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Quantification of Exploration Risks for Hydrogeothermal Wells

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ABSTRACT

Exploration risk concerning hydrogeothermal wells is defined as the risk of not achieving a geothermal reservoir by one (or more) well(s) in sufficient quantity or quality.

The term quality in the definition can in general be interpreted as fluid composition (fluid chemistry). Component parts (gas, salinity, oil, etc.) can appear in the fluid, which, if they exceed certain limiting values, hinder or complicate the thermal utilization. The term quantity is defined by the (thermal) power which can be achieved by one well (or more wells). Therefore, the essential parameters regarding the quantity for the exploration risk are flow rate Q and aquifer temperature T. Both parameters are decoupled und independently measurable. The flow rate Q will be determined by production tests, the temperature T can be measured by wireline measurements.

A geothermal well is successful, if minimum level of thermal water production (minimum flow rate) Q at maximum drawdown ? s and if minimum level of reservoir temperature T are achieved; for that the depth of the aquifer is determined as exactly as possible from seismic reflection surveys.

Information about the hydraulic parameters of the aquifer can mostly be determined in a regional scale only. Information from boreholes nearby or other boreholes having similar conditions can be weighted in a suitable manner. For the temperature prognosis, local conditions must be considered besides regional trends. An area of 1000 km² was normally chosen in the previous assessments. Because of the small data base, the simplest way to calculate the POS of a project is to multiply the single POS of flow rate and temperature.

The composition of all fluids explored in deep aquifers in Central Europe has not stopped geothermal utilization. But sometimes the technical effort can be great and induce additional costs. Nevertheless, there is no approach to assess the possibility of success for the quality.

1. INTRODUCTION

The quantification of exploration risks for geothermal wells, respectively the estimation of probability of success is one of the most important factors for investors and decision makers. Although the data base is often not optimal because of nonexistent comparing objects, a good quantitative assessment of the exploration risks is required. Extensive investigations and methods for the assessment of exploration risks are known in the oil and gas industry (e.g. Rose 1987, Lerche 1998). The data base in oil and gas exploration is much greater than in geothermal exploration, so the sophisticated methods of oil and gas exploration are not applicable in geothermal energy.

We have gained experience by writing several expert reports about exploration risks for geothermal wells for insurance companies and investors. A concept of the assessment of probability of success (POS) will be discussed in this paper.

2. EXPLORATION RISK

2.1 Definition of Exploration Risk

Exploration risk *concerning hydrogeothermal wells is the risk of not achieving a geothermal reservoir by one (or more) well(s) in sufficient quantity or quality.*

Synonym terms are risk of success or sometimes geological risk. But the term “geological risk” should not be used as synonym, because it describes different, partially extended facts (s. b.). The UNEP-Study (2004) defines exploration risks as follows:

Exploration risk *is the risk of not successfully achieving (economically acceptable) minimum levels of thermal water production (minimum flow rates) and reservoir temperatures.*

Both definitions are identical, as it will be shown below, except the insufficient quality. But the quality (i.e. composition) of the fluid plays a tangential role for the exploration risk.

The term **quantity** is defined by the (thermal) power which can be achieved by one well (or more wells):

(1) $$P = r_F \cdot c_F \cdot Q \cdot \left(T_i - T_o\right)$$

with
P power [W],
$?_F$ fluid density [kg m^{-3}],
c_F specific heat capacity (at constant pressure) [J kg^{-1} K^{-1}],
Q flow rate [m³ s^{-1}],
T_i, T_o (input resp. output) temperature [K] or [°C].

The output temperature T_o is that temperature, which is yielded by cooling the geothermal fluid in overground installations (heat exchanger, power plant); it is determined by technical and/or economical conditions, only, and does not depend directly on the success of the well. The input temperature T_i is that temperature, which is measured at the well head; thermal losses by transport from well head to the thermal installation can be neglected.

The term **quality** in the definition can in general be interpreted as fluid composition (fluid chemistry).

Component parts (gas, salinity, oil, etc.) can appear in the fluid, which, if they exceed certain limiting values, hinder or complicate the thermal utilization.

2.2 Other Risks

Other risks will be listed here to make clear the term exploration risk. These risks are not part of the exploration risk.

Operation risk (sustainability): Operation risk means all changes of quantity (flow rate, temperature) or quality (composition) of the fluid during the geothermal lifetime of the well(s). This risk includes changes in the technical installations of the geothermal cycle caused directly or indirectly by the fluid, e.g. corrosion or scaling.

Part of the operation risk is also a change in input of geothermal energy. The energy achieved from a well is given by

$$E = P \cdot \Delta t \qquad (2)$$

with	E	energy	[J],
	P	power, see Eq. (1)	[W],
	Δt	operation time	[s].

The essential parameters, flow rate Q und temperature T_i, should not significantly drop during the operation time (20-30 a). One condition for that is a sufficiently extensive reservoir.

Drill risk: Drill risk means all *technical* risks concerning well rig and drilling operation. These are risks of the drilling company; they can be covered by insurance contracts.

Geological risk: This term is normally used in petroleum exploration. It is more comprehensive than the exploration risk. It also contents the risk, whether a certain geological underground structure interpreted by seismic exploration exists or not. This question is not so essential in geothermal exploration, although seismic surveys have to be carried out for exploration of geothermal aquifers. Geological risk also contains geological problems during drilling, e.g. not expected layers, in-situ pressure or fluids.

2.3 Parameter for Assessment of Exploration Risks

Looking at the definition (chapter 3.1), the essential parameters regarding the quantity for the exploration risk are flow rate Q and temperature T_i. T_i is the temperature at the well head; it depends directly on the temperature T_A of the geothermal aquifer. Temperature T_i is normally lower as the aquifer temperature T_A. In general, T_i is a function of flow rate Q, aquifer temperature T_A, and operating time Δt. Assuming long operating time and high flow rate, the well head temperature approximates the aquifer temperature; the difference between both temperatures can be neglected. Therefore, the following interrelation is yielded from Eq. (1):

$$P \sim Q \cdot T_A \ . \qquad (3)$$

Both parameters are decoupled und independently measurable. The flow rate Q will be determined by production tests, the temperature T_A can be measured by wireline measurements.

The project manager has to declare, at which flow rate (with which drawdown) and at which temperature the geothermal well will be successful. Then the exploration risk, respectively the POS, can be assessed for these certain values. These values are normally derived from economical conditions (business plan).

A geothermal well is **(partly) successful**,

- if minimum level of thermal water production (minimum flow rate) Q at maximum drawdown **Δs** and
- if minimum level of reservoir temperature T are achieved;
- for that the depth of the aquifer is determined as exactly as possible from seismic reflection surveys.

The composition of all fluids explored in deep aquifers in Central Europe has not stopped geothermal utilization. But sometimes the technical effort can be great and induce additional costs. Nevertheless, there is no approach to assess the possibility of success for the quality.

3. HYDRAULIC PARAMETERS

3.1 General Remarks

Information about the hydraulic parameters of an aquifer can mostly be determined in a ***regional scale***, only. Information from boreholes nearby or other boreholes having similar conditions can be weighted in a suitable manner.

In general, it is difficult to estimate the expected production rates because of the local variability in thermal water flow. The borehole might for instance penetrate a highly productive fracture whilst another borehole drilled close by could miss the fractures completely. In addition, there are also regional differences reflecting facies and tectonics. Reliable conclusions about the prospectivity are only possible when data is available from a large number of boreholes in a specific region. To gain a handle on the probability of success, the data on thermal water flow rates and drawdowns from boreholes, drilled into the specific aquifer has to be compiled.

3.2 Model Case

The concept for the assessment of possibility of success for hydrogeothermal wells is given in Schulz et al. (2005). The assessment for the Unterhaching geothermal power plant (Schulz et al. 2004) will be described as an example in a shortened manner for clarity. The stratigrafic layer which was investigated is the Malm aquifer (Upper Jura) in the South German / Upper Austrian Molasse Basin (16,500 km²). The data from boreholes, drilled into the Malm in this area were compiled. These 32 boreholes indicate a wide range of flow rates (mostly production flow rates, in a few cases, also injection flow rates) and drawdowns (also rises in water level in the case of injection wells), as Fig. 1 shows. There is also some information available on transmissivity – the product of permeability coefficient and thickness.

To use these details to estimate the probability of success, the expected drawdowns s_i were calculated for the specified production flow rates Q´. Three cases were assumed:

laminar flow (best case),

(4) $s_1 = s \cdot Q'/Q$

pure turbulent flow (conservative case, but not realistic),

(5) $s_2 = s \cdot Q'^2/Q^2$

laminar-turbulent flow (most probable case).

(6) $s_3 = a' \cdot Q' + a' \cdot (b/a) \cdot Q'^2$

with Q measured flow rate [m^3/s],
s measured drawdown [m],
$a' = s / (Q + b/a \cdot Q^2)$.

The coefficients a [s/m^2] and b [s^2/m^3] are determined by interpretation of multi level production tests in existing geothermal wells.

Existing values show that the turbulent part of the flow is relatively small. This approach should be considered for high flow rates (50 l/s and more); the case of pure turbulent flow can be excluded. Secondary effects, like temperature dependency or friction losses, are overlooked; they would yield a little higher POS.

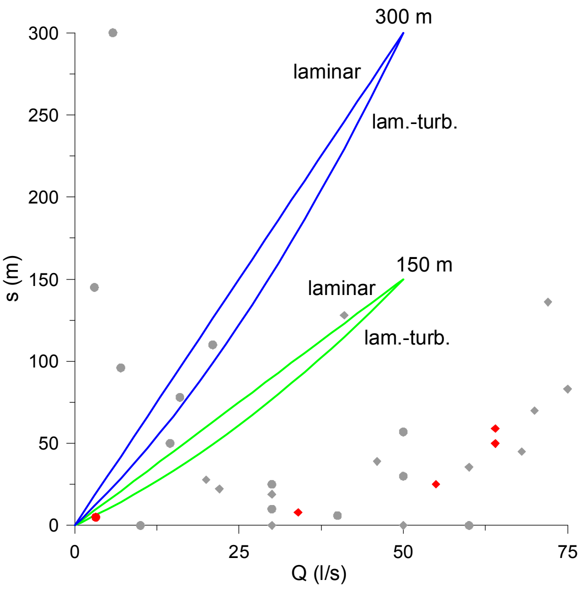

Figure 1: Production rates Q with drawdown s for wells in the South German Molasse Basin (rectangles: geothermal wells, circles: other wells, in red: wells in the central basin; for locations see Fig. 2). Theoretical curves for production rates of a max. drawdown of 300 m (blue) and 150 m (green); straight line: laminar flow, parabola: laminar-turbulent flow.

The parameters for the assessment of probability of success (POS) in the given model case are a flow rate of 50 l/s with a drawdown of 150 m (or 300 m). The expected drawdown for the production rate of 50 l/s is less than 300 m for 29 (of 32) boreholes as laminar flow and for 27 boreholes as laminar-turbulent flow is assumed (Fig. 1). The data points of the successful boreholes are located below the blue curves in Fig. 1: in the laminar case below the linear line, in the laminar-turbulent case below the parabola. If a drawdown of only 150 m can be realized, the green curve in Fig. 1 is valid.

There are wells for water demand and balneology as well as for geothermal utilization among the 32 boreholes considered here (Fig. 2). It is apparent that the productivity of geothermal wells is higher than that of wells drilled for other purposes. The reason is that geothermal wells which were dry were stimulated for instance with acid treatment. This fact can be taken into account in the assessment of POS. Therefore using of weight factors is suggested: Wells drilled for geothermal utilization are higher weighted, e.g. doubled. Additionally, the spatial distance (this means also the geological similarity) to the planned well can be considered. With these constrains, the POS are calculated as follows:

(7) $POS = (\Sigma\, u_i \bullet w_i \bullet a_i) / (\Sigma u_i \bullet w_i)$

with Σ : sum i = 1....N;

u_i, w_i weight factors
$u_i > 1$ for wells nearby; otherwise 1;
$w_i > 1$ for geothermal wells, otherwise 1;
$a_i = 1$ for successful wells (i.e. $s \leq 150$ m, 300 m), otherwise 0.

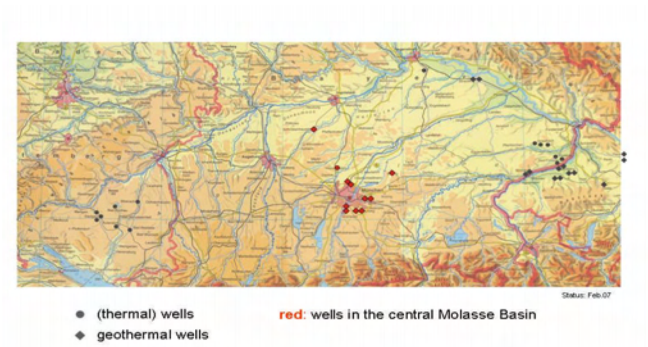

Figure 2: Locations of wells with production tests of the Malm aquifer in the South German Molasse Basin.

3.3 Data Base

An assessment of POS for the flow rate should be based on a minimum level of wells with quantitative hydraulic data. The number of data points is not strictly obliged, but a minimum of 20 wells seems to be acceptable; insurance companies seem to be content in any case with 30 wells.

This small number of wells with quantitative data does not allow any subdivision regarding special geological conditions, for example facies or tectonics.

4. TEMPERATURE PROGNOSIS

4.1 General Remarks

For the temperature prognosis, *local conditions* must be considered besides regional trends. An area of 1,000-2,500 km^2 was normally chosen in the previous studies.

In Germany, there is a database containing information on around 10,000 boreholes and their temperatures (Kühne et al. 2003). In addition to temperature logs, the analysis mainly used bottom hole temperatures (BHT). These BHT logs are made in almost all industrial wells at the deepest part of the well immediately after the end of each drilling phase and are thermally disturbed by the drilling activity (mud circulation). It is possible to correct (extrapolate) these BHT figures to calculate the undisturbed temperatures because the disturbance caused by mud circulation on the temperature field is lowest in the deepest part of the borehole. Different extrapolation methods can be used depending on the time since the end of drilling, the mud circulation period and the number of BHTs measured in the well (Schulz et al. 1990). In addition, the figures are compared with a statistical evaluation of all available borehole data in the study area. Unlike undisturbed temperature logs, the results still have an error of approx. ± 5 K despite the corrections.

4.2 Determining the Depth of the Aquifer

Optimal development for a geothermal project requires exploration of the geological structure. The results of all deep boreholes nearby have to be analyzed for stratigraphic information and hydraulic data as well. They constitute the framework for the interpretation of the seismic measurements. Normally, old seismic lines measured for petroleum exploration have to be reprocessed focussing on geothermal aquifer(s). If the information from boreholes and seismics is insufficient, e.g. the distance from the location of the planned geothermal plant to the seismic lines is too far or the quality of the seismic data for the target depth is too low, new seismic lines, better a 3D seismic survey, have to be measured.

Besides the information on the geological structure, one of the main objectives of seismic (re-)processing is to determine the depth of the top of the geothermal aquifer. The temperature T_A cannot be forecasted without this information. The temperature gradient within an aquifer with high hydraulic conductivity, this is where we are looking for, is often very low because of the good vertical mixing of the hot water. Therefore, the temperature at the top of the aquifer is a conservative, but good estimation of the production temperature of the geothermal well.

The thickness of the aquifer should also be determined by seismic interpretation. The transmissivity, and derived from that the production rate, can be estimated by knowing this thickness and hydraulic permeability.

4.3 Model Case

The structural interpretation of the seismic lines in the model location (see 3.2) reveals that the top of the aquifer lies at a depth of slightly more than 3,000 m at that location (Schulz et al. 2004).

The study area encompassed nine TK25 sheets, i.e.1,000 km^2, around the location. BHT measurements from only 19 boreholes are available in the study area. No wells with temperature information existed in the immediate vicinity of the planned borehole. Data availability decreases sharply below 2,500 m. The available figures were extrapolated or interpolated to a depth of 3,000 m for the temperature prognosis of the planned borehole. The entire figures lie between 95-115 °C, only the extrapolation of the temperature in the N, outside of the study area, yields a significantly higher temperature. A temperature of 100 °C minimum required for power generation is expected with a probability of 0.86 (Schulz et al. 2005). Temperatures of 120 °C are also possible; temperatures above 130 °C can be excluded.

5. PROBABILITY OF SUCCESS

The probability of success (POS) can be defined in the simplest way by determining the probability of each risk separately and multiplying the single probabilities. But this method is also problematic to use in geothermal exploration assessing quantitatively the probability of each parameter, because the data base is normally very small.

5.1 POS for the First Well

In the model case, the condition of the temperature of 100 °C can be fulfilled with a high probability (p_1=0.86). The probability of a production rate of 50 l/s (100 l/s) at a drawdown of 300 m is assessed with p_2 = 0.95 (0.85). Stimulation measures to reduce the exploration risk such as optimum seismic information, acid treatment or deviation of drilling are presumed.

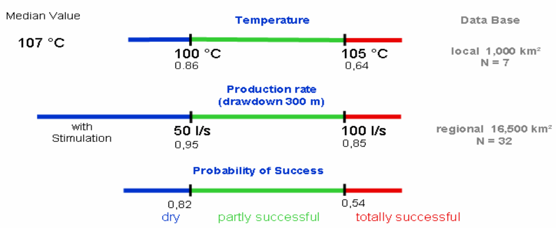

Figure 3: Probability of Success for the model case (1st well)

A POS for a geothermal well with a production rate of 50 l/s at a drawdown of 300 m and a temperature of minimum 100 °C is yielded with these figures:

$p = p_1 \bullet p_2 = 0.82.$

The project design of the model case included geoscientific prospect evaluation with a special seismic reprocessing and interpretation (Thomas and Schulz 2007), a local analysis of the temperature distribution and a regional assessment of the hydraulic parameters. Stimulation measures as deviation and acid treatments are an integral part of the financial design for the geothermal plant. The borehole is privately insured against the risk of non-discovery. This was based on the estimated probability of success outlined here. According to our information, this is the first geothermal borehole in the world which has been privately insured against failure.

Drilling stopped in September 2004 at 3350 m TVD (Top Malm 3002 m TVD). The geothermal well was successful confirmed by production tests and temperature measurements. The production rate is 65 l/s with a draw-down of ca. 70 m. The water temperature exceeds 122 °C.

5.2 POS for the Second Well

A second well as injection well is needed for geothermal doublets. The exploration risk of the second well in the Unterhaching geothermal project should be insured, too.

Since the Unterhaching Gt 2 well would be intended as injection well, a temperature prognosis was not required. This also means that an insurance against the temperature risk is not necessary. Only the production rate should be insured.

Planning the geothermal plant, a production rate of 150 l/s was now assumed because of the extremely high productivity of the Unterhaching Gt 1 well. The parameter for the new assessment of the POS was changed: It was not the production rate for a given drawdown, but the drawdown for a given production rate. The data base for this assessment was a little bit enlarged; the total number is 34 wells instead of 32 wells (Fig. 2, 4).

The same procedure as in chapter 3.2 can be applied in principle. The probability of a drawdown of 500 m (200 m) for a production rate of 150 l/s is assessed with p_2 = 0.91 (0.78), see Fig. 4.

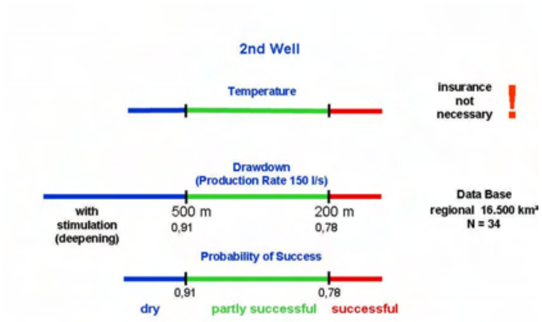

Figure 4: Probability of Success for the 2nd well

The injection borehole Gt 2 was drilled June 2006 to January 2007. A first hydraulic test was not successful, the well was relatively dry. After deepening the well down to 3590 m TVD and stimulation with acid treatment, a second hydraulic test has proven a water temperature of about 134 °C and the productivity was even higher than in the first borehole Gt 1. It can be extrapolated that the drawdown is less than 200 m for production rate of about 150 l/s.

5.3 General Remarks

A POS of 0.82 or 0.91 as in the model case is extremely high, if it was assessed in the oil and gas exploration; it should be considered that the (energy) value of a production well in the carbon industry is much higher than in geothermal energy. Nevertheless, the high probability in the geoscientific meaning is low from underwriting's point of view. The insurance premium amounts 5-25 % of the drilling costs.

We have gained experience by some expert reports (Fig. 5) about exploration risks for geothermal wells, worked out for insurance companies and investors. The number increased in the last two years after the Renewable Energy Sources Act (EEG: Erneuerbare Energien Gesetz) entered into force on 1st August 2004. One core element of the EEG is a consistent fee for renewable electricity paid by the grid operators, generally for a 20-year period, for commissioned installations. This fee accounts 0.15 € per kWh for geothermal electricity.

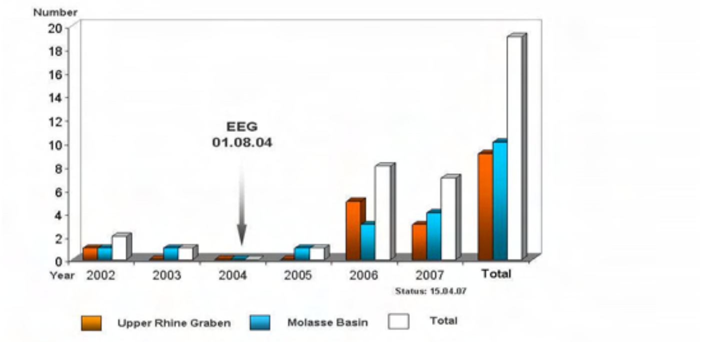

Figure 5: Number of expert reports, worked out for insurance companies and investors, for the main hydrogeothermal reservoirs in Germany: Upper Rhine Graben (Muschelkalk, Bunter) and South German Molasse Basin (Malm). EEG: The Renewable Energy Sources Act (Erneuerbare Energien Gesetz) entered into force on 1st August 2004.

The results of our expert reports show that the method for assessing the POS is very realistic; it seems that the assessment underestimates the real value, particularly if stimulation measures will be carried out.

6. CONCLUSIONS AND OUTLOOK

A concept of the assessment of probability of success for geothermal wells was discussed for the Unterhaching geothermal plant. The project design included geoscientific prospect evaluation with a special seismic reprocessing and interpretation, a local analysis of the temperature distribution and a regional assessment of the hydraulic parameters. Stimulation measures as deviation, deepening and acid treatments are an integral part of the financial design for the geothermal plant. Local analysis (study area approx. 1000 km^2) indicates that a temperature of 100 °C minimum required for power generation was expected with a probability of 0.86. Because of the karstification, estimating the potential production rates proved to be problematic. Regional analysis for the whole Molasse Basin (16,500 km^2) reveals that production rates of 50 l/s with a maximum drawdown of 300 m can be achieved with a probability of approx. 90 %. The overall POS of the geothermal well was 0.82. The geothermal well drilled in 2004 was successful confirmed by production tests and temperature measurements with much higher values as expected.

The borehole was privately insured against the risk of non-discovery. This was based on the estimated probability of success outlined here. According to our information, this is the first geothermal borehole in the world which has been privately insured against failure.

Since the second well will be mostly intended as injection well, an insurance against the temperature risk is not necessary. Only the production rate should be insured. The parameter for an assessment of the POS for the second well can be changed: In the Unterhaching case, it was not the production rate for a given drawdown, but the drawdown for a given production rate. The Unterhaching Gt 2 well was drilled in 2006/07. A first hydraulic test was not successful. But after deepening the well, a hydraulic test has proven that the productivity is even higher than in the first borehole.

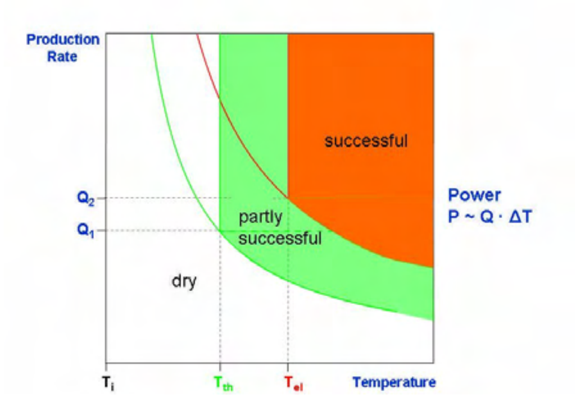

Figure 6: At present, a geothermal project is defined as (partly) successful, if the temperature and the production rate are greater than a certain value. In reality, a geothermal project is (partly) successful, if the power, i.e. the product of temperature and production rate, is greater than a certain value (coloured areas).

The essential parameters regarding the exploration risk are flow rate Q and temperature T. Both parameters are decoupled und independently measurable. The project manager has to declare, at which flow rate (with which drawdown) and at which temperature the geothermal well will be (partly) successful. For example (see Fig. 6), temperature T_{el} and flow rate Q_1 are necessary for a (totally) successful well drilled for a geothermal power plant; on the other hand, lower temperature T_{th} and flow rate Q_2 are sufficient for the same well, if only a geothermal heat installation can be realized (partly successful).

The exploration risk, respectively the POS, is assessed for these certain values, which are normally derived from business plan. But economical conditions in general do not yield certain values Q and T, but the energy output P, and that means the product Q•T. Lower flow rate can be compensated by higher temperature and vice versa (see Fig. 6).

In the future, it should be possible to assess the POS of the capacity to be installed (P ~ Q•T) instead of the product of the certain values (Q and T). This approach needs more values and perhaps other methods, e.g. Monte Carlo Simulation. All relevant data, especially hydraulic data, will be compiled in a geothermal information system for Germany, which will be online before the end of 2008 (Agemar et al. 2007).

Acknowledgements

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