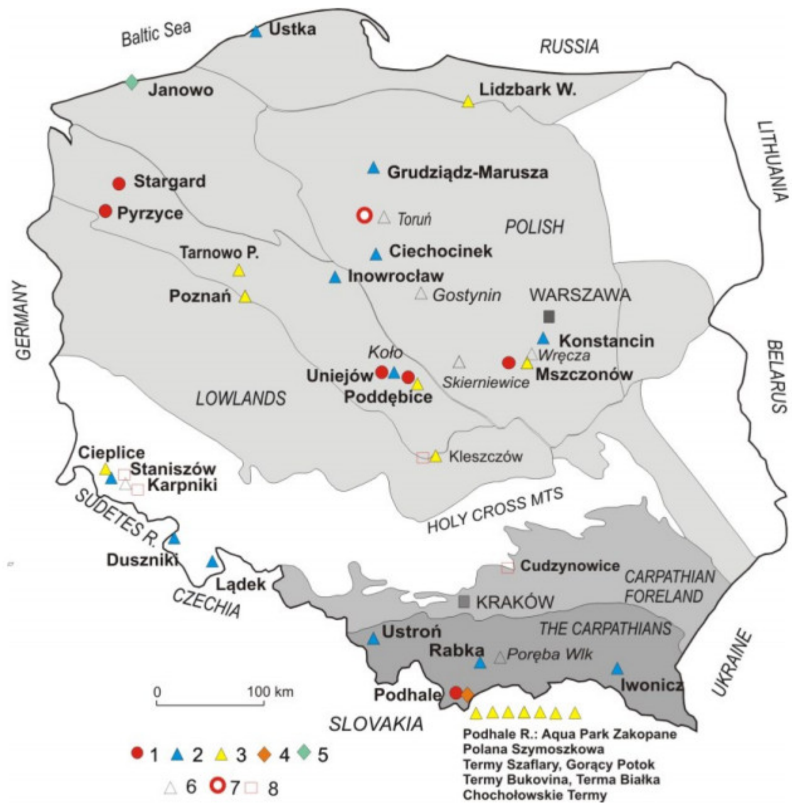

Figure 1. Geothermal uses in Poland in 2018: 1. District heating plants; 2. Health resorts; 3. Recreation centers; 4. Wood drying; 5. Fish farming; 6. Some recreation centers in realization; 7. Heating system in realization; 8. Individual heating systems (individual heating systems in some recreation centers are not marked) [87].

Indicators of the ratio between the depth of geothermal boreholes and their power were proposed. The depth/efficiency ratio indicator was first proposed, according to the formula:

$$N_{\dot{V}} = \frac{\sum \dot{V}}{\sum H} \quad (1)$$

where $\dot{V}$ is the flowrate of possible geothermal water and H is the depth of the borehole.

Qualification of boreholes to be included in the indicator is a debatable issue (1). The issue of selection is difficult because irrespective of the end use of the borehole (whether exploitation or injection), pumping tests are performed to determine the serviceability of the boreholes. Hence, the depth/efficiency ratio can be defined for different borehole configurations. Among the geothermal boreholes in Poland are: exploited production and injection boreholes, negative boreholes (boreholes planned and drilled in order to exploit geothermal water, in which the water was not found), boreholes not in operation. Efficiency is also debatable due to differences in values between multiple sources (cf. Table 1). Geothermal boreholes have approved resources of efficiency (productivity) and absorbency. Taking into account all geothermal boreholes for which data are available, the value of the indicator is $N_{\dot{V}}$ = 0.04879 $m^3/h/m$. The indicator takes into account all efficiency values, including injection boreholes (e.g., the Biały Dunajec PGP-2 has the approved productivity of 175 m^3/h and an absorbance of 400 m^3/h, so only the first value was included in the calculation). Approved productivity means water resources determined by research conducted during pumping tests.

If the number of negative boreholes increases, the value of the indicator decreases. Considering, for example, the best geothermal borehole operating in Poland, its indicator equals 0.154 $m^3/h/m$. Another issue is the depth of the boreholes, which previously served as reconnaissance boreholes. For example, the Bańska IG-1 well has a depth of 5261 m, while the aquifer which is being exploited occurs at a much smaller depth. The difference between the depth of the geothermal borehole and the depth of the bottom of the aquifer varies for each borehole. The proposed indicator illustrates the "unitary" effort incurred for drilling for geothermal energy (from geothermal waters) in relation to the flow rate of water available for exploitation.

The second indicator proposed is the ratio of depth/theoretical power, according to the formula:

$$N_P = \frac{\sum P}{\sum H} \tag{2}$$

In which P is the theoretical heating power, assuming water cooling from the well head temperature to 0 °C according to:

$$P = \dot{V} \cdot \rho(T_{wh}/2) \cdot c(T_{wh}/2) \cdot T_{wh} \tag{3}$$

where: $T_{wh}/2$ is the average temperature of geothermal water.

The assumed cooling of water to 0 °C was adopted as a simple rule, easy to calculate and compare. By referencing the final temperature to 0 °C, it is not necessary to know additional parameters, such as the average annual temperature of the atmospheric air, which is used to calculate the available geothermal resources (theoretical resources) under a given surface area [88]. Cooling water down to 0 °C is not feasible and technically impossible. Nevertheless, this value is quite universal and enables comparison of the energy resources (heating power) between wells. This is possible for both the high-temperature waters and the shallow water wells and natural hot springs. However, when providing such resources, it is good to also specify the water temperature, which, apart from the heating power, also indicates the quality of the obtained energy. Material parameters (density and specific heat) for calculating the amount of energy were assumed for the average temperature $T_{wh}/2$, which is a simplification of the method and facilitates the comparison of geothermal wells.

Similar observations regarding depth and heating power relate to this indicator. Its value with the same assumptions as for the $N_{\dot{V}}$ equals N_P = 3523 W/m. Respectively, for the best Polish borehole (Bańska PGP-1), this indicator equals 16,589 W/m.

Figure 2 depicts the heads of selected geothermal boreholes in Poland.

(**a**) (**b**) (**c**)

Figure 2. *Cont.*

Figure 2. Well head of borehole: (**a**) Bańska IG-1, (**b**) Bańska PGP-1, (**c**) Bańska PGP-3, (**d**) BiałkaTatrzańska GT-1, (**e**) Bukowina Tatrzańska PIG/PNiG-1, (**f**) Chochołów PIG-1, (**g**) Kleszczów GT-1, (**h**) Mszczonów IG-1, (**i**) Poddębice GT-2, (**j**) Uniejów PIG/AGH-1, (**k**) Uniejów IG-1, (**l**) Uniejów PIG/AGH-2.

3. Borehole Heat Exchangers

The advantages of the collection of the Earth's heat with borehole heat exchangers include the lack of risk connected with prospecting drilling, very high durability (lifetime) and minimal impact on the environment [89]. This chapter presents the materials most commonly used in borehole heat exchangers, as well as the innovative constructions of BHE at AGH UST in Krakow.

3.1. Materials Used in Geothermal BHEs

Borehole heat exchangers have basic construction [89]:

- Single U-pipe,
- Double U-pipe,
- Multi U-pipe,
- Coaxial exchanger.

Types of plastics are most often used as the material for borehole heat exchangers. Their main advantage is the lack of corrosion on contact with water. The most commonly used materials are [88]:

- Chlorinated polyvinyl chloride,
- Polybutylene,
- Polyethylene,
- Polypropylene.

Table 2 summarizes the basic properties of materials used in borehole heat exchangers.

Table 2. List of basic properties of materials used in borehole heat exchangers.

Material	Density, ρ_p, kg/m^3	Thermal Expansion Coefficient, Δl, 1/K	Thermal Conductivity, λ_p, W/(mK)	Specific Heat, c_p, kJ/(kgK)	Young's Modulus, E, GPa
chlorinated polyvinyl chloride	960	8×10^{-5}	0.41	1.84	2.5
polybutylene	939	-	0.22	-	0.34
polyethylene	940–970	10^{-5}	0.42	1.15	0.2
polypropylene	909	$1.5 \cdot \times 10^{-5}$	0.22	1.7	1.5–2.0

The most appropriate materials, according to the authors [89,90], for the production of borehole heat exchangers' tubes are polypropylene and polyethylene.

For the grouting of borehole heat exchangers, most commonly used are mixtures with trade names Calidutherm by Terra Calidus, Hekoterm by Hekobentonity, RaugeoTherm by Rehau, StüwaTherm by Stüwa and Thermocem Plus by Górażdże. Hekoterm is also known under brands such as TermorotaS or MuoviTerm [91]. The key parameter that should be specified for grout is increased thermal conductivity.

Grout with increased thermal conductivity is a constantly evolving research topic. The use of graphite as an additive to grout was considered by many authors, such as Lee et al., Sliwa et al., Delaleux et al., Sapińska-Sliwa [92–97].

Studies of the heat flow through BHE can be found in the literature. One of the methods is the use of the laboratory model described by Shirazi and Bernier to simulate the well conditions. Moreover, they compared the numerical and experimental results [98]. In classic methods of analyzing a ground heat exchanger, the heat capacity of boreholes is often neglected. Analytical solutions to this issue are presented in the works of Lemarche [99,100]. Taking into account the influence of the thermal capacity of the borehole on the thermal response of the ground was also described by Nian and Cheng [101].

3.2. Borehole Heat Exchangers at AGH UST in Krakow

Borehole heat exchangers are the subject of research both in Poland and around the world. The Laboratory of Geoenergetics at the Faculty of Drilling, Oil and Gas at AGH UST in Krakow has two research stations equipped with borehole heat exchangers of various constructions (Table 3). The first installation includes five BHEs made in January and February 2008 [102]. The second geothermal field station was constructed in the summer of 2017 on the occasion of the 10th anniversary of the Geoenergetics Laboratory. This installation consists of 14 borehole heat exchangers made using the rotary method [10].

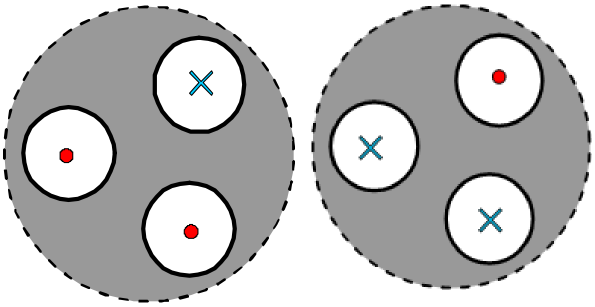

Figure 3. Innovative system [103]; with two options of circulating heat carrier (LG-11b in Table 3).

Table 3. Constructions of borehole heat exchangers (Laboratory of Geoenergetics at the Faculty of Drilling, Oil and Gas at AGH UST in Krakow) [10,103].

Name of Borehole Heat Exchanger	Constructions of Borehole Heat Exchanger	Type of Grout	Outer Diameter of Inner Pipes, D_z (d_z), mm	Wall thickness of Pipes, b, mm	Type of Pipes Material
LG-1a	coaxial	cement slurry	Casing (outside) pipe D_z = 90 mm and b = 5.4 mm; inner pipe d_z = 40 mm and b = 2.4 mm		PE, internally smooth pipe (laminar collector)
LG-2a	single U-pipe	cement slurry	40	2.4	PE, internally smooth pipe (laminar collector)
LG-3a	single U-pipe	cement slurry with increased value of thermal conductivity (ThermoCem)	40	2.4	PE, internally smooth pipe (laminar collector)
LG-4a	single U-pipe	gravel, size 8–16 mm and two clay plugs (Compactonit)	40	2.4	PE, internally smooth pipe (laminar collector)
LG-5a	double U-pipe	cement slurry	32	2.4	PE, internally smooth pipe (laminar collector)
LG-1b	double U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	32	3.0	PE, internally smooth pipe (laminar collector)
LG-2b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	32	3.0	PE, internally rough pipe (turbocollector)
LG-3b	double U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	40	3.0	PE, internally rough pipe (turbocollector)
LG-4b	double U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	40	3.0	PE, internally rough pipe (turbocollector)
LG-5b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	40	3.0	PE, internally smooth pipe (laminar collector)
LG-6b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	40	3.0	PE, internally rough pipe (turbocollector)

Table 3. *Cont.*

Name of Borehole Heat Exchanger	Constructions of Borehole Heat Exchanger	Type of Grout	Outer Diameter of Inner Pipes, D_z (d_z), mm	Wall thickness of Pipes, b, mm	Type of Pipes Material
LG-7b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	45	3.0	PE, internally rough pipe (turbocollector)
LG-8b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	32	3.0	PE, internally rough pipe (turbocollector)
LG-9b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS) in interval 0–20 m	32	2.9	PE, internally rough pipe (turbocollector)
LG-10b	innovative system (Figure 3)	cement slurry with increased value of thermal conductivity (TermorotaS)	40	3.0	PE, internally rough pipe (turbocollector)
LG-11b	innovative system (Figure 3)	typical mortar	40	3.0	PE, internally rough pipe (turbocollector)
LG-12b	single U-pipe	cement slurry	32	2.9	PE, internally rough pipe (turbocollector)
LG-13b	double U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS)	First U-pipe -d_z = 32 mm, turbocollector, b = 3.0 mm d_z = 32 mm, turbocollector, b = 3.0 mm Second U-pipe: d_z = 40 mm, laminar collector, b = 3.0 mm d_z = 40 mm, laminar collector, b = 3.0 mm		
LG-14b	single U-pipe	cement slurry with increased value of thermal conductivity (TermorotaS) with graphite	32	2.9	PE, internally rough pipe (turbocollector)

For borehole heat exchangers, there is no reason for the $N_{\dot{V}}$ indicator. Similar to the geothermal boreholes, one can be tempted to determine the value of the indicator N_p. BHEs work with varying loads. The way to determine BHE's energy efficiency is to perform a Thermal Response Test [19]. TRT allows for the determination of the effective thermal conductivity. Thermal conductivity can also be determined by analyzing the undisturbed temperature profile in the borehole [104]. The natural temperature profile can be examined with the NIMO-T probe. Many of the temperature–depth plots show some correctness. In general, the temperature in the near-surface layers varies depending on the season. In some profiles, a decrease in the rocks' temperature to a great depth can be observed. High heat penetration from the surface is related to the city infrastructure, not only solar radiation. The main factor influencing the soil environment is the extensive urban infrastructure, e.g., the presence of pipelines (water supply, sewage, heat pipelines), asphalt, and black road surfaces, which cause the absorption of additional amounts of solar heat from the surface. The foundations of heated buildings also cause heat transfer to the subsurface rocks. In cities, the depth of periodic heat penetration is usually greater than in non-urban areas [103]. The easiest, but least accurate approach is to determine the thermal conductivity of the ground, based on lithology and literature data [89,105].

Since the proper operation of the plate of geothermal systems is planned for decades, an important issue is to show the long-term behavior of exchangers. The thermal response of slender geothermal boreholes to subannual harmonic excitations is described by Hermanns and Ibanez [106]. Simple empirical formulas correlate the effective thermal conductivity with the unitary heating power of BHEs [107]:

$$q_1 = 20 \cdot \lambda_{eff} \tag{4}$$

and

$$q_2 = 13 \cdot \lambda_{eff} + 10 \quad (5)$$

However, it is not possible to determine the global (national) value of the indicator N_P for BHEs, due to the lack of data on the number and depth of BHEs made in Poland, and the small percentage of TRTs conducted. The collection of data on the created heat pump installations with borehole exchangers is not required, hence it is impossible to identify and collect all information about the created systems. Moreover, there is no legal regulation in Poland regarding the obligation to perform TRT, therefore these tests are performed sporadically and only on large investments. Specification of the individual values for local geology and a given depth is very much possible. For example, for boreholes located in the Laboratory of Geoenergetics AGH UST, the thermal conductivity value of rocks based on literature data (for BHEs LG1a-LG5a) equals 2.039 W/(mK) [89]. The N_P value as the mean of q_1 and q_2 from Equations (4) and (5) is 38.64 W/m. It is many times less than the value N_P = 3523 W/m for boreholes that exploit geothermal water. As opposed to geothermal waters, which do not occur everywhere, BHEs can be created regardless of geological conditions, and using increasingly affordable methods [108].

TRT tests are currently underway for BHEs belonging to the Laboratory of Geoenergetics AGH UST. Their results will determine the impact of various design parameters on the effective heat conductivity, borehole thermal resistance [109,110] and operational parameters [101].

A not very common variant of BHE is the deep borehole heat exchanger (DBHE). Until now, they have been studied and used only in the USA, Germany, Switzerland and Poland [111], and most recently also in China.

In 1999, one of the world's deepest borehole heat exchangers (2780 m) was made in Poland. It has been used for research purposes only. Due to the use of an inadequate centric tube column, satisfactory results were not obtained [112]. A key structural element in DBHEs is the internal insulating pipe column [99]. The longest-running DBHE is now an exchanger in Prenzlau (Germany), which has been in operation since 1992 [113].

Deep borehole heat exchangers are not currently used for economic reasons. Such installations are unprofitable at current heat prices. They are, however, a forward-looking source of heat when one considers™ hundreds of millions of drilled oil wells around the world.

Research on systems based on exploited and negative oil and gas wells should be carried out, as such installations can be used for heating in the future. Areas with old, decommissioned, or intended-for-decommissioning wells may then become more valuable due to the availability of an independent heat source. Only the energy which drives the heat pump (not always necessary—depending on the borehole depth) and the circulation of the heat carrier in the exchanger would have to be provided.

For instance, in the years 2016–2017, more than 120,000 oil and gas exploration and reconnaissance boreholes with a total depth of over 337.5 million meters [114] were made worldwide. With a careful approach, they could exchange heat with a rock mass reaching the heating power of more than 8 GW. It seems prudent to consider drilling new boreholes with potential future use in the form of deep borehole heat exchangers. For example, appropriately modified sealing slurry (with adjustable thermal conductivity) could be used.

Table 4 shows the present deep geothermal district heating plants and other uses for heating. Table 5 summarizes the data on geothermal heat pumps in Poland.

Table 4. Present deep geothermal district heating plants and other uses for heating in 2018 [87].

Geothermal District Heating		Geothermal Heat in Agriculture and Industry		Geothermal Heat for Buildings		Geothermal Heat in Balneology and Other	
Capacity, MW	Production, GWh/y	Capacity, MW	Production, GWh/y	Capacity, MW	Production, GWh/y	Capacity, MW	Production, GWh/y
74.6	250.4	4	6	>10	>25	>12	>35

Table 5. Geothermal heat pumps in Poland [87].

Description	Number	Capacity, MW	Production, GWh/y
In operation end of 2017	56,000	650	861
Projected total by 2020	74,000	860	1140

4. Conclusions

Renewable energy sources are increasingly used around the world. These include geothermal energy, which is exploited by geothermal boreholes and borehole heat exchangers. The authors came to the following conclusions:

1. In Polish geothermal wells, casing pipes are usually made of steel.
2. The first geothermal boreholes in Poland were vertical and made of steel pipes. Currently, directional boreholes and fiberglass pipes are present, which reflects the development of techniques and technology.
3. Borehole heat exchangers (BHEs) are increasingly used. The advantages of collecting Earth's heat with borehole heat exchangers include no risk connected with prospecting drilling, very high durability (lifetime) and minimal impact on the environment.
4. There are two installations of borehole heat exchangers on the site of the AGH UST in Krakow. The first consists of 5, while the second of 14 borehole heat exchangers with an innovative system. It is the largest installation of BHEs with different designs in the world.
5. Comparative indicators for drilling efficiency for geothermal boreholes in Poland have been proposed. These indicators can be determined in any country where exploitation boreholes for geothermal heat are made. This applies both to geothermal boreholes (i.e., those related to geothermal water) as well as borehole heat exchangers (i.e., openings which obtain the Earth's heat without hydraulic contact with the rock mass).
6. Two indicators for the effectiveness of drilling were proposed for geothermal boreholes. The first is the "unitary" cost of obtaining geothermal water's one unit of efficiency $N_{\dot{V}}$, the second is the indicator of theoretical power per one meter of existing and created boreholes N_P. For geothermal boreholes in Poland, $N_{\dot{V}}$ = 0.04879 m^3/h/m and N_P = 3523 W/m. For borehole heat exchangers, it is impossible to determine the values of these indicators for the entire country due to the reasons described in the article. Local (individual) N_P values can be determined based on the rock's heat conductivity. For BHEs located in AGH UST, N_P equals 38.64 W/m. The difference is also reflected in the cost. The unitary cost of drilling the BHE is many times less than the unitary cost of drilling a geothermal borehole.
7. Boreholes drilled in the past (including those already decommissioned) and those which will be drilled in the future can be adapted for geothermal purposes. If there is no aquifer present, they can be used for deep borehole heat exchangers. For this purpose, they can currently be designed taking into consideration future geothermal applications.

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Nomenclature

H	borehole depth, m,
$\dot{V}_i$	borehole injection rate, m^3/h,
$\dot{V}$	borehole production rate, m^3/h,
$N_{\dot{V}}$	depth/efficiency ratio, $m^3/h/m$,
N_P	depth/theoretical power ratio, W/m,
λ_{eff}	effective thermal conductivity, W/(mK),
T_{wh}	geothermal water temperature at the wellhead, °C,
ρ_p	density of the material, kg/m^3,
c_p	specific heat of the material, kJ/(kgK),
λ_p	thermal conductivity of the material, W/(mK),
Δl	thermal expansion coefficientof the material, 1/K,
D_x	outer diameter of inner pipes, mm,
P	potential theoretical heat flow, MW,
q	unitary heating power, W,
b	pipe wall thickness, mm,
E	Young's modulus, GPa.

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