Interreg North-West Europe
EUROPEAN UNION

DGE-ROLLOUT

Decision workflow and support

Standardised decision making to develop a Deep Geothermal Energy project in the Upper Rhine Graben

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VULCAN ENERGY SUBSURFACE SOLUTIONS

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1. Introduction

The proposed decision workflow provides an overview on deep geothermal project (DGE) development in the Upper Rhine Graben. It's target group are developers and investors. The workflow cannot substitute the experience from designated geothermal experts (exploration geologists, geophysicists, hydrogeologists, reservoir engineers, and drilling engineers) in planning, exploring, and evaluating regional to local geothermal conditions.

This decision workflow is part of a suite of deliverables from the DGE-Rollout programme. Some of the relevant related deliverables are described below.

Deliverable	**Description**
WP T1 D 1.3 Transnational harmonized depth and thickness map of deep geothermal potential in project area	Construction of a harmonized depth and thickness map (methodology and nomenclature), showing deep geothermal reservoirs in the project area. Level of knowledge and uncertainty will be considered.
WP T1 D 4.1 - Decision making tool	Online map tool to create a decision support system. This tool will be applied to identify investment hotspots, considering regional specificities & heterogeneities in parallel to investor profiles.
WP T1 D 2.3 - Socio-economic potential mapping for DGE	Demand, infrastructure, and land access are the main socio-economic factors influencing geothermal project assessment at surface and are presented through maps covering the target regions of NW-Europe.
WP T2 D 2.3 ThermoGIS Doublet Calculation – adaptation and application	Construction of a harmonized map (methodology and nomenclature) showing deep geothermal reservoirs in the project area (merging the results of D1.1.1, D 1.1.2 and D. 1.1.3). Level of knowledge and uncertainty will be considered.

These deliverables are accessible via https://www.nweurope.eu/projects/project-search/dge-rollout-roll-out-of-deep-geothermal-energy-in-nwe/

Preparation

Some of the steps described in this document are cost, time, and resource intensive. Before embarking on these, they should be made part of an overall development plan. This should preferably be a plan supported by all public and private stakeholders and at local, regional, and national level.

Scope

This document focuses on the project development. It provides an overview on necessary steps and decisions to be made to run through each development phase and decrease the planning risks of a geothermal project – financially as well as operationally.

Additional considerations

While it is not within the scope of this document, for development of a DGE-project the surface situation is at least as important. Within the DGE-Rollout project there is ample attention for this. In short, relating to the surface, it is important to get, in parallel with exploration, insight in at least the following things:

- **Demand for low emission heat –** Is there an expectation that consistent demand can be found to provide a steady basis for a DGE-project?
- **Public acceptance for geothermal energy –** To what extent will the local community positively perceive a geothermal energy project?
- **Support from local and regional governments –** Are local governments supportive of DGE, is it part of their policy, and are they willing to support a DGE-project, if not financially then at least politically?
- **Considerations and concerns around seismicity –** Seismicity risk can be a real and often is a perceived risk for DGE-projects. It is important to know about the risk categorization for seismicity at an early stage and engage with local stakeholders on this topic.

While we have provided links to existing knowledge and data, local knowledge and interaction is always required to ensure local support. The general rule is that early engagement helps in the long run. Ideally this is at least a year before the final choice for the project location.

2. The Upper Rhine Graben – an overview

Geographical overview

The Upper Rhine Graben (URG) extents from Frankfurt (Main) in the north to Basel in the south. It is a morphological graben structure with a roughly 300 km long and 30 to 40 km broad lowland plain, surrounded by sharply defined mountains. The Rhine River acts as natural first and second order political and administrative boundary between Rheinland-Pfalz, Hessen, and Baden-Württemberg (Germany), Alsace (France) and Basel (Switzerland) (Figure 1B).

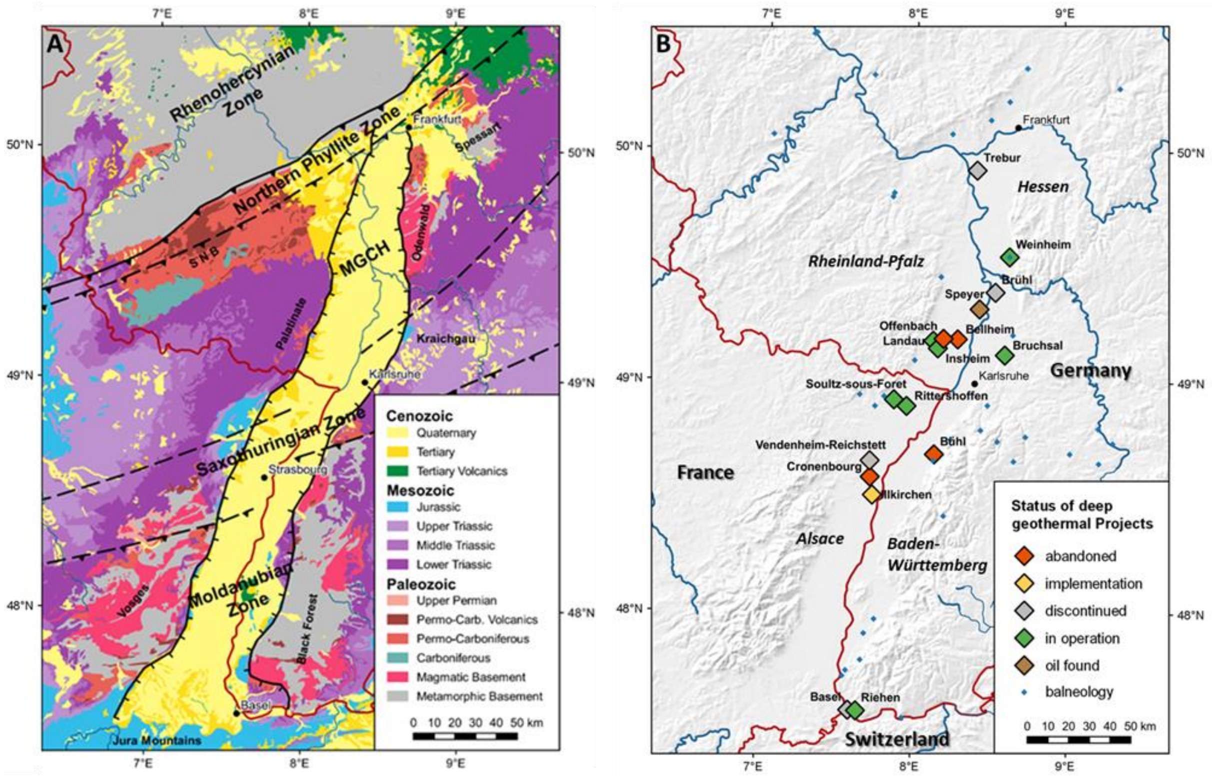

Figure 1: A) Geological map of the URG including the main stratigraphic units (adapted from BGR 2016). MGCH: Mid-German-Crystalline High, SNB: Saar-Nahe Basin. B) Overview of the geothermal projects in the URG and their status (Frey et al. 2021).

Geological overview

The regional geology of the URG can be subdivided into three parts (Figure 1A):

1. The crystalline basement is dominated by low- to high-grade metamorphic rocks and magmatic intrusions related to the Variscan orogeny. It comprises three different Variscan zones with distinctly different lithology and composition. From North to South, these are the Northern Phyllite Zone, the Mid-German-Crystalline High as part of the Saxothuringicum and the Moldanubicum.

2. In the aftermath of the Variscan orogeny intra-mountainous troughs such as the Saar-Nahe trough, Kraichgau trough or the Breisgau trough were filled by mainly volcanic, volcanoclastic, and siliciclastic debris during Late Carboniferous to Permian times. In late Permian times (Zechstein) the entire area thermally subsided as a part of the evolving Mid-European basin (sometimes called German basin) and developed as a sedimentary basin that accumulated 1-2 km thick terrestrial and marine successions during Triassic times:

Age			Environment	Main lithology	Thickness range
Triassic	Keuper	201,2–239,2 Ma	mainly terrestrial	sandstone, siltstone, marlstone, claystone, evaporites, dolomite	0 – 380 m
	Muschelkalk	239,2–246,2 Ma	marine	limestone, dolomite, evaporites, marlstones	0 – 200 m
	Buntsandstein	246,2–252,5 Ma	terrestrial	mainly sandstones, clay-siltstones	0 – 500 m
	Permo-carboniferous		terrestrial, volcanic	claystone, siltstone, sandstone, conglomerate, andesite, rhyolite	0 – 2000 m

Thereafter the area was submerged by an epi-continental sea during Jurassic times for more than 50 million years leaving a succession of marine, mainly carbonatic sediments:

Age			Environment	Main lithology	Thickness range
Jurassic	Malm	145,0–163,5 Ma	marine	limestone, dolomite, marlstone	0 – 180 m
	Dogger	163,5–174,0 Ma	marine	claystone, marlstone, limestone, Fe-oolith, sandstone	0 – 450 m
	Lias	174,0–201,2 Ma	marine (frequently euxinic conditions)	marlstone, limestone	0 – 190 m

Cretaceous sediments are not documented in the area of the URG. A stratigraphic overview of the URG is displayed in Figure 2.

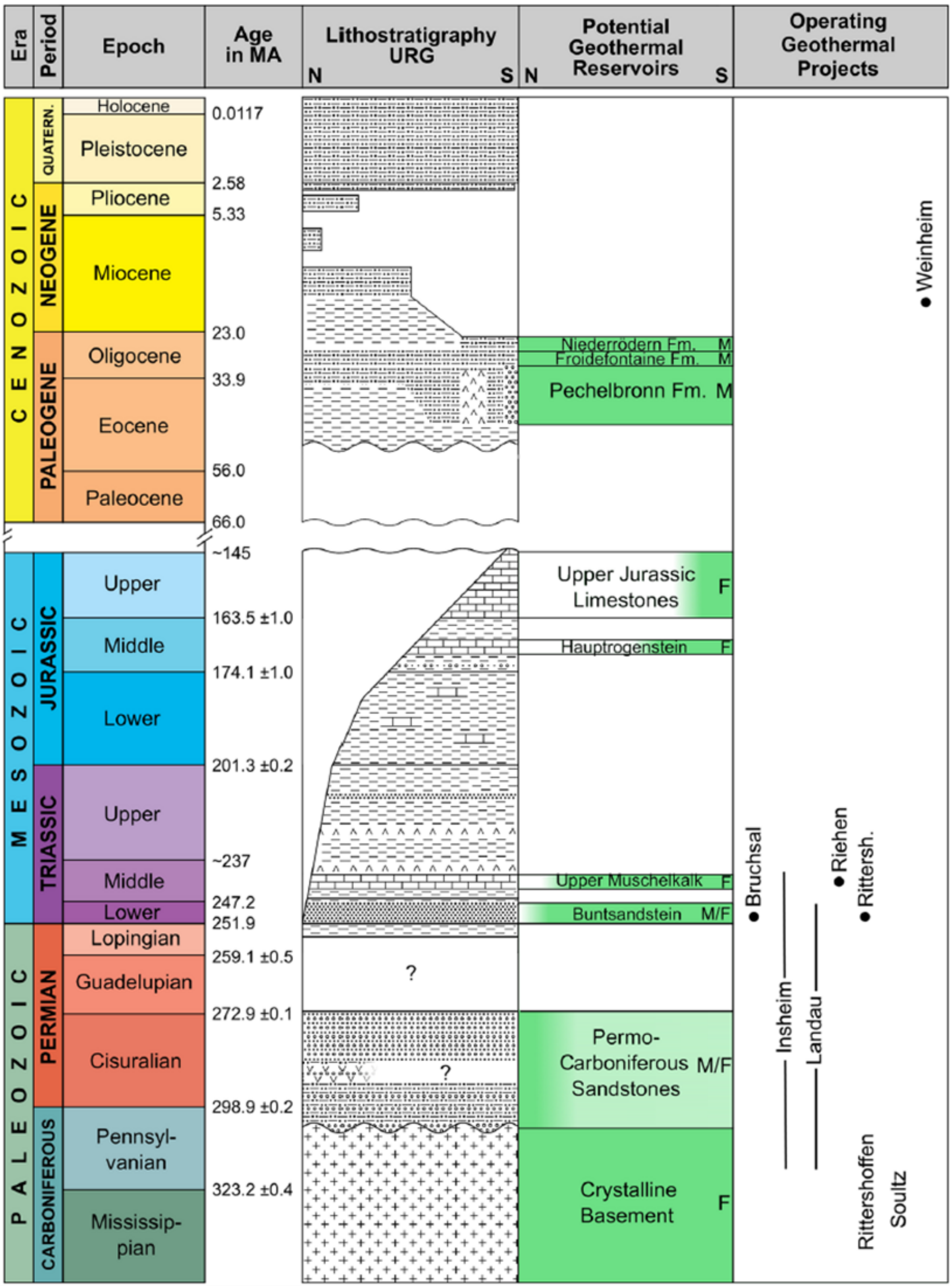

Figure 2: Lithostratigraphic sequence in the URG with the potential geothermal reservoir units (modified after GeORG Projektteam (2013) and Deutsche Stratigraphische Kommission (2016)). It is indicated whether the fluid flow in the reservoir horizon is dominated by fractures (F) or matrix (M). The regional importance of each horizon is indicated by the colour gradient.

The whole succession of Permo-Mesozoic sediments has been uplifted in the northern part of the URG, slightly tilted towards south and partly eroded during late Cretaceous and early Tertiary times. Therefore, towards north subsequently deeper stratigraphic units are discordantly covered by Tertiary sediments (Fig. 2).

3. The URG, in the narrow sense, is a relatively young tectonic feature and its sedimentary infill comprises of Cenozoic (Tertiary to Quaternary) sediments. The URG is part of the European Cenozoic Rift System extending across Central Europe and its evolution started in the Eocene at c. 47 Ma. The graben structure is rather complicated and changes from north to south as well as from east to west. The structural geology is characterized by many normal and strike-slip faults running roughly parallel to the graben border faults.

The graben interior was successively filled by fluvial and marine sediments of up to 3.5 km thickness. Sedimentation is laterally unevenly distributed due to changing depocenters through time and influenced by occasionally marine ingressions from the north or the south. Main lithologies of Tertiary formations are claystone, marlstone, siltstone, sandstone, limestone, dolomite, and evaporites. Quaternary sediments are unconsolidated and consist mainly of clay, silt, sand, and gravel.

Miocene volcanism related to the tectonics of the URG occurred locally, of which the Kaiserstuhl volcano close to Freiburg is the most prominent volcanic edifice.

Geothermal play type

The URG forms a classical non-magmatic convection-dominated and fault controlled geothermal play system in an extensional domain (Moeck 2014). Fluid flow and effective heat transport is predominantly along active fault zones with increased fracture permeability. High radiogenic heat production in granites of the basement, different thermal properties characteristic for the Mesozoic and Tertiary sediments as well as high permeable fault zones crosscutting the entire sequence have led to a complex thermal field with conductive and convective elements. Especially thermal insulation by thick clay-rich sediments results in increased geothermal gradients within the Tertiary formations, whereas in active convection cells along fault zones the geothermal gradient may be quite different.

Characteristics of potential hydrothermal reservoir formations

Potential hydrothermal reservoir formations for heat and power co-generation are all located in the Mesozoic and Permian-Carboniferous successions below the Tertiary graben filling sediments.

For the former, fractured formations of Hauptrogenstein (Dogger), Lower Keuper/Upper Muschelkalk, Middle/Lower Buntsandstein and the crystalline basement (granites) are considered. In contrast, the clay rich Tertiary formations do not support open fracture networks for fluid flow necessary for economic medium-enthalpy hydrothermal application. The aim of exploration is to find naturally occurring thermal water bearing structures that are bound to hydraulical highly conductive fracture networks in the vicinity of fault zones in potential reservoir formations.

The Hauptrogenstein (Dogger) forms a fractured and karstified limestone reservoir in the southern part of the URG. Formation thickness is up to 100 m. The Hauptrogenstein is exploited by a few geothermal wells in the south of the URG near Freiburg (Bremgarten 1; Schliengen 2; Mooswald 1, 2; Bad Krotzingen TB2, TB3, TB4; Bad Bellingen) for balneology and house heating. Brine temperatures are rather low (less than 100 °C) reflecting normal geothermal gradients and shallower depth relative to the other reservoir formations. Realised flow rates derived from the Hauptrogenstein are up to 8 l/s.

The Upper Muschelkalk (Middle Triassic) forms a fractured and karstified limestone reservoir in the southern and central part of the URG. Formation thickness is up to 110 m. Karstification may only be present in the northern area where the formation was close to surface during the Cretaceous. The Upper Muschelkalk is partly overlain by sandstones of the Lower Keuper (Upper Triassic) which form a porous and fractured reservoir. Formation thickness of the Lower Keuper is up to 25 m. Both formations can be exploited simultaneously when present. Deep geothermal wells exploiting one or both formations are Insheim GTI2 in the central part of the URG and Riehen 1 and 2 in the south. Several shallower wells for balneology and house heating exist close to the eastern graben border fault in Bad Schönborn.

The Middle / Lower Buntsandstein (Lower Triassic) forms a fractured and porous sandstone reservoir extending throughout the URG except for the northernmost part, where it has been eroded during late Cretaceous to early Tertiary times. (Note that the Upper Buntsandstein is not regarded as a reservoir formation due to the relatively high clay content). Formation thickness is up to 560 m. The Buntsandstein reservoir is by far the most promising reservoir due to its high formation thickness, reasonable matrix porosity and its ability to host stable, open, and well-connected fracture systems. The high reservoir quality is proven by several deep geothermal wells within the study area like Brühl GT1, Insheim GTI1 and GTI2, Landau Gt-La1, Rittershoffen GRT2, Bruchsal GB-BR1a and GB-BR2, Cronenbourg GCR-1 as well as by recently drilled wells in the Speyer oil field (Römerberg).

The Rotliegend (Lower Permian/Upper Carboniferous) forms a fractured and partly a porous reservoir of sandstones, conglomerates, breccia, and volcanic rocks. Due to its setting / deposition in intra-montane Variscan basins (e.g., Saar-Nahe-Basin in the northern URG) and valleys, reservoir extent may be very limited and of very heterogeneous nature. Formation thickness is up to 2000 m. Between the troughs no Rotliegend has been deposited or has been eroded prior to Triassic deposits. Geothermal exploitation of deep seated Rotliegend reservoirs has not been successful so far.

The deepest and therefore potentially hottest reservoir formation is the Variscan basement. As the effective matrix permeability of basement rocks are effectively close to zero, only open and well-connected fracture networks associated with larger fault zones may yield sufficient permeability for convectional systems. Granites are more suitable to host such fracture systems than gneisses due to its mechanical behaviour. The Variscan granitic basement is tapped in Insheim (GTI1/1b, GTI2), Landau (Gt-La1, Gt-La2), Rittershoffen (GRT1, GRT2) and Soultz (GPK1, GPK2, GPK3, GPK4). The use of the crystalline basement as a reservoir implies an increased risk of induced seismicity and often needs to be technically enhanced by hydraulic or chemical stimulation.

All these reservoirs are exploited with high flow rates using wide and active cross-cutting fault zones interconnecting the reservoirs described above. The exploration methods targeting these fault zones and the evaluation of the results leading into the target zones for deep drilling is described in chapter 3.

3. Project development – overview

Project phases from the idea to realization

Geothermal project development poses a variety of risks (financial, geological/technical, environmental, and social/political). The investment to be taken until the reservoir is proven by drilling is high and therefore regarded as venture-capital. To minimise the financial risk a step-by-step approach dividing the development into distinct project phases is reasonable (Figure). Completion of each phase represents an increase in the developer's understanding of the geothermal system, a decrease in the overall uncertainty of the project's financial viability, a project decision point, and (usually) a requirement for significant financial investment. Typically, investment is low at the beginning (low-cost investigations) and increases with more expensive exploration techniques (Figure 4). The biggest cost driver is drilling a well. In case the geothermal resource is proved by drilling and testing a well the overall project risk is significantly decreased.

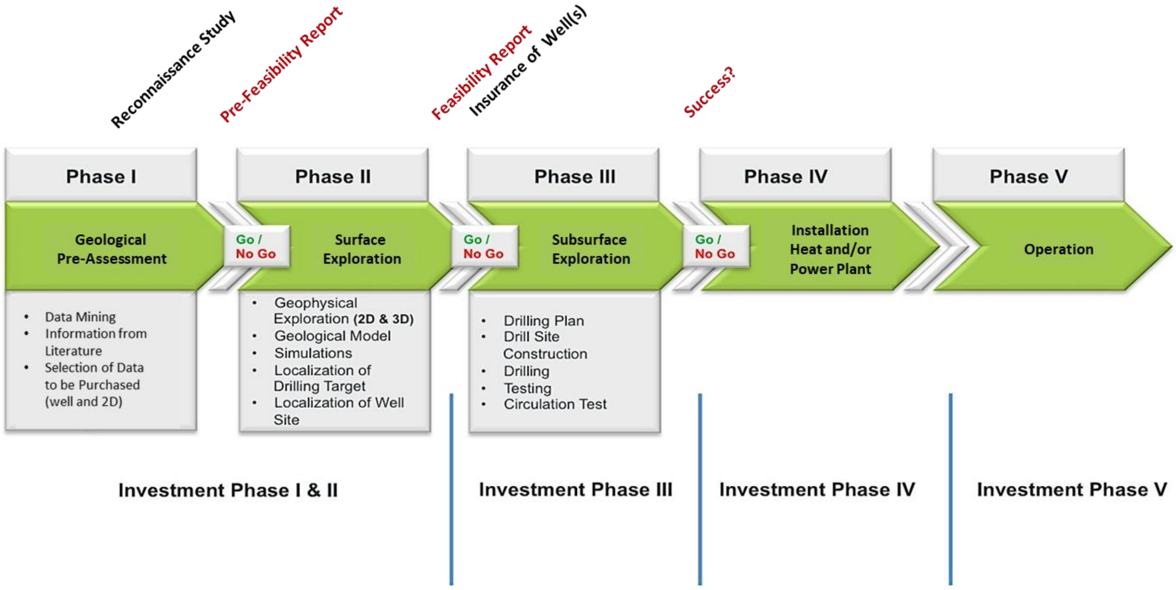

Figure 3: Overview on development phases of a geothermal project. Major financial decisions must be made after evaluation of distinct phases. This development scheme is of course not mandatory and may be modified according to the needs.

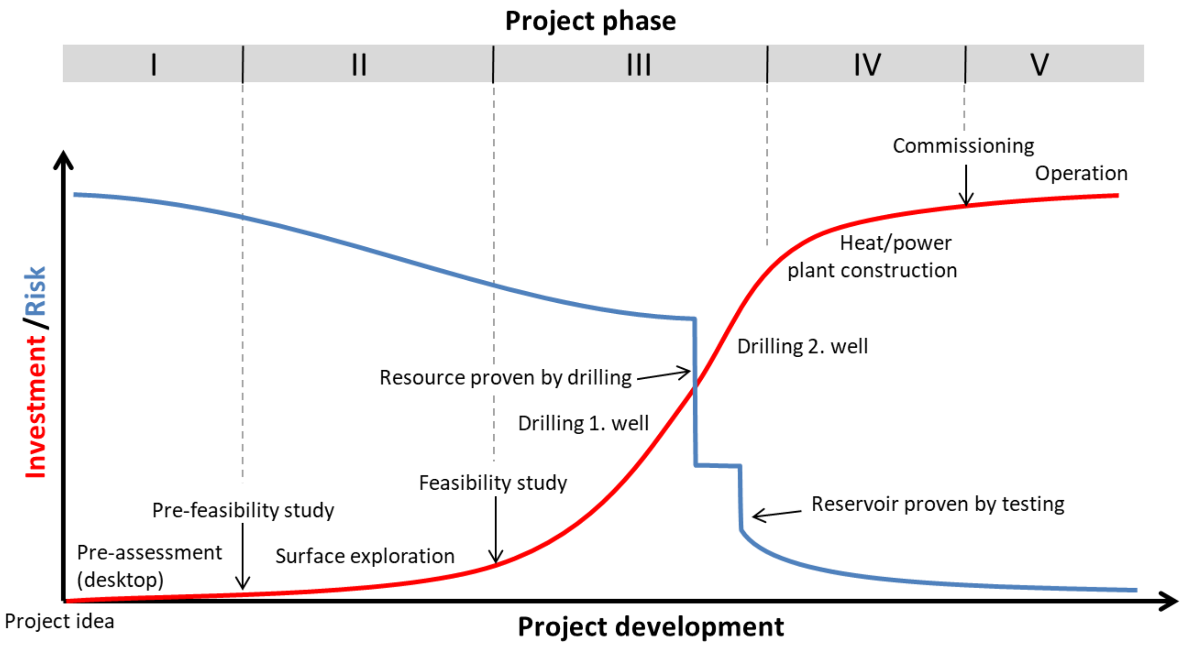

Figure 4: Evolution of costs and risks during deep geothermal project development.

Phase I (Geological Pre-Assessment) involves a work program to assess the already available evidence for geothermal potential within a specific area and to identify relevant geothermal play types to guide subsequent activities. At the highest level, the survey seeks to identify geological settings that might host economically viable geothermal systems. In practice, the survey essentially involves a 'desktop' review of geological, hydrological and/or hot spring/thermal data, drilling data, 'anecdotal' information from local populations, and remote sensing data from satellites, if available. If the area has a history of petroleum (as the URG), mineral, and/or water resource exploration, then records of these activities may provide very useful background and subsurface information.

Basic background information collected during the preliminary survey phase typically covers

- the power market and possible power purchase agreements (PPA) or feed-in tariff,
- the use for geothermal energy and defining the parameters for heat offtake,
- infrastructure issues (roads, water, communication, transmission),
- resource ownership issues,
- environmental and social issues,
- institutional and regulatory frameworks,
- issues relating to political and financial stability,
- compilation and interpretation of available seismic survey and well data,
- information from available literature and studies on any known geothermal systems, including geological, hydrological, and thermal data.

All these factors need to be considered to identify possible barriers to development or potential roadblocks that might derail or slow down a development program. Based on the outcomes of this scoping and *Reconnaissance Study*, the developer may decide to proceed to the surface exploration phase.

Obtaining finance and/or partners to share the risks and expenses of this phase may also be necessary. There may be several potential sites to investigate, which could effectively spread the risk but require higher overall expenditures. A *Pre-Feasibility Report* with an assessment of all the technical and non-technical data within the framework of a risk-weighted financial model may be helpful planning the more expensive next phase. This is a very significant milestone since proceeding with surface exploration or even drilling into the proposed reservoir involves major financial commitments to the project. This is at a time when uncertainty about the local reservoir characteristics is still high. The *Pre-Feasibility Report* should recommend either for or against continuing the project after considering all relevant factors.

The purpose of **Phase II (Surface Exploration)** is to cost-effectively collect new geoscientific data to minimize uncertainty related to estimates of key reservoir parameters (temperature, depth, thickness and extent, porosity, permeability, etc.) prior to the drilling phase. Exploration may start at a regional level and progressively focus on smaller target areas as data reveal the most attractive locations. Exploration typically begins with gathering samples and data from existing wells and seismic surveys. Exploration then proceeds to surface and sub-surface surveying using geological, geochemical, and geophysical methods. All data are used to set up a detailed structural reservoir model, which serves the basis for reservoir evaluation, target definition, well path planning and thermo-hydraulic(-mechanical) simulation. Environmental studies during the exploration phase establish key background (or baseline) information. A detailed environmental impact assessment (EIA) may be required.

For most projects, the decision to mobilize and contract equipment for the drilling phase is a significant financial commitment. For this reason, uncertainties about the characteristics of the drilling target and conditions should be reduced as much as cost effectively practical during the exploration phase. In order to make an exploration program cost effective while reducing uncertainty, this typically begins with relatively low-cost regional reconnaissance methods and then proceeds to more complex and expensive surveys over smaller identified areas of interest (e.g., 3D seismic surveys).

By the end of the exploration phase, sufficient data should have been collected and analysed to prepare a *Feasibility Report* and select sites and targets for the subsurface exploration phase, in which the first deep wells are drilled directly into the predicted reservoir.

In **Phase III (Subsurface Exploration)** a major investment of venture-capital must be made. Drilling is a large cost driver and geological/technical risks may be high, in the worst case through losing a well or being unsuccessful in finding the resource. At the end of this phase a production and an injection well (usually a well doublet) with large diameter in the reservoir section should be drilled, completed, and tested. Well diameter needs to be chosen by considering desired flow rates, friction losses and dimension of the pump chamber (for the production well). Instead of starting to drill a full size well a slim exploration well might be drilled first to reduce the financial risk proving the resource. The slim exploration well however will not be economically suitable for high flow rates. High friction losses result in high pumping energy to maintain high flow rates. This risk mitigation measure will – in case of success – result in additional costs in drilling the full size well afterwards. If larger scale development of a region is planned with the drilling of several well doublets on the mid-term, slim hole exploration wells might be a very useful approach to prove the reservoir potential.

After well completion, each well needs to be tested (production and injection tests) to evaluate the performance of the wells. After finalising the doublet, the performance of the reservoir and its interplay with the two wells needs to be evaluated by a long-term circulation test. The acquired data will be used to benchmark a thermo-hydraulic reservoir model.

Before starting drilling operations, a local seismological monitoring network needs to be installed to observe induced seismicity. A response plan describes the actions to be made in case of occurring induced seismicity above pre-defined thresholds. Additionally, groundwater monitoring may be required for groundwater protection (leakage or spill from drill site). Groundwater monitoring as well as seismological monitoring should be maintained throughout the lifetime of the project and the following operation.

The following **Phase IV (Installation Heat and/or Power Plant)** and **Phase V (Operation)** highly depend on the flow rates and temperatures at well head as well as on the reservoir behaviour (induced seismicity), hydrochemistry (mainly scaling issues) and local/regional energy consumer (Greenhouses, district heating grids). Early estimations after drilling the first well serve key input parameters to start detailed planning and constructing the plant.

For effective and sustainable reservoir management the thermo-hydraulic reservoir model needs to be maintained and regularly updated by operating parameters. If induced seismicity proves to be a problem, the model must be extended to a thermohydraulic-mechanical model.

Workover actions must be taken seriously to ensure well integrity and maintain performance of the system (pumps, heat exchanger).

Project timeline (idealized)

A project timeline is needed to force project development. However, some dependency exists by external stakeholders which might slow down or even hinder the development. Therefore, the project timeline is subject to continual adjustment.

The time from the first idea to commissioning the geothermal plant may be shorter than the sum of all individual phases as some work from different phases might be performed in parallel.

Typical lengths of the individual phases are:

Phase I	3 months
Phase II	9-18 months, depending on acquisition of seismic data
Phase III	12-18 months
Phase IV	12-24 months
Phase V	up to 3 years to ramp up

In total 4 to 5 years are currently needed to realise a geothermal project in the URG. This might be shortened in the future by increased experience and changes in the regulatory processes.

Financial expense (typical)

The costs for project development are dependent on the individual needs of the project, the investors, and – as usual – on the actual market situation. Drilling a borehole without much of preceding surface exploration will lower the investment costs, but the risk of being unsuccessful is very high. Reducing the risk of a project is always increasing the plannable costs.

The report on “Preparation and Support in the Preparation of an Experience Report according to § 97 Renewable Energy Act, Sub-project II b): Geothermal Energy” (Gec-co 2019, https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/bmwi_de/gec-co-vorbereitung-begleitung-eeg.html) compiles the investment costs incurred on average for a project development in Germany.

The investment costs are incurred before the geothermal project is commissioned and are divided into costs for planning and research/analysis, subsurface costs, and costs for the above-surface system. Planning and investigations include project management; the above-surface plant includes the power plant, the thermal water cycle, the thermal water pipeline, grid connection costs and buildings. The subsurface costs include costs for drilling, pumps, hydraulic tests, exploration and, if necessary, stimulation (reservoir enhancement). Other costs include items that cannot be allocated to the three areas, such as insurance.

Approx. 55% of the investment costs are incurred for the subsurface part of the project (exploration, boreholes, testing, and pump), 31% for the above-surface installations, 6% for planning and 8% for other.

Drilling costs are the biggest component of investment and vary from project to project and drilling depths, and range between 8 and 20 M€ per well.

Electricity production from deep geothermal projects is funded using a feed-in tariff from the Renewable Energy Act (EEG). From an energy market perspective as well as from the political guidelines in Germany the future of geothermal energy will be heating and cooling. The publication of the “Roadmap Tiefe Geothermie für Deutschland” (2022) by German Institutions like Fraunhofer and Helmholz are the basis of the turn of the focus to heating and cooling. Therefore, current (e.g., Bundesförderprogramm Effiziente Wärmenetzte, BEW) and future funding programs support geothermal heating/cooling projects. While the EEG is still serving as a bridge to geothermal heating as the existing heating grids are fed by mainly conventional sources (coal, gas, and oil), the future will be geothermal heating and cooling. Also, the power plants will produce energy in times of low heat demand. More programs and support mechanisms (insurance mechanism for exploration risk) will be available in the future. These programs are needed to allow all the local and regional initiatives of communities, utilities, and private developers to start and implement the geothermal projects, which are currently discussed all over Germany.

In the following we give an indication of major costs for each phase of project development of a geothermal power plant with following basic target parameters typical for projects in the URG:

Reservoir depth	4.000 m TVD
Temp. @ well head	165 °C
Flow rate	70 l/s
Thermal output	27 MW_{th}
Electrical output	4 MW_{el}

Phase	Items	Approx. costs
I	Reconnaissance Study (Pre-Feasibility Report)	50 k€
II	Legal (application for permits, fees) Acquisition of existing 2D seismic lines (assuming 30 km) Acquisition of new 2D seismic lines (including planning; assuming 10 km) Acquisition of new 3D seismic survey (including planning; assuming 70 km^2) (Re-)Processing of seismic data Interpretation of seismic data Acquisition of borehole data Acquisition and interpretation of magnetic survey (optional) Acquisition and interpretation of gravimetry survey (optional) Hydrochemical (and soil gas) exploration (optional) Seismological hazard assessment Environmental impact assessment Feasibility Study (Feasibility Report) including modelling and simulations Public relations	2 M€
III	Legal (application for permits, fees) Insurance for exploration success (optional) Acquisition of real estate for drilling and power/heat plant (project site) Drill site planning, well planning, test planning, operation plans Drill site preparation/construction Drilling 2 wells (including all services; 2.300 €/m) Well logging (borehole geophysics) Testing (production, injection, long term circulation) Reservoir enhancement (thermal, chemical, hydraulic) Seismological monitoring network (installation and operation) Groundwater monitoring (installation and operation)	30 M€
IV	Legal (application for permits, fees) Contractors' all risks insurance Plant planning, operation plans Surface thermal system and line shaft pump Buildings, electrical and control technology ORC plant (3 M€ per MWel) Heat plant (0,3 M€ per MWth) Infrastructure (connection to existing grid) District heating distribution	24 M€
V	Legal (application for permits, fees; per annum) Reservoir management (per annum) Seismological and groundwater monitoring (per annum) Maintenance and workover (per annum)	1.5 M€/a
	SUM	**50-60 M€**

4. Regulatory framework

Germany

In Germany geothermal exploration and approval of deep geothermal plants is subject to various federal and state regulations and rules. Various mining permits are required for exploration, exploitation, operation, and cessation of operations. These are issued upon written application to the mining authority of the federal state. The mining authority oversees the necessary administrative procedures.

Main laws and regulations to be considered are:

- Federal Mining Act (Bundesberggesetzes - BBergG)
- Water Resources Act (Wasserhaushaltsgesetzes - WHG)
- Building Code (Baugesetzbuch - BBauG) concerning planning and building regulations

Furthermore, to be considered:

- Nature Conservation Act (Bundesnaturschutzgesetz - BNatSchG)
- Soil Protection Law (Bundes-Bodenschutzgesetz - BBodSchG)
- Mining ordinance for all mining related aspects (Allgemeine Bundesbergverordnung - ABBergV)
- Immission Control Act (Immissionsschutzgesetz - BImSchG)
- Waste Act (Kreislaufwirtschaftsgesetz - KrWG)
- Social and technical occupational health and safety regulations (Arbeitsschutzgesetz - ArbSchG)
- Monument Protection Law (Denkmalschutzgesetz - DSchG)
- Act on the search and selection of a site for a repository for high-level radioactive waste (Standortauswahlgesetz - StandAG)

Depending on the size of the plant, the Regional Planning Act (Raumordnungsgesetz - ROG) and the Environmental Impact Assessment (EIA) Act (Umweltverträglichkeitsprüfung - UVPG) may also have to be applied as part of a planning approval procedure.

For further details see '*Regulatory framework for the realisation of a geothermal project in Germany'.*

France

In France the code civil forms the basis for mining regulations. The territorial authorities (communes, regions) play a key role showing the will to welcome/develop deep geothermal energy on their territories and often participating in its funding. The right to search for a geothermal resource (autorisation de recherches) and the exclusive research permit (permis exclusif de recherche) is granted by the local deconcentrated authority (préfecture) and the central authority (ministère), respectively. The right for exploitation of geothermal energy <20 MW (permis d'exploitation) is granted by the local deconcentrated authority (préfecture). The right for exploitation of geothermal energy >20 MW (Concession) is granted by the state council (conseil d'état).

The main laws to be considered are the regulations of the mining code (code minier) and decrees.

Furthermore, to be considered:

- Environmental Code and the Water Act (code de l'environnement)
- Health Public Code (code de la santé publique)
- Labour Code (code du travail)

For further details see *'Regulatory framework for the realisation of a geothermal project in France'*.

Switzerland

In Switzerland mining law is a cantonal business and governed by cantonal law. There is neither a federal law regarding mining and geothermal usage nor a coherent practice in Switzerland. Each canton has its own sovereignty to set up regulations. For the URG area regulations by the canton of Basel-Stadt and Basel-Landschaft may apply.

Main laws and regulations to be considered are:

- Law on Environmental Protection (Umweltschutzgesetz - USG)
- Law on Spatial Planning (Raumplanungsgesetz - RPG)
- Law on Water Protection (Gewässerschutzgesetz - GSchG)

Furthermore, to be considered:

- Subsoil Utilization Act (Gesetz für die Nutzung des Untergrunds - GNU)
- Energy Act (Energiegesetz - EnG BL)
- Regulation on Environmental Impact Assessment (Verordnung über die Umweltverträglich-keitsprüfung - UVPV)
- Noise Protection Regulation (Lärmschutz-Verordnung - LSV)
- Regional Planning Regulation (Raumplanungsverordnung - RPV)
- Chemicals Risk Reduction Regulation (Chemikalien-Risikoreduktions-Verordnung - ChemRRV)

5. Stakeholder Management

Surveying and addressing public awareness is essential in the earliest phase of a project. The explorer must understand local perceptions regarding geothermal development. Identifying concerns is an essential component of early geothermal investigations. Local communities should be made aware of the impacts, positive and negative, of any geothermal development. Public meetings and surveys should be undertaken to determine pre-existing public attitudes towards development and to provide information in response. Having good communications with local communities is essential from the outset of any program. Already phase I should include an assessment of key environmental issues or factors that might affect or be affected by a geothermal development. As with any major infrastructure development, geothermal power plants have their own unique social and environmental impacts and risks that require awareness and management. Developing relationships and communication channels with all stakeholders at the early stages of investigation is critical if the developer is to identify potential sociological or environmental roadblocks that may need to be addressed during the project.

6. Risks

In addition to the typical general risks associated with large infrastructure projects, exploration and drilling risks are the main risks in connection with geothermal projects. All technical risks described are also economic risks, as they involve additional costs and/or delays. In the worst case, it can lead to the abandonment of the drilling or the project. Insofar as these risks can be influenced by planning, there are ways to mitigate these risks.

A distinction can be made between risks that can be influenced, which exist in the field of planning and implementation, and risks that can be little or not at all influenced, which are beyond the control of the project planner or operator.

Group of risk	**Type**
geological risk	conditional to not influenceable, but technically solvable
technical risk	influenceable
economic risk	partly influenceable
environmental risk	influenceable
political risk	little to not influenceable

These groups of risk cannot be clearly separated from each other as they largely influence each other and are therefore directly dependent on each other. In this context, a distinction must be made between predictable risks, which can be foreseen and may be expected and where mitigation measures can already be defined as remedy in advance, as well as unforeseeable and unexpected risks, which may have an impact on third parties and thus on the acceptance of the project.

A risk is generally described as the product of the probability of an event occurring and its effects, related to the deviation from set targets. In general, risks in deep geothermal projects can be mitigated by thorough planning and careful implementation. More in depth information on risks related to geothermal projects and their financial mitigation developed by the GEORISK project can be found in https://www.georisk-project.eu.

The resource discovery is the decisive success factor for a deep geothermal project. At the same time, it is regarded as the main risk with drastic consequences for investors, operators, and project developers. At the beginning of the project, these define the minimum production rate, reservoir temperature and pressure reduction under which the planned (heating) power plant will achieve the expected output and the calculated return and can thus be operated economically.

If and under which conditions insurance solutions for a geothermal project are feasible must be negotiated with insurance brokers or directly with the insurance companies. Several companies are available as contractual partners for both the brokers and the insurance companies.

7. Exploration methods

Objectives

Major objective of exploration is to find the resource, i.e., thermal water with high temperatures in reservoir volumes with high permeability. Choosing the appropriate method should be guided by scientific and economic (value for money) arguments. The exploration campaign should always start with an overview and evaluation of existing and available data, representing a cost-effective approach. Further exploration is meant to minimise the residual uncertainty to an acceptable level, based on which costly drilling will be performed and/or the reservoir is proven.

Desktop study (publicly available data)

A desktop study usually is one of the first steps in project development and as such an essential part of the scoping and reconnaissance study. In order not to waste time and money a desktop study is performed to collect and evaluate already existing and publicly available surface and subsurface data (topographic, geologic, geophysical, (hydro-)geochemical, and hydrological).

Data sources typically are:

- Governmental services (e.g., LGRB-BW, BRGM)
- Public funded R&D projects (e.g., GeORG, GeotIS, Hessen 3D)
- Scientific publications
- Public information on nearby running projects

The aim of the desktop study is to gain a comprehensive overview on the regional to local situation and on the existing data. The georeferenced data will be collected and displayed in a geographic information system (GIS). A first rough model of the subsurface may be derived and its uncertainties may be assessed.

Important parameters, such as on stratigraphy and petrophysics, relevant for geothermal characterisation will be collected in the form of a database for later modelling and calculation.

- Importance / usefulness: very high
- Cost level: low

Analogue study (outcrops)

Studies on well-selected reservoir analogues create a good database for predicting reservoir characteristics in the deeper subsurface. Such studies are particularly useful in areas with little information from deep wells to reduce the risk of exploration. In the URG area most of the reservoir formations can be found along the graben shoulders and several outcrop analogue studies have been performed for hydrocarbon and geothermal exploration already of which some have been published (e.g., Reinecker et al. 2015, Bossennec 2019; see compilation in Frey et al. 2022).

Outcrop analogue studies made e.g., in quarries allow statements with respect to near-surface conditions. A transformation to a statement for conditions at reservoir depths is not straight forward. Most obvious changes of mineralisation and hydrothermal alteration are dependent on temperature, pressure, and fluid chemistry, which varies with depth. This requires an empirically supported correlation to the conditions at target depths. Differing conditions influencing fracture network or fault zone characteristics and mineralisation are in particular

- history of subsidence/uplift, burial/exhumation, diagenesis,
- deformation history and associated stress changes,
- present-day in-situ stresses and stress regime,
- orientation and offset of the fault zone,
- pore pressure,
- interactions with (paleo-)fluids (weathering/solution/precipitation/alteration) and
- heat flux and temperature field through time.

However, there is no question that correlations between outcrop analogues and real reservoirs must be made with as many boreholes as possible to improve the transfer of the parameters obtained in the outcrop analogue to reservoir depth.

- Importance / usefulness: limited to high (depending on analogues)
- Cost level: low

Geophysical surface survey (seismic, gravimetry, electro-magnetic)

Most effort is made in conducting geophysical surveys. 2D and 3D seismic surveys are by far the most common exploration methods made in the URG starting with 2D seismic lines in the mid-20th century. Because of the still high uncertainty in the interpretation between different 2D seismic lines, 3D seismic surveys became standard in the last years. A 3D seismic survey has the advantage of continuous spatial information of relatively high resolution (around 25 m x 25 m), which can be used to image structural geology (stratigraphic horizons, faults, and folds) of the subsurface. This 3D subsurface image usually provides the 3D geometry needed for well path planning. Seismic attribute analyses reveal additional information on petrophysical parameters, which can be studied for lateral changes of reservoir characteristics.

Gravimetric and electro-magnetic surveys are less common in the URG but serve the advantage of resolving lithological differences especially in the crystalline basement, which is not well imaged by seismic surveys. The spatial resolution of gravimetric and electro-magnetic surveys is much less (several hundred meters) than of 2D or 3D seismic surveys. Electro-magnetic surveys in the URG are challenging because of a high-level of anthropogenic noise (railroad lines, power lines etc.) which disturb the signal.

- Importance / usefulness: very high (for seismics), medium (for gravimetry, electro-magnetic)
- Cost level: high (for seismics), medium (for gravimetry, electro-magnetic)

Offset boreholes (stratigraphy, borehole geophysics)

In contrast to geophysical surface surveys, borehole data reveal direct 'encountered' information from the subsurface, although only punctually in 1D. Detailed litho-stratigraphic information by drill cuttings (and/or cores), high resolution petrophysics through borehole geophysical logging or core analysis, information on fluids in pores and fractures, as well as on formation porosity, permeability, pore-pressure, and in-situ stresses may be found in reports from offset boreholes. All these data are crucial for reservoir characterisation. Additional important information for mitigating drilling risks are reported drilling experiences in local geology.

Borehole data serve important information (e.g., formation depths along the well path) for correlation and depth calibration of geophysical surface surveys such as 2D or 3D seismic. Such well ties of 3D surveys improve the quality significantly.

- Importance / usefulness: very high
- Cost level: low to medium when purchasing available data

Reservoir modelling and simulations

The aim of reservoir modelling is to combine geometrical, quantitative, and qualitative information of the subsurface for visualisation and reservoir characterization in 3D. The coherence of different information in the model is a measure of quality. This in turn is reflected in the planning of well paths into geothermal target zones and the drilling. There is no better way to improve the predictability of a drilling project and therefore mitigating drilling and geological risks. Reservoir models can be strongly improved by joint inversion approaches of the different geophysical surface exploration methods.

Thermo-hydraulic simulations of a hydrothermal reservoir tapped by a proposed well doublet help to evaluate its sustainability. Such simulations, based on the reservoir model, should be performed before drilling to find the best geometry of the doublet. Additional geomechanical or hydrochemical simulations help to evaluate operation related issues regarding induced seismicity or scaling (in the reservoir or subsurface facilities) at an early stage.

- Importance / usefulness: very high (mandatory)
- Cost level: medium

Drilling

Drilling is the most important method in subsurface exploration and mandatory to prove the resource. As drilling is a costly and risky step in project development a thorough planning is critical. All necessary risk mitigation measures must be applied.

There are several exploratory objectives on drilling a borehole:

- Proving the resource
- Providing detailed litho-stratigraphic information by drill cuttings (and/or cores)
- High resolution petrophysical data of the reservoir through borehole geophysical logging
- Information on formation fluids of the reservoir
- Information on formation porosity, permeability, and pore-pressure of the reservoir
- Information on-situ stresses and geomechanics

Implementation of a comprehensive measurement programme should be applied when drilling the first well. This information may help to further mitigate drilling risk of subsequent wells.

A typical geological-geophysical measurement programme includes:

Mud logging: sampling and analysis of cuttings during the drilling process to document the encountered litho-stratigraphy.

Wireline logging: borehole geophysical data acquisition of petrophysical parameter (such as spectral gamma-ray, density, sonic), borehole parameter (such as oriented caliper, casing-collar locator, cement bond), and reservoir parameter (such as temperature, pressure, flow meter).

Hydraulic testing: testing of the actual hydraulic reservoir conditions through the borehole by means of production test (e.g., air lift) and injection test.

Whether the first well should be drilled in full size for final use or as a slim hole to reduce the economic risk is up to a risk assessment. In the latter case the slim hole exploration well lowers the initial drilling costs to prove the resource/reservoir. On the other hand, a slim borehole is limited in enabling economic flow rates due to high friction losses. However, in both scenarios the borehole may be regarded as an exploration well but with different costs and further usage.

- Importance / usefulness: very high (mandatory)
- Cost level: very high (most expensive part)

8. Decision support

Decision-making in energy planning and investing in energy projects is influenced by many different factors. These factors are often conflicting and include quantifiable and non-quantifiable criteria. Multi-criteria decision-making (MCDM) methods may be used as an integrated platform for solving this kind of problems by using a few defined criteria and a scheme to weight these criteria to mitigate the problem. However, the solution also highly depends on the preferences of the decision-maker. Therefore, a final solution is always a compromise of different points of view.

Definition of 'project success'

The success of a geothermal heat and/or power project depends on the expectations of the operator/investor. Hydrothermal projects described in this document are considered to be successful when

1) the flow rate at wellhead reaches a minimum production rate Q at a maximum drawdown Δs,
2) a minimum temperature T is reached,
3) operation is sustainable for at least 25 years,
4) operation can be maintained without induced seismicity above a certain threshold, and
5) the project has public acceptance.

Threshold values for minimum production rate and temperature for economic use must be determined by the operator/investor (e.g., in a business case based on the Feasibility Study). However, business case calculations may change during project development due to political, ethical, or technical reasons.

Project success may be defined after drilling and testing the first well (i.e., prove of the resource) or after long term circulation test between the two wells (i.e., prove of sustainable geothermal energy extraction). In case of not reaching the desired values during planned project development, enhancement/stimulation measures or drilling a side-track to better connect the well to the reservoir can be applied. *(The topic of well enhancement/stimulation is outside of this deliverable and requires a detailed geological and risk analysis and should comprise a separate decision-making workflow to consider all relevant aspects in sufficient detail (legal aspects, public, geological, geomechanical, ground water protection etc.))*

In case of not being successful because the envisaged reservoir is dry, the well may be used either as a deep borehole heat exchanger or other potential reservoirs at shallower levels might be targeted.

In case of giving up the well because of not being successful/used or due to technical failure, the well must be permanently plugged and abandoned (based on the national regulations).

Workflow checklist

The following checklist cannot be exhaustive as each project has its own characteristics, issues and boundaries. There might be additional obligations by the appropriate mining authority. Hence, this list may be regarded as an orientation only.

Pre-development Phase 0 (Drafting the Idea)

- ☐ Define potential commercial/private consumer and their energy demand in the area of interest
- ☐ Propose coarse business case (desire) with envisaged energy output (MW_{el}, MW_{th}, minimum temperature, …),
- ☐ Drafting the idea and setting up a project development strategy
- ☐ Discuss idea and strategy with geothermal consultants experienced with the local conditions and first order stakeholders

Phase I (Geological Pre-Assessment)

- ☐ Define area of interest by geographical and geological criteria (scoping)
- ☐ Apply for an exploration licence (exploration permit) covering the area of interest
- ☐ Search for publicly available data and literature
- ☐ Set up a GIS project for spatial analysis of georeferenced data
- ☐ Define geothermal potential (reconnaissance)
- ☐ Respect environmental regulations (water protection, nature conservation, …)
- ☐ Respect competition in subsurface usage
- ☐ Evaluate the regional energy demand (consumer) and power/heat grids (Infrastructure)
- ☐ If necessary, acquire additional existing close-by 2D seismic lines (low-cost)
- ☐ Pre-Feasibility Report showing the general feasibility of a hydrothermal project in the area of interest with different opportunities and recommendations for further project development
- ☐ GO/NO GO decision whether to continue and make further investment

Phase II (Surface Exploration)

- ☐ Acquisition of exploration data (mainly 2D and/or 3D seismic survey, borehole data)
- ☐ Setting up a detailed geological/structural reservoir model integrating all available data
- ☐ Geomechanical assessment of mapped fault zones bearing open fracture networks
- ☐ Validation of deep reaching convective structures (e.g., by means of an isotope study in groundwater wells or geothermal gradient wells)
- ☐ Outcrop analogue study
- ☐ Reservoir definition (spatial)
- ☐ Reservoir characterisation (geological, geothermal, hydrological, hydro-chemical)
- ☐ Target definition
- ☐ Exploitation strategy (possible well path trajectories from various potential drill sites)
- ☐ Numerical thermo-hydraulic simulation of long-term hydrothermal operation
- ☐ Environmental impact assessment (EIA)
- ☐ Seismological hazard assessment (regarding induced seismicity)

- Perform a site-specific Feasibility Study of a hydrothermal project including a detailed risk assessment and a financial evaluation (Feasibility Report)
- Adjust business case calculations to real conditions
- Discuss findings and possible other scenarios with local stakeholders to find acceptance for the project
- GO/NO GO decision whether to continue and make further investment
- Preliminary building application for the power/heat plant, grid infrastructure (building code)

Phase III (Subsurface Exploration)

- Acquisition of real estate for drilling and power/heat plant (project site)
- Detailed planning of well path and well design
- Prepare operation plan for drilling, logging, and testing
- Prepare special operation plan for seismic monitoring
- Prepare special operation plan for ground water monitoring
- Apply for drilling approval (mining authority)
- Call/Tender for proposals and assignment of work (drill site construction, drilling, services)
- Preparation/construction of drill site and testing pond
- Installation of a local seismological monitoring network
- Installation of shallow groundwater monitoring wells
- Drilling, logging, and testing the first well
- Evaluation of success (GO/NO GO decision)
- Drilling, logging, and testing the second well
- Evaluation of success (GO/NO GO decision)
- Long term circulation testing
- Evaluation of success (GO/NO GO decision)
- Update numerical thermo-hydraulic simulation of long-term hydrothermal operation
- Assess area/volume of thermo-hydraulic influence
- Prepare operation plan for long term operation
- Apply for an exploitation approval (mining authority)

Phase IV (Installation Heat and/or Power Plant)

- Apply for a building permit (building code)
- Planning and installation of the entire surface energy system
- Planning and installation of infrastructure to the existing grid

Phase V (Operation)

- Commissioning
- Set up and maintain reservoir management
- Maintain seismological and groundwater monitoring
- Regular workover actions
- Apply regularly for renewal of exploitation approval (mining authority)

9. Cited references

BGR (2016): Geologische Karte der Bundesrepublik Deutschland 1 : 1 000 000 (GK1000).

Bossennec C (2019): Evolution of transfer properties of sandstones by diagenesis and deformation: Case study on Buntsandstein Gp. sandstones, Upper Rhine Graben. – PhD thesis, Université de Lorraine.

Deutsche Stratigraphische Kommission (2016): Stratigraphische Tabelle von Deutschland 2016: Potsdam (Deutsches Geo-ForschungsZentrum).

Frey M, Bär K, Stober I, Reinecker J, van der Vaart J, Sass I (2022): Assessment of deep geothermal research and development in the Upper Rhine Graben. – Geothermal Energy, 10:18, https://doi.org/10.1186/s40517-022-00226-2.

Gec-co (2019): Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz Teilvorhaben II b): Geothermie. – Wissenschaftlicher Endbericht (in german).

GeORG Projektteam (2013): Geopotenziale des tieferen Untergrundes im Oberrheingraben: Fachlich-Technischer Abschlussbericht des INTERREG-Projekts GeORG.

Moeck IS (2014): Catalog of geothermal play types based on geologic controls. – Renewable and Sustainable Energy Reviews, 37:867–882.

Reinecker J, Bauer JF, Bechstädt T, Drews T, Filomena M, Grobe R, et al. (2015): Verbundprojekt AuGE: Aufschlussanalogstudien und ihre Anwendbarkeit in der geothermischen Exploration—Entwicklung von Methoden zur Ermittlung von Permeabilitäten und Transmissivitäten aus Reservoir-Informationen des Oberrheingrabens. AUGE—Outcrop analogue studies in geothermal exploration: Schlussbericht Teilprojekt A; 2015.

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