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# Acquisition and economic use of geothermal energy

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**Summary.** Geothermal energy (GE) is heat from within the earth, accumulated inside the Earth in the form of hot water and steam or within hot dry rocks. The total world resources of GE exceed 35 trillion times the current, global demand for energy. GE is renewable, common, clean, abundant and independent of climatic conditions, thus it provides opportunity to be exploited. Resources of GE range from the shallow ground to hot water found a few kilometers beneath the Earth's surface, and deeper to the extremely high temperatures of magma. Many technologies have been developed to take advantage of GE. The paper presents the basic information on GE, ways to obtain and utilize it. The methods of calculation of GE resources were also presented.
**Key words:** geothermal energy, renewable energy sources.

## INTRODUCTION

Over the decades, conventional energy will not be able to meet the growing world energy demands, mainly due to the limited and rapidly dwindling sources of conventional fuels. Renewable energy sources and especially geothermal energy (GE) may be the panacea for the world's energy problems [18, 20, 21, 26].

Geothermal comes from the Greek words "geo" meaning earth and "therme" meaning heat. It is the natural heat of the earth which presents a potentially sustainable and commercial solution to problems of pollution, green house gas emissions, rising prices and long term supply problems associated with fossil fuels. GE is thermal energy generated and stored in the Earth, especially in the magma, rocks and fluids [34]. GE sources are hydrothermal systems, and hot dry rocks [7].

The use of thermal energy stored in hot rocks and groundwater for recreation and therapeutics has been known since ancient times. However, the use of such energy resources to produce heat and electricity began with the development of drilling techniques and modern geology. It has been proved that GE has great potential for supplying many areas with heat and electricity [2].

GE is independent of weather conditions, has a natural ability to accumulate, it is pure energy, contributes to the reduction of harmful combustion products of fossil fuels used for direct application, as well as with other renewable energy sources for electricity generation. Using of GE reduces the deterioration of our land, air, and water, which will allow future generations to live in the clean environment [19, 31].

The aim of the work was to present the basic information on GE. The methods of calculation of GE resources were also showed.

## GEOTHERMAL ENERGY RESOURCES

The increased interest in renewable energy sources makes a number of geothermal installations increase rapidly. According to the forecast of the European Renewable Energy Council (EREC), in October 2008, the percentage of the total geothermal renewable energy production will increase from 3.1% in 2005 to 18.5% in 2050 [11].

World geothermal resources are estimated at about $8 \cdot 10^{30}$J. However, only a small part can be used economically, due to the current technical capability and cost-effectiveness [30]. Geothermal resources to the depth of 5000 m (limit of technical feasibility of drilling) are about $1.4 \cdot 10^{26}$ J [21].

According to the way of energy production, there are two basic geothermal system types

– hydro-geothermal resources, which are a two-component mixture of water and steam, at the temperature ranging from 200 to 3000°C, and hot water at temperature of 50 to 70°C, the water being the natural medium in which GE is recovered,
– petro-GE resources – the energy is stored in dry, porous hot rocks and hot salt domes [30], there is no natural medium in these formations and the heating agent in

this case is water which is artificially introduced into the layer of rock and after heating up is turned back to the surface [33].

According to the temperature of water, geothermal resources can be divided into the following classes:
- class I – temperature < 100°C,
- class II – temperature from 100 to 150°C,
- class III – temperature from 150 to 250°C,
- class IV – temperature > 250°C [28].

Taking into account the prospects of geological regions, environmental, technical and economic provisions, operation and use of the potential of geothermal resources, the following categories can be distinguished [1]:
- available geothermal resources,
- static resources of GE,
- static-recoverable resources of GE,
- disposable resources of GE,
- exploitation of GE resources.

Available geothermal resources are defined as part of the total available drilling of geothermal resources. This is the amount of heat energy stored in the Earth's crust to the depth of 3 km or to the ceiling of crystalline substrate, relative to the annual average temperature on the ground surface. Available geothermal resources are calculated as follows [34]:

$$EDZG = VS \times rS \times cS \times (Th_{(3000)} - To)/2A \quad [\mathrm{J \cdot m^{-2}}], \quad (1)$$

where:
$VS$ – volume of rock from the Earth's surface to the depth of 3000 m [m³],
$rS$ – average density of rocks to the depth of 3000 m [kg·m$^{-3}$],
$cS$ – average specific heat of the rock matrix [J/kg˚C],
$Th_{(3000)}$ – temperature at the depth of 3000 m [˚C],
$To$ – annual average temperature on the Earth surface [˚C],
$A$ – surface area calculation [m²].

Static energy resources of hydro-geothermal reservoirs determine the amount of heat accumulated in the volume of free water contained in the pore space or gaps in the rock skeleton of the rock layer, or aquifer. Static resources of GE is the total amount of heat stored in the free water and in the rock matrix with the respect to the computation surface and average Earth surface temperature [34]. Static geothermal resources can be calculated as follows:

$$EZS = A \times mp \times [(1 - pe) \times rS \times cS + pe \times rw \times cw] \times (TS - To) \quad [\mathrm{J}], \quad (2)$$

where:
$mp$ – total volume of aquifers in the reservoir [m],
$rS$ – mean rock density to the depth of 3000 m,
$cS$ – average specific heat of the rock matrix [J/kg˚C],
$pe$ – effective porosity,
$rw$ – average density of water [kg·m$^{-3}$],
$cw$ – average density of water [J/kg˚C],
$A$ – surface area calculation [m²],
$TS$ – ceiling temperature of geothermal reservoir [˚C],
$To$ – annual average temperature on the Earth surface [˚C].

The static-recoverable GE resources are part of the static resources of a given level or hydro geothermal layers, which can be extracted to the surface of the Earth, taking into account the specific operating system of using geothermal water (spinner operating system or the operation by using one hole). The recoverable portion of geothermal resources determines the production rate ($R_o$), described by the formula [4]:

$$Ro = As/Ac[(Ts - Tz)/(Ts - To)], \quad (3)$$

where:
$AS$ – cooled-off operating system [m²],
$AC$ – the total surface area of the operating system [m²],
$TS$ – temperature at the ceiling of hydrothermal reservoir [ºC],
$TZ$ – chilled water temperature turned up to the hydrothermal level (usually 25 °C),
$To$ – annual average temperature on the Earth surface [ºC].

The static-recoverable resources of GE can be calculated as follows:

$$EZWS = EZS \times Ro \quad [\mathrm{J}], \quad (4)$$

where:
$EZS$ – static resources [J],
$Ro$ – factor of production.

The available resources of GE are determined for those areas that promise hope and possibility of economic use of geothermal heat [4].

The disposable resources of GE are calculated based on the expression:

$$EZdysp = Vw \times (TS - 25) \times rw \times cw \times 8760 \ [\mathrm{J/rok}], \quad (5)$$

where:
$Vw$ – nominal capacity of the mining hole [m³·h$^{-1}$],
$TS$ – temperature at the ceiling of hydrothermal reservoir [˚C],
$rw$ – average density of water [kg·m$^{-3}$],
$Cw$ – average specific heat of water [J/kg˚C].

Exploitation of GE resources is the amount of free geothermal water possible to obtain under the geological and environmental circumstances with shots of an optimal technical and economic parameters [1, 4].

In order to evaluate the geothermal reservoirs of resources, dimensionless ratio is calculated called the power factor ($F$), which is defined as the ratio of the effective power output ($Pwy$) to efficient power input ($Pwe$):

$$F = Pwy/Pwe. \quad (6)$$

The power factor is an indicator which expresses how many times the output power of geothermal shot exceeds the thermal power, which is an equivalent representation of capital expenditure and operating costs of this shot. It is assumed that $Pwy$ – the effective power output corresponds to the average annual intake capacity of geothermal heat:

$$Pwy = 1{,}14 \times 10^{-3} \times Vw \times (TS - TZ) \quad [\mathrm{W}], \quad (7)$$

where:
$Vw$ – the nominal capacity of potential mining hole [m³·h$^{-1}$],
$TS$ – temperature at the ceiling of hydrothermal reservoir [˚C],

*TZ* – chilled water temperature turned up to the hydrothermal level [˚C].

The effective power input (*Pwe*) relates to the capital outlay for the construction of geothermal shot and the costs of its operating, expressed as an equivalent of thermal power. It can be interpreted as the amount of heat that can be obtained per unit of time with an alternative way of financial resources:

$$Pwe = 3{,}17 \times 10^{-8} \times (I/t) + Ka \times W/CP \ \ [\mathrm{W}], \qquad (8)$$

where:
*I* – total capital expenditures for construction of intake [zł],
*I/t* – annual capital expenditures [zł/r],
*W* – the calorific value of the alternative fossil fuel [MJ/j.p.],
*Ka* – annual operating costs [zł/r],
*CP* – alternative of fossil fuel price [zł/j.p.].

## ACQUISITION OF GEOTHERMAL ENERGY

Acquisition of GE requires the use of appropriate systems for the extraction of the surface [33]. GE systems can be divided into direct use systems and systems with forced flow of heat-transfer medium [6]:
- the natural geyser system in which heat-transfer medium is extracted to the surface in the form of a geyser,
- the natural hot springs in which heat-transfer medium is extracted to the surface in the form of warm, hot or overheated geothermal water,
- the natural system in which the heat transfer medium is isolated from volcanic outbreaks,
- the artificial system in which the natural heat transfer medium under the effect of artesian hydrostatic pressure is input into the surface to the operating system,
- the artificial system in which the access to the deposit of magma is obtained by artificially made hole ending near the magma,
- the artificial volcanic system in which to the fire of volcanic or magma a smooth shaft or large-diameter hole runs at the bottom of which explosives are placed. As a result of the outbreak a stream of magma comes to the surface and creates a lava lake in a suitably prepared container.

The basic elements of the system's acquisition and development of GE are:
- the geothermal deposit – usually in the form of geothermal aquifer,
- the access channels to the deposit, that connect the operating level with the surface,
- the liquid heat transfer medium,
- the underground equipment such as submersible pumps, heat exchangers,
- a set of devices that enable the use of geothermal water for heating and technological purposes,
- a set of devices capable of converting GE into electricity (for the relevant parameters of geothermal water),
- a set of assistive devices in the case of a low-temperature of thermal energy carrier [6].

An essential part of each mining system is access channels to the bed. There are natural and artificially created channels. Artificial channels make it easy to design the geothermal intake according to the needs of customers.

Among the GE systems using artificially made access channels to geothermal deposits the following can be distinguished:
- the single hole operating system with automatic outflow of geothermal water with low degree of mineralization with artesian pressure,
- the single hole operating system with low degree of water mineralization a low degree of mineralization from the aquifer and by use of submersible pump,
- the single hole open operating system of geothermal with low degree of water mineralization and by use of submersible pump with artificially increased permeability of the deposit near the mining hole,
- the single hole mining and forcing water into the ground system used for the extraction of geothermal water with high degree of water mineralization. In this case it is taken from the field in the lower part of the bed and injected into the bed located above,
- two holes system, which a is closed system used in the case of mineralized geothermal waters with two holes: mining and forcing water into the ground.
- two holes energy receiving system from hot rocks artificially generated water permeability, where heat removal takes place in a forced water circulation [27].

The effectiveness of the construction of the geothermal approach can be determined by cost index (κ), which expresses the ratio of expenditure of underground works (boreholes) to the nominal heat power of geothermal water stream [34]:

$$K = Ko \cdot Nt^{1} \ \ [\mathrm{zł/MW}], \qquad (9)$$

where:
*Ko* – cost of the drilling [zł],
*Nt* – the nominal heat power of geothermal shot [MW].

The value of *Ko* is dependent on the depth of aquifer and can be expressed as [29]:

$$Ko = a\exp(bH) \ \ [\mathrm{zł}], \qquad (10)$$

where:
*H* – hole depth [m],
*a* and *b* – the cost factors, the value of which depends, among others from the structure and hardness of the rock in a drill place.

The nominal heat power of geothermal shot (geothermal dublet) can be calculated as follows:

$$Nt = V\rho \ cp(T - Tz)2{,}78 \cdot 10^{-7} \ \ [\mathrm{MW}], \qquad (11)$$

where:
*V* – the flow of extracted water [$m^3 \cdot h^{-1}$],
*ρ* – geothermal water density [$kg \cdot m^{-3}$],
*cp* – the heat of geothermal water [kJ/kgK],
*T* – temperature of geothermal water [K],
*Tz* – the temperature of forcing water into the ground [K].

The volume flow of geothermal water possible to extract from a geothermal deposit is calculated from the formula described by Darcy-Dupuita [28]:

$$V = 2\pi kmS/\ln(R/r) \quad [\mathrm{m^3 \cdot s^{-1}}], \qquad (11)$$

where:
$k$ – bed filtration coefficient [$\mathrm{m \cdot s^{-1}}$],
$m$ – squashing of geothermal deposit [m],
$S$ – depression of water in the hole [m],
$r$ – radius of hole mining near the filter [m],
$R$ – radius of the cone of depression [m].

It follows from the formula that the amount of extracted geothermal water depends on the mining hole design, filtration properties and volume of rocks forming the geothermal water reservoir.

## ECONOMIC USE OF GEOTHERMAL ENERGY

GE is used directly and indirectly. The direct, or "non-electric" use of GE is energy used directly (swimming pools and spas, use in agriculture, in water farms, use in industrial, heating and cooling facilities, including district heating and heat pumps) and indirect use of GE is converting it into electricity [2, 13, 24].

The use of geothermal water for spas and recreation goes back to prehistoric times. Warm bath water is one of the oldest procedures used to improve or maintain health [22]. Iceland is well known to be the world leader in the use of geothermal district heating. The island operates 130 pools of the area. 27 tys.m², filled with water at the temperature of 35 – 42°C, which are generally available. The most famous ones are Medical Clinic in Hveragerdi and Blue Lagoon Geothermal Spa. Japan has more than 2.200 resorts with hot springs, for example, in the town of Beppu geothermal waters are recommended for diseases of the digestive system, nervous system and skin problems. There are many medical and thermal baths and spas all over Hungary. For example, the thermal spa in Hajduszoblszlo is characterized by a source of geothermal water at the temperature of 73°C, rich in iodine, bromine, sodium chloride, and trace elements. The spa is recommended for musculoskeletal disorders, arthritis, myositis, hypothyroidism, dermatitis. Slovakia has more than 30 resorts with swimming and therapeutics based on geothermal waters, the most famous centers are: Lucky and Oravice of geothermal pools with water temperatures above 30°C.

Spa tourism and balneotherapy are popular in Turkey. There are about 1000 known natural geothermal water sites in Turkey and 194 geothermal spas where geothermal water at the temperature of 36°C are used to treat heart and skin disease and hypertension. In Poland, there are currently 7 spas using geothermal water at temperature from 19 to 45°C form natural sources and wells. They are located in: Ciechocinek, Cieplice Śląskie, Duszniki Zdrój, Iwonicz Zdrój, Konstancin, Lądek Zdrój i Ustroń. The oldest resort in Poland is Lądek Zdrój, the first information comes from 1241. There are six sources of water treatment at the temperature from 20 to 45°C deposited at the depth of 700 m, used in the treatment of the musculoskeletal system, nervous system, skin diseases and respiratory diseases [11]. The seven new swimming and leisure facilities are created In Poland, in the years 2006 – 2011. The most famous of them are located in: Zakopane, Bukowina Tatrzańska, Uniejów and Białka Tatrzańska [15].

GE is used in agriculture for greenhouses heating, soil heating and irrigation, as well as for the decay of biomass. Geothermal heating of greenhouses is practiced in Tunisia, Hungary, Russia, New Zealand, Japan, Iceland, China and the United States. The use of GE for heating reduces the cost of production, which can be as much as 35% of the value of the product. Besides this, GE can be used in colder climate where normal commercial-scale greenhouses would not be cost-effective [25].

GE is directly used in production of mushrooms, fish and animals. There have been successes in water cultures: catfishes, shrimps, eels, trout, snails, alligators conducted in Japan, China, the USA and New Zealand. The use of geothermal heat allows to adjust the temperature of joints, thereby optimizing the growth of breeding material. The use of GE on the farm animals, by adjusting heating and cooling environment stimulates domestic growth, reduces the mortality rate of young, increases litter size, allows to control the disease, facilitates the removal of waste. Geothermal solutions are also used for cleaning, sterilizing and drying facilities for the animals, as well as the alternative in the production of biogas from waste [26].

The geothermal heat is used directly in the industrial scale for drying: agricultural products, fish meal, seaweed, wood construction and dehydration of highly concentrated solutions. Examples of industrial applications of GE are boric acid extraction from geothermal brine (Italy), drying of diatomaceous earth (Iceland), processing of wood and pulp (New Zealand), fermentation of sludge (USA) [26]. GE can also be used directly for the production of drinking water by distillation of sea water [30].

GE is widely used in air conditioning room, which includes both heating and cooling. Heating by the central heating network depends on the delivery hot water or steam from a central source to individual buildings, apartment blocks by the piping network. Supplied thermal energy is used for heating and cooling and for domestic hot water. The primary source of heat is geothermal deposit, but depending on the temperature of the geothermal water and the demand of consumers, district heating can be supplied by the associated system, including fossil fuel and/or heat pumps. Geothermal district heating systems exist in at least 12 countries, including Iceland, France, Poland, Hungary, Turkey and the USA.

Today, in many countries, especially the United States, Switzerland and Germany a lot of heat pump systems are installed with the ground or ground water (groundwater, geothermal heat pumps).

The temperature of groundwater reservoirs and ground use in these systems ranged from 5 to 30°C. Ground source heat pumps use ground water or receive heat through borehole heat exchangers. Geothermal heat pump can be used for both heating and cooling. Types of heat pumps which can be adapted for use of GE are the water-to-water pumps and water-to-air pumps.

According to Mokrzycki [26], the use of GE in the world is as follows: heating – 37%, spa, swimming pools, baneology – 22%, heat pumps for cooling and heating – 14%, greenhouses – 12%, fish farmers – 8%, industrial – 7%.

Generation of electricity using GE is carried out in 24 countries. The countries which generate more than 15% of the total amount of electricity include: USA, Philippines, Indonesia, Mexico, Italy, Japan, New Zealand, Iceland, El Salvador, Costa Rica, Kenya [3].

There are two basic types of geothermal power plants: steam power plants and binary plants. In steam power station generation of electricity is by using the geothermal water vapor. This system is not widely used, because the use of this solution is limited to the areas of the world where during the extraction of geothermal fluid the dry saturated steam is obtained. In the world there are two such deposits: Larderello in Italy and Geysers in the U.S. [8].

Binary circuit – (two-medium) is used when the geothermal water is highly mineralized, chemically aggressive and its temperature is below 1500°C. In the binary power stations two fluids are working: geothermal water and the working medium with temperature is much lower than temperature of geothermal water. The technological processes used to produce electricity in binary systems are an organic Rankine cycle (ORC) and the Kalina cycle. In both cases, the geothermal water gives off heat in the evaporator, evaporating it at the same time. In the case of ORC, there are organic agents, while in the case of installation based on the Kalina cycle, the ammonia-water mixture [8]. Globally, there are 75 geothermal power plants, where production of electricity is based on the Kalina Cycle or ORC. Especially noteworthy are plants operating in Kalina cycle, since they are characterized by the highest values of electrical power. These are the plants situated in Hsaviku (Iceland), in Unterhaching and Bruchsal (Germany) [10].

## THE USE OF GE IN THE WORLD AND IN EUROPE

According to the data presented at the World Geothermal Congress 2010, GE is used directly in 78 countries, and the generation of electricity takes place in 24 countries around the world. At the end of 2009 the total installed capacity for direct use in the world was 50585 MW and heat consumption reached 438073 TJ. The largest share in the world in terms of installed power and consumption of heat belongs to central heating, recreation and therapeutics. In 2009, the total installed capacity for direct use in European countries was 23469 MW and heat consumption 233 737 TJ, representing, respectively, 46.7% and 50.8% share in the world. In terms of total use of geothermal heat, the top five countries are China, the U.S., Sweden, Turkey and Japan, which account for the total of 55% of annual consumption in the world [16].

In 2010, the total installed power of all the geothermal power plants in the world reached the value of 10716 MW and electricity production was 67246 GWh. At the forefront of countries producing electricity in geothermal power plants in the world are: the United States, the Philippines, Indonesia, Mexico and Italy.

In 2010, the total installed capacity of geothermal power plants in Europe amounted to 1553 MW of electricity and the production of electricity had the value of 12372 GWh, making up respectively 14.5% and 18.4% of the "geothermal" generation of electricity in the world [16].

## CONCLUSIONS

GE is a renewable source of energy that can be used economically in many parts of the world, both directly and indirectly to generate electricity. It provides not just heat and steam, but electricity itself. Geothermal power generation is completely clean, and releases no harmful gas emissions. GE can be used in aquaculture, horticulture, industry, food processing, and for providing heat for heating buildings.

There is a continuous increase in the development of GE, which could have a significant contribution to mitigating climate change as well as in the implementation of sustainable energy development. In many countries, it is a promising source of renewable energy, which in contrast to other renewable energy sources is available without restrictions throughout the year and not very sensitive to changes in the prices of traditional energy in the world markets.

GE increases local energy security, therefore it is a reliable source of energy and, according to the Declaration of the World Geothermal Congress 2010 – "GE can change the world"

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## POZYSKIWANIE I GOSPODARCZE WYKORZYSTANIE ENERGII GEOTERMALNEJ

**Streszczenie.** Energia geotermalna to energia pochodząca z wnętrza Ziemi, zakumulowana w wodzie, parze wodnej oraz gorących suchych skałach. Całkowite zasoby energii geotermalnej przekraczają one 35 bilionów razy obecne, globalne zapotrzebowanie na energię. Energia geotermalna jest odnawialna, występuje powszechnie, jest niezależna od zmieniających się warunków klimatycznych co daje możliwość jej gospodarczego wykorzystania. W artykule przedstawiono podstawowe informacje dotyczące energii geotermalnej, sposobów jej pozyskiwania i wykorzystania. Omówiono również metody obliczania zasobów energii geotermalnej.

**Słowa kluczowe:** energia geotermalna, odnawialne źródła energii.