BVEG

Guideline

Economic assessment of geological risks of deep geothermal projects

Status: 12/2024

DGMK

Prepared in co-operation with the German Scientific Society for Sustainable Energy, Mobility and Carbon Cycles (DGMK Deutsche Wissenschaftliche Gesellschaft für nachhaltige Energieträger, Mobilität und Kohlenstoffkreisläufe e.V.) as part of the DGMK Risk Assessment Project Group.

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This is the English translation of the effective German version “Leitfaden wirtschaftliche Bewertung geologischer Risiken von tiefengeothermischen Projekten“.

1. Introduction

1.1. Objective of the guideline

This guideline was compiled in cooperation between the DGMK and the BVEG and is aimed at all institutions and individuals involved in deep geothermal energy, such as insurers, investors, operators, planners, project developers, supervisory or licensing authorities.

The guideline provides a standardised and generally applicable methodology for dealing with geological uncertainties in hydrothermal and petrothermal energy production. The aim is to provide a transparent, transferable, and reusable guideline for assessing and quantifying the geological probability of success and natural geological variability.

Such a geological assessment is essential for the responsible and economical use of investments and subsidies. Quantifying the geological probability of success is the necessary basis for or against investment decisions. In addition, the proposed assessment approach enables a traceable forecast of the range of possible geological scenarios and their probability of occurrence. This creates the necessary basis for a proper subsurface and surface planning and realistic cost estimates.

This guideline describes a generally applicable assessment process. The technical and geological methods to be used may vary depending on the specific geological conditions.

The guideline primarily relates to individual projects but can also be applied to a portfolio approach with several projects.

1.2. Context and scope

This guideline primarily focuses on hydrothermal systems with several boreholes that are to be drilled deeper than 400 metres. The feasibility and economic viability of geothermal systems are analysed, where thermal water flows not only through the boreholes and surface facility but also through the subsurface geological formations. A categorisation of the different geothermal energy production methods is shown in Figure 1. The guideline is applicable to both exploration wells (initial wells in the region) and production wells (follow-up wells in a proven geothermal system). The guideline has been written primarily for the German market and similar low-enthalpy regions. For closed and other petrothermal systems or for underground heat storage, the guideline is also applicable when adapted to project specifics.

Regardless of the energy application (heat, electricity), only the geological factors that influence the economic success of a deep geothermal project, are considered, such as temperature, production and reinjection rate or water chemistry. The key aspects of safe and optimised operational execution of drilling and completion work are described in detail in other BVEG guidelines.

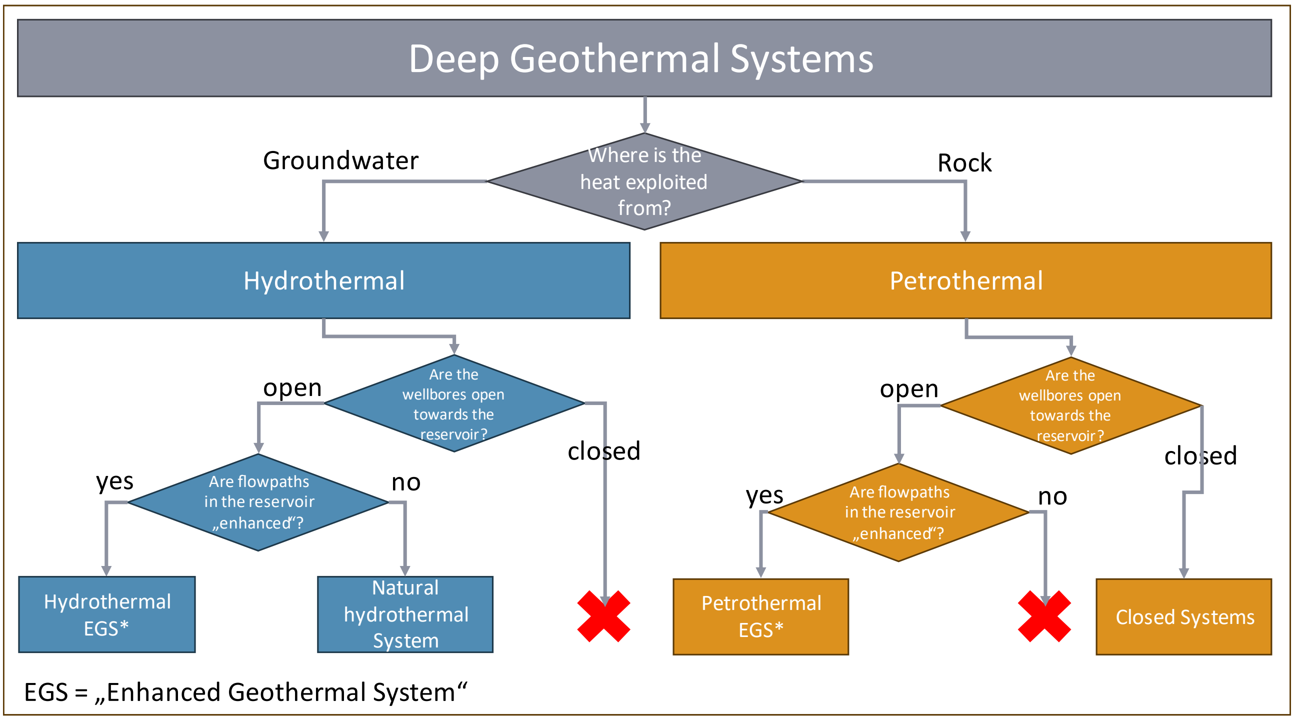

Figure 1: Categorisation of deep geothermal systems

This guideline describes a risk assessment methodology. There are different definitions of risk. The definition used here is the one commonly used in the insurance, drilling, and many other industries, which roughly means impact multiplied by probability. In contrast, "geological risk" (probability of occurrence of an undesirable event), which is often used in geological circles, is essentially expressed in this guideline with one minus "geological probability of success".

1.3. Geological uncertainties

This guideline distinguishes between geological probabilities of success and geological parameter distributions. Both must be quantified prior to final concept design and investment decision.

- The geological probability of success quantitatively defines the chance of success of a geologically (not necessarily economically) successful project. Geological non-success can result in the complete failure of the open geothermal system and thus to the complete write-off of the investment. Geological failure of a well can occur, for example, due to the absence or complete natural cementation/tightness of the aquifer (see Chapter 4).
- In contrast, the geological parameter distributions describe the natural variability and thus the limited predictability of almost all geological parameters that can lead to different performance or economic efficiency within a functioning geothermal system. Examples of this are the temperatures encountered or the permeability of an aquifer with a direct influence on the flowrate (see Chapter 6).
  The economic success of geothermal projects is therefore directly determined by the properties of the geological subsurface. The geological subsurface in Germany as in many other countries is characterised by considerable regional differences. Accordingly, the suitability for open geothermal systems varies greatly from region to region and requires precise geological analysis.

1.4. The geological database

In addition to natural variability, the predictability of geological drilling results also depends on the quality and density of the geological data. The less data and knowledge about the geological subsurface available in the project area, the greater the range of possible drilling results, including the possibility of not finding a viable system at all. A sufficient database and data analysis is therefore essential both for (or possibly against) the investment decision and for the correct project design. A sufficient database on the deep geological subsurface is essential:

- Data from nearby boreholes (typically stratigraphy, borehole measurements of reservoir properties, facies information, temperature measurements, core samples and respective laboratory analysis, etc.),
- Information on water chemistry and
- Seismic data, ideally in 3D with high resolution at least down to the target depth.

Technical equipment and professional expertise are prerequisites for a high-quality analysis of the available data sets. Even good quality geological data is often ambiguous and requires integrated evaluation by experienced geologists, geophysicists, and reservoir engineers.

2. Terms and abbreviations

2.1 Terms

- **Aquifer:**
  An aquifer is a porous layer of rock with interconnected pores filled with water. In addition to the pores, open fractures, and cavities in karstified rock layers can also carry deep water and improve the flow properties. An aquifer is essential for hydrothermal energy production from an open geothermal system. The net/gross ratio indicates the percentage of the aquifer with sufficient flow properties.
- **Core sample analysis:**
  While drilling in deep rock layers, geological core samples can be brought to the surface, providing direct information about rock properties, e.g. of an aquifer.
- **Doublet / Cluster:**
  A doublet is a pair of wells in a geothermal system - a production well from which hot water is pumped to the surface and a reinjection well from which the cooled water is reinjected into the same reservoir. Geothermal clusters are extended systems with several production and reinjection wells.
- **Energy generation, hydrothermal:**
  In a hydrothermal system, hot thermal water is pumped from a deep reservoir to the surface in order to utilise the heat for heating or electricity generation.
- **Energy production, petrothermal:**
  The petrothermal system is independent of water-bearing horizons in the subsurface. Water (or other media) is injected from the surface into natural or specially created deep fracture systems (three-dimensionally connected fracture system, e.g. in granite). The water (medium) heated there is pumped back to the surface, where the heat is utilised. Alternatively, in closed systems, the water circulates underground only in the borehole and absorbs the geothermal energy via the borehole wall.

- **Facies:**
  The totality of properties relating to the composition and depositional conditions (e.g. structure, microstructure, geometry) of a rock layer that was deposited under specific conditions. The properties that are important for geothermal energy, such as porosity and permeability, can often be correlated from this.
- **Flow properties, sufficient**
  The properties of a reservoir, particularly with regard to permeability and fractures, which must be present at a minimum in order to realistically enable circulation with a minimum geothermal flow rate for technical realisation.
- **Flowrate:**
  In this context, the maximum possible flowrate of thermal water from a reservoir (usually in litres per second).
- **Flowrate, technical:**
  A technical flow rate presupposes a functioning flowing system and describes the technically possible flow rate, which does not necessarily include economic efficiency.
- **Geothermal systems, closed:**
  In closed systems, there is no direct contact between deep groundwater and the thermal medium. Instead, the medium circulates underground exclusively within boreholes ("closed-loop systems").
- **Geothermal systems, open:**
  In open systems, the water/brine is in direct contact with the underground rock formations as a thermal medium. Either the hot thermal water is pumped to the surface (hydrothermal energy production) or the water is injected from the surface into natural or artificial pathways in the hot subsurface and pumped back (petrothermal energy production).
- **Log evaluation:**
  "Logs" in this context are time- or depth-based series of physical downhole measurements that provide information about the properties of the drilled rock formations. Log correlation allows the extrapolation of geological structures between boreholes (in combination with seismic data). Log analysis also allows the quantitative determination of rock parameters, such as the porosity of the aquifer.
- **Peer review:**
  A peer review is the evaluation of a complex analysis by independent experts in the same field(peers). In the context of this guideline, the peers are experienced geoscientists and engineers - either from other departments (in the case of large companies) or from other companies. The aim of the geological risk assessment is to critically question the assumptions and conclusions of the geological analysis in order to identify errors or bias at an early stage.
- **Probability of success, economic:**
  The probability that a geologically functioning geothermal system can be operated economically at the respective location under the existing regulatory and economic framework conditions.
- **Probability of success, geological:**
  The probability that a geological reservoir will be found that in principle permits geothermal utilisation.

- **Probability of success, operational:**
  The probability that the development of a geological reservoir can be realised by drilling.
- **Probability of success, technical:**
  The probability that a geological reservoir will be found that in principle permits technical development.
- **Reservoir:**
  A reservoir is a rock formation from which liquids or gases can be extracted. In hydrothermal systems, this is either a stratified aquifer of permeable sand or carbonate rocks or a naturally fractured rock body in which an interconnected network of open fractures provides the permeability.
- **Risk:**
  Risk is the negative impact multiplied by its probability of occurrence. In the context of this guideline, the negative impact relates to the profitability of the project.
- **Scaling:**
  Chemical-physical process in which solids precipitate out of the thermal water e.g. due to pressure or temperature changes. This can occur in the rock near a borehole, in the borehole or in the above-ground facilities and can, for example, narrow or block flow paths.
- **Seismic:**
  An established measurement method in which sound waves generated above ground are transmitted into the geological subsurface, reflected at physical interfaces between different rock layers underground and then recorded by sensors on the surface. From this, the position and shape of the rock layers in the subsurface can be determined. 2D seismic is recorded along a line and generates the image of a vertical section through the subsurface. With 3D seismic, a three-dimensional image of the subsurface is generated. For this purpose, vibration sources and sensors are arranged in a checkerboard pattern on the surface. A 3D seismic survey is more complex than a 2D seismic survey, but also much more informative.
- **Seismic time-depth conversion:**
  Seismic recordings are based on sound wave images. To convert them into depth predictions, the travel times of the sound waves are multiplied by the assumed sound wave velocities of the affected rocks.
- **Stage-gate process:**
  This describes an established management process for deciding in favour of or against the implementation of major investment projects.
- **Stratigraphy; stratigraphic:**
  As a sub-discipline of geology, stratigraphy is the study of the Earth's layered structure. It assigns a specific age to each geological layer sequence and helps to correlate individual geological elements such as aquifers and predict their depth extent.
- **Uncertainty, geological:**
  Geological uncertainty includes both the probability of success and the variability of individual parameters.

- **Underground, geological:**
  The geological subsurface often varies greatly from region to region. It determines whether and with which method geothermal energy generation is possible in an area.

2.2 Abbreviations

- **DHC**
  dry hole costs (costs of a well bore which did not find a working geothermal system)
- **EMC**
  expected monetary value
- **NPV**
  net present value
- **P10**
  Point on a cumulative probability curve where there is a 10 % probability that the value actually achieved later is greater (this typically represents the optimistic case)
- **P50**
  Point on a cumulative probability curve where there is a 50 % probability that the value actually achieved later will be greater (or less). This median typically represents the base case.
- **P90**
  Point on a cumulative probability curve where there is a 90 % probability that the value actually achieved later is greater (this typically represents the conservative case)
- **POS_g**
  Probability of Success (geological)
- **POS_o**
  Probability of success (operational)
- **POS_t**
  Probability of Success (technical), (**POS_g** x **POS_o**)
- **$POS_{e(t)}$**
  Probability of success (economic), the dependent economic probability of success under the assumption of technical success
- **POS_{Total}**
  the economic probability of success of the overall project (**POS_t x $POS_{e(t)}$**)

3 Geological assessment as part of geothermal project management

For the planning and decision-making of deep geothermal projects, a simplified stage-gate process, as shown in Figure 2, is assumed (for more complex projects, Gate 2 can also be carried out in two stages).

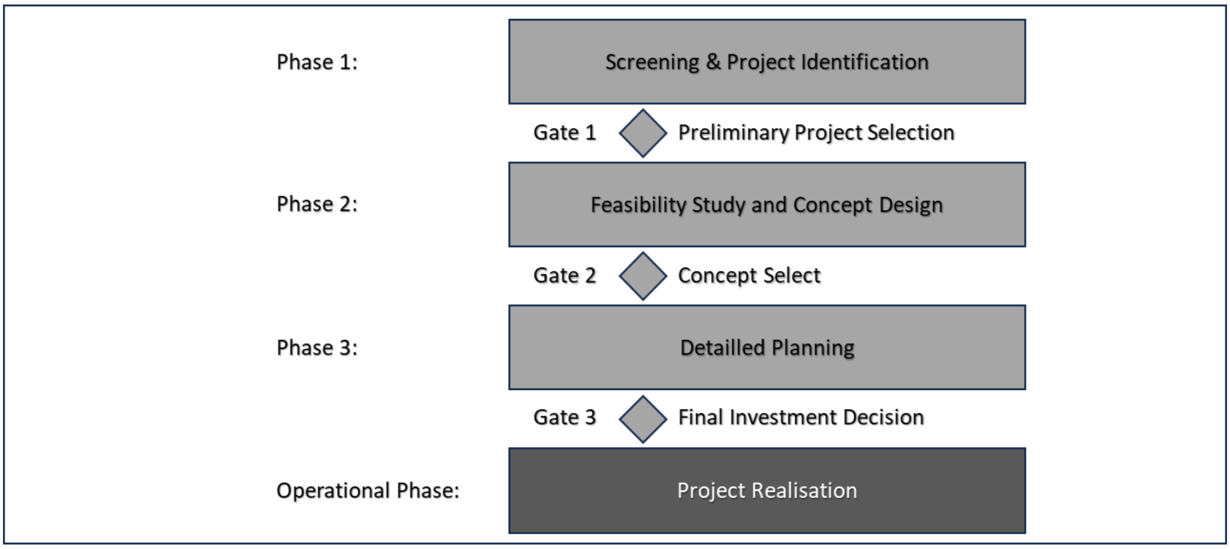

Figure 2: Geothermal stage-gate process

3.1 Geological assessment within the project identification phase (phase 1)

During the screening phase basic investigations are carried out to determine the suitability of an area for deep geothermal energy generation above and below ground. This phase generally requires a small budget only. An initial assessment of the possible geothermal potential is made on the basis of existing geological data. The origin of the geological database (governmental, public, private) may differ from country to country.

In Germany, various sources may be considered: governmental data (LIAG, studies by the federal states), data from private companies (e.g. the oil and gas industry) and from scientific publications. In accordance with the German Geological Data Act (GeoIDG), a significant proportion of the data obtained by the private sector is made publicly available by the State Geological Surveys. Additional data might be obtained from other companies.

The following questions should be answered during the screening phase:

- What are the possible geothermal reservoirs?
- Which geological parameters harbour the greatest uncertainties for geothermal use?
- What are the depths, temperatures, and flow rates of neighbouring projects?
- What geological database is available? (See chapter 1.4.)
- Are there already deep boreholes in comparable geological conditions in the vicinity?
- What are the success statistics and thermal outputs of the geothermal wells that have already been drilled in the region?
- What parameters are assumed in the absence of neighbouring reference projects and what are the assumptions based on?
- What additional data may need to be collected (e.g. data acquisition, seismic reprocessing, new 2D or 3D seismic)?

If the screening phase shows good indications for geothermal potential, the results are summarised in a preliminary study, which includes the following points for economic project identification (Gate 1):

- Cost-estimate for any necessary data procurement

- Result analysis of neighbouring wells
- Depth-dependent estimation of drilling costs
- Rough estimate of the geological probability of success according to Chapter 4
- Range estimation of the possible thermal output (temperature, ΔT, bulk density) according to chapter 6

These basic geological framework conditions, together with the preliminary assessment of the above ground conditions (e.g. local heat demand, heat grid expansion planning), lead to an initial, still rough estimate of the economic viability. This forms the basis for the first decision point (Gate 1), at which the project is either terminated or transferred to the next phase: feasibility study and concept design. During Phase 1, also the technology decision is made as to whether a project is better pursued in an open (hydrothermal or petrothermal) or closed (closed-loop) system, possibly as a backup option.

3.2 Geological assessment within the feasibility study and concept design phase (phase 2)

In phase 2, all detailed geological work is carried out, from data acquisition to reservoir modelling:

- Data procurement usually includes
  - Data purchase from existing well and seismic data
  - Acquisition of own 2D and 3D seismic data
  - Procurement of data from respective sources; in Germany this is primarily available from the responsible state geological surveys, e.g. in accordance with the GeolDG
- Well data analysis
  - Log evaluation and quantitative parameter determination (temperature, porosities, etc.); fracture analysis in case of availability of image logs
  - Regional log correlation
  - Core sample analysis if possible
  - Facies determination, facies mapping, parameter maps
  - Investigations into water chemistry
- Analysis of seismic and other exploration data
  - Seismic data processing and time-depth conversion
  - Seismic interpretation and mapping
  - Seismic attribute analysis for porosity and connectivity investigations
  - Analysis of the fault and fracture network
  - If necessary, analysis of data from other exploration methods such as hydrochemistry or gravimetry
- Detailed fault mapping
  - Stress plan analysis
  - Assessment of the extent to which fractures are open or sealed
  - Identification of the preferred direction of open fractures
- Analysing the risk of induced seismicity
  - Investigation of natural seismicity for baseline determination
  - Hydraulic analysis of the seismological reactivability of faults
  - Investigation and modelling of the possible consequences of downhole pressure and temperature changes due to water extraction and reinjection
- Modelling and simulations
  - Thermal modelling and simulation
  - Reservoir modelling and simulation

The listed work items are summarised in a comprehensive feasibility study. On this basis, the specific geological probability of success is estimated in accordance with Chapter 4 and the natural parameter variabilities are estimated in accordance with Chapter 6. At the end of Phase 2, all input parameters for a probability-based economic analysis should be available. This should also take into account the operational probability of success in accordance with Chapter 5. All of this forms the basis for the second decision point, which, if positive, leads to the selection of the concept for the subsequent detailed planning.

For more complex projects, phase 2 can also be divided into phase 2a feasibility study and phase 2b concept development. Each sub-phase then passes through a corresponding gate.

3.3 Geological evaluation within the detailed planning phase (phase 3)

In this phase, the geological investigations of the underground geothermal system have already been completed. Geological operational risks, e.g. with regard to seismicity, corrosion, or scaling, are considered in this phase and minimised in the detailed planning. Key planning elements for the geothermal boreholes are also derived here, including a more detailed elaboration:

- Preliminary geological well profile, identification of problematic rock formations (trouble zones) in terms of drilling technology
- Pressure predictions and mud weight determination
- Determination of the casing scheme and stratigraphic casing setting positions and depths

and:

- Well planning, also depending on stress field and fracture directions
- Creation of the decision tree for the operational drilling phase

The final refinement of the economic model leads to the last decision point, the final investment decision.

4 The geological probability of success

One aim of the extensive geological analyses is the quantitative determination of the geological probability of success. Irrespective of the potential economic success, the following three geological prerequisites are essential for a functioning open hydrothermal geothermal system, combined with three questions to be answered:

1. A geothermal reservoir must be stratigraphically present.

   → $POS_{Reservoirexistence}$

   What is the probability that the reservoir is stratigraphically present in both boreholes of a doublet, regardless of its quality, i.e. that it is primarily existent and has not been eroded during later geological times nor suppressed by fault displacement?

2. The quality of the reservoir (matrix or fractured reservoir or combination of both) must be sufficient for a technical flowrate, both on the production side and on the reinjection side.

   → $POS_{Reservoirquality}$

   What is the probability that the reservoir is of sufficient quality for a sustained technical flowrate, e.g. in terms of permeability, thickness, or the presence of open fractures?

3. The two wellbores of a doublet must be sufficiently hydraulically connected to ensure long-term pressure equalisation. At the same time, a "short circuit" between the two boreholes must be prevented by ensuring sufficient distance between the boreholes.

   → $POS_{Hydraulics}$

   What is the probability that the geothermal reservoir between the two boreholes of a doublet has sufficient hydraulic communication so that neither the extraction point depletes, nor the injection point continuously builds up pressure, but also without the cooled water being immediately recycled again (thermal breakthrough)? In addition to the matrix permeability (i.e. the permeability of the host rock), fractures and fault systems have to be considered here.

The product of the individual probabilities listed here corresponds to the geological probability of success **POS_g:**

$$POS_g = POS_{Reservoirexistence} \times POS_{Reservoirquality} \times POS_{Hydraulics}$$

The probability of success here is explicitly calculated for the geological success case, i.e. that warm water sustainably flows and can be sustainably reinjected. Important economic variables such as a sufficiently high extraction temperature (and thus also the temperature spread ΔT that can be used above ground) or the minimum economic flow rate are not taken into account here. These are considered in more detail when analysing the geological parameter distributions (Chapter 6). For petrothermal systems, other components of the **POS_g** may be relevant.

The main risk elements of individual projects can vary from case to case. Accordingly, the elements of risk mitigation must also be developed individually.

To support the geological probability analysis, the use of the so-called Chance Adequacy Matrix developed by P.R. Rose (2001) is recommended (see a modified version in Figure 3). Each of the three probability factors defined above is assigned to a defined compartment of the matrix and to a specific chance factor between 0.0 and 1.0. The geological tendency of the information ("good" or "bad" news) is plotted on the horizontal axis and the data density and quality on the vertical axis. For example, a widespread regional extension of an aquifer would be categorised as "good news" (right-hand column of the matrix) for **$POS_{Reservoirexistence}$**. The more wells prove this in the vicinity of the planned project, the better the database, the higher the factor can move upwards within the right-hand column.

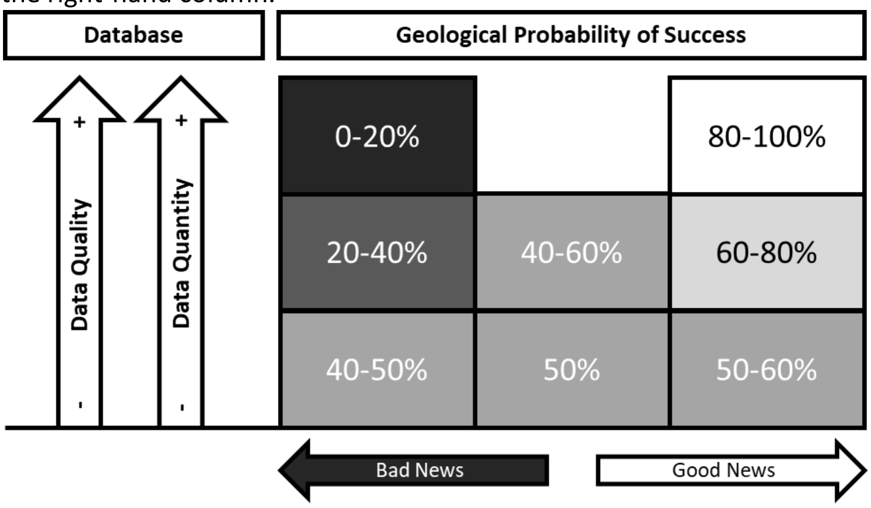

Figure 3: Chance Adequacy Matrix, modified after P.R. Rose (2001)

The particular strength of this matrix lies in the fact that, in addition to the geological findings, it also takes into account the data quality when determining the geological probability of success. High-resolution data sets can both disqualify a project (top left) or mature it (top right). Insufficient data can make the individual probability factor barely greater than 0.6-0.8, even in the positive case.

To illustrate the application of the concept, two examples for POS_g calculations are given in Figure 4:

The first example represents a generic exploratory concept in an area with very little data and no existing deep geothermal projects. It is assumed that from the regional geology, the presence of a possible reservoir at a sufficient depth can be inferred with a high probability, which is represented by a high $POS_{Reservoirexistence}$ (here 0.9). However, there is hardly any data available on reservoir quality or hydraulic properties. $POS_{Reservoirquality}$ and $POS_{Hydraulics}$ can only be 0.5 in the absence of further determinations. POS_g as a product of the three individual POS factors is initially not to be considered higher than 25%. However, seismic exploration and exploratory drilling offer considerable potential for derisking, which can lead to an increase or decrease in the geological probability of success. In the example selected, the uplift could move POS_g above 60%.

The second example represents a hydrothermal system that has been established through many successful projects, e.g. the Malmian carbonates in the Munich area. In the selected example, all available existing wells were analysed qualitatively and quantitatively (e.g. the Malmian carbonate within the “evaluation Geothermal Master Plan”, TUM 2020); the few failed wells are due to a lack of reservoir quality. Overall, further projects within the fairway area are likely to have a high geological probability of success of around 90%.

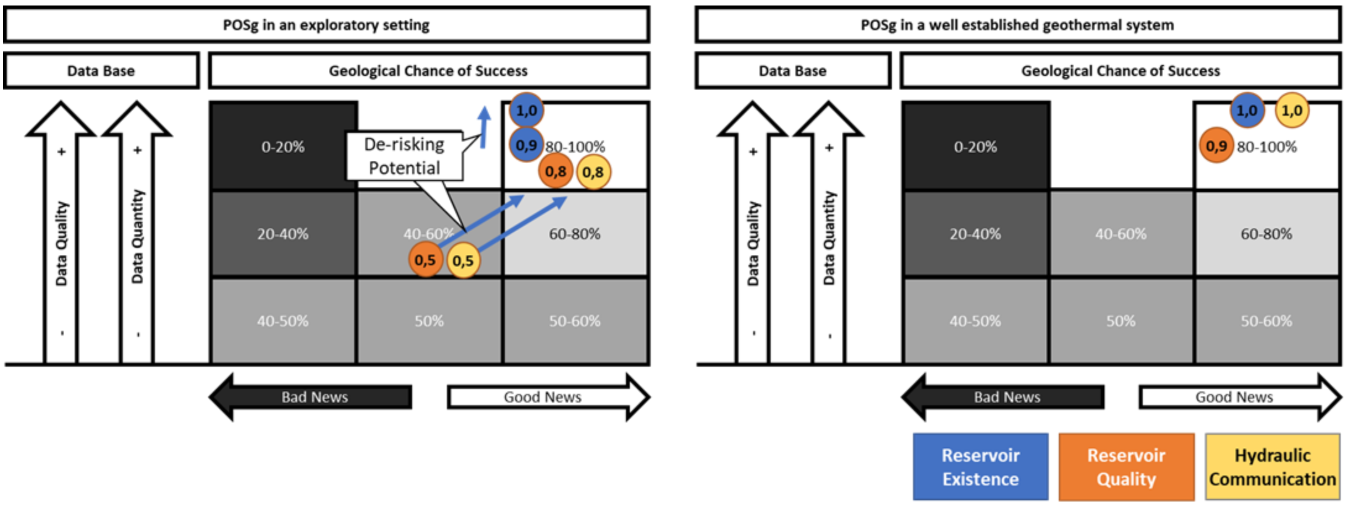

Figure 4: Examples for determining the geological probability of success: Example 1 represents an exploratory concept with little geological data to date, example 2 represents an established and already proven geothermal reservoir, explanations in the text.

5 The technical probability of success

The probabilities of success presented in Chapter 4 relate to the geological system in general, regardless of the individual drilling plan. However, the latter can significantly limit the chances of success if, for example, the geological target cannot be optimally reached from the existing drilling site. Even in an established geological system, dry wells can be drilled due to the remaining uncertainty of the database. Consequently, a dry borehole does not automatically devalue the entire system but requires a specific dry-hole analysis.

The operational probability of success **POS_o** quantifies the probability of successfully developing the geothermal target operationally with the two wells of a doublet. When determining **POS_o**, the complexity of the well design and the drilling, completion, and other construction techniques to be applied as well as the boundary conditions of the well site are considered. Drilling risk management and its influence on the operational probability of success are the subject of a second BVEG guideline on drilling risk management for deep geothermal projects.
The product of the geological and operational probability of success describes the technical probability of success **POS_t.**

$$POS_t = POS_g \times POS_o$$

6 Analysis of the geological parameter distributions

The technical probability of success **POS_t** of a project calculated in Chapters 4 and 5 quantifies the technical success of a doublet: hot water can be produced and reinjected. This also explicitly includes uneconomical cases.

The distribution of geological parameters must be considered to determine both the economic viability and a suitable design of the project. An exact prediction of the geological parameters at depth is not possible due to incomplete data and, above all, due to natural variability. Statistical prediction methods are therefore used instead, which are then calibrated against analogue or nearby real data sets.

The recoverable thermal power P_{th} results from the product of the fluid density ρ_f, the heat capacity of the fluid c_p, the temperature spread between produced and reinjected water ΔT and the flowrate Q.

$$P_{th} = \rho_f \cdot c_p \cdot Q \cdot \Delta T$$

Temperature spread (ΔT) and flow rate (Q) are the parameters with the highest variability and are therefore decisive for estimating the thermal output and thus the economic efficiency.

6.1 Temperature

The temperature (and hence **ΔT**) of a geothermal system is controlled by the following variables:

- Geothermal gradient: This is widely known in the various geological basins and regions of Germany and elsewhere but can be subject to local fluctuations.
- Depth of the aquifer (the deeper, the warmer): The prediction accuracy of the depth depends on the seismic quality, the seismic time-depth conversion, and the level of control through neighbouring wells.

6.2 Thermal water flowrate

The flowrate **Q** for a given pressure drawdown (in the production well) and reinjection pressure (in the reinjection well) is calculated from the following mainly geological parameters, which generally exhibit a high degree of geological variability:

- Thickness of the tapped reservoir
- For porous aquifers, the porosity, and the net/gross ratio
- Permeability of the aquifer, derived, among other things, from production tests or log-porosity via the poro/perm relationship
- In the case of fractured reservoirs, an estimate is generally only possible on the basis of regional analogies
- Planned borehole geometry (length of reservoir intersection, diameter, direction and distance to fractures, distance of the two wells of a doublet, pump selection and location, etc.)

Experience shows that geological parameters often follow a log-normal distribution. With sufficient data density, individual distribution geometries may be selected using statistical methods.

All geological parameter distributions must be defined in such a way that they allow for sustained technical flowrates. The technically unsuccessful case was already excluded in Chapter 4 while calculating the geological probability of success ($POS_{Reservoirquality}$) and must not be included in the calculation again here.

6.3 Probability distribution of geothermal output

As a result, both the flowrate and the geothermal output of a planned, as yet undrilled project ("pre-drill forecast") can only be predicted as a probabilistic distribution curve:

Expected probability distribution of geothermal power =
distribution Q x distribution ΔT x distribution fluid density x distribution of specific heat capacity

A distribution curve should therefore be derived for each important geological parameter.

The mathematical calculations can be made via Montecarlo methods supported by respective software tools. The open-source tool "DoubletCalc" from the Dutch Organisation for Applied Scientific Research, TNO, DoubletCalc1D | Thermogis, which is tailored to geothermal systems with predominant matrix permeability, is recommended here.

If there is insufficient data available to derive individually dedicated distribution curves, statistical tools such as DoubletCalc (or e.g. GeoX or @RISK) help to generate a distribution from the assumed distribution geometry (usually lognormal) and the possible maximum and minimum values.

Figure 5 shows the cumulative probability distribution for all possible geothermal outputs in the geological success case of a doublet that has not yet been drilled (with random values). In the cumulative probability function, the specified "P-values" are defined as follows:

- P90: 90 % of all possible outcomes are above
- P50: 50 % of all possible outcomes are above
- P10: 10 % of all possible outcomes are above

Assuming technical feasibility, the conditional economic probability of success of $\mathbf{POS_{e(t)}}$ can be determined for an economic threshold value. The economic threshold value denotes the minimum geothermal output (in

MW$_{therm}$) required to realise the specific geothermal project economically. The economic probability of success for the overall project is calculated as follows:

$$POS_{Total} = POS_t \times POS_{e(t)}$$

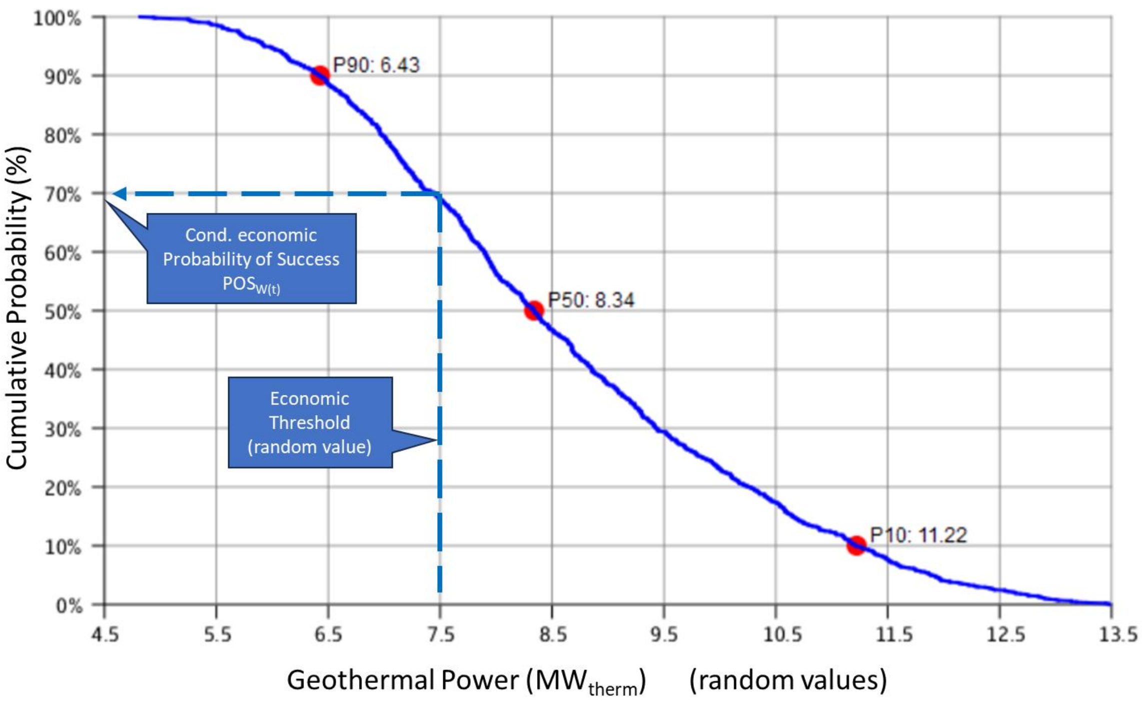

Figure 5: Probability distribution of geothermal power in MW$_{therm}$

6.4 Other geological parameters with an influence on the economic viability of geothermal projects

Water chemistry

The chemistry of the extracted thermal water may potentially interfere with the geothermal infrastructure used underground and above ground. For example, high mineral/salt contents can lead to precipitation (scale formation) or corrosive water can attack the materials used for pipe walls and valves. Both can lead to more expensive material specifications or higher maintenance of pumps or systems, i.e. operating costs.

Seismicity

Especially in areas with natural seismicity, the reinjection of cooled geothermal water can lead to induced seismicity. Preliminary seismological studies and seismic monitoring with expert seismological support are therefore recommended. Mitigation can be achieved during production operations by reducing reinjection pressures or rates and temperature spreads. Reinjection pressures can also be minimised by adapting the well design, e.g. over longer intersections in the reservoir. Both can influence the economic efficiency of the project, which is calculated in Chapter 8.

7 Quality control of the geological assessment

An interdisciplinary approach is strongly recommended both for the calculation of the geological probability of success and for the quantitative evaluation of the geological parameter distributions. Professional experience from the various "subsurface" disciplines (structural geology, facies mapping, seismic interpretation, log evaluation, reservoir engineering, drilling engineering, etc.) should be applied. Where geothermal wells already exist, own geological calculations should always be compared with the regional track record (relating to the same geothermal reservoir). In any case, the results should be independently verified in peer reviews.

8 Selection of scenarios for the profitability calculation

Operational planning for underground and surface facilities or economic valuations cannot be carried out on the basis of the probability distributions presented in Chapter 6 alone. Suitable scenarios must be selected for this purpose. The three scenarios shown in Figure 5 are recommended for this purpose:

- conservative case ("low case") = P90 Geothermal output
- Base case = P50 Geothermal output
- optimistic case ("high case") = P10 Geothermal output

Complete profitability calculations are carried out for each of the three cases. This involves a simplified comparison of all costs (investment costs for drilling and surface installations, operating costs, etc.) with all incomes (heat/power output and price, full load hours, etc.). A specific net present value (**NPV**) can be calculated for each scenario. This can also be negative, particularly in the low case.

An average value that is as representative as possible for the profitability (in the case of technical success) is calculated using the so-called "Swanson's Mean":

$$\mathbf{NPV_{mean} = 0.3xNPV_{P10} + 0.4xNPV_{P50} + 0.3xNPV_{P90}}$$

Although this value averages the geological parameter distributions, it does not reflect the geological risk calculated earlier. The principle of EMV analysis ("Expected Monetary Value" analysis) is used for this purpose. This enables the calculation of probability-weighted profitability. The basic principle is shown in Figure 6.

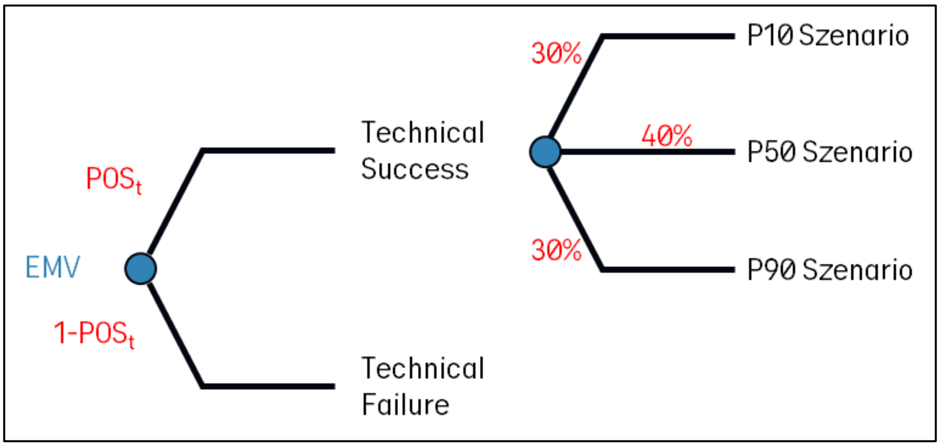

Figure 6: The EMV analysis for calculating the probability-weighted project profitability

The calculation of the probability-weighted expected value is carried out in accordance with:

$$\mathbf{EMV = POS_t \, x \, NPV_{mean} - ((1\text{-}POS_t) \, x \, DHC)}$$

This approach considers both the average success value and the costs of failure, both of which are discounted with probability. The dry hole costs (DHC) include all costs that were invested before the potential failure occurred. As a rule, these are the costs of the first well. The number of expected full-load hours must also be considered for profitability.

9 Selection of scenarios for detailed technical planning

For the detailed technical planning, the same three scenarios from the geological parameter distribution are used as for the profitability calculation (see Chapter 8): Low Case, Base Case and High Case. However, scenarios for which the profitability calculation resulted in a negative NPV are not considered further.

The base case as the median (P50) of the cumulative probability distribution (see Figure 5) should be the starting point for the planning of underground and surface facilities. However, the variation ranges of the most important geological parameters investigated in Chapter 6 show that the results found at depth can deviate very significantly from the base case, in both directions. This applies to almost all geological parameters such as the depth of the reservoir, temperature, permeability, flowrate, water chemistry, etc. The planning must be adapted to these natural variants, ideally in the form of a decision tree for the drilling and construction phase, which already in the planning phase defines "if-then" decision points for certain geological outcomes. In this way, so-called "surprises", which can often be very expensive, can be avoided from the outset or considered in the planning.

10 Recommendations for dealing with geological uncertainties and risk diversification

Geological uncertainties are part of every mining project, including deep geothermal projects. This guideline describes geological analysis methods and shows how geological probabilities and natural variabilities of geological parameters can be included in the economic evaluation and detailed technical planning.

When realising one or a very limited number of fully financed individual projects, the investor can use the methodology presented here to counteract the aforementioned uncertainties through adapted planning but cannot avoid them.

There are therefore established methods for further limiting economic risks. With the same investment volume, risks can be **shared** and **distributed** if several projects with smaller stakes are realised instead of fully financed individual projects. Consortial partnerships or joint ventures, which are widely used in the raw materials industry for the reasons mentioned above, are a good option here. This approach makes it possible to build up a portfolio in which projects from different geological settings, with different reservoirs and risk structures are combined. Within a well-diversified portfolio, a less good (or failed) project can be compensated for.

The analysis described in this guideline provides the key decision criteria for good portfolio management and the right project selection:

- the probability of success POS_{Total}
- the average profitability NPVmean
- and the (probability-weighted) expected present value EMV

Negative EMVs should be avoided in the portfolio approach under all circumstances; EMV-positive projects can be combined in a geothermal portfolio depending on the investor's risk profile. Projects can be compared and prioritised on the basis of a transparent and uniform evaluation procedure as presented here.

11 Further reading

Literature on geological risk assessment:

- Moeck, I.S. (2014): Catalog of geothermal play types based on geologic controls, Renewable and Sustainable Energy Reviews 37, 867-882.
- Reinicke, K.; Hollmann, G.; Reichetseder, P. (2022): Probabilistische Risiko- und Wirtschaftlichkeitsbewertung von Geothermieprojekten, in EEK issue 11/2022 https://www.energie-archiv.de/SingleView.aspx?show=4319999
- Rose, P. (2001): Risk analysis and management of petroleum exploration ventures, AAPG Methods in Exploration Series, Issue 12
- Schulz, R., Jung, R., & Schellschmidt, R. (2005): Assessment of Probability of Success for Hydrogeothermal Wells. Proceedings World Geothermal Congress 2005
- Schumacher, S., Pierau, R., Wirth, W. (2020): Probability of success studies for geothermal projects in clastic reservoirs: From subsurface data to geological risk analysis, Elsevier, Geothermics, Volume 83, 101725: https://www.sciencedirect.com/science/article/pii/S0375650517304236?via%3Dihub
- Wilmarth, M., Stimac, J. and Ganefianto, G.: Power Density in Geothermal Fields, 2020 Update, Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland, April - October 2021 https://www.geothermal-energy.org/cpdb/record_detail.php?id=34577

Literature on deep geothermal energy in general:

- AGFW Praxisleitfaden Tiefengeothermie: A 67-page manual (pdf or printed) that introduces deep geothermal energy https://www.agfw-shop.de/agfw-fachliteratur/erzeugung-sektorkopplung-speicher/agfw-praxisleitfaden-grosswaermepumpen-2714.html
- BVEG Leistungsspektrum Geothermie: A generic project plan that shows in a structured way which steps are necessary in the life cycle of a deep geothermal energy project (and also puts them into context in terms of time using a Gantt chart) https://www.bveg.de/die-branche/tiefe-geothermie-in-deutschland/das-leistungsspektrum-geothermie/leistungsspektrum-geothermie/
- Various BVEG guidelines, mostly on environmentally or safety-relevant topics relating to drilling and installations, e.g. on well integrity: https://www.bveg.de/umwelt-sicherheit/technische-regeln/
- Geothermal guidance documents by German federal states: In various federal states, geological surveys or mining authorities have described processes and/or topics relating to deep geothermal energy, e.g. in
    - Lower Saxony: Geoberichte 42 https://nibis.lbeg.de/doi/DOI.aspx?doi=10.48476/geober_42_2021
    - Baden-Württemberg: https://www.lfzg.de/63.php
- Technical University of Munich (2020): Bewertung Masterplan Geothermie (eine Betrachtung der Geothermie in Bayern) https://www.researchgate.net/publication/364994945_Bewertung_Masterplan_Geothermie