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Geological Analysis and Assessment of Geothermal Energy Resources in the Polish Lowlands

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ABSTRACT

This paper presents the results of geothermal energy resources calculation of the main geothermal aquifers and possibilities of utilization of geothermal waters in the Polish Lowlands.

Research studies undertaken in 2004-2006 at the AGH-University of Science and Technology - Department of Fossil Fuels enabled the recognition of geothermal potential accumulated in Mesozoic and Palaeozoic groundwater horizons (from the Cambrian to the Lower Cretaceous).

The main purpose of the study was to estimate geothermal water and energy resources in respective categories and to indicate areas which are characterized, in a regional scale, by favourable geothermal conditions that would evidence their industrial usability.

The results of calculation were published in December 2006 in the form of “Atlases of geothermal resources in the Polish Lowlands” (Górecki [Eds.], 2006a; Górecki [Eds.] 2006b).

Research project covers majority of the area of Poland (87 percent) and focus mainly on the regional scale assessment.

1. INTRODUCTION

As a member of the European Union Poland aims at achieving sustainable development in which the economy, environment and mineral resources protection are integrated into a coherent system. For Poland, important is the standpoint of the European Union where current preferences aim at the reduction of greenhouse-gas emissions and other pollutant releases by an extension of the role of renewables. Among the various renewable energy sources available in Poland, geothermal energy may play an important role in both the local and regional energy balances.

The country is characterised by significant low-enthalpy geothermal potential, connected mostly with the Mesozoic sediments. Space heating represents the most important type of direct uses.

The principal resources of geothermal waters in the Polish Lowlands are reservoired in the Mesozoic groundwater horizons. Geothermal waters are accumulated first of all in the Lower Jurassic and Lower Cretaceous formations but significant resources of geothermal energy are reservoired also in the Upper Jurassic, Middle Jurassic, Upper Triassic and Lower Triassic formations.

Research studies undertaken in last years at the Department of Fossil Fuels enabled the recognition of geothermal potential accumulated in Palaeozoic groundwater horizons (from the Cambrian to the Permian). Identification of geothermal conditions in Palaeozoic sequences is an important supplement to our knowledge on domestic resources of geothermal energy in the Polish Lowlands.

The obtained results of calculation offer new prospects for the extension of geothermal energy use and may influence increasing of contribution of renewables in Poland in the near future.

2. GEOLOGICAL BACKGROUND

The Polish Lowlands occupy the area between the Baltic Shield in the northeast, the Sudetes Mountains massif in the southwest and the Lower San River Anticlinorium in the southeast. The Lowlands form an intercratonic deep, filled with Palaeozoic and Mesozoic sediments overlain by a thin Cainozoic cover.

Based on seismic investigations, the total thickness of the sedimentary cover in the deepest area of the Palaeozoic part of the basin can reach as much as 20 km (Guterch et. al., 1999). The sediments are, however, much thinner within the Precambrian craton. The thickness varies from 200 to 500 m in NE Poland, where the Cainozoic-Mesozoic sediments directly overlie the crystalline Precambrian basement, up to 8 km southwest of the craton. Two structural complexes are present: a lower unit of Cambrian to Silurian age and an upper unit of Permian to Cainozoic age. The basement of the Permian-Mesozoic sedimentary basin within the Palaeozoic Platform consists of Carboniferous, Devonian and older formations, folded during the Variscian Orogenesis. The base of the Permian sediments reaches 5-7 km depths in central Poland and at the northwest margin of the Palaeozoic platform, decreasing to the southwest, south, east and northeast. Upper Permian strata consists mostly of evaporate sediments which were formed during the Laramide tectonic phase. The large Mesozoic sedimentary basin was deformed during the Laramide tectonic phase between the Cretaceous and Tertiary periods. During this phase the plastic salt layer was pressed up to the surface, piercing almost 6 km thick overlying Triassic, Jurassic and Cretaceous deposits. Increasing tectonic movements split the basin into two sub-basins: the Szczecin-Lodz synclinorium and the Grudziadz-Warsaw synclinorium. Between them the Central-Polish anticlinorium was formed. Mesozoic structures were eroded after this deformation, and later covered by flat-lying Tertiary and Quaternary horizontally lying sediments.

Figure 1: The extent of the main geothermal aquifers in the Polish Lowlands.

3. METHODOLOGY OF CALCULATION OF GEOLOGICAL RESOURCES AND ESTIMATION OF DISPOSABLE RESERVES

Estimation of geothermal energy reserves in respective categories and indication of areas characterized, in a regional scale, by favourable geothermal conditions required analysis of the basic economical parameters influences the industrial usefulness of geothermal waters as a source of heat.

All calculations were run with the use of OpenWorks integrated geological data processing system developed by the Landmark Graphics Co. The software is licensed under the conditions of educational license No. 2003-COM-020272 and 2003-COM-020273, granted to the Department of Fossil Fuels UST-AGH. Numeric data processing methods commonly used in petroleum exploration as well as implementation of specialized software let of automation of calculations and make possible to run multi-variant analysis of principal hydrogeothermal parameters.

3.1 Economic evaluation of hydrogeothermal aquifers

Disposable reserves of geothermal energy of given aquifer constitute an assessed part of static-recoverable resources, which utilization is efficient from economic point of view. Estimation of disposable reserves requires the effectiveness analysis of geothermal energy utilization in order to select those parts of geothermal aquifer where exploitation of thermal energy will be cost-effective. Below, the methodology of economic evaluation is presented, based upon financial criteria. It must be emphasized that, although financial criteria are crucial for investment decisions, these are not always the only factors considered during evaluation of geothermal reservoir, particularly if infrastructural investments are discussed, which stimulate development of various existing and new, environmentally friendly branches of local economy. However, additional, social and economic benefits can be known in detail not earlier than during the analysis of particular investment project whereas the regional analyses should provide rather information on potentially most profitable localizations of future investments.

3.1.1 Methodology of economic evaluation of hydrogeothermal aquifers

Principal factors affecting the economic effectiveness of geothermal energy can be categorized into three groups related to:

a) reservoir properties,

b) utilization modes of extracted heat,

c) social and economic constrains.

Properties of hydrogeothermal aquifers are controlled by geological and hydrogeological factors, which values are objective and constant. On the contrary, the remaining two categories are only partly and indirectly dependent (and, in most cases, independent) on reservoir properties. Taking into account specific assumptions and identifying relationships between the variables, it is possible to present the economic effectiveness of geothermal energy exploitation in particular aquifer as a function of only its reservoir properties. Determination of investment expenditures, production costs of installation and recovery of accumulated thermal energy in reference to reservoir properties of a hydrogeothermal aquifer leads to the selection of a criterion, which can justify the incipient decision on exploitation of the reservoir. Resulting mathematical formulae should consider those reservoir properties which decisively influence the economic efficiency. i.e.:

- hydraulic transmissivity of rocks - which determines the capacity of rocks to convey fluids and which influences the power of production and injection pumps;

- temperature of produced geothermal water - which controls the thermal power of heating installation;

- depth to geothermal reservoir - which decisively controls drilling costs, i.e. the main component of investment expenditures.

In order to assess the resources of geothermal aquifer, these properties can be expressed as dimensionless coefficient, so-called „power factor" given by the following formula (Gosk, 1982):

$$F = \frac{\text{effective power output}}{\text{equivalent thermal power}} = \frac{P_{out}}{P_{inp}}, [\ -\ ] \qquad (1)$$

3.1.2 Effective power output

It is assumed that effective power output corresponds to mean annual thermal power of geothermal waters intake (=geothermal installation, understood here as a set of devices enabling production of geothermal waters and recovery of accumulated heat), which is given by the following formula:

$$P_{out} = LF \cdot Q \cdot q_w \cdot c_w \cdot \left(T - T_z\right), [\ \mathrm{W}\ ] \qquad (2)$$

where:
LF - mean annual load factor of an intake; Q - rated discharge of geothermal water [m^3/s]; ρ_w - density of geothermal water [kg/m^3]; c_w - specific heat of geothermal water [J/kg^oC]; T - temperature of produced geothermal water [^oC]; T_z - temperature of waste water (i.e. geothermal water after heat recovery) [^oC].

Mean annual load factor of an intake (LF) reflects the degree to which rated thermal power of a geothermal intake is utilized. Its value depends on planned system of heat utilization and falls into the range 0 to 1. The LF=1 corresponds to continuous operation of an intake at constant, rated thermal power. Assuming some parameters and constants (ρ_w c_w=4.1 MJ/kg^{o}C) and assuming the temperature of waste water as 25^{o}C, the effective power output can be expressed as:

$$P_{out} = 1.14 \cdot 10^{-3} \cdot LF \cdot Q \cdot \left(T - T_z\right), [\text{ W }] \tag{3}$$

If LF = 1, the rated thermal power of geothermal waters intake (=geothermal installation) is:

$$P_{out} = 1.14 \cdot 10^{-3} \cdot Q \cdot \left(T - T_z\right), [\text{ W }] \tag{4}$$

3.1.3 Equivalent thermal power

Equivalent energy input corresponds to capital expenditures required for construction of geothermal waters intake and its running cost, expressed as an equivalent of thermal power. It can be interpreted as the amount of heat, which can be recovered in time unit if given financial resources were used for construction and operation of an alternative energy source:

$$P_{inp} = 3.17 \cdot 10^{-8} \cdot \left(I/t \right) + K_a \cdot W/CP, [\text{ W }] \tag{5}$$

where:
I - total capital expenditures spent for geothermal waters intake [USD]; t - life time of installation in years (25 years was taken for calculations); I/t - annual investment expenditures [USD/year]; Ka - annual running costs of geothermal doublet [USD/year]; W - calorific value of alternative fossil fuel [MJ/unit] (unit of fuel, e.g. ton or cubic meter); CP - unit price of alternative fossil fuel [USD/unit].

Estimation of capital costs necessary for construction of geothermal waters intake requires the calculation of expenditures for principal installations: production and injection wells, heat exchangers, pumps, supply pipeline, buildings and engineering works. Additionally, development and incidental expenditures must be included. All these costs were estimated basing upon cost calculations and applying the exponential and factor expenditure interpolation methods, and expressing them as functions of e.g., hydrogeothermal reservoirs properties. In order to simplify the estimation of running costs of geothermal water intakes, these costs were divided into the two groups: costs determined as percentage of investment expenditures spent for construction of intakes (including repairs, maintenance, overheads, administration) and costs proportional to production rates of intakes (costs of electric energy used for pumping). Similarly to capital expenditures, the running costs were expressed as functions of hydrogeothermal reservoirs properties.

3.1.4 Power factor

Basing upon formulae and assumptions discussed above, the following dependence between of power factor F and the principal reservoir properties of hydrogeothermal aquifers was determined:

$$F = \frac{1.14 \cdot 10^{-3} \cdot LF \cdot Q \cdot \left(T - 25\right)}{1.078 \cdot 10^{-3} \cdot \left(312 \cdot 10^{-3} \cdot \exp\left(0.00078 \cdot H\right)\right)}$$

$$\overline{+825 \cdot \left[Q \cdot \left(T - 25\right)\right]^{0.6} + 2.55 \cdot \left[\frac{Q^2}{\left(k \cdot m\right)}\right]^{0.6}}$$

$$\overline{+1.033 \cdot 10^{-5} \cdot \left[\frac{Q^2}{\left(k \cdot m\right)}\right]} \tag{6}$$

where:
k - hydraulic conductivity coefficient [m/s]; m - thickness of groundwater reservoir [m]; H - depth to groundwater reservoir [m]; LF - mean annual load factor of an intake; Q - rated discharge of geothermal water [m^3/h]; T - temperature of produced water [^{o}C].

It was assumed that alternative fuel considered in the calculations will be hard coal of calorific value 25 GJ/ton and unit price 50 USD/ton. Power factor is a value which expresses how many times thermal power of a geothermal intake exceeds thermal power equivalent of capital expenditures and running costs of this intake. Such definition corresponds to effectiveness criterion, i.e. the ratio of effects to expenditures, which means that the higher is the ratio, the higher is the effectiveness. The power factor value <1 points out that „thermal equivalent" of expenditures is higher than thermal energy produced. Hence, this is an indicator which reflects both the energetic value of geothermal resources and the economic sense of their exploitation. The power factor is a quasi-economic indicator as it is a comprehensive representation of economic and energetic aspects of groundwater heat exploitation. However, it cannot be the base for conclusions on competitiveness of geothermal heat production in relation to conventional heat-generation technologies.

3.1.5 Estimation of disposable reserves

The power factor was applied to determination of disposable geothermal energy resources of studied aquifers (Górecki [Eds.], 1995). Such resources were calculated for the areas in which power factor value F > 1 and load factor value LF = 1, i.e. for the areas where economic efficiency of geothermal waters utilization is probable. The condition LF = 1 results from an assumption that for disposable reserves calculations the power factor value should not be obligatory limited depending on planned utilization mode of geothermal energy.

Disposable reserves (E_{disp}) defined as the assessed part of static-recoverable resources, which exploitation is economically efficient, were determined as the amount of energy which can be generated during the year.

4. CLASSIFICATION OF GEOTHERMAL RESOURCES.

In the world literature the standard, uniform terminology defining unequivocally the categories of geothermal resources does not exist (Dickson, Fanelli, 2004). The most commonly applied classification criterion is the temperature (= enthalpy) of thermal energy carriers.

Practically, this classification is based upon the energetic value of geothermal resources. Due to such value, Bonneviale (1990) selected the resources suitable for electricity generation (temperatures over 150°C) and the resources suitable for direct utilization (temperatures below 150°C).

In Poland geothermal energy is accumulated in groundwaters of temperatures usually below 90°C or, rarely, somewhat higher than 100°C. Therefore, these resources can be classified into the low-temperature (low-enthalpy) class. Another classification system considers the geological recognition of geothermal resources together with ecological, technical and economic aspects of their development, exploitation and utilization. The resulting classification is following (Górecki et al., 1993, 1994, Górecki [Eds.], 1995):

- the accessible geothermal energy resources mean the amount of thermal energy accumulated in the Earth's crust down to 3 000 m depth or to the top surface of crystalline basement, referred to the mean annual temperature of the Earth's surface and expressed in [J]. For areas where geothermal waters of low unit enthalpy occur the accessible geothermal resources E_{acc} (expressed as the amount of accumulated heat per area unit) are calculated according to the following formula:

$$E_{acc} = V_s \cdot \rho_s \cdot c_s \cdot \frac{T_h - T_o}{2A}, \; [\,J/m^2\,] \qquad (7)$$

where:
V_s - volume of rocks from the Earth's surface down to 3 000 m depth [m^3]; ρ_s - mean density of rocks down to 3 000 m depth [kg/m^3] (taken as 2 200 kg/m^3); c_s - mean specific heat of rocks down to 3000 m depth [J/kg°C] (taken as 840 J/kg°C); T_h - temperature at 3 000 m depth or at the top surface of crystalline basement [°C]; T_o - mean annual temperature at the Earth's surface [°C]; A - area of calculation block [m^2].

- the static resources of geothermal waters and energy are the amounts of free (gravitational) geothermal water hosted in pores, fractures or caverns of given hydro geothermal horizon, expressed in [m^3] or [km^3], recalculated into the energy units [J]. These resources are calculated if the recognition of continuous groundwater reservoirs or horizons is possible in the given area. Basing on determined properties of groundwater horizons: lithology, thickness, porosity and permeability, the identification of producing reservoirs and horizons is possible. The static geothermal resources E_{stat} are calculated according to the following formula:

$$E_{stat} = A \cdot m_p \cdot \left[(1 - pe) \cdot \rho_r \cdot c_r + p_e \cdot \rho_w \cdot c_w\right] \cdot \left(T_s - T_o\right), \; [\,J\,] \qquad (8)$$

where:
mp - cumulative thickness of groundwater horizons in the reservoir [m]; pe - effective porosity [-]; Ts - temperature at the top surface of groundwater reservoir [°C]; To - mean annual temperature at the Earth's surface [°C]; ρr and ρw - mean density of rock framework and water, respectively [kg/m^3]; c_r i c_w - mean specific heat of rock framework and water, respectively [J/ kg°C]; A - area of calculation block [m^2].

It can be concluded from this formula that Estat is a total amount of heat accumulated in free water and in rock framework, referred to given area of calculation block.

- the static-recoverable geothermal waters and energy resources constitute only a part of the static resources diminished by the recovery index Ro, expressed in [m^3] or [km^3], recalculated into the energy units [J]. The static-recoverable geothermal waters and energy resources are a part of static resources of given groundwater reservoir or horizon, which can be produced with the given exploitation systems: doublet (triplet, etc.) system (production and injection wells) in which produced geothermal water is injected back to the reservoir or horizon after heat recovery and single system (production well) in which produced geothermal waters are not returned back to the reservoir. It is applied for geothermal reservoirs or their fragments in which fresh or low-TDS waters occur. As in the hydrogeothermal reservoirs of Polish Lowlands only high-TDS groundwaters occur, the static-recoverable resources were calculated for doublet system. The recoverable part of geological resources is represented as the recovery index Ro of thermal energy from given reservoir or horizon. For geothermal doublet this parameter is calculated from the following formula:

$$R_o = \frac{A_{cool}}{A_{tot}} \cdot \frac{T_{top} - T_{inj}}{T_{tot} - T_o}, \; [\,-\,] \qquad (9)$$

where:
A_{cool} - cooled area of the doublet [m^2]; A_{tot} - total area affected by the doublet [m^2]; T_{top} - temperature at the top surface of groundwater horizon [°C]; T_{inj} - temperature of water injected back to the horizon (=25°C); To - mean annual temperature at the Earth's surface [°C].

The ratio of cooled area to total area affected by geothermal doublet was taken as empirical constant value based upon long-term experience gained from the operating geothermal installations in the Paris Basin (France). The following, simplified values of this parameter were taken for calculations: for geothermal doublet - 1:3 = 0.33; for single well - 1:10 = 0.1. The map of recovery index was constructed by the superposition of two maps: map of temperatures at the top surface of given geothermal horizon and map of mean annual temperatures at the Earth's surface. The map of unit static-recoverable resources for geothermal doublet was constructed with the superposition of two maps: map of recovery index and map of unit static resources, according to the following formula:

$$E_{statr} = E_{stat} \cdot R_o, \; [\,J\,] \qquad (10)$$

where:
R_o - recovery index; E_{stat} - static resources [J].

- the disposable geothermal waters and energy resources are the amounts of free (gravitational) geothermal water within the horizon or other calculation unit, which can be developed under given conditions but without detailed localization as well as technical and economic specification of an intake, expressed in [m^3/day], [m^3/year], [J/year] or [TOE/year]. Estimation of disposable reserves should be preceded by parametric/economic evaluation of given geothermal reservoir. The methodology of such evaluation is given in Chapter 4. The disposable reserves constitute a part of assessed static-recoverable resources, which utilization would be economically effective. The disposable reserves E_{disp} were determined as the amount of energy recoverable during 1 year from a geothermal doublet:

$$E_{disp} = Q \cdot \left(T_{top} - 25\right) \cdot \rho_w \cdot c_w \cdot 8760^{*} \text{, [J/year]} \quad (11)$$

where:
Q - rated discharge of potential production well [m^3/h], (Q_{max}=300 m^3/h); Ts - temperature at the top surface of groundwater horizon [^oC]; ρw - water density [kg/m^3]; cw - water specific heat [J/kg^oC], (=4180 J/kg^oC); * - coefficient resulting from lifetime of geothermal doublet (1 year= 8 760 hours).

For calculation of disposable reserves it was assumed that maximum discharge of geothermal water intake will not exceed 300 m^3/h. This limit results from technical constrains, among others from delivery rate of submersible pumps and quality of boreholes.

- the exploitable geothermal waters and energy resources are the amounts of free (gravitational) geothermal water, which can be produced at given geological and environmental settings with intakes of optimum technical and economic parameters, expressed in [m^3/h], [m^3/day] at relevant drawdown, recalculated into [J/year] or [TOE/year]. The exploitable resources are assessed basing upon the results of all hydrogeothermal studies and tests made in exploration and production wells, and are determined for a single production well or for a cluster of wells.

Both the accessible and the static geothermal energy resources have exclusively the cognitive meaning whereas the disposable and, particularly, the exploitable resources are of practical importance. Therefore, the geothermal energy resources in Poland commonly cited in various papers and reports as tens of billions, or even over 100 billions TOE are only the theoretical values of heat accumulated in groundwaters. These values, by no means, cannot be identified as resources, which can be practically (= commercially) recovered and utilized under economic effectiveness conditions (even if preference financing is available).

Evaluation of exploitable resources and feasibility studies of geothermal installation construction must consider the following conditions:

- energy recovered from geothermal waters can be utilized at the production site, hence, the exploitable resources will be limited to urban and/or rural areas, industrial zones and recreational centres;

- due to high capital costs of geothermal investments, local heat market must be very attractive for potential investors;

- construction of geothermal installations is naturally limited to the areas where geothermal waters of optimal parameters occur.

The estimation of geothermal energy resources requires the determination of energy carrier reserves (i.e. geothermal waters). In the calculations these reserves were omitted and only the energy resources accumulated in these waters were calculated.

5. METHODOLOGY OF CALCULATION OF GEOTHERMAL WATERS AND ENERGY RESOURCES

The methodology estimation of geothermal energy of resources accumulated in geothermal aquifers in the Polish Lowlands was compiled from various publications, e.g.: Muffler (1975), Gringarten and Sauty (1975), Gringarten (1979), Muffler and Cataldi (1979), Gosk (1982), Haenel (1982), Koppe et al. (1983), Sorey et al. (1983), Haenel and Staroste, (1988), Górecki et al. (1993), Górecki [Eds.], (1990, 1995).

Calculations of geothermal energy resources were based upon the volumetric model (Muffler and Cataldi, 1979) with the application of digital mapping methods. Determination of geothermal resources (particularly the disposable and the exploitable resources), which unifies the geological and the economic aspects required the different attempt and the redefinition of some resources categories given in the relevant hydrogeological regulations and publications (e.g. in the „Guide to the methodology of determination of disposable groundwater resources” by Paczyński et al., 1996). The commercial utilization of groundwaters usually means only their discharge. Such attempt differs from groundwater utilization with geothermal doublet system where produced water is injected back to the reservoir after heat recovery. Thus, for such production system it could be assumed that the calculation of dynamic resources is unnecessary because hydrodynamic balance within the given reservoir or horizon remains undisturbed.

6. CHARACTERIZATION OF DOCUMENTARY MATERIALS AND METHODOLOGY OF INTERPRETATION

The included materials can be divided into several groups, according to their sources:

- well data: for construction of 11 structural maps data from 5030 wells drilled in the Polish Lowlands were taken into consideration. After data processing of 2831 well were selected for assessment of geothermal aquifers in the Polish Lowlands. Apart from lithostratigraphy, some of them supplied petrophysical and hydrogeological information collected during sampling, drill-steam tests, test pumpings, etc. Well-log geophysics provided logs from 211 deep wells completed in the Polish Lowlands were used. Interpreted well-logs obtained from the State Geological Institute were supplemented by additional identification of groundwater horizons made for 550 wells at the Department of Fossil Fuels. From this number 294 wells penetrated the full thickness of considered lithostratigraphic units and only these wells provided input data for further interpretations.

- archival materials (digital and analogue maps, sketch maps, geological cross-sections) obtained during earlier studies were also included. Moreover, for construction of structural maps the analogue data were used together with sketch maps and tables. In order to determine the hydrochemistry of geothermal waters, chemical analyses from 232 wells were incorporated. Groundwater dynamics evaluations were based upon measurement in 263 deep wells and measurements in 586 shallow wells, which develop groundwater horizons of Cambrian to Lower Cretaceous age. Analysis of surface distribution of heat flow was made for 232 wells drilled in the Polish Lowlands. Temperatures at the top of particular stratigraphic units were measured in 177 wells and crustal temperatures were measured at the following depths: 1 000, 2 000, 3 000, 4 000 and 5 000 metres.

7. METHODOLOGY OF DATA INTERPRETATION

Due to broad spectrum of considered problems, large number of collected data and high diversification of datasets, various interpretation methods and techniques were applied supported by database tools (mostly MS Access) and basic statistical data processing procedures. The basic materials originated from:

- interpretation of lithostratigraphic columns: analysis of depths to structural surfaces and thicknesses of lithostratigraphic units. Works focused mostly on completion, unification and verification of archival well data.

- interpretation of well-log data: the interpretation included identification of groundwater and sealing horizons, and thickness proportions between horizons and seals in Palaeozoic and Mesozoic formations. Full stratigraphic columns were analyzed, excluding Cainozoic strata. All available data were taken into consideration: petrophysical properties of rocks, lithological and petrographic descriptions of drill cores and cuttings, available geophysical data (including Average Velocities Logs). Moreover, results of hydrogeological samplings in analyzed wells were incorporated. Unified interpretation criteria were applied for the full columns of Mesozoic and Palaeozoic formations with particular attention paid to hydrogeothermal aquifers. Basic element of interpretation was the construction of lithological profile based upon the well-log data. Analyses were run for single wells. The resulting lithological profiles are a geophysical generalizations of data contained in geological descriptions. Furthermore, parameters used in the interpretation were calibrated with the results of laboratory measurements. Parameters were determined with the iteration method and the selection accuracy of parameters was controlled by consistency of the results (i.e. general porosity and density) with laboratory measurements. If laboratory results for particular depth interval and particular formation were lacking, calibration parameters were estimated by analysing data from other wells. If even such data were unavailable, the arbitrary interpretation was made under general interpretation rules. Basic source data for porosity interpretation originated from Gamma and Neutron Logs supported by well diameter logs. These are the only well-logs which enable true porosity calculations for wells drilled in the Polish Lowlands. Obtained true porosity was then recalculated into effective porosity using statistical parameters determined for given lithotypes. Analysis of criteria applied for identification of groundwater horizons and seals indicates the complex influence of various parameters on final result. Basic petrophysical parameters: effective porosity and permeability, which were the crucial parameters, reveal high variability within the particular lithotypes. Additional complications were caused by fracturing of rocks, which might increase reservoir properties. Fracturing may become a dominating factor influencing the reservoir properties of Middle Triassic, Cambrian, Devonian and Carboniferous aquifers. Numerous analyses enabled the identification of potential groundwater horizons with the complicated criterion based upon both the lithology and the porosity. Among 84 lithologies defined in an integrated interpretation system four lithotypes were selected as potentially most effective groundwater horizons in the Polish Lowlands: sandstones, limestones, dolomites, gaizes. Additionally, all these lithotypes must show at least 5% true porosity. Both analyzed porosity types reveal strong linear correlation. Thus, the linear correction formula for true porosity was accepted for interpretation procedures. Relative error of porosity determination increases with the decreasing true porosity. Similar relationships were found for limestone, dolomite and gaize lithotypes.

- interpretation of hydrochemical data: first step of groundwater physical and chemical data verification was the evaluation of analytical procedures. For full analyses (including at least main components) relative balance error was calculated resulting from the difference between the number of positive (total cations expressed as normal concentration) and negative charges (total anions expressed as normal concentrations). If data on total solids were available, analytical error was evaluated by comparison with the TDS values resulting from ion balance. In the next verification steps the analyses were rejected for which „abnormal” concentrations of some components were encountered or if mutually exclusive analyses were found of waters from the same well or the same screen interval. Final verification of hydrochemical parameters (mostly the TDS) was run during three-dimentional interpretation of parameters. It enabled the control of both the vertical (geochemical gradient) and the horizontal TDS distribution, which led to a single, coherent model of TDS distribution in the top parts of groundwater aquifers in the Polish Lowlands.

7.1 Analysis of interpretation results of well-log geophysics and quantitative evaluation of hydrogeothermal parameters.

A separate interpretation problem was quantitative evaluation of well-log parameters: cumulative thickness of groundwater horizons and porosity of reservoir rocks in particular lithostratigraphic units from the Polish Lowlands. Results of well-log data interpretation for all wells are contained in the Access database. Density of measurements in particular geothermal aquifers were different. The highest number of wells documents the reservoir parameters (effective porosity) of Upper Jurassic aquifer (168 wells) and the lowest number deals with the Cambrian one (36 wells). It must be emphasized that regional ranges (areas) and depths to the top surfaces of particular aquifers are highly variable. In order to determine reservoir properties and to calculate geothermal resources accumulated in selected geothermal aquifers in the Polish Lowlands, effective porosity was estimated, according to the following formula:

$$\bar{p}_e = \frac{\sum m_w \cdot p_e}{\sum m_w}, [\,-\,] \qquad (12)$$

where:

p_e - weighted mean effective porosity of reservoir rocks in the column [%]; p_e - effective porosity of single groundwater horizon [%]; m_w - thickness of groundwater horizon [m].

For calculations of weighted mean effective porosity all identified groundwater horizons were taken, i.e. those which effective porosity was above zero. Analysis of averaged effective porosities (Figure 2) indicates that best reservoir properties occur in Lower Cretaceous (21.77%) and Lower Jurassic (18.85%) aquifers. Palaeozoic aquifers: Cambrian, Devonian and Carboniferous, reveal apparently lower averaged values of effective porosity. However, these formations may locally show favourable reservoir properties (high discharges) due to fracturing. Analysis of interpretation results of well-log geophysics provided essential information leading to quantitative evaluation of thicknesses of groundwater horizons (including the cumulative thickness) within the particular formations. For calculations of percentages of groundwater horizons only those datasets were considered which documented horizons in the full lithostratigraphic column (i.e. which penetrated the full thicknesses of given lithostratigraphic units).

8. METHODS OF ANALYSIS OF PRINCIPAL HYDROGEOLOGICAL PARAMETERS OF. GEOTHERMAL AQUIFERS IN THE POLISH LOWLANDS

Application of numerical data processing methods commonly used in petroleum exploration as well as the implementation of specialized software enabled to run multivariate analysis of principal hydrogeothermal parameters and automation of calculations. Calculations were run with the OpenWorks integrated geological data processing system developed by the Halliburton-Landmark Graphics Co.

Main interpretation of geothermal system parameters and quantitative calculations were run with the Z-MAP Plus software, which enables to interpret data with three-dimentional spatial grid (GRID). The software uses advanced, mathematical and geostatistical methods.

For accomplishment the principal aim of evaluation of geothermal energy resources in selected geothermal aquifers in the Polish Lowlands, several calculation steps had to be completed. Results of these steps were displayed in the form of the following maps:

- topographic map of the Polish Lowlands,

- map of mean annual temperatures,

- structural maps of the top surfaces of hydrogeothermal aquifers,

- maps of geothermal gradients (constructed from temperature interpretations in 231 wells completed in the Polish Lowlands:

$$G_T = \frac{T_s - T_p}{Z} \cdot 100 \text{ , [} ^oC/100m \text{]} \qquad (13)$$

where:
G_T - geothermal gradient [^{o}C/100m]; T_s - temperature at the top surface of geothermal aquifer [^{o}C]; T_p - mean annual temperature at the surface [^{o}C]; Z - depth to the top surface of studied hydrogeothermal horizon [m b.s.].

- maps of temperatures at the top surface of aquifers:

$$T_s = G_T \frac{Z_p - Z_s}{100} + Tp \text{ , [} ^oC \text{]} \qquad (14)$$

where:
T_s - temperature in the top part of particular aquifer [^{o}C]; G_T - geothermal gradient for the particular aquifer [^{o}C/100 m]; Z_p - altitude of the measurement site [m a.s.l.]; Z_s - altitude of the top surface of particular aquifer [m.a.s.l.]; T_P - mean annual temperature [^{o}C].

- maps of hydrochemical gradient, constructed from drillings data, obtained according to the following formula:

$$G_M = \frac{M_s}{Z} \cdot 100 \text{ , [} kg/m^3/100m \text{]} \qquad (15)$$

where:
G_M - hydrogeochemical gradient of particular aquifer [kg/m^3/100m]; M_S - TDS of groundwaters in the top part of particular aquifer [kg/m^3]; Z - depth to the top surface of particular aquifer [m b.s.].

- maps of the TDS of reservoir waters in the top part of hydrogeothermal aquifer - constructed by superposition of three maps, according to the following formula:

$$M_s = G_M \frac{Z_p - Z_s}{100} \text{ , [} kg/m^3 \text{]} \qquad (16)$$

where:
M_s - TDS of groundwaters in the top part of particular aquifer [kg/m^3]; GM - hydrogeochemical gradient of particular aquifer [kg/m^3/100m]; Zp - altitude of the measurement site [m a.s.l.]; Zs - altitude of the top surface of particular aquifer [m a.s.l.].

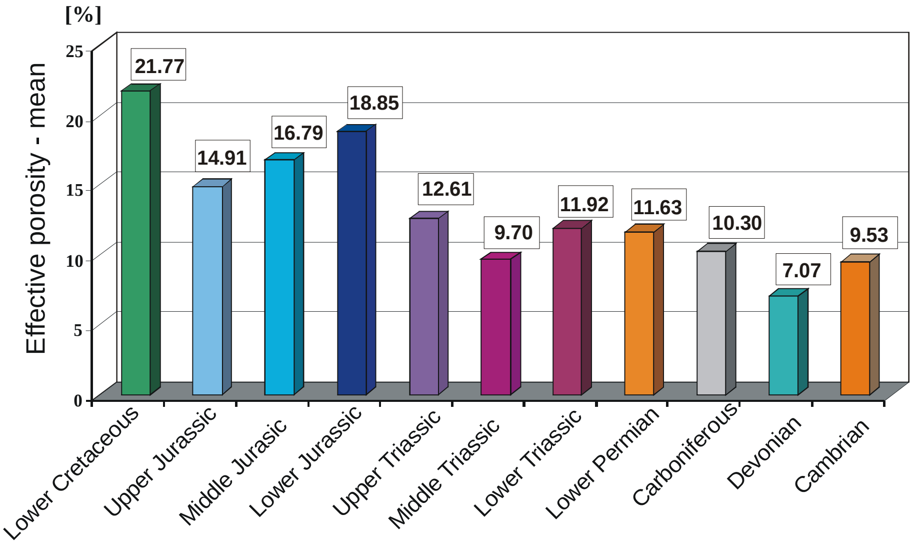

Figure 2: Averaged values of effective porosity in reservoir layers in the Polish Lowlands.

- maps of density of reservoir waters in the top part of hydrogeothermal aquifer- constructed by superposition of two maps, according to the following formula:

$$\rho_W = (998.2 + [\frac{700 \cdot M_S}{M_S + 998.2}] - 0.375 \cdot (T_S - 20) \text{ , [kg]} \quad (17)$$

where:
ρ_w - density of groundwaters in particular aquifer [kg/m^3]; M_s - TDS of groundwaters in particular aquifer [kg/m^3]; T_s - temperature in the top part of particular aquifer [^{o}C]; 998.2 - water density at M_s=0 i T_s=20^{o}C.

- maps of total thickness of particular stratigraphic units;

- maps of percentage of groundwater horizons in stratigraphic column;

- maps of cumulative thickness of groundwater horizons: calculated as a product of total thickness of strata and percentage of groundwater horizons in the stratigraphic column of particular stratigraphic unit, according to the following formula:

$$m_p = m_c \cdot m_{\%} \text{ , [m]} \quad (18)$$

where:
m_p - cumulative thickness of groundwater horizons in particular hydrogeothermal reservoir [m]; m_c - total thickness of particular hydrogeothermal reservoir [m]; $m_{\%}$ - percentage of groundwater horizons in total thickness of particular reservoir [%].

- maps of hydraulic conductivity coefficient: construction of these maps was based upon archival, laboratory permeability measurements of drill cores, carried on for the purpose of earlier research projects and collected in the hydrogeothermal database. In order to determine credible values of permeability coefficients for particular stratigraphic units, statistical data analysis was run for each parameter. Determination of permeability coefficients had to consider the fact that measurements results commonly refer to only a fragment of stratigraphic column and, thus, are not fully representative for the whole hydrogeothermal reservoir. Hence, averaged values of permeability coefficient were used for particular groundwater aquifers. These maps were constructed by superposition of three maps, according to the following formula:

$$k = \frac{k_p \cdot (1 - 0.002 \cdot M_S) \cdot \rho_w \cdot 9.81}{239.4 \cdot 10^{-7} \cdot 10^{\frac{248.37}{T_S + 133.15}}} \text{ , [m/s]} \quad (19)$$

where:
k - hydraulic conductivity coefficient [m/s]; kp - permeability coefficient [m^2]; MS - TDS of reservoir water [kg/m^3]; ρ_w - density of reservoir water [kg/m^3]; T_s - temperature of reservoir water [^{o}C].

- maps of hydraulic transmissivity of groundwater horizons - constructed by superposition of two maps, according to the formula:

$$T = k \cdot m_p \text{ , [m}^2\text{/s]} \quad (20)$$

where:
T - hydraulic transmissivity [m^2/s]; k - hydraulic conductivity coefficient [m/s]; m_p - cumulative thickness of groundwater horizons [m].

- maps of potential discharge of hydrogeological wells - discharge calculations of hypothetical wells producing waters from particular geothermal aquifers in the Polish Lowlands required the determination of technical details of exploitation. Analysis of basic hydrogeological parameters: permeability, hydraulic conductivity and hydraulic transmissivity coefficients indicated high diversity of values among studied aquifers. Both the Lower Cretaceous and Lower Jurassic aquifers revealed relatively high values of analysed hydrogeological parameters, which proves favourable reservoir properties. Calculations of potential discharges of hydrogeological wells assumed the optimum development modes of groundwater horizons. Therefore, calculated parameters were diversified within analyzed aquifers under the following theoretical assumptions:

- diameter of working part of screen in production well is Φ =12" (0.305 m) for the Lower Cretaceous and Lower Jurassic and Φ=15" (0.381 m) - for remaining aquifers.

- drawdown during production will not exceed 100 m in a well or half of total pressure head, or half of thickness of groundwater horizon in the exposures;

- regional drawdown will not exceed 33 m;

- thickness of exploited groundwater horizon (100 m) is equal to the working part of a screen. For sub-Tertiary subcrops the working parts of screens were equal to the total thickness of groundwater horizons in the stratigraphic column.

Discharges were calculated with the Darcy-Dupuit formula, applied for unlimited groundwater horizon exploited under stationary conditions. Theoretical discharge from a production well was calculated by superposition of three maps: permissible drawdown, hydraulic conductivity coefficient and thickness of groundwater horizons, according to the following formula:

$$Q = 2\pi \cdot k \cdot m_p \cdot \frac{S}{\ln \frac{R}{r}} \text{ , [m}^3\text{/s]} \quad (21)$$

where:
Q - discharge of production well [m^3/s]; k - hydraulic conductivity coefficient [m/s]; m_p - thickness of groundwater horizon (limited by working length of screen) [m]; S - permissible drawdown [m]; r - radius of production filter [m]; R - radius of depression cone [m].

- maps of permissible drawdown (unpublished): constructed from isobaths maps of the bottoms of hydrogeothermal aquifers and general assumptions applied to calculations of potential discharges (see above). Radius of depression cone was calculated with the Sichardt's formula:

$$R = 3000 \cdot S \cdot \sqrt{k} \text{ , [m]} \quad (22)$$

where:
S - drawdown [m]; k - hydraulic conductivity coefficient [m/s].

9. RESULTS OF CALCULATION OF GEOTHERMAL RESOURCES IN THE POLISH LOWLOWLANDS

The area for which resources calculation was carried on includes 272 126 km^2, which constitutes above 87% of the territory of Poland.

Calculation of energy resources in the selected geothermal aquifers was carried within their geological (erosional) extent in the area of Polish Lowlands as well as within the extent resulting from recognition of hydrogeological and thermal conditions. Additionally, the calculations were limited to 4 500 meters depth to the top of particular unit due to poor recognition of deeper parts of aquifers.

Considering the areas of the Mesozoic and Paleozoic geothermal aquifers, i.e. their regional extent in the Polish Lowlands, the studied aquifers can be arranged in the following order: Lower Triassic (228 758 km^2 - 73% of the territory of Poland), Middle Jurassic (204 868 km^2- 66%), Upper Jurassic (197 841 km^2 - 63%), Upper Triassic (178 149 - 57%), Lower Jurassic (160 398 km^2 - 51%) and Lower Cretaceous (127 873 km^2 - 41%).

The largest calculation area among all Paleozoic geothermal aquifers is occupied by the Lower Permian aquifer: 101 913 km^2, which constitutes 37% of total area of the Polish Lowlands and 33% of the whole territory of Poland.

The Devonian aquifer covers 48 424 km^2, i.e. 18% of total area of the Polish Lowlands and 16% of the whole territory of Poland, whereas the smallest, Carboniferous aquifers occupies 46 709 km^2, i.e. 17% of total area of the Polish Lowlands and 15% of the territory of Poland.

The total accessible geothermal resources accumulated in the rock formations down to 3 000 meters depth or down to the top surface of crystalline basement amount 7.75x10^{22} J, which is an equivalent of 1.85x10^{12} TOE.

The total static geothermal resources accumulated in groundwaters and rocks in the selected geothermal aquifers were estimated as 1.05x10^{22} J, which corresponds to 2.51x10^{11} TOE (Table 1).

In this resources category the most valuable is the Lower Jurassic aquifer (Figure 3) for which accumulated energy of 2.99x10^{21} J was calculated, i.e. 28% of total static resources of all Mesozoic geothermal aquifers in the Polish Lowlands (Table 1).

The distribution of static geothermal resources within particular aquifers are shown on Table 1.

Considering the distribution of static resources per area unit, the best parameters among the Mesozoic aquifers are revealed by the Lower Jurassic aquifer - 1.86x10^{16} J of energy per 1 km^2. Mean unit static resources for the Mesozoic aquifer are 9.41x10^{15} J/km^2.

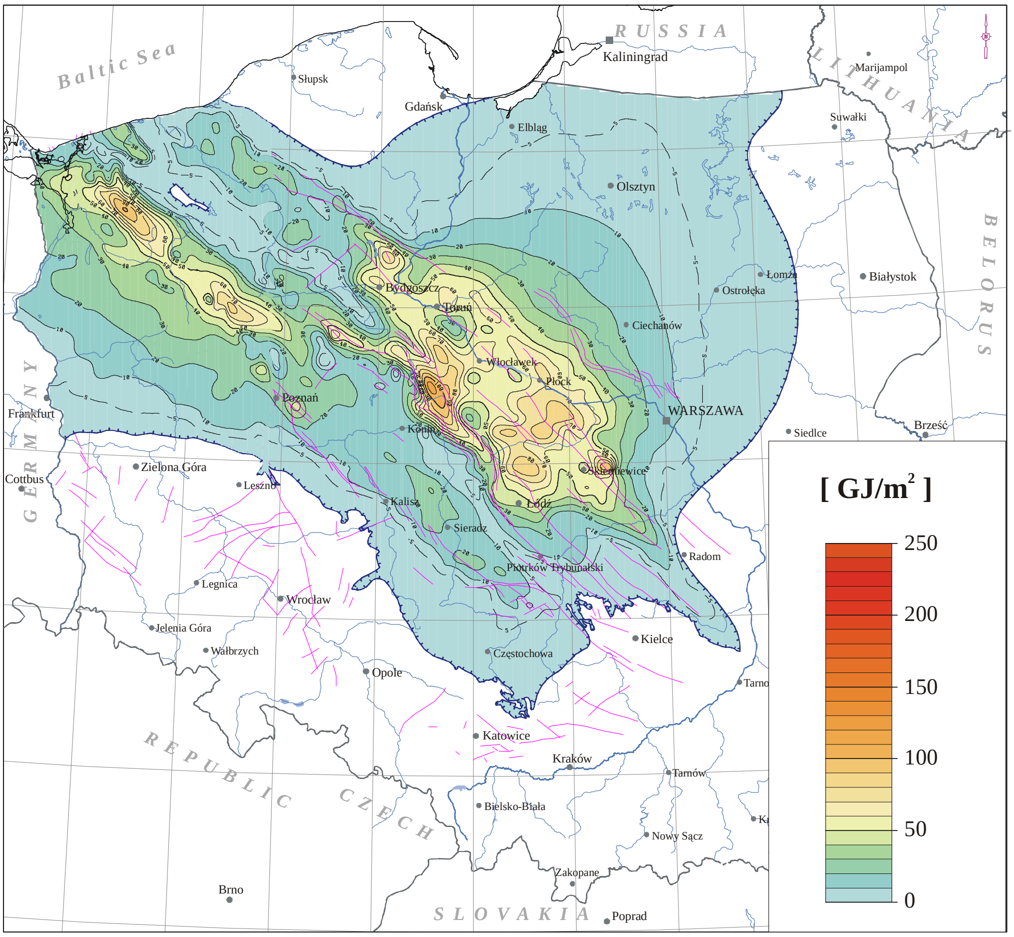

Figure 3: Map of unit static resources of Lower Jurassic aquifer in the Polish Lowlands.

Formation	**RESOURCES**					
	Area	**Static Resources**	**Static Recoverable Resources**	**Disposable Reserves**		
				Area	**Energy**	**Energy**
	[km^2]	**[J]**	**[J]**	**[km^2]**	**[J/year]**	**[TOE/year]**
Lower Cretaceous aquifer	127 872.60	4.23E+20	6.59E+19	24 235.84	3.95E+17	9.43E+06
Upper Jurassic aquifer	197 841.48	2.37E+21	3.04E+20	7409.00	2.54E+17	6.07E+06
Middle Jurassic aquifer	204 867.78	8.44E+20	1.44E+20	35 637.09	8.90E+17	2.13E+07
Lower Jurassic aquifer	160 398.25	2.99E+21	5.64E+20	81 389.82	1.88E+18	4.48E+07
Upper Triassic aquifer	178 148.52	1.15E+21	2.35E+20	29 776.00	1.14E+18	2.72E+07
Lower Triassic aquifer	228 758.00	2.74E+21	6.13E+20	38 839.00	1.73E+18	4.13E+07
MESOZOIC	-------------	**1.05E+22**	**1.93E+21**	-----------	**6.28E+18**	**1.50E+08**
Lower Permian aquifer	101 912.91	1.70E+21	4.53E+20	28 613.13	2.03E+18	4.84E+07
Carboniferous aquifer	46 708.65	4.87E+20	1.04E+20	10 375.42	5.26E+17	1.26E+07
Devonian aquifer	48 424.41	1.84E+21	4.15E+20	7 304.21	3.74E+17	8.94E+06
PALAEOZOIC	-------------	**4.03E+21**	**9.72E+20**	------------	**2.93E+18**	**6.99E+07**
POLISH LOWLANDS	**272 126.00**	**1.45E+22**	**2.90E+21**	**2.64E+05**	**9.21E+18**	**2.20E+08**

Table 1: Compilation of geothermal energy resources in the Polish Lowlands.

The total static resources accumulated in rocks and groundwaters of the Paleozoic formations are estimated as 4.03×10^{21} J, which corresponds to 9.61×10^{10} TOE (Table 1). Largest static resources are accumulated in the Devonian aquifer, where the energy of 1.84×10^{21} J was calculated. i.e. 46% of total static resources of all Paleozoic aquifers.

Considering the static resources per area unit of Paleozoic aquifers in the Polish Lowlands, the highest value of this ratio was found for the Devonian aquifer: 3.80×10^{16} J/km^2 whereas the average value of unit static resources for Paleozoic aquifers is 2.17×10^{16} J/km^2.

The amount of static-recoverable resources informs how big part of geological (static) resources can be theoretically recovered under defined technical parameters of exploitation and utilization of geothermal medium. i.e at given cooling temperature and with given exploitation method. The value of Ro index depends on exploitation method (single- or double-well system) and on relationships between the reservoir temperature, the injection temperature (in doublet system) and the mean annual temperature at the Earth's surface. Averaged values of recovery index calculated for all aquifers of the Polish Lowlands are from 12.8% for the Upper Jurassic aquifer to 26.7% for the Lower Permian one. Average Ro value for all Mesozoic aquifers from the Polish Lowlands is 18%. Average Ro value calculated for all 9 geothermal aquifers of the Polish Lowlands is 19.9%.

These results demonstrate that under geological and temperature conditions dominating in the Polish Lowlands it will be possible to recover less than 20% of geological resources of accumulated geothermal energy. Distribution of recovery index values in particular geothermal aquifers calculated as ratios of static-recoverable resources to static resources in given temperature classes varies from 6.6% to 28.2%. Values of recovery index within the temperature classes reveal distinct stability.

Economic verification of recovered geothermal heat can be carried on with various methods of various precision. Hydrogeothermal aquifers can be evaluated economically in a simplified way in order to identify and classify the perspective zones from which the geothermal heat can be commercially produced and utilized. In economic evaluations the so-called „power factor" was applied (Gosk, 1982). This value indicates how many times the thermal power of given geothermal water intake exceeds the thermal power equivalent of capital expenditures and running costs of this intake. The power factor value below 1 indicates that the „energetic value" of incurred costs is higher than the obtained effects. The power factor is a quasi-economic indicator, which comprehensively combines both the economic and the energetic aspects of heat recovery from geothermal waters. However, this factor cannot be the base of conclusions on competitiveness of geothermal heat production in relation to conventional heat-generation technologies. The power factor was applied to selection and systematization of perspective areas within the aquifers from the point of view of commercial production of hot groundwaters. The power factor was applied also to determination of disposable geothermal resources. The disposable geothermal energy resources were determined for these parts of studied aquifers in which the power factor values were F>1 at the load factor values of intakes LF=1. Hence, the areas were selected in which commercial production of geothermal heat is possible. With the decreasing load factor of geothermal intake the areas for which the LF=1 also decrease.

Areas of particular geothermal aquifers of the Polish Lowlands applied in the calculations of disposable reserves are shown in Table 1. The largest area covered by disposable reserves occurs in the Lower Jurassic aquifer. Moreover, the Lower Jurassic groundwater horizons reveal the largest disposable reserves among all geothermal aquifers of the Polish Lowlands, which amount $1.88\text{x}10^{18}$ J/year (corresponding to $4.48\text{x}10^{7}$ TOE/year). Relatively low disposable geothermal resources occur in the Upper Jurassic aquifer - $2.54\text{x}10^{17}$ J/year, which corresponds to $6.07\text{x}10^{6}$ TOE/year (Table 1). Such low resources result from poor reservoir properties (see Figure 2) and unfavorable hydrogeological conditions of this aquifer, as revealed by average permeability about 90 mD, low hydraulic transmissivity and relatively low predicted production rates of wells developing the Upper Jurassic geothermal horizons in the Polish Lowlands.

SUMMARY

The calculated disposable reserves of geothermal energy in the Polish Lowlands can be correlated with the geothermal energy resources obtained for Europe by Cataldi (1993, 1994), who quoted „geothermal reserves" of $6.00\text{x}10^{19}$ J/year, i.e. $1433\text{x}10^{6}$ TOE/year. According to his opinion, geothermal resources in Europe can be utilized in the relatively limited areas of, totally, several thousands of square kilometers, where about 5 - 10% of these resources are accumulated. In these areas the reservoir properties of geothermal aquifers are particularly favourable and, simultaneously, the heat markets are attractive for potential investors.

The principal resources of geothermal waters in the Polish Lowlands are reservoired in the Mesozoic groundwater horizons. Geothermal waters are accumulated first of all in the Lower Jurassic and Lower Cretaceous formations but significant resources of geothermal energy are reservoired also in the Upper Jurassic, Middle Jurassic, Upper Triassic and Lower Triassic formations.

Total disposable reserves accumulated within all the Mesozoic aquifers of the Polish Lowlands are $6.28\text{x}10^{18}$ J/year, which corresponds to the energy of $150\text{x}10^{6}$ TOE/year.

Total disposable reserves accumulated within all the Paleozoic aquifers in the Polish Lowlands are $2.93\text{x}10^{18}$ J/year, which corresponds to the energy of about $70\text{x}10^{6}$ TOE/year.

Total disposable reserves of geothermal energy in the Polish Lowlands, accumulated in 9 geothermal aquifers are $9.21\text{x}10^{18}$ J/year, i.e. about $220\text{x}10^{6}$ TOE/year.

Assuming the recovery of 1.5 - 2.5% of disposable reserves, the exploitable reserves of geothermal energy are estimated as $1.38-2.30\text{x}10^{17}$ J/year ($3.3\text{-}5.5\text{x}10^{6}$ TOE/year). Theoretically, such resources are sufficient for supply of 270 - 460 geothermal installations, each producing annually the energy of about 500 TJ.

The obtained results of calculation offer new prospects for the extension of geothermal energy use and related uses (balneology, recreation etc.) in areas situated beyond the limits of occurrence of hot underground waters of Mesozoic formations.

It should be emphasized that geothermal energy can be commercially utilized in vast areas of the Polish Lowlands. However, the scale of this utilization will depend on numerous factors. Very important problem is to break the still existing bad habits and improper standards, which have dominated the State energy policy in last decades.

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