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CONDITIONS FOR THE UTILISATION OF LOW-ENTHALPY HYDROGEOTHERMAL RESOURCES IN GERMANY – AN INTERDISCIPLINARY APPROACH

K. Erbas;¸ E. Huenges

GeoForschungsZentrum Potsdam
Projektgruppe Geothermie, Telegrafenberg
D-14473 Potsdam, Germany
kerbas@gfz-potsdam.de, huenges@gfz-potsdam.de

ABSTRACT

The utilisation of geothermal energy is regarded as a promising possibility to cover a substantial part of mankind's ever increasing energy demand. Today the hydrogeothermal resources used in Germany for low temperature heat supply cover only a small part of the current energy demand. Restrictions for a more widespread application result from a variety of factors of different nature and scale. Regional geological settings (supply) and consumer structures (demand) are well known with some degree of uncertainty and technical solutions for the exploitation of different resources are available. Due to the mentioned uncertainties reliable cost predictions depend on very detailed location specific information, as the technological layout is strongly affected by the above mentioned parameters and their interaction.

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

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

The investigations contribute to a better 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 tools developed show, that the utilisation can be competitive with the fossil fuel combustion of their alternatives. Environmental effects associated with the later are avoided to a great extent. As a result, special geological, customer market, and ecological conditions can be examined more precisely and lead to recommendations for local utilisation of geothermal energy.

INTRODUCTION

Recent estimates on the possible ultimate hydrocarbon recovery show that the end of the hydrocarbon era is very close (Edwards, 1997). It is, therefore, essential to discuss feasible alternatives which can contribute now and in future to the various energy demands.

In Germany currently the demand for warmth 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 (Clauser, 1997; Kayser et al., 1998b). Over the last years a number of efforts were made to develop a technology for utilising low-enthalpy hydrothermal resources for centralised urban heating. Several larger power plants entered the working phase, e. g. the plant in Neustadt-Glewe started operating in 1995 with an installed geothermal power of 6.5 MW (Huenges et al., 1998). The constructions of these plants are 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, ecological, and economical aspects within the framework of a project supported by the German Ministry of Education, Science, Research and Technology (BMBF, contract no. BEO 0326969). Detailed investigations were performed on:

- the geologic-petrophysical characterisation of the resources (Frosch et al., 1999; Günzel et al., 1999; Seibt et al., 1999)
- the conditioning of the thermal water loop with (Naumann et al., 1999; Seibt et al., 1999)
- modelling of the long-term behaviour of the utilised aquifers, (Wenderoth et al., 1997, 1998; Frosch et al., 1999)
- the economical analysis of drilling alternatives and various design plants, and optimisation of district heating systems (Straubel et al., 1998; Siebertz et al., 1998; Schallenberg, 1997)

- and on the energy-economical analysis (Kayser et al., 1998b).

This paper gives an overview of the project results including short reviews on the above mentioned topics.

METHOD

Barbier (1997) and others quoted that experts on renewable energy generation are normally engineers, physicists, or economists, whose expertise ranges further than that of Earth scientists. He concluded that, however, 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 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. Similar approaches were used to analyse the cost of heat mining (Herzog et al., 1995). For example the cost–benefit analysis requires knowledge on:

- the temperature and realisable thermal water flow from the underground e. g. from the depth range between 1300 – 3000 m (see fig. 1) – from the geoscientists **-** ,
- the completion of the drill holes, and plant technology to yield a sufficient production rate e. g. about the component 1 to 9 in fig. 1 **-** from the engineers **-**, and
- market analyses including possible district heating loops (see fig. 1) – from the economists**-**.

To investigate these aspects in terms of their complex interactions all of the above mentioned topics must be examined in conjunction with each other. The contributions from these disciplines cover the consideration of several scales as follows:
The reliable potential of hydrogeothermal energy in Germany is about 1 magnitude higher than the demand. However, the regional German scale gives no general answer to the question for a reliable technology layout. The local demand, e. g. with the given geological setting and the possible heat supply for a district heating loop, 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. Access to the information compiled and evaluated in this research project can help consulting and engineering companies in designing geothermal systems and may convince people to invest in the utilisation of geothermal energy.

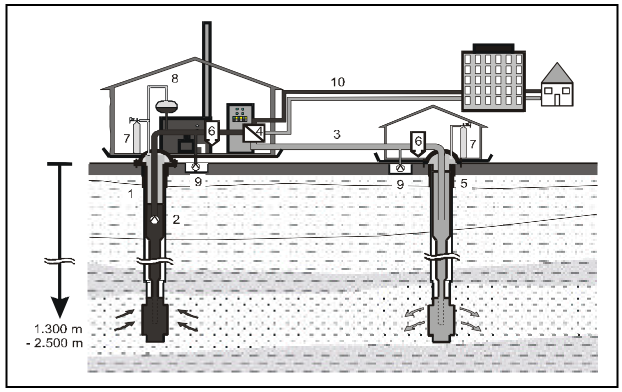

Fig. 1. Concept of a thermal water loop for high saline water with components: production well (1), production pump (2), production tube (3), heat exchanger (4), injection well (5), filter (6), N_2-inertgas- (7) and pressure control system (8), slop deposal (9), and district heating loop (10).

Experience in operation: Since 1984 a number of plants are in operation in Germany and Switzerland. Table 1 which shows parameters of some of the larger plants.

Location operational (modernised)	installed power [MW] total	geothermal	**heat supply (per year) [GWh]** total	**geoth.**	depth of production and reinjection wells [m]	Flow-rate [m³/h]	Temperature [°C]
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 (planned)	**28 (planned)**	2350	86,4	65
Riehen (Switzerland) 1994	15,1	2,75	30,4 (96/97)	**12,7 (96/97)**	1547/1247	72	66

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).

All plants provide sufficient energy to their customers. Until today there have been no major problems in plant operation with regard to insufficient technical solutions for possible difficulties based on properties of the underground. Some technical problems observed are: defects in the district heat system, in the technical surface completion of the plant, or at the subsurface water pumps. Nevertheless, there still exists a potential for optimisation of the whole system with respect to its reliability and its economic conditions. Reservoir exploitation, based on a better knowledge of the aquifer characterisation, technical completion of a plant, and economical-ecological boundary conditions has to be taken into account. The further considerations will focus on the North German Basin because of the availability of a good geoscientific data base and experiences from plants in operation.

GEOLOGICAL-PETROPHYSICAL CHARACTERISATION OF THE HYDROTHERMAL RESERVOIRS

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

Potential reservoirs are 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, knowledge on their temperature conditions, chemical and microbiological analysis of the formation waters and the estimation of possible fluid-rock interactions were compiled within the framework of this project (Hoth et al., 1997) to provide a basis for a locally successful technical exploitation.

Temperature: Good temperature maps exist for the North German Basin (Diener et al., 1984; Hänel et al., 1988). The main conclusions from the investigations on temperature conditions (Förster, 1997) are that the boreholes must have at least a depth of 1000 m in order to have sufficient high temperatures for hydrothermal energy recovery. In addition special geological features in greater depth e. g. produced by salt tectonics must be correlated systematically with heat flow data for local predictions.

Reservoir characterisation: Hydrothermal reservoirs, porous or fissured and/or cavernous rocks filled with thermal water, must be characterised to get a base for an evaluation of the feasibility of the utilisation of geothermal energy (Hoth et al., 1997). The reservoir properties given in Fig. 2 are typical for the utilised reservoirs in the North German Basin.

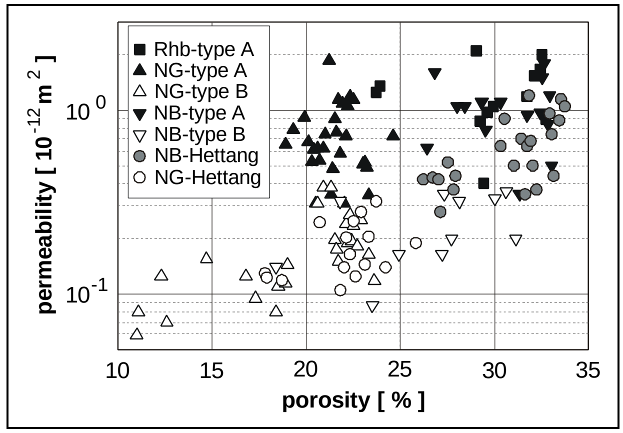

Fig. 2. Crossplot of porosity and permeability of sandstones of Lias and Keuper from the boreholes Neubrandenburg (NB), Neustadt Glewe (NG), and Rheinsberg in the North German Basin. Type A: content of sheet silicates lower 5 % , Type B: content of sheet silicates higher 5 % (Hoth et al., 1997).

The mean porosity should exceed 20 %, the effective permeability should be in the order of $0{,}5 \cdot 10^{-12}$ m² and higher and the effective thickness of the utilised reservoir layer should be greater than 20 m. To understand possible processes e. g. fluid-rock-interactions (Hoth et al., 1998; Frosch et al., 1999) information on the pore space structure is essential. Typical pore radii of 25 µm contribute to the utilisable porosity of sandstones (Figs. 3). The long time behaviour of rocks with lower mean pore radii must still be investigated.

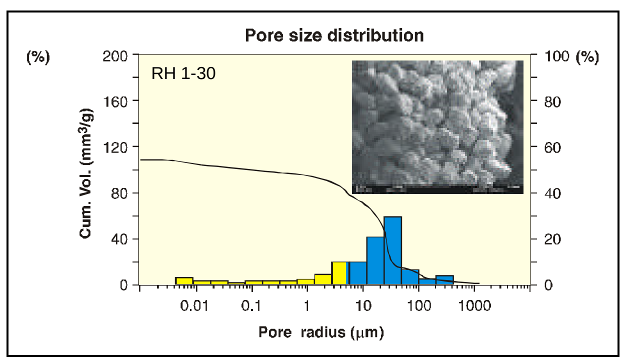

Fig. 3. Pore radii distribution and pore space of a sandstone from the borehole Rheinsberg from a depth of 1700 m with about 30 % porosity and 10^{-12} m^2 permeability. This type of curve is characteristic for favourable aquifers (Hoth et al., 1997).

Neighbourhood rocks of the aquifers must also be included in the reservoir characterisation. They are important as so called cap rocks 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). Fig. 4 shows that a general depth dependence of the mineralisation of the thermal water exists only for Tertiary, Cretaceous, Jurassic, and Upper Triassic aquifers. Hereby, depth dependencies varying different to the trend are observed close to the surface (influence of meteoric waters) and close to salt structures.

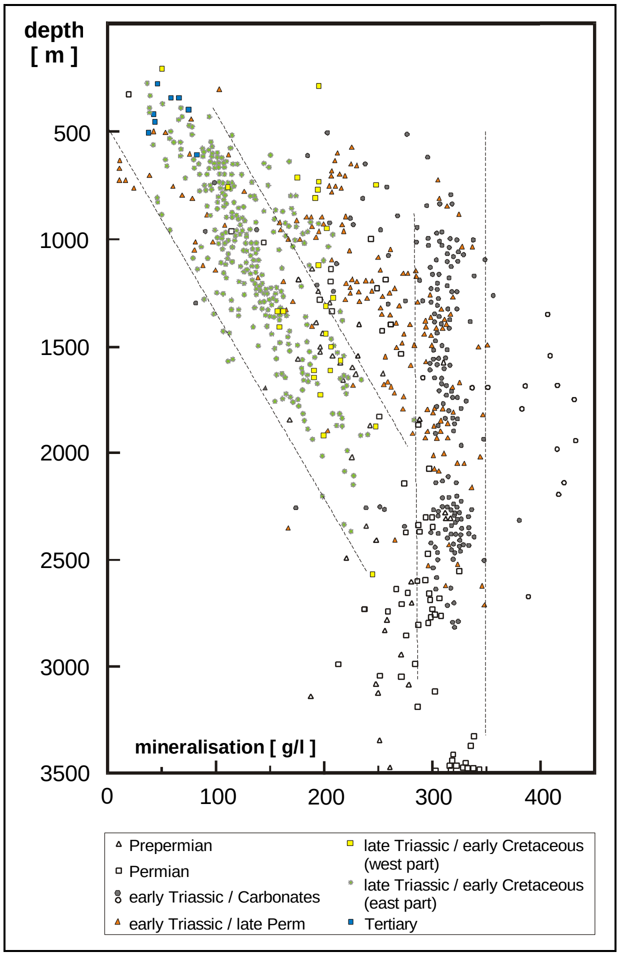

Fig. 4. Compilation of values for the mineralisation of the thermal water in the North German Basin It is clearly evident, that all suitable aquifers for hydrothermal energy utilisation have mineralisation greater than 100 g/l (Hoth et al., 1997).

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 loop 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 of the aquifers (Köhler et al., 1997). A reduction of the permeability within the reservoir may be the result of bacteria, as is reported elsewhere, e. g. in the Paris basin (Honegger et al., 1989).

Conditioning of the thermal water loop: The salinity in the aquifers of the North German Basin varies from 130 to 350 g/l depending on depth (see Fig. 4) and temperature (55-95 °C). Because of the high salinity of the geothermal brines, the operation of thermal water loops are usually designed with two boreholes, a production well and a re-injection well (see Fig. 1). 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 reservoir 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 loop and/or protection by nitrogen.

Injection of slop water (see Fig. 1, component 9), i.e. water from the thermal water loop with oxygen contact, must be performed under sufficient dilutant conditions.

Other types of thermal water – e. g. with higher calcium- and sulphur-content- and their interaction with the reservoir rocks are not considered here, as they do not apply in the case of the North German Basin.

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., 1998; Ondrak et al., 1998). 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 borehole concept. Under special conditions an inefficient working plant can be brought to economical operation using this concept.

Economical and ecological system analysis

Economical system analysis: The commercial feasibility, depends to a great extend 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 of the sidetrack costs were then compared to the saving in technical surface completion. Within a 5 % divergence there was no difference between the total costs of all alternatives investigated.

Depending on the economic boundary conditions, completion of the plant including a fossil driven peak load equipment, and special district heating parameters, the costs were analysed in terms of capital expenditure, operational and consumable costs. A 12 MW plant supplying a direct heating system and connected to a 80 °C-reservoir (no heat pump necessary) uses 56 % of the resulting heat production costs for investments (calculated for 30 years), 31 % for operation and 13 % for consumables. Fossil heat production in comparison needs 12 % of the heat production costs for investments, 22 % for operation and 66 % for consumables (Straubel et al., 1998).

A further lesson can be derived from such calculations. The heat production costs are strongly affected by the geological setting and decrease with increasing plant size. Fig. 5 shows that geothermal heat production from Type II reservoir seems to be economic in comparison to conventional 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 vary related to the reservoir productivity as demonstrated by Herzog et al. (1995). In Fig. 6 depth and temperatures were kept constant.

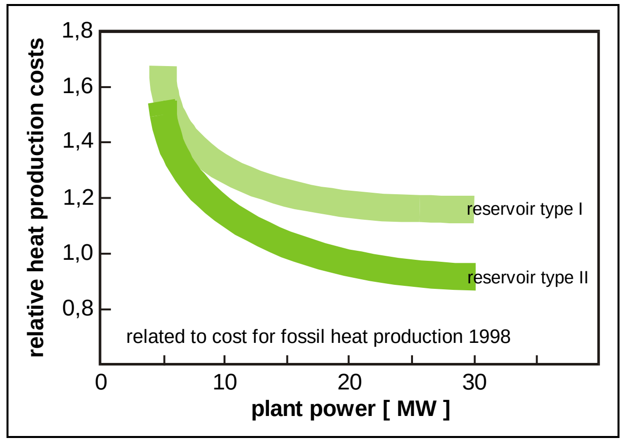

Fig. 5: Quotient of calculated heat production costs of geothermal plants and conventional heated plants (= relative costs) as a function of plant power. Main difference in reservoir type is depth and temperature: type II is at greater depth and no additional heat pump is needed.

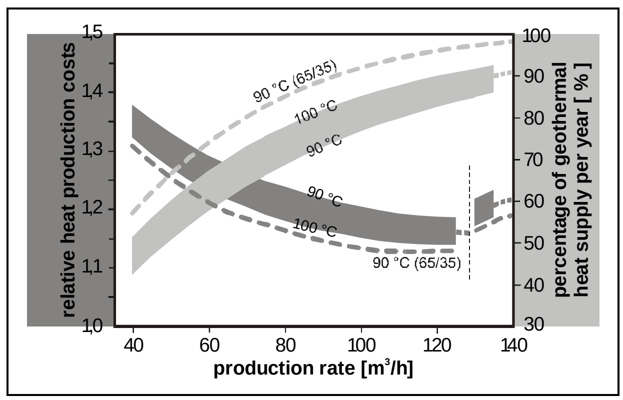

Fig. 6. Quotient of calculated heat production costs of geothermal plants and conventional heated plants as a function of production rate and thermal water temperature (90 °C to 100 °C). The percentage of geothermal coverage of the yearly heat supply (30 GWh) is given in the second shaded graph. For production rates greater than 125 m^3 h^{-1} a production tube with a greater diameter is needed. Calculations based on: peak power: 15 MW, district heating loop temperatures: 90/70 °C, full load hours: 2000 h/a. Optimised heating networks could significantly contribute to cost reductions as is shown by the dotted line which was calculated for district heating loop temperatures of 65/35 °C.

The peak load is covered by a fossil plant. 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 (see Fig 6). A reduction of the district heating temperatures leads to a further increase in the economics of a plant significantly. Fig. 6 shows the saving of peak load due to the possibility to enter a higher amount of geothermal energy into the district heating water loop.

Ecological system 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 production. Kayser and Kaltschmitt (1998a) performed a balancing method called life-cycle-analysis, which takes plant construction and disposal into account. Based on the same customer supply the emissions of CO_2-equivalents amount 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-emission 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. 7 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 efficient energy supply.

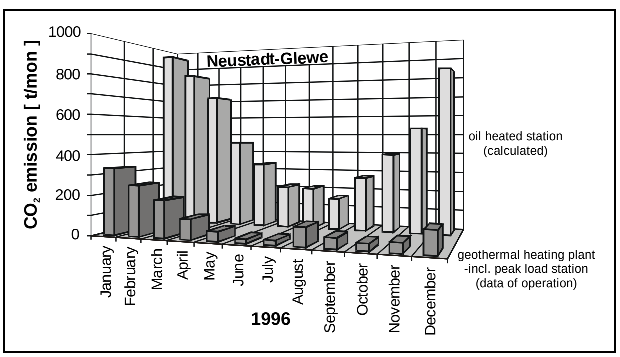

Fig. 7 Comparison of CO_2-emissions derived from operation data of the Neustadt Glewe plant with calculated data for an equivalent oil heated station.

Energy-economical analysis: 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 et al. (1998b) concluded that terrestrial heat is capable of covering quite a substantial part of the heat demand. This conclusion is very important with respect to the contribution of geothermal energy to the energy system in Germany and is triggered by actual political and economical boundary conditions. The above mentioned 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, give other boundary conditions and increase the importance of geothermal energy.

CONCLUSIONS

The utilisation of low-enthalpy hydrothermal resources was investigated with an interdisciplinary approach of geoscientists, engineers and economists. The results are very clear with respect to technical feasibility, ecology, and economy.

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. From the geochemical side some recommendations were given for a sure operation of the geothermal water loop. The long time behaviour of a plant can be related to some geometric considerations of the borehole set-up.

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 Oberrheinthalgraben, operated by colleges in Switzerland, the technical feasibility is shown and similar experience to that of the French colleges was gained. Reliable technical solutions exist even for the highly concentrated geothermal brines 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 comparison to fossil heat production. However, the economical evaluation leads to a restriction in the application of hydrogeothermal energy to existing district heating systems and similar customer structures. It is therefore important to continue investigations on the potential of geothermal energy using an interdisciplinary approach with special emphasis on the reliability, variability and scale of the considered parameters. The future market for hydrothermal heat production lies at the end of the hydrocarbon era.

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