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GEOLOGICAL AND ECONOMIC CONDITIONS FOR THE UTILISATION OF LOW-ENTHALPY HYDROTHERMAL RESOURCES

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ABSTRACT

The utilization of geothermal energy is regarded as a promising possibility to cover a substantial part of mankind's increasing energy demand. Today the role of hydrothermal resources used in Germany for low temperature heat supply is subordinated with respect to the energy demand. A more widespread application is limited by a variety of factors of different nature and scale such as regional geological conditions (supply) and consumer structures (demand). Technical solutions for the exploitation of the different resources are available, but especially geological factors are only known with some degree of uncertainty. Therefore, reliable predictions for heat generation costs are difficult to obtain. They depend on very detailed specific information on local conditions, as the technological layout is strongly affected by the above mentioned parameters and their interdependence.

Within an interdisciplinary working group of geoscientists, engineers, and economists the following topics and their coupling was investigated:

- geologic-petrophysical characterisation of the resources,
- conditioning of the geothermal water cycle,
- long-term behaviour of the utilised aquifers,
- economic analysis of drilling alternatives and various design plants
- optimisation of district heating systems, and
- environmental and economic analysis.

The investigations contribute to a better general understanding about mechanisms and processes during the exploitation of hydrothermal resources. Recommendations for the layout of geothermal heating plants and their operational regimes are derived.

The investigations showed that geology, technology and demand are suitable for a more widespread utilisation. The technically available hydrothermal energy is approximately4 orders of magnitude higher in Germany than the present exploitation. The tools developed show, that environmental effects associated with the utilisation of fossil energy are avoided to a great extent by using geothermal energy. Therefor providing this energy alternative would reduce CO_2-emissions significantly and very cost effective. For large installations heat production costs are even competitive with the fossil fuel combustion of their alternatives. As an outlook can be said that supplying a given local demand needs research to reservoir stimulation with the aim to reduce the drilling risk.

1. INTRODUCTION

Currently the heating demand in Germany is four orders of magnitude higher than the present geothermal exploitation. Available geothermal resources are even six orders of magnitude greater than what is utilised.

Fig. 1 gives an overview to hydrothermal resources in Germany. During the last decades a number of efforts were made to develop a technology for the utilisation of low-enthalpy hydrothermal resources for district heating and since 1984 plants are in operation in Germany and Switzerland (Table 1). One often used system layout with a production and an injection well is shown in Fig. 2.

All plants provide sufficient energy to their customers. There have been no major problems in plant operations due to insufficient technical solutions for possible difficulties based on underground properties. Observed problems are mainly: failures in the district heating system, the surface installation of the plant or at the subsurface water pumps. Nevertheless, there still exists a potential for optimisation of the whole system with respect to reliability and economics.

The constructions of the plants were more or less supported by public money. However, future technology for energy supply must be competitive with other alternatives under economic conditions. With respect to the future demand, the utilisation of low-enthalpy hydrothermal resources was investigated under technical, environmental, and economic aspects within a project supported by the German Ministry of Education, Science, Research and Technology (BMBF, contract no. BEO 0326969). This paper gives an overview of the results. More details are given in Erbas et al. (1999).

Engineers, physicists, or economists are usually unaware of the potential of geothermal energy. On the other hand it is insufficient to assume the enormous potentials of geothermal resources, as geoscientists often do, without a careful look at the economy and reliability of the technology. Thus, the main objective of the project was to bring together a group of engineers, physicists, economists, and geoscientists to work out an interdisciplinary approach to the topics involved. The contributions from the complex interacting disciplines cover the consideration of several scales as follows:

The potential of hydrothermal energy in Germany is 5 times greater then the demand for heating energy. However, there is no common technological layout on the regional German scale because it is affected by local factors. The given geological setting and the customer structure determines the economy. At the lower end of the scale the feasibility is constrained by processes in the pore space. The variation of each parameter in space and time adds up to a general uncertainty in this interdisciplinary evaluation. Therefore, all topics investigated cover the complete range from detailed specific studies with local implications up to general investigations of relationships between the disciplines with their global implications.

2. GEOLOGICAL-PETROPHYSICAL CHARACTERISATION OF THE HYDROTHERMAL RESERVOIRS

In Germany nowadays low enthalpy thermal waters with temperatures between 40 and 100 °C, realisable flow rates between 50 and 100 m³/h and productivity greater than 50 $m^3h^{-1}MPa^{-1}$ form the hydrothermal reserves. A sufficient lateral extent and an easy re-injection of the water into the aquifers are additional requirements for efficient economic exploitation. Therefore the usage is restricted to certain geologic conditions and special reservoir properties.

Potential reservoirs (Fig. 1) are sediments in the Oberrheingraben area, the Molasse Basin and Cretaceous, Jurassic and Triassic sandstones in the North German Basin in a depth range between 1000 and 3000 m. Detailed geologic and petrophysical investigations of the reservoir rocks, temperature conditions, chemical and microbiological analysis of the formation waters and the estimation of possible fluid-rock interactions were compiled (Hoth et al. 1997). They provide a basis for a locally successful exploitation.

Reservoir characterisation: Hydrothermal reservoirs, porous or fissured and/or cavernous rocks filled with thermal water, must be characterised to have a base for an evaluation of the feasibility of the utilisation of geothermal energy. The reservoir properties given in Fig. 3 are typical for the utilised reservoirs in the North German Basin.

The effective thickness of the utilised reservoir layer should be greater than 20 m, the mean porosity should exceed 20 % and the effective permeability should be in the order of $0.5 \cdot 10^{-12}$ m² and higher. To understand fluid-rock-interactions processes information on the pore space structure is essential. Typical pore radii of $25 \cdot 10^{-6}$ m contribute to the utilisable porosity of sandstones. The long time behaviour of rocks with lower mean pore radii must still be investigated.
Adjacent rocks, so called cap rocks, of the aquifers must also be included in the reservoir characterisation. They are important due to their sealing properties and their interaction with the thermal water. They may produce gas which can than be found in the thermal water.

Characterisation of the thermal water: The salinity of the thermal water in the North German Basin ranges from a low saline consistency up to highly concentrated saline fluids (Hoth et al. 1997) with concentrations greater than 280 g/l. A general depth dependence of the mineralisation of the thermal water exists only for Tertiary, Cretaceous, Jurassic, and Upper Triassic aquifers. Depth dependencies varying different to the trend are observed close to the surface (influence of meteoric waters) and close to salt structures.
The gas content varies locally, the measured total gas contents of the investigated brines reach values up to 10 vol. % (Naumann et al. 1999). The gas phase is dominated by N_2, CO_2 and CH_4, the concentrations of the minor constituents He, H_2, Ar and other gases are less than 1 vol. % each. The gas content must be predicted in advance and should be observed carefully as the production of free gas due to pressure release in the thermal water cycle could cause technical problems. In spite of hostile conditions in the aquifers bacteria were observed in the high saline, high temperature, and high pressure environment some of the aquifers (Köhler et al. 1997). A reduction of the permeability within the reservoir may be the result of bacteria activity, as is reported elsewhere, e. g. in the Paris basin (Honegger et al. 1989).

Conditioning of the thermal water cycle: Because of the high salinity of the geothermal brines, the operation of thermal water cycles are usually designed with two bore holes: a production well and a re-injection well (see Fig. 2). The initial Fe^{2+} content of the reducing Na-Cl-brines and the possible precipitation of iron hydroxides induced by oxygen entry between production and re-injection is of main technical importance. Due to the usual low oxygen-content in the natural reservoirs general recommendations can be derived from oxygen-measurements during the operation of a plant:

- During normal operation and high flow rates (e. g. > 40 m^3h^{-1} in Neustadt-Glewe) the diffusion of oxygen into the thermal water is negligible. Therefore, oxygen inflow prevention is only necessary in sensible reservoirs.
- During standstill of a plant the oxygen inflow must be prevented e. g. by pressurising the water cycle and/or protection by nitrogen.
- Injection of slop water, i.e. water from the thermal water cycle with oxygen contact, must be performed with sufficient dilution (Seibt and Hoth, 2000).

Modelling of the long-term behaviour of the utilised aquifers: The evolution of utilised reservoirs, characterised by tectonic and sedimentary structures, was modelled in space and time, using a 3D-finite-elemente program (Wenderoth et al. 1997). Varying physical properties of the fluids and rocks and varying production and injection concepts were used as input parameters. The following can be derived:

- The life time of a plant is related to the distance between the production and injection well. Increasing distance leads to an over-proportional increase in the life time.
- The fluid flow through the reservoir is strongly influenced by the temperature dependent viscosity of the brines. Thus, for example, by neglecting this dependency a faster decrease of production temperature would be calculated.
- An optimised amount of thermal energy from a plant can be yielded using a multiple bore hole concept. Under special conditions an inefficient working plant can be brought to economic operation using this concept.

3. ECONOMIC AND ENVIRONMENTAL ANALYSIS

Economic analysis: The commercial feasibility depends to a great extent on the cost for drilling and the completion of the wells. Siebertz et al. (1998) investigated the realisation costs for drilling alternatives in hydrothermal reservoirs of the North German Basin in the depth range between 1500 and 2200 m. Costs of vertical and sidetrack wells were calculated. The increase in costs were then compared to the saving in technical surface completion. Within a ± 5 % range there was no difference between the total costs of all alternatives investigated.

The costs were analysed in terms of investments and operation costs. They mainly depend on technical and economic boundary conditions (i.e. the necessity for including a fossil driven peak load equipment) and the parameters defining the district heating system. The resulting heat production costs are strongly affected by the geological setting and decrease with increasing plant size. Fig. 4 shows that geothermal heat production from Type II reservoir is economic in comparison to conventional fossil heat production. While geothermal heat recovery in such cases is competitive with conventional energy supply the drawback for a more widespread utilisation is a psychological barrier for the investor who has to wait some years for the economic win.

The heat production costs also vary related to the reservoir productivity as shown in Fig. 5. As mentioned above the peak load is covered by a peak load plant fired by fossil fuel. Low production rates, for a given drilling depth and reservoir temperature, imply higher costs due to higher specific capital expenditures (e. g. for drilling). High flow rates result in a greater amount of geothermal heat supplied to the customer and less usage of the fossil fuel fired peak load system. This results in decreasing costs as long as the corresponding costs for completion (tubes, pumps, etc.) and operation (e. g. electricity) do not raise over proportional. A reduction of the district heating temperatures leads to a further increase in the economics of a plant significantly. Fig. 5 shows the saving of peak load due to the possibility to enter a higher amount of geothermal energy into the district heating water loop. Optimised heating networks could significantly contribute to cost reduction.

Environmental analysis: The exploitation of geothermal energy resources and the low temperature heat generation is regarded as a promising possibility of reducing the environmental impact of energy consumption.

Kayser and Kaltschmitt (1998) and Kaltschmitt (2000) performed a life-cycle-analysis, which takes plant construction and disposal into account. Based on the same customer supply the emissions of CO_2-equivalents amounts to 100 tons per TerraJoule [TJ] for a conventional oil heating station, 72 t/TJ for a gas heating station, 50 t/TJ for the Riehen geothermal plant, and 18 t/TJ for the Neustadt-Glewe plant. Schallenberg et al. (1999) confirm a quotient of about 20 % CO_2-emissions based on measured operation data of the Neustadt-Glewe plant in comparison to a conventional oil heating station, which was calculated for the same supply scenario. Fig. 6 shows the comparison for the emissions during operation in a monthly resolution. Therefore, we conclude that geothermal energy can drastically contribute to an environmentally and climatically more sound energy supply.

Potential and use: The theoretical potential of geothermal energy in Germany is significantly higher than the yearly heat demand. Considering the technical scenarios, i.e. including all restrictions due to technical feasibility and the demand structure Kayser and Kaltschmitt (1998) and Kaltschmitt (2000) concluded that terrestrial heat is capable of covering quite a substantial part of the heat demand. While the present use of hydrothermal resources is approximately 0,5 PJ/year, this technical potential sums up to roughly 5140 PJ/year (Kaltschmitt, 1999) and is thus in the order of the yearly demand for warmth in Germany. The significance of the possible contribution of geothermal energy to the energy system in Germany is evident from these numbers but the future use is triggered by actual political and economic boundary conditions.

4. CONCLUSIONS

The utilisation of low-enthalpy hydrothermal resources was investigated with an interdisciplinary approach of geoscientists, engineers and economists.

The geoscientific conditions for the utilisation of hydrothermal resources can be reduced to a number of parameters to characterise the reservoir and the thermal water within the temperature field of the resource. The main parameters, among others, are porosity, permeability, and thickness of the reservoir rocks, consistence of the fluids, and the temperature of the reservoir. Some recommendations for a secure operation of the geothermal water cycle, such as prevention of oxygen entrance, resulted from geochemistry. The long time behaviour of a plant was modelled numerically. It can be related to some geometric considerations of the bore hole set-up. So life time of a plant can be increase by increasing the distance of production and injection well.

Data from running plants were compiled. With several plants in the North German Basin, in the Bavarian Molasse Basin and in the southern part of the Oberrheingraben, operated by colleges in Switzerland, the technical feasibility is shown and similar experiences to that of the French colleges were gained. Reliable technical solutions exist even for the highly concentrated geothermal brines with mineralisations up to 280 g/l TDS of the very permeable but sensitive sandstone aquifers in North Germany and can be controlled over years.

Life cycle analysis and observation of geothermal plants during operation showed a very significant reduction of CO_2-emissions in the order of 80 % in comparison to fossil heat production. However, the economic evaluation leads to a restriction in the application of hydrothermal energy to large district heating systems and industrial use with high demand of low enthalpy heat. It is therefore important to continue interdisciplinary investigations on the potential of geothermal energy with special emphasis on the reliability, variability and scale of the considered parameters. The current market support large geothermal plants. The future market for hydrothermal heat production lies at the end of the hydrocarbon era within the next century or with respect to special conditions in other countries, e. g. the Baltic states with a high demand on local energy. So the future boundary conditions will lead to an increase of the importance of geothermal energy.

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Figure 1: Hydrothermal resources in Germany.

Table 1. Parameters of plants for hydrothermal heat production in the North German Basin (Waren, Neubrandenburg, and Neustadt Glewe), in the Bavarian Molasse Basin (Erding with a one well system), and in the Southern Part of the Upper Rhine Graben (Riehen, Switzerland) (Huenges et al. 1998).

Location	operation (moder-nised)	installed power, MW		**heat supply (per year), GWh**		depth of production & injection well, m	flow rate m³/h	temperature, °C
	since	total	geotherm.	total	**geotherm.**			
Waren	1984 (94 – 95)	5,2	1,6	13,4 (1995)	**8,5 (1995)**	1566/1470	60	62
Neubrandenburg	1988 (92 – 94)	15,4	3,5	20 (1995)	**9 (1995)**	1270/1285	100	54
Neustadt-Glewe	1995	16,9	6,5	16,2 (1996)	**13,7 (1996)**	2250/2303	120	98
Erding	1998	18	4,5	52 geplant	**28 planned**	2350	86,4	65
Straubing	June 1999		4		**7,6 planned**	825/800	144	36
Riehen (Schweiz)	1994	15,1	2,75	30,4 (96/97)	**12,7 (96/97)**	1547/1247	72	66

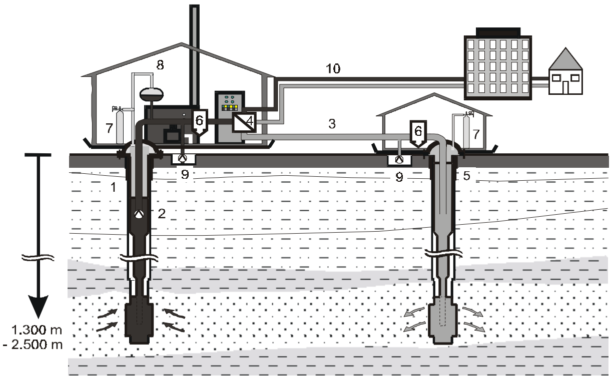

Figure 2. Concept of thermal water cycle for high saline water with production well (1), production pump (2), production tube (3), heat exchanger (4), injection well (5), filter (6), N_2-inertgas-(7) and pressure control system (8), slop disposal (9), and district heating loop (10).

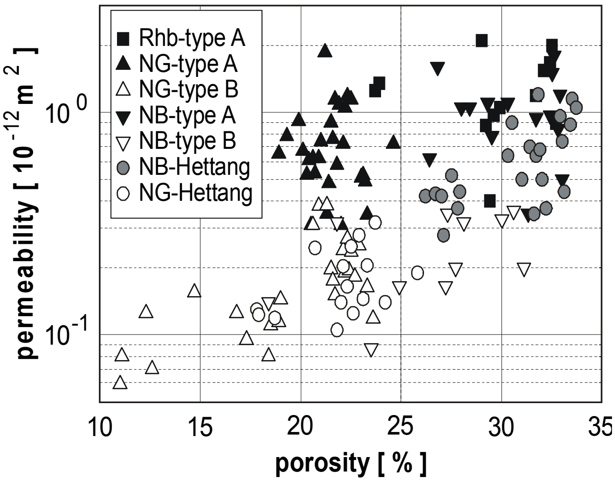

Figure 3. Crossplot of porosity and permeability of sand stones of Lias and Keuper from the bore holes Neubrandenburg (NB), Neustadt Glewe (NG), and Rheinsberg (Rhb) in the North German Basin. Type A: content of sheet silicates lower 5 %, Type B: content of sheet silicates higher 5 % (Hoth et al, 1997).

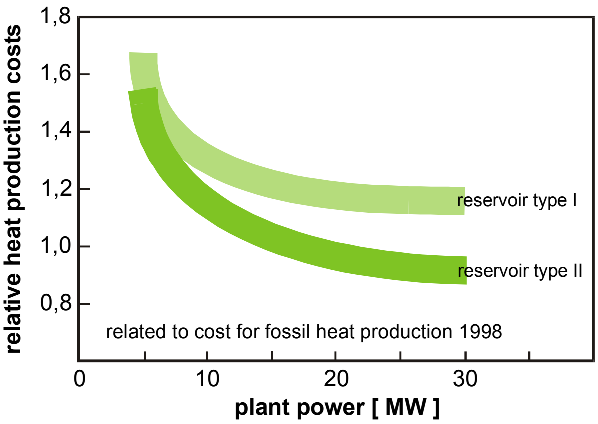

Figure 4. Quotient of calculated heat production costs of geothermal plants and conventional heated plants (= relative costs) as a function of plant power. Main difference in reservoir type is depth and temperature: type II is at greater depth and no additional heat pump is needed.

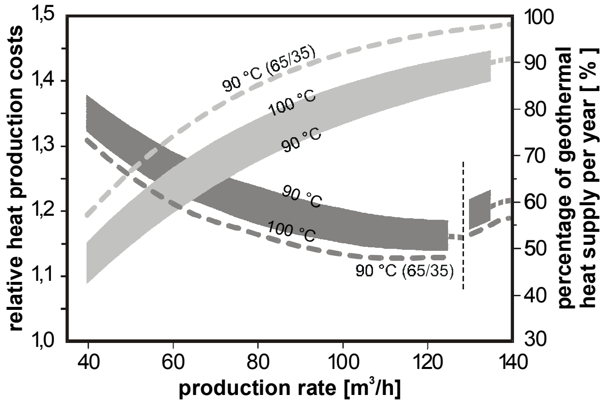

Figure 5. Quotient of calculated heat production costs of geothermal plants and conventional heated plants as a function of production rate and thermal water temperature (90 °C to 100 °C). The percentage of geothermal coverage of the yearly heat supply (30 GWh) is given in the lighter shaded graph. Calculations based on: peak power: 15 MW, district heating loop temperatures: 90/70 °C, (65/35 °C: dotted line) full load hours: 2000 h/a.

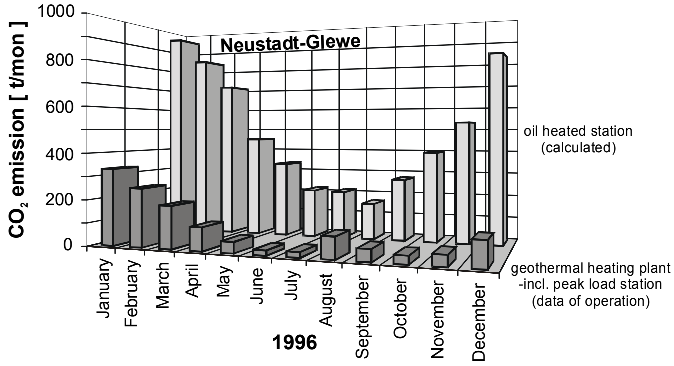

Figure 6. Comparison of CO_2-emissions derived from operation data of the Neustadt Glewe plant with calculated data for an equivalent oil heated station.