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Quantification of Exploration Risks as Basis for Insurance Contracts

Rüdiger Schulz, Sandra Pester, Rüdiger Schellschmidt, Rüdiger Thomas

Leibniz Institute for Applied Geophysics (LIAG), Stilleweg 2, D-30655 Hannover, Germany

ruediger.schulz@gga-hannover.de

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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 can in general be interpreted as fluid composition. Component parts 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. A geothermal well is successful, if minimum level of thermal water production (minimum flow rate) Q at maximum drawdown Δs and 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 an aquifer can mostly be determined in a regional scale only. For the temperature prognosis, local conditions must be considered besides regional trends. Because of the small data base, the simplest way to calculate the probability of success (POS) of a project is to multiply the single POS of flow rate and temperature. Expert reports for about 40 geothermal projects in Central Europe have been written using this method. They established the basis for insurance contracts and investors' decisions.

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. Some public insurance proceedings were implemented for geothermal wells on national levels as Rybach et al. (2000) and Partowidagdo (2000) reported, but private insurance contracts covering geological risks have been unknown until 2004. The Unterhaching Gt 1 well (Schulz et al. 2004) was the first geothermal borehole in the world which has been insured against failure (Schulz et al., 2005).

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

2. EXPLORATION RISK

2.1 Definition of Exploration Risk

First at all the exploration risk is to be defined:

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):

$$P = \rho_F \cdot c_F \cdot Q \cdot (T_i - T_o) \quad (1)$$

where P, ρ_F, c_F, Q, T_i and T_o are power in W, fluid density in kg m^{-3}, specific heat capacity (at constant pressure) in J kg^{-1} K^{-1}, flow rate m³ s^{-1}, input resp. output temperature in K.

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 (durability): 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

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

where E, P, Δt are energy in J, power in W (see Eq. (1)), operation time in 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.

Seismic risk: If the water production has to be improved by stimulation, e.g. by hydraulic fracturing, normally microseismic events occur. This induced seismic activity is recorded by seismometers, only. But in the worst case, seismic events with magnitudes $M > 3$ can occur, especially in regions with natural seismicity. Such an event can be perceived by humans, as it happened in the Basel Project (Häring et al., 2007). Induced seismicity caused by other kinds of stimulation, like acid treatment, is not proven.

2.3 Parameter for Assessment of Exploration Risks

Looking at the definition (chapter 2.1), 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 up to now no approach to assess the possibility of success for the quality.

2.4 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. Neglecting the risk of the water quality, the exploration risk of a hydrogeothermal well depends on temperature and flow rate, only (Eq. 1, 3). Therefore, the probability of success (POS) for the 1st well for hydrogeothermal utilization is defined as

$$p = p_1 \cdot p_2$$

where p1, p2 are POS for flow rate and POS for temperature.
Because the data base is normally very small, this method can be problematic to use in geothermal exploration assessing quantitatively the probability of each parameter. The concept to determine the POS for flow rate and temperature will be discussed in chapter 3 and 4.

3. FLOW RATE

3.1 Data Base

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.

The data from 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).

There is also some information available on transmissivity the product of permeability coefficient and thickness. All quantitative hydraulic data for deep geothermal aquifers in Germany have been compiled in the Geothermal Information System (Pester et al. 2010).

3.2 Theoretical Drawdowns

To use the data of the existing boreholes to estimate the probability of success (POS) for the planned borehole, the expected drawdowns s_i were calculated for the specified production flow rates Q´ which has to be declared by the project manager (s. Ch. 2.3). Three cases for the kind of flow into the borehole were assumed:

laminar flow (best case)

$$s_1 = s \cdot \frac{Q'}{Q} \qquad (4)$$

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

$$s_2 = s \cdot \frac{Q'^2}{Q^2} \qquad (5)$$

laminar-turbulent flow (most probable case)

$$s_3 = a' \cdot Q' + a' \cdot \left(\frac{b}{a}\right) \cdot Q'^2 \qquad (6)$$

where Q, s are measured flow rate in m³/s and measured drawdown and m

$$a' = \frac{s}{\left(Q + \frac{b}{a} \cdot Q^2\right)}$$

The coefficients a [s/m²] and b [s²/m³] 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 (b/a ≈ 10). 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.

Calculating the POS by Eq. (7) for the planned geothermal well, an existing well rates as successful, if the theoretical drawdown s_i for the specified production flow rate Q´ is less than the maximum drawdown Δs which has to be declared by the project manager (s. Ch. 2.3).

3.3 Assessment of POS for Flow Rate

There are wells for water demand and balneology or petroleum as well as for geothermal utilization among the boreholes with flow rate data. A thermal well for a spa might be successful, if the flow rate amounts in the order of 3 l/s. Geothermal wells for district heating system may be successful, if the flow rate amounts in the order of 30 l/s. A hydrogeothermal well for power generation needs water flow rates of 70 l/s or more to be successful. If such wells were dry or partly successful, they were stimulated for instance with acid treatment. Therefore, it is apparent that the productivity of geothermal wells is higher than that of wells drilled for other purposes.

This fact should be taken into account in the assessment of possibility of success (POS). The 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. Other facts for introducing weight factors can be facies, tectonics, or faults.

With these constrains, the POS are calculated as follows:

$$p_1 = \frac{\sum u_i\, w_i\, a_i}{\sum u_i\, w_i} \qquad (7)$$

where u_i, wi are weight factors, e. g.

- $u_i > 1$ for wells nearby; otherwise 1;
- $w_i > 1$ for geothermal wells, otherwise 1;
- $a_i = 1$ for successful wells, otherwise 0.

and Σ is sum i = 1...N (number of wells with flow rate data).

A quantification of POS for the flow rate should be based on a minimum level of wells with quantitative hydraulic data. The number of data points (N in Eq. 7) 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. If the database is much smaller, it seems to be convenient to divide the cases in POS classes instead of a numerical quantification.

4. TEMPERATURE

4.1 Data Base

For the temperature prognosis, *local* conditions must be considered besides regional trends. An area of 1,000-2,500 km² 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 (Hartmann et al. 2008).

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 Temperature Prognosis

Normally, the study area encompassed ca. 1,000 km² around the location of the planned geothermal well. All temperature measurements should be compiled within a temperature depth profile. If the number of wells with temperature data is too small, the study area has to be enlarged. In order to get an overview about the regional and local temperature distribution, a temperature map for the depth of the top of the aquifer is created. If the database for that depth is too small, e.g. less than 15 wells, the depth has to be chosen at which enough temperature points exist.

The temperature data set is quite often not sufficient for an assessment. In these cases one should try to calculate the temperature existing in the target depth. Assuming purely conductive condition and assuming that there is no relevant variation of thermal conductivity in the top layer, the temperature for greater depth can be calculated using the temperature gradient measured in shallower depth:

$$T(z) = T_0 + z \cdot grad\ T \qquad (8)$$

where T_0 is the annual mean surface temperature. Then the POS for the given (minimum) temperature T_t at the target depth z_t is calculated by

$$p_2 = \frac{\sum \frac{a_i}{R_i^2}}{\sum \frac{1}{R_i^2}} \qquad (9)$$

where $a_i = 0$ for $T(z_t) < T_t$ otherwise $a_i = 1$; R_i is distance between well and planned geothermal well, and $i = 1 \ldots n$ (number of wells with temperature data in the study area). $T(z_t)$ is either the measured or the calculated (Eq. 7) temperature. The POS (Eq. 8) is weighted by the square distance (R^2) due to temperature dependence in the heat conduction equation.

4.4 POS for the Injection Well

Geothermal power or heating plants using hydrogeothermal energy normally need at least 2 wells, a production and an injection well. A temperature prognosis is not required for the injection well. This also means that an insurance against the temperature risk is not necessary:

$$p_2 = 1$$

Only the production rate should be insured:

$$p = p_1$$

5. MODEL CASE

5.1 Essential Parameters

The assessment of POS will be described for a fictive, but realistic geothermal project as an example in a shorten manner for clarity. The Southern German / Upper Austrian Molasse basin (Fig.1) is one of the most important hydro-geothermal energy reservoirs in Central Europe. The Malm (Upper Jurassic) which is present throughout almost the whole of the area is a highly-productive aquifer which dips from north to south to increasing depths and temperatures. In addition to high temperatures, the critical factor for the economic efficiency of geothermal energy utilization is primarily the production rate achievable during continuous operation.

The parameters for the assessment of probability of success in this model example are

- flow rate of 55 - 90 l/s with a drawdown of 300 m,
- temperature of 100 °C at the top of Malm; this depth was determined to 4300 m deduced from some 2D seismic profiles.

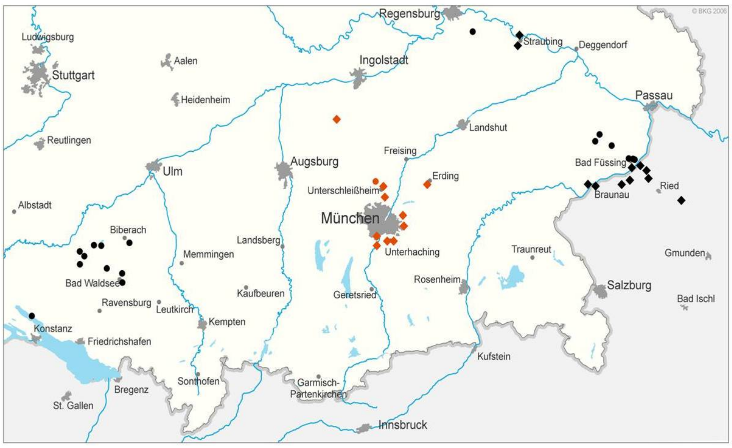

Figure 1: Borehole locations in the South German / Upper Austrian Molasse basin with hydraulic parameters in the Malm (cf. Fig. 3); rectangles: geothermal wells, circles: other wells, in red: wells in the central basin).

5.2 Assessment of POS for Flow Rate

There are wells for water demand and balneology as well as for geothermal utilization among the 41 boreholes considered here (Fig. 1). Therefore weight factors are used: Wells drilled for geothermal utilization (squares in Fig. 1) are doubled weighted. Additionally, the spatial distance (this means also the geological similarity) to the model well can be considered: The success values a_i of the wells drilled in the central Molasse basin (red in Fig. 1) are also doubled. With these constrains, the POS are calculated after Eq. (7).

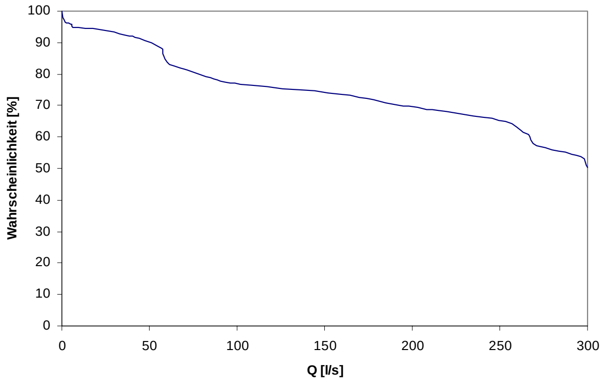

Figure 2: Probability distribution calculated with Eq. (7) for reaching different production rates with a maximal drawdown of 300 m.

For a production rate of 55 l/s and a drawdown of 300 m the probability of success is estimated at 89.4 % (Fig. 2). If a production rate of 90 l/s is assumed, the probability of success is still 80.4 % (Fig. 2 and 3).

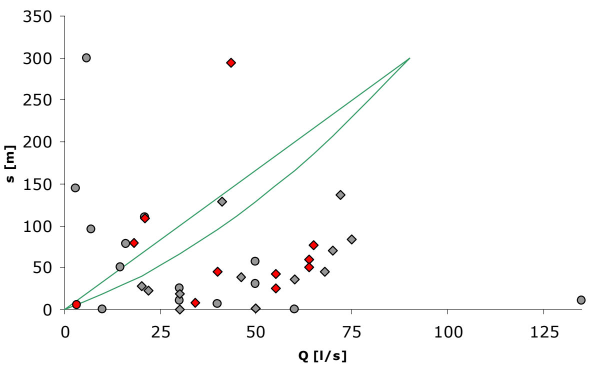

Figure 3: Production rates Q with drawdown s for wells in the Molasse basin (rectangles: geothermal wells, circles: other wells, in red: wells in the central basin). Theoretical curves for production rates of 90 l/s with a max. drawdown of 300 m; straight line: laminar flow (Eq. 4), parabola: laminar-turbulent flow (Eq. 6).

5.3 Temperature Prognosis

The geothermal should be successful, if a temperature of 100 °C at the depth of 4300 will be achieved. But there is only one temperature datum at that depth in the study area; even for 3000 m depth, there are only 8 data (Fig. 4). Therefore, temperature extrapolation as described in Ch. 4.3 has to be used.

The temperature data of 31 boreholes lying in a circumcircle of 12.5 km, i.e. an area of 980 km² enter in the POS assessment (Eq. 9).The POS achieving a temperature of 100 °C in 4300 m amounts p_2=0,81. Fig. 5 shows the probability distribution for reaching different temperatures. 90 °C will be reached with a very high possibility. The POS for 110 °C amounts approximately 70 %; the 50 % percentile is located at 113 °C; the expectation value is 116 °C.

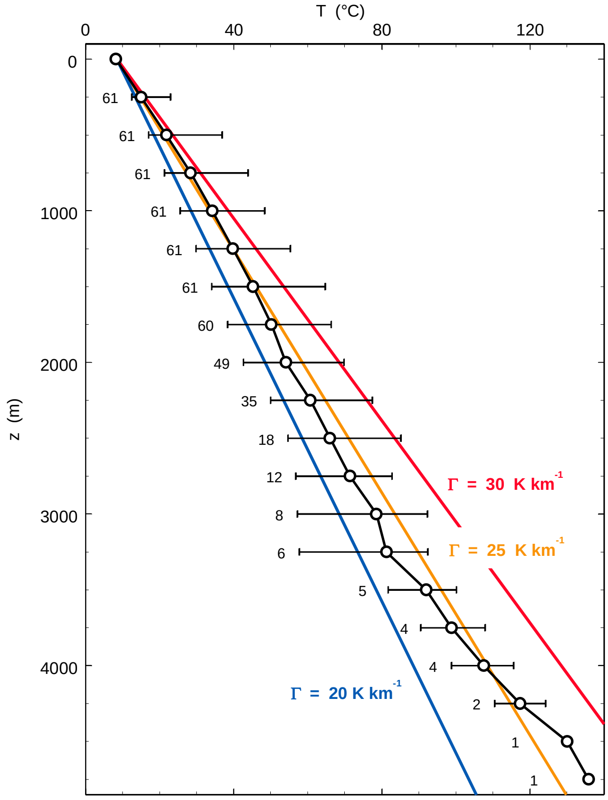

Figure 4: Temperature depth profile in the Study area (approx. 1000 km²) with details on observed minimum and maximum temperatures. The figures next to the observed minimum values show how many measurements exist for each depth; the averages are calculated with a weighting function taking into account the different reliability and accuracy of the data. The lines correspond to temperature gradients of 20, 25 and 30 K/km.

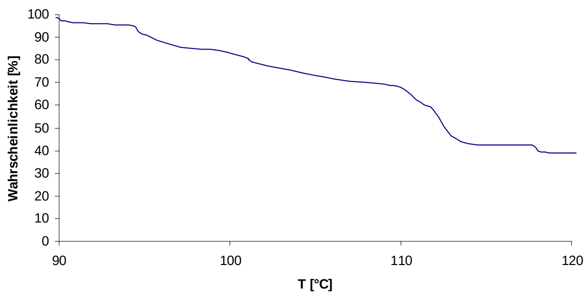

Figure 5: Probability distribution calculated with Eq. (9) for reaching different temperatures at 4300 m.

5.4 Probability of Success

The probability of success (POS) is defined in the simplest way by determining the probability of each risk separately and multiplying the single probabilities.

Therefore, the probability of success (POS) in the model case (55 l/s with a maximal drawdown of 300 m and 100 °C) is

p = 0.72.

If the planned production rate is increased to 90 l/s, the POS is reduced down to 0.65.

5.5 General Remarks

A POS of 0.72 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. 6) 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. After an amendment on 1st January 2009, this fee accounts 0.16 € per kWh for geothermal electricity and together with some boni up to 0.24 € per kWh.

6. CONCLUSIONS AND OUTLOOK

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. 7), 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. 7).

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, are now compiled in a geothermal information system for Germany, which is online under www.geotis.de (Pester et al. 2010).

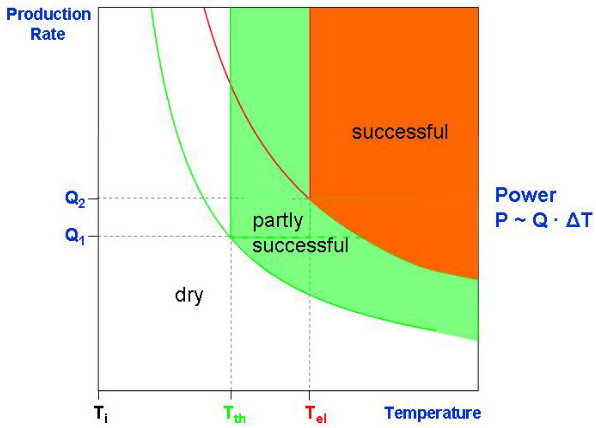

Figure 7: At present, a geothermal project is defined as (partly) successful, if the temperature and the production rate are greater than a certain value. In reality, a geothermal project is (partly) successful, if the power, i.e. the product of temperature and production rate, is greater than a certain value (coloured areas).

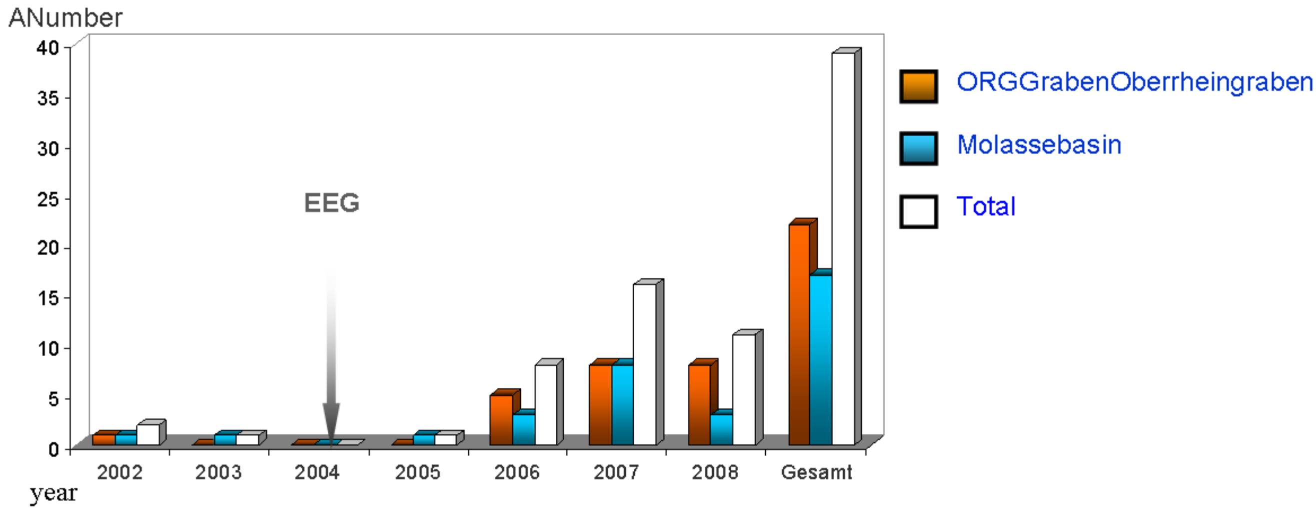

Figure 6: Number of expert reports, worked out for insurance companies and investors, for the main hydrogeothermal reservoirs in Germany: ORG - Upper Rhine Graben (Muschelkalk, Bunter) and South German Molasse Basin (Malm). EEG: The Renewable Energy Sources Act (Erneuerbare Energien Gesetz) entered into force on 1st August 2004.

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