GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2018 Volume 34 Issue 1 Pages 25–40

DOI 10.24425/118642

MAREK RASAŁA*

Possibilities for the industrial use of cooled geothermal brines by borehole salt mines in the Polish Lowlands

Introduction

The area of Poland is one of the more affluent areas in Europe for obtaining geothermal energy, which is particularly true in the case of central Poland, where deep structural troughs of Permian-Mesozoic formations of combined thickness of up to 7 km abound. Formations richest in geothermal water include Lower Jurassic and Upper Triassic sandstone and Middle Jurassic carbonate formations. Waters present in these deposits at a depth of 2–3.5 km have a temperature ranging from 70 to 120°C (Górecki ed. 2006).

The main drawback of geothermal waters in central Poland, however, is their level of mineralization, generally exceeding 100 gNaCl/L (Górecki ed. 1990; Bojarski ed. 1996). This is due inter alia to hydrochemical impact of numerous halotectonic structures, including salt domes (Zuber and Grabczak 1991; Grube 2000; Górski and Rasała 2008). At the same time, the high thermal conductivity of salt contributes to high thermal energy potential of the area of Kujawy and NE Wielkopolska. However, due to – among others – water salinity, the usage of geothermal resources in this region is negligible. The disincentives include the high cost of building 2–4 borehole systems including injection boreholes, and operational and technical problems commonly occurring with brine injection (for example

* Ph.D., Adam Mickiewicz University in Poznan, Faculty of Geographical and Geological Sciences; Institute of Geology, Department for Hydrogeology and Water Protection, Poznan, Poland; e-mail: mrasala@amu.edu.pl

Zięba and Grzesiak 2010; Biernat et al. 2010). A good example was the geothermal heating plant (14 MW) in Stargard Szczeciński (NW Poland) using brines with mineralization of approx. 130 g/L (Cl-Na type, a working temperature of 87°C) which due to – among others – the high costs of injection struggled financially over a long period (Kubski 2008), which led ultimately to its bankruptcy (currently the plant functions under new ownership). Some Polish geothermal heating plants use freshwaters, which after heat depletion are used as drinking water (Mszczonów, Poddębice) (Fig. 1) – these are, however, the exceptions, and cooled waters are usually injected back into the source reservoir. With a lower geothermal water extraction rate (about 10 m^3/d), as is the case of installations used mainly for balneology and recreation purposes, waters after use are discharged into surface water or local sani-

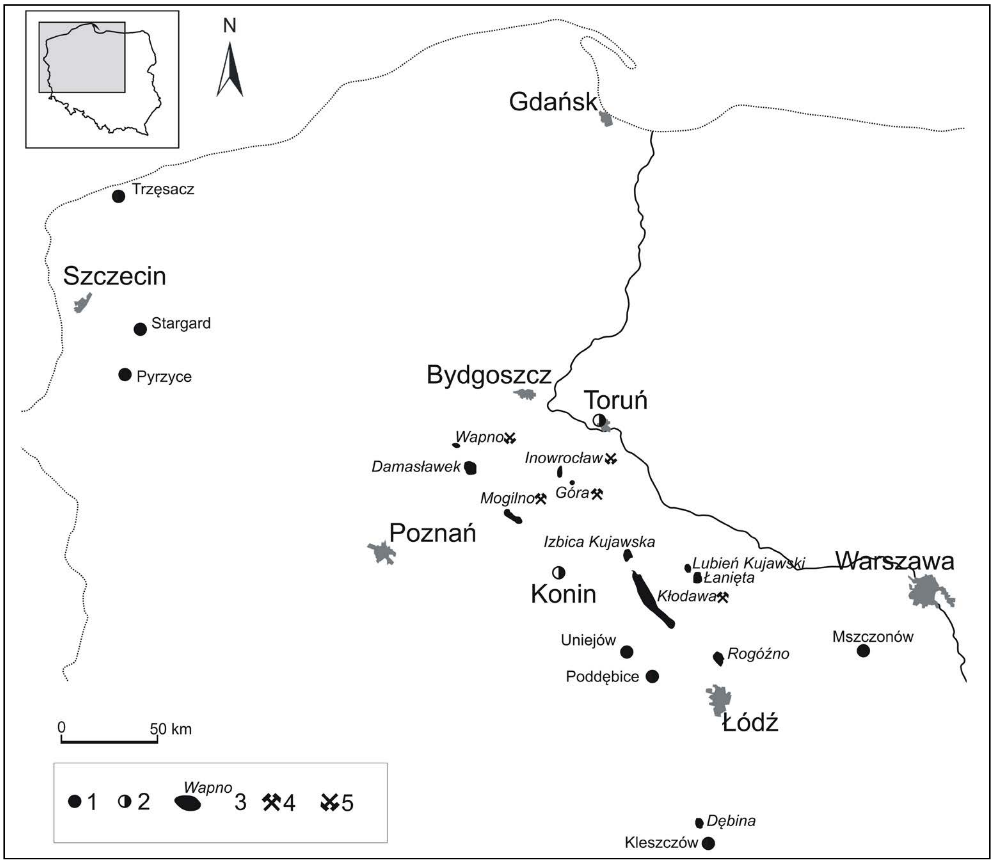

Fig. 1. Location of geothermal heating plants and salt diapirs and mines in the Polish Lowlands
1 – active geothermal heating plants, 2 – geothermal heating plants in construction,
3 – diapiric salt formations, 4 – active salt mines, 5 – closed salt mines

Rys. 1. Lokalizacja zakładów geotermalnych oraz wysadowych złóż soli
wraz z kopalniami na terenie Niżu Polskiego
1 – czynne zkłady geotermalne, 2 – zakłady geotermalne w budowie, 3 – wysadowe złoża soli,
4 – czynne kopalnie soli, 5 – zamknięte kopalnie soli

tary sewage systems (for example Tarnowo Podgórne, Poznań-Malta, Grudziądz, Lidzbark Warmiński). Due to the fairly widespread salinity of geothermal waters in Poland alternative ways of their disposal, e.g. through demineralization before discharge into surface waters (Bujakowski and Tomaszewska 2009), or re-use are sought.

However, the above options are not the only methods for the disposal of or the re-use of geothermal brines of Cl-Na type. An alternative solution, especially suited for highly mineralized geothermal waters from the central Poland area, could be their use in borehole salt mines. Here, they could be used to produce industrial-quality brine through saturation with sodium chloride in the process of salt cavern leaching. Then, they would be supplied to chemical plants in the same manner as it happens now (Rasała 2014).

1. Concept of re-use of heat-depleted geothermal brines

Three salt mines exploiting Zechstein diapiric salt formations are currently operating on the territory of Poland (Fig. 1). The Kłodawa mine is a traditional underground salt mine using a room and pillar mining system. The "Przyjma" and "Góra" salt mines operated by IKS "Solino" (which in turn is owned by the Orlen Group) mine the salt using borehole solution mining system.

The Mogilno salt dome in the center of the Mogilno Trough has a shape of a flat ellipsis, the long axis of which (along the WNW-ESE axis) has a length of 5 km, with a width of 370 to 900 m (Sokołowski 1966; Wilkosz 2001). In the 1970s and 1980s two salt mining fields were documented: Mogilno I located in the S part of the dome, and Mogilno II in its N section. Since 1986 the southern field has been exploited by IKS "Solino" using the borehole mining method (Salt Mine "Przyjma"), while the Mogilno II deposit has been used since 1997 as an Underground Gas Storage Facility. The degree of depletion of leaching caverns in the mine is already significant, and currently the mining company is working on opening the SE part of the salt deposit for exploitation.

The Góra salt dome was formed within the marginal (western) part of the Kujawy Swell. It is one of the smallest Polish salt diapirs, and takes the shape of an irregular oval with a diameter of about 900 m. Salt leaching has been ongoing since 1968, and since 2002 some of the leached chambers have been adapted for the purpose of storage of liquid hydrocarbons (Salt Mine and Underground Oil and Fuel Storage Facility "Góra"). It is the only cavern-based oil and fuel underground storage reservoir in Poland with a capacity of more than 6 million m^3.

For the purposes of leaching, both borehole mines currently acquire surface water from the Noteć river catchment (mineralization <1 g/L), and after its saturation with NaCl (>305 gNaCl/L) through leaching of salt caverns, brine suitable for industrial applications is sold to nearby chemical plants in Inowrocław (Soda Mątwy) and Janikowo (Janikosoda), both belonging to the Grupa Ciech SA capital group. The production of industrial brine is carried out on a continuous basis, and for each of the mines is at the level of 500–550 m^3/h.

The predominant chemical type of geothermal waters in the Polish Lowlands – that is, Cl-Na type – makes them suitable as a potential source of water supply for mines. The condition is the suitable chemical composition of water (see below). Chemical plants would then be the target recipient and final disposal site for heat-depleted geothermal waters, which would take the form of their industrial demineralization and discharge into the Noteć river, similarly as is currently taking place (Fig. 2).

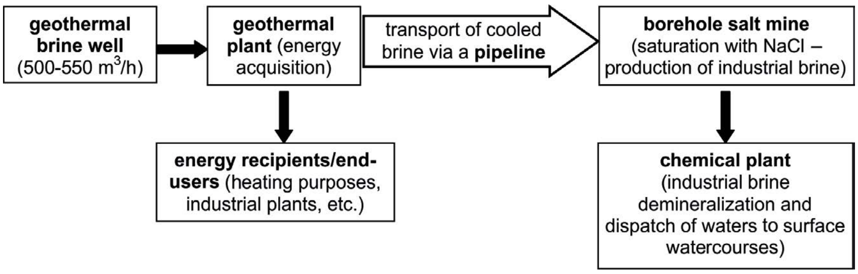

Fig. 2. Concept of cooperation of a borehole salt mine with geothermal and chemical plants

Rys. 2. Schemat koncepcji kooperacji otworowej kopalni soli z zakładami geotermalnymi i chemicznymi

Acquisition of geothermal water and energy production could be realized by:

- geothermal plants belonging directly to IKS "Solino" SA constructed in the future, and/or
- by external plants (not owned by IKS "Solino") currently under construction (e.g. Toruń, Konin) or planned in the future.

With the assumption of meeting the entirety of the mines' demand for water (about 1000 to 1100 m^3/h) and in light of the favorable geothermal conditions in the region, it is possible that the resulting energy production capacity could be so large that geothermal plants would operate in a viable manner in parallel even in several localities. The optimal solution would be to link the mine brine installations to geothermal plants producing energy year-round, on a stable level, i.e. not only during the heating season – for example as a source of energy for district tap water heating purposes in the larger nearby towns (Inowrocław, Mogilno, Pakość, Strzelno, Trzemeszno, Żnin), and/or to meet the needs of local industrial plants (for example the vegetable fats manufacturer in Kruszwica, agricultural processing plants in Gniewkowo, chemical plants "Soda Mątwy" in Inowrocław and "Janikosoda" in Janikowo).

Heat-depleted geothermal water – known as "half brine" in mining terms – would need to be transported to the mines via a pipeline. For technological reasons this solution requires the existence of a special half brine installation next to a standard surface water transport system as part of the mine infrastructure. The existence of the latter stems inter alia from the need to have an alternative (emergency) source of water supply for leaching. A favorable circumstance is the existence of such a half brine installation already in the mine "Przyjma", where it was built to receive less than fully saturated brine produced when leaching natural gas storage caverns in the "Mogilno II" deposit. Such an installation would need to be built in the "Góra" Salt Mine.

2. Analysis of options for cooperation between a geothermal plant – a salt mine – a chemical plant

Potential collaboration of borehole salt mines with geothermal plants can have several variants. At the present – conceptual – stage of the analysis, we can only indicate their respective advantages and limitations. Nevertheless, to illustrate the multi-dimensional nature of the issue, some preliminary (simplified) analysis in terms of energy-generation potential and economic viability and initial conditions is presented below for two such variants:

- Cooperation of the "Przyjma" Salt Mine with its own hypothetical geothermal plant for Mogilno;
- Cooperation of the "Góra" Salt Mine and Underground Oil and Fuel Storage Facility with an external geothermal power station in Toruń (currently under construction).

"Przyjma" – Salt Mine Mogilno

According to the existing hydrogeological preliminary assessment of the Lower Jurassic formations in the area, water of a temperature of about 95°C and content of NaCl even up to 150 gNaCl/L is present in the region of Mogilno (Górecki ed. 1990, 2006 – Fig. 3). The discharge of 550 m^3/h of water can be attained with two production wells (appropriately positioned relative to each other) with a depth of about 3 km. Calculations (according to formulas presented by Górecki ed. 2006, p. 156 and 163) show the total effective thermal power output (usable) from the system can reach up to 50 MW. The system efficiency, taking potential waste into account, is envisaged at about 85% – thus the actual usable energy would be approximately 1,320,000 GJ/year. However, if the plant was to produce energy on a seasonal basis only, it can be assumed that the annual load coefficient of the system would be about 60%, which would reduce energy production to about 800,000 GJ/year.

Major capital investments will be required for the following items (approximate cost):

- design documentation, geological and environmental documentation for completion of the wells, the geothermal plant and the pipeline, etc. = PLN 2.0 million,
- drilling of 2 production wells with a depth of about 3 km and well completion = PLN 50 million,
- construction of a geothermal plant and its equipping = PLN 40 million,
- construction of a half brine pipeline between Mogilno and the mine (together with a pumping station) of a length of approx. 12 km = PLN 24 million (average price of about PLN 2 mln per 1 km of pipeline based on information from construction companies operating in the market),

- adaptation of mine infrastructure (e.g. additional storage tanks for half brine) = PLN 2 million.

Total investment cost is estimated at about PLN 120 million.

If the 0.8 MGJ of thermal energy per annum – or 1.32 MGJ as would be generated from the proposed 2 wells with a cumulative discharge of 550 m^3/h – cannot be consumed by Mogilno, the station should still try to meet the mine's demand for half brine. To do so, a suggested solution would be to position a second geothermal water intake in a nearby town to maximize ecological benefits. In such a case, the total cost of two geothermal plants and the pipeline installations may reach PLN 150 million due to the cost increase associated with construction of the second geothermal installation and connected pipeline. In view of numerous pro-ecological grant programs (EU funds, Polish National Fund for Environmental Protection and Water Management, etc.), the actual capital investment required for the cooperating entities can be reduced by up to 50–70%.

The use of cooled brines for salt leaching would generate saving for the IKS "Solino" mine due to:

- resulting lack of charges for consumption of surface water: PLN 0.275 million /year (PLN 0.057 /m^3 in 2016),
- reduced mining fee for mining the salt deposits: approx. PLN 4.9 million /year (fee of PLN 2.18 /t charged in 2016). (Due to the pre-existing NaCl content of about 150 NaCl g/L in the thermal waters – such NaCl content in half brine transported in the pipeline would thus already provide about 49% (by weight) of the total mineralization required for industrial brine (>305 g NaCl/L).

With the assumption of continued lack of fees charged by the state for extraction of geothermal waters, one can expect the savings generated in the mine to be able to approximately offset the cost of ongoing maintenance and repairs of the wells and the pipeline transporting half brine to the mine.

With sale of geothermal energy in the amount of 800,000 GJ/year for the Thermal Plant in Mogilno at a rate of, for example, 1/3 of the rate per GJ this plant charges its customers (in 2016 the standard rate was PLN 42.92 net/GJ), annual revenue would be about PLN 11.44 million – hence the payback period for the entire investment should not exceed 15 years (for the most expensive variant assuming also that no grants are extended), and be even two times shorter for the lower cost variants with grant-based financing of 50% of the investment.

Toruń – "Góra" Salt Mine and Underground Oil and Fuel Storage Facility

The geothermal plant closest to the Góra salt dome is the investment by Lux Veritatis Foundation (LVF) from Toruń. The discharge of the Toruń GT-1 well has been confirmed at Q = 320 m^3/h (Szuflicki et al. eds. 2014). Waters of a temperature of 64°C and total mineralization of 107 g/L have been acquired from a Lower Jurassic geothermal aquifer (Noga et al. 2013). Injection well Toruń GT-2 was drilled for the disposal of heat-depleted brine. Noga et al. (2013) report that a successful production-injection test at 350 m^3/h was performed for these wells. The above data suggests that there is a possibility of even entirely (if the injection well is used for production as well) meeting the demand for industrial waters of the "Góra" Salt Mine. In such a case, NaCl content in geothermal brine transported in the pipeline (about 105 gNaCl/L) would already provide about 34% (by weight) of the total mineralization required for industrial brine (so half brine only needs to be "additionally" saturated in a leaching process to >305 gNaCl/L).

Due to the location of installations of these two companies, it would be necessary to build a brine pipeline with a length of about 40 km, which would generate the greatest share in total capital investment required. The pipeline would run in part through the city of Toruń (here the option of using for example existing sewage infrastructure should be considered) and would require crossing over the Vistula river (eg. using existing bridges). Next, the pipeline could be routed along the main road between Toruń and Inowrocław. A favorable factor is the presence of a water supply pipeline along this road already, as the water intake for the city of Toruń, "Mała Nieszawa", also partly supplies water to Inowrocław. The last stretch of about 10 km would have to be routed through agricultural areas or along the existing roads. The cost of the pipeline construction along with all necessary infrastructure should not exceed PLN 80 million, especially as it would not require fitting with anti-freeze thermal insulation (brine). In addition to new design and environmental documentation, the construction of surge tanks and/or connections will also be needed. The mine would also need to bear the cost of building the half brine installation. The total investment cost of this cooperation variant, including the cost of modernizing the mine infrastructure, should not exceed approx. PLN 100 million.

Current annual savings from implementation of the proposed cooperation model for the mine would be the same as described for the "Przyjma" Salt Mine case (about PLN 5 million/ /year). However, on the part of LFV the currently borne costs will also be reduced by the amount spent to keep the injection well operational (while additional extraction cost would be generated, it would still be cheaper than operation of an injection well, no costs associated with ensuring appropriate injection rate). Average annual savings associated with the above can be estimated at around PLN 2–3 million. It can be assumed that savings generated for both companies would at least offset the cost of ongoing maintenance and repairs of the pipeline transporting half brine to the mine.

For the geothermal plant in Toruń, an immediate benefit is the possibility of increasing capacity of the heating system resulting from increased consumption of geothermal water by about 200 m^3/h. This represents an increase in effective heat production of the system (with annual load coefficient for the well at 60%) of about 180,000 GJ/year, while revenue from potential sale of this thermal energy could increase by about PLN 4 million /year. The above estimation suggests that the payback period for building a brine pipeline between the plant and the mine would, thanks to increasing the thermal power of the geothermal system, be about 25 years since commissioning of the installation. Taking the reduction in spending associated with removal of injection costs to dispose of the cooled brine into account, and assuming (in the most optimistic variant) that an additional well would not need to be drilled, this time could in fact be shortened to about 15 years. Additional revenue may be generated also by increased volume of CO_2 emission rights that could be sold as a result.

It is currently impossible to even carry out an approximate analysis of profit from such co-operation for the mine, as the matter of payment for the half brine supplied to the mine remains open. For the geothermal plant, heat-depleted brine is a waste product, hence they could be expected to pay for its disposal. If half brine was to be transported to the mine without a fee charged by the latter, there would be no direct revenue associated with such arrangements for the mine. There is even a chance the geothermal plants may demand payment for what they may consider as the supply of an intermediate to the mines. Still, in the short-term, the issue of whether water used for salt leaching would be surface water or heat-depleted geothermal brine is only secondary for the mine, because it does not change the level of production of saturated brine in any way – the latter stems directly from the volumes contracted in a supply contract with its final recipient, i.e. a chemical plant. Hence is should be assumed that the mine would not be interested in purchasing half brine from the geothermal plant.

In conclusion, the above variant analysis clearly indicates that the better solution is implementing such an arrangement between a mine and its own geothermal plant. Mines may, however, still be interested in cooperation with external geothermal plants in light of long-term benefits.

3. Opportunity for rationalizing the management of salt dome mineral resources

The acquisition of cooled geothermal brine with NaCl content of 100–150 gNaCl/L by the two borehole salt mines is profitable for them from a strategic, long-term perspective. A significant part of both salt diapirs has already been largely mined out, and currently work on an opening for mining further parts of the deposits, located in the marginal parts of the salt domes, is ongoing. Due to evolutionary halokinetic deformations, however, the dominant formations in these zones would be Zechstein PZ3/PZ4 cyclothems (Wachowiak 2015). Large share of gangue (commercially worthless) minerals in these deposits causes problems during leaching (Kunstman et al. 2002), which limits their viability as usable reserves.

Borehole mining of the salt domes based on half brine would extend the operational life of the mines, and thus allow them to longer generate revenues from the sale of industrial brine with a 30–50% share of halite salt derived from geothermal waters, depending on their level of salinity. The author has no data on revenues of IKS "Solino" from the sale of brine to chemical plants, but it may be presumed that income from sales of sodium chloride already present in half brine would reach about a dozen million PLN/year for each of the mines. Exploitation activity for each deposit could, in effect be prolonged by at least 15 years – hence huge costs associated with drilling works and the construction of mining facilities and brine transport installations for the salt deposits newly opened for mining could be postponed in time, thus benefitting the mines. Such an opportunity for the longer generation of revenues should therefore encourage mines to at least partially finance the costs of building a brine pipeline from external geothermal plants, even if the heat-depleted brine was to be disposed of in that manner without any accompanying fee from the geothermal plant. The construction of own geothermal wells by the mines would be even more viable in economic terms.

The simultaneous rationalization of salt mining and of the exploitation of geothermal resources through cooperation with a geothermal plant is of particular importance to viability of underground fuel storage operation in the Góra salt dome. The withdrawal of fuels stored in salt caverns is done through a bottom-up injection of saturated brine produced in the mines, to avoid an uncontrolled expansion of storage salt caverns (Kunstman et al. 2002). It is therefore necessary to continue parallel salt mining operations (to produce saturated brine). In a crisis situation on the fuel market it is necessary to quickly withdraw hydrocarbons stored in underground facilities. At present the withdrawal rate (deliverability rate) of fuel is conditioned by the difference between the total intake of surface water and the volume of water that needs to be transferred (as brine) to chemical plants on a continuous basis. Using a new source of industrial water while still maintaining the installations and permits for intake of surface water would allow fuels to be withdrawn from the storage caverns several times faster, which is important for the Polish economy. However, for the purpose of continued operations of the mine and the underground storage facility the intake capacity of surface water from the Noteć river is currently being expanded. Although this expansion is in necessary conflict with the presented concept, it is at the moment.

4. Drawbacks and limitations of the concept

The analyzed method of disposal of geothermal brines of Cl-Na type generates significant potential financial gains for geothermal plants, and at least strategic benefits for salt mines. It allows for the better utilization of both the geothermal and salt deposits, but in terms of production both plants become interdependent. This interdependence of the two entities involved is the most important drawback of the system, especially during breaks in operation of the geothermal plant. A solution could be, for example, the construction of storage tanks for half brine or parallel maintenance of the current system of surface water supply for the mine. The latter installation must be maintained even if the geothermal plant operates seasonally only. The logistics of this co-operation would be significantly simplified in the case of a mine setting up its own geothermal water intakes.

In the case of the inevitable liquidation of the salt mine at some point in time after the depletion of the deposits, an alternative method for the disposal of heat-depleted brine would need to be set in place.

The possibility of setting up cooperation between a borehole salt mine and a geothermal plant is of course significantly limited in its applicability. The most important limitations are:

- availability of borehole salt mines with production level of brine ≥ the demand of the geothermal plant (otherwise disposal of part of the cooled brine by other methods is required);
- geothermal plant distance from the mine – an estimate of 30–40 km maximum due to costs (particularly when geothermal water production Q < 200 m^3/h);
- impossibility to implement when only creating underground waste disposal facilities or storage facilities without accompanying mining operations in salt deposits, as in such a case the investment relies on the quick – i.e. using normal waters – leaching of salt deposits to attain projected storage capacity;
- optimal content of sodium chloride in heat-depleted waters ≥100g/L – lower is also possible, provided economic viability conditions are satisfied (for example the distance to surface water sources is at least equal to or greater than to the location of the geothermal plant);
- quality requirements of the chemical plants. Waters transported to the mines must be the Cl-Na type, preferably containing: SO_4^{2-} < 2.4 g/L, Ca^{2+} < 1.0 g/L, K^+ < 2.0 g/L, Mg^{2+} < 0.65 g/L due to quality standards for industrial brines supplied to chemical plants (standard BN-86/6011-07). See more detailed comments below;
- exploitation of a rich and/or renewable geothermal aquifer.

The lack of a parallel injection of cooled waters into the geothermal reservoir leads to the depletion of resources in non-renewable or weakly renewable aquifers. For low-volume geothermal reservoirs the level of water consumption cannot be higher or significantly higher than the rate of the natural recharge. In the case of large volume (regional) geothermal aquifers (here: sedimentary-structural basins of the Polish Lowlands) which are weakly renewable, the maximum assumed rate of water acquisition from them (1000–1100 m^3/h) would most likely still not have a significant impact on local water resources. Before choosing a location for the geothermal plant co-operating with the salt mine, determining the volume of disposable resources of water for the given section of the geothermal aquifer is recommended.

The geothermal potential for the area close to the existing mines has been analyzed with a view to optimizing the possible cooperation, however taking into account however the above specified limitations.

5. Geothermal potential of the area around the discussed borehole salt mines

The implementation of co-operation of the borehole salt mines with geothermal plants is limited mainly by the geothermal potential, resources available in the geothermal aquifers and the chemical composition of geothermal water. Hence the above parameters should be analyzed in the area of the mines. Such analyses has been performed on the basis of available geological and hydrogeological data (Górecki ed. 1990; Bojarski ed. 1996; Górecki ed. 2006). The results suggest that tapping into the saline water with even higher mineralization (150–250 gNaCl/L) occurring at depths greater than 3 km (which is the assumed maximum depth for the economic viability of geothermal water production) and thus with a much higher energy potential would not only be possible, but even recommended in this case.

The structural-tectonic characteristics of central Poland mean that virtually all aquifer formations of the Jurassic and Triassic age – due to their regional occurrence – satisfy the above condition of sufficiently abundant water resources (cf. Górecki ed. 2006), and within the Mogilno Trough the Lower Cretaceous aquifer is also sufficiently rich. The effects of halotectonics, however, produce of, shallowing of or reduction in individual Mesozoic stratigraphic units in the area local a lack, which should be considered when finding locations for geothermal wells (Sokołowski 1966; Dadlez and Marek 1974).

The lithology of Mesozoic stratigraphic units to a very large extent determines the chemical composition of waters which occur in them (cf. Bojarski ed. 1996). Within carbonate horizons water may be characterized by elevated contents of calcium, magnesium and sulfates, thus ruling out the possibility of their utilization in the production of industrial brine. Unquestionably more favorable hydrochemical parameters are shown by waters present in Lower Jurassic and the Lower Cretaceous sandstones. Higher effective porosity of these formations in comparison with carbonate horizons occurring at similar depths also speaks in favor of these types of geothermal aquifers. However, waters from the Lower Cretaceous aquifer are characterized by a relatively low mineralization (usually <50 g/L) and temperature (typically <70°C), and are therefore not an optimal choice in terms of the longest extension of operating life of the salt mines and maximizing environmental benefits related to the suggested cooperation model.

In view of the potential for the production of geothermal waters at the level of 1000––1100 m^3/h in total, with relatively lower costs of investment, drilling and exploitation operations at the same time, the better option seems to be water production from a Lower Jurassic geothermal aquifer. To increase the energy production capacity of the system and thus achieve higher environmental benefits it would be advisable to limit the location of wells only to the area of the Mogilno Trough, even in the case of transporting waters to the “Góra” Salt Mine. This would allow Liassic waters with temperature at the outflow >80°C to be reached (Fig. 3). In light of the structural and tectonic characteristics of the area, to obtain the most favorable hydrogeological and energy parameters of the wells, locating them in the axes of local sub-troughs arising between salt structures. Water with high salinity (>150 gNaCl/L) should be present in these zones due to the palaeo-subrosion of the salt structures, which would be another favorable factor in terms of the extension of operating life of the mines.

Currently limited knowledge about hydrochemical parameters of waters from the Liassic formations in the Mogilno Trough (Górecki ed. 1990; Górski and Rasała 2008) points to

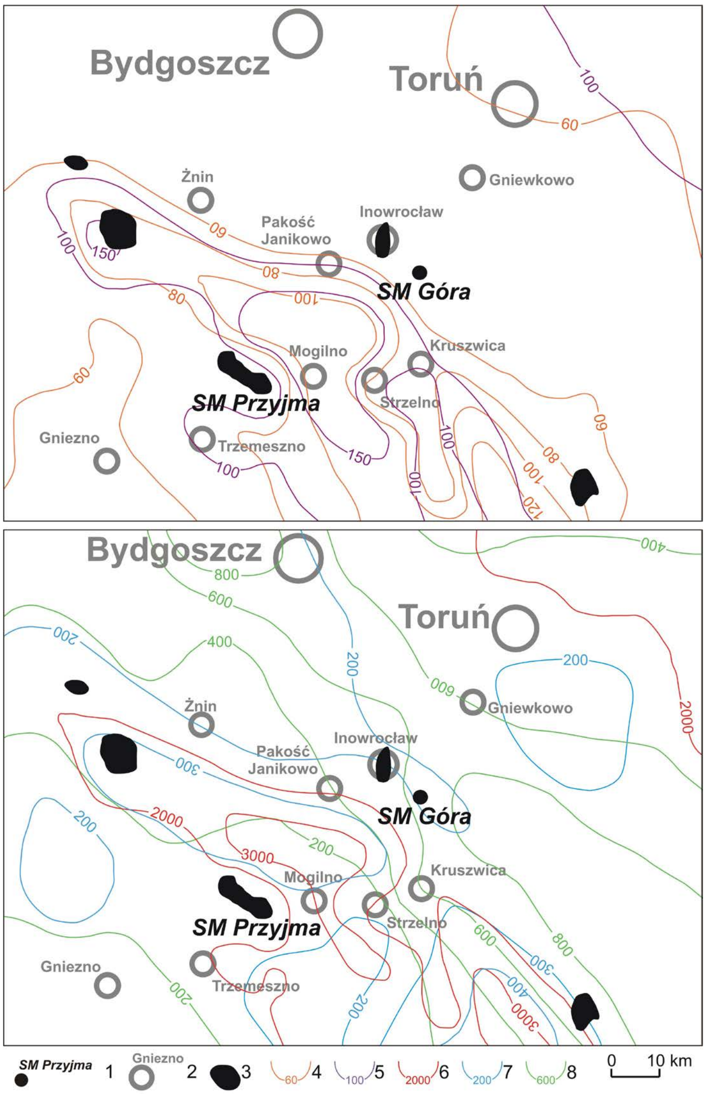

Fig. 3. Selected parameters of a Lower Jurassic geothermal aquifer around the polish borehole salt mines (Górecki ed. 2006)

1 – location of borehole salt mines, 2 – larger towns, 3 – salt domes, 4 – isoterms at the top of Lower Jurassic [°C] (shown >60°C), 5 – isolines of TDS at the top surface of Lower Jurassic formations [g/L] (shown >100 g/L), 6 – isohypses of the top of Lower Jurassic [m a.s.l.] (shown >2000 m a.s.l.) 7 – isolines of potential discharge of wells [m^3/h] (shown >200 m^3/h), 8 – isolines of cumulative thickness of Lower Jurassic formations [m]

Rys. 3. Wybrane parametry dolnojurajskiego zbiornika wód geotermalnych w rejonie polskich otworowych kopalń soli (Górecki red. 2006)

1 – lokalizacja otworowych kopalń soli, 2 – większe miejscowości, 3 – wysady solne, 4 – izotermy w stropie utworów jury dolnej [°C] (pokazano >60°C), 5 – izolinie mineralizacji ogólnej wód w stropie utworów jury dolnej [g/l] (pokazano >100 g/l), 6 – izohipsy stropu jury dolnej [m p.p.m] (pokazano >2000 m p.p.m.), 7 – izolinie potencjalnej wydajności otworów [m^3/h] (pokazano >200 m^3/h), 8 – izolinie całkowitej miąższości jury dolnej [m]

vertical and lateral variation of groundwater chemistry, significantly correlated with presence of salt structures. NE of the Mogilno salt dome, at a distance of 1600 m, borehole Mog-2 allowed – at the depth interval of 2217–2335 m – for presence of water with mineralization order of 112–115 g/L to be prospected. In the area of the Damasławek salt dome borehole D-22 (approximately 4 km S of the diapir) permitted water with outflow temperature of 105°C and mineralization of nearly 172 g/L at the depth interval of 3364–3442 m to be identified. Unfortunately, in both cases, the analyses found elevated content of calcium (2–4.75 g/L) in the Cl-Na type waters, which is the only mineral the content of which does not meet the requirements of the industrial brine standard in place. Within the Mogilno Trough, locally also waters from the Liassic aquifer with calcium content <1 g/L were prospected. However, they were located in the marginal parts of the Mogilno Basin, and their mineralization was of less than 50 g/L with lower temperature parameters as well.

It should be noted the calcium content in the brine defined in the standard for industrial brine reflects the solubility of the product of calcium sulfate. In the case of waters from the Lower Jurassic aquifer, calcium has a greater affinity for chlorides than for sulfates (in geothermal waters from Liassic formations, sulfate concentration is not excessive). Calcium chloride is one of commercial products of chemical plants, and thus in fact elevated content of calcium in geothermal waters may be even preferable due the wide range of its applications across the industries. Otherwise, if the geothermal water production rate is much lower than the industrial brine production capacity of the mine, cooled half brine can be diluted with surface water acquired in parallel from the already existing intakes. Another alternative might be the acquisition of water from the Lower Cretaceous aquifer – in which the calcium content only occasionally exceeds 1.3 g/L. However, their mineralization is of only up to 50 g/L on average, and thus both environmental and economic benefits would be lower.

Conclusions

The suggested model of the use of heat-depleted geothermal brine for the production of industrial brine by borehole salt mines could streamline the management of geothermal resources and chemical deposits.

Given the very favorable geothermal conditions in Kujawy and NE Wielkopolska, as well as current volume of production of industrial brine by both mines considered in the present article (=demand of chemical plants), the total production capacity of geothermal installations would reach about 80–100 MW. This energy generation potential is so large that geothermal plants could operate in parallel even in several localities, optimally – all year round, to produce heat, hot tap water for several towns or even generate electric power and meet the demand of local industrial plants. It is a chance for the Orlen Group, owner of salt mines, to become a national leader in the production of geothermal energy.

In practice, the volume of geothermal waters produced by a geothermal plant is often co-determined (next to energy demand) by injectivity of the injection wells. In the analysed cases, the injectivity problem is nonexistent, what might also contribute to improved financial returns of the geothermal plants.

The implementation of the suggested mine – geothermal plant cooperation would:

- contribute to extending the mine operating life and thus expanding the revenue-generating potential from the sales of brine (by approximately 30–50%);
- permit quicker drawdown for the fuel storage facility in Góra in crisis conditions;
- save jobs in salt mines due to their prolonged operation;
- postpone capital expenditures related to starting new mining operations in other salt diapirs.

Capital expenditure requirements when setting up cooperating where borehole salt mines are used for disposal of cooled brine would be – in light of subsidies available from the Polish National Fund for Environmental Protection and Water Management for at am least initial investment in boreholes – mainly related to the construction of the geothermal power installations and the brine pipeline. The outlined cooperation reduces long-term investment costs for geothermal plants due to the absence of drilling, maintenance and rehabilitation costs for injection wells, including replacement wells and is also associated with lower operating costs compared to traditional doublet systems. Generated savings and earnings from energy production would allow the plant to complete the required injection system in case of the liquidation of the salt mine(s) and the need to dispose of the cooled brine in a different manner.

In the event the above cooperation model is not taken up in any of the suggested configurations, making use of this potential of both borehole mines by external entities is recommended and entirely viable.

REFERENCES

Biernat et al. 2010 – Biernat, H., Kulik, S. and Noga, B. 2010. Problems associated with exploitation geothermal plants to use thermal water with rock pores. *Technika Poszukiwań Geologicznych. Geotermia. Zrównoważony Rozwój – Geological Exploration Technology. Geothermics, Sustainable Development* 1–2, pp. 17–28 *(in Polish)*.

BN-86/6011-07 Brine *(in Polish)*.

Bojarski, L. ed. 1996. *Hydrochemical and hydrodynamic atlas of the Paleozoic and Mesozoic formations and ascent salinity of groundwater in the Polish Lowlands 1:1000000*. Warsaw: Cartographic Publishing House of the Polish Agency for Ecology *(in Polish)*.

Bujakowski, W. and Tomaszewska, B. 2011. A conception of Geothermal Water desalination to improve Water Balance. *Bulletin of the Polish Geological Institute* 436, pp. 17–22 *(in Polish)*.

Dadlez, R. and Marek, S. 1974. General features of the complex tectonics Zechstein-Mesozoic in the central and north-west Poland. *Bulletin of the Geological Institute* 274, pp. 111–142 *(in Polish)*.

Górecki, W. ed. 1990. *Atlas of the Geothermal Waters of Polish Lowland. Early Jurassic and Early Cretaceous Reservoirs*. Krakow: AGH University of Science and Technology Institute of Fossil Fuels, 369 p. *(in Polish)*.

Górecki, W. ed. 2006. *Atlas of Geothermal Resources of Mesozoic Formations in the Polish Lowlands*. Krakow: GOLDRUK Publishing, 485 pp. *(in Polish)*.

Górski, J. and Rasała, M. 2008. Hydrogeology of the chosen salt domes of the Kujawy region – cognitive and utilitarian aspects. *GEOLOGOS* 13, *Monographiae* 5. Poznań: Bogucki Scientific Publishing, 152 pp. *(in Polish)*.

Grube, A. 2000. Widespread geogenic salt water occurrence in North Germany – demonstrated on the basin of a generalized map [In:] Sadurski, A. ed. *Hydrogeology of the coastal aquifers: Proceedings of the 16th Salt Water Intrusion Meeting*. Miedzyzdroje-Wolin, 12–15 June 2000. Torun: UMK Nicholas Copernicus University Publishing, pp. 55–61.

Kubski, P. 2008. Geothermal heating plant in Stargard and its insolvency case. *Instal* 2.

Kunstmann et al. 2002 – Kunstmann, A., Poborska-Młynarska, K. and Urbańczyk, K. 2002. *Introduction to borehole salt leaching. Current development directions.* Krakow: AGH University of Science and Technology Press, 145 pp. *(in Polish)*.

Noga et al. 2013 – Noga, B., Biernat, H., Kapuściński, J., Martyka, P., Nowak, K. and Pijewski, G. 2013. Possibility of obtaining more Geothermal heat in the view of the new investments completed on Polish Lowland. *Technika Poszukiwań Geologicznych. Geotermia. Zrównoważony Rozwój – Geological Exploration Technology. Geothermics, Sustainable Development* 2, pp. 75–84 *(in Polish)*.

Rasała, M. 2014. The possibility of using of salt mines in obtaining geothermal energy [In:] Jaworska, J. et al. eds. *Proceedings of the XIX International Salt Symposium "QUO VADIS SAL"*. Wągrowiec, 8–11 October 2014. Krakow: Polish Salt Mining Association Publishing, pp. 38–45 *(in Polish)*.

Sokołowski, J. 1966. Role of halokinesis in evolution of Mesozoic and Cenozoic deposits of the Mogilno structure and the Mogilno–Łódź synclinorium area. *Publications of the Institute of Geology* 50, pp. 5–94 *(in Polish)*.

Szuflicki et al. eds. 2016 – Szuflicki, M., Malon, A. and Tymiński, M. eds. 2016. *Balance of mineral deposits in Poland as at 31 XII 2015,* Warszawa: Polish Geological Institute – National Research Institute Publishing House, 476 pp. *(in Polish)*.

Wachowiak, J., 2015. Lithostratigraphic and bromine profile of the Zechstein salt series in the area of borehole M-29 of the Mogilno salt dome. *Przegląd solny – Salt Review* T. 11, pp. 91–97.

Wilkosz, P. 2001. *Geological evolution and kinematics of the Mogilno structure in the Cenozoic period*. PhD Dissertation. Poznań: Archives of UAM Adam Mickiewicz University Institute of Geology *(in Polish)*.

Zięba, Z. and Grzesiak, E. 2010. Impact of water chemical composition on exploitation costs of geothermal heating plant in Pyrzyce. *Infrastructure and Ecology of Rural Areas* 8/1, pp. 39–45 *(in Polish)*.

Zuber, A. and Grabczak, J. 1991. On origin of mezozoic brines in central and northern Poland [In:] *Proceedings of the 5th National Symposium "Current Challenges In Hydrogeology"*. Warszawa-Jachranka, 25–27 April 1991. Warszawa: SGGW-AR Publishing, pp. 202–207 *(in Polish)*.

MOŻLIWOŚCI GOSPODARCZEGO WYKORZYSTANIA WYCHŁODZONYCH SOLANEK GEOTERMALNYCH PRZEZ OTWOROWE KOPALNIE SOLI NA NIŻU POLSKIM

Słowa kluczowe

stacja geotermalna, utylizacja solanek geotermalnych, otworowa kopalnia soli, solanka przemysłowa, rentowność przedsięwzięć

Streszczenie

Zaprezentowano koncepcję gospodarczego wykorzystania (utylizacji) wychłodzonych solanek geotermalnych poprzez przekazywanie ich do otworowych kopalń soli, celem dalszego dosycenia chlorkiem sodu. Docelowym odbiorcą wód, już w postaci solanki przemysłowej, byłyby zakłady chemiczne. Aktualnie kopalnie te produkują solankę przemysłową, ługując sole cechsztynu wodami powierzchniowymi. Na przykładzie potencjalnej współpracy zakładów geotermalnych (hipotetycznego w Mogilnie i budowanego w Toruniu) z istniejącymi kopalniami soli (Przyjma i Góra) wykazano, że główne nakłady inwestycyjne (wiercenia, rurociąg), mogłyby zwrócić się w ciągu 10–15 lat.

Rozwiązanie to przyniosłoby wymierne korzyści dla zakładu geotermalnego (brak kosztów związanych z wykonaniem i utrzymaniem otworu do zatłaczania wychłodzonych wód). Dla kopalń soli byłyby to co najmniej korzyści strategiczne poprzez wydłużenie okresu eksploatacji złóż. Wobec braku konieczności zatłaczania wychłodzonych solanek wdrożenie rozwiązania umożliwiałoby prostszą technologicznie eksploatację wód geotermalnych o wysokim zasoleniu. Z przeprowadzonej oceny potencjału geotermalnego w rejonie kopalń wynika, że dla uzyskania maksymalnych parametrów energetyczno-ekologicznych, zalecane byłoby zaopatrywanie kopalń wodami o zawartości >100 gNaCl/dm^3 ze zbiornika dolnojurajskiego z terenu niecki mogileńskiej. Stacje mogłyby pracować równolegle w kilku pobliskich miejscowościach i przy pełnym zaopatrywaniu kopalń w solankę (1000–1100 m^3/h) i temperaturze pozyskiwanych wód >80°C, łączna moc energetyczna instalacji geotermalnych, przy wychłodzeniu do 25°C, mogłaby sięgnąć 80–100 MW.

POSSIBILITIES FOR THE INDUSTRIAL USE OF COOLED GEOTHERMAL BRINES BY BOREHOLE SALT MINES IN THE POLISH LOWLANDS

Keywords

geothermal plant, disposal of geothermal brine, borehole salt mine,
industrial brine, economic viability

Abstract

The paper presents the concept of thedisposal of cooled geothermal brines by re-use in borehole salt mines where they are further saturated with sodium chloride. The target recipients of the brines – saturated to reach industrial brine requirements – would be chemical plants. At present mines produce industrial-quality brine with surface water. Using the model options of cooperation of geothermal plants (a hypothetical plant in Mogilno and one under construction in Toruń) with salt mines (Przyjma and Góra), it follows shown that the payback period for major capital expenditures (drilling, pipeline) would be 10–15 years. The solution would provide tangible benefits for geothermal plants (elimination of costs associated with drilling and maintenance of injection wells). Strategic advantages for salt mines would be extending the lifespan of the salt deposit. As there would be no longer a need for the re-injection of heat-depleted brine, the implementation of the solution would also enable simpler – in technological terms – production of geothermal waters with high level of mineralization. The assessment of geothermal potential in the area of these mines indicates that to achieve maximum energy performance and ecological benefits, it would be advisable to supply the mines with waters with mineralization of >100 g NaCl/L from the Lower Jurassic aquifer in the area of the Mogilno Trough. The geothermal plants could operate in parallel in several towns and, assuming they would be supplying enough brine to fully meet the mines' demand (1000–1100 m^3/h) and the temperature of obtained waters would be >80°C, the total capacity of these geothermal installations, could reach 80–100 MW when cooling to 25° C.