SAPHEA

INTEGRATING GEOTHERMAL HEATING
AND COOLING NETWORKS IN EUROPE

Catalogue of spatial datasets including data preparation guidelines and protocols

Deliverable 2.3

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D 2.3 Catalogue of spatial datasets including data preparation guidelines and protocols

This document begins with standardized guidelines for integrating data into the WP3 decision-support toolbox, focusing particularly on the publication and harmonization of geoscientific datasets. These steps are essential for ensuring consistent and accurate analyses.

In the second chapter, the catalogue of collected datasets is presented, organized into publicly accessible pan-European datasets and local datasets contributed by SAPHEA project partners. This catalogue supports and integrates with thematic work packages (WP3 to WP5) and serves as a foundational data resource.

The final chapter builds on the scenario catalogue (D2.2) by introducing customized protocols for assessing geothermal potential within each specified scenario. This approach incorporates the technological catalogue from Task 2.2, merging the scenarios into sets by integrating specific key geoscientific constraints. These constraints are crucial for addressing resource and usage limitations relevant to geo-HC networks. Additionally, each scenario set is linked to publicly available pan-European datasets included in the data catalogue (Table 1), reinforcing the effectiveness and adaptability of strategic geothermal planning across diverse regional and geological contexts.

Data preparation guidelines for the WP3- Decision support toolbox

The decision support toolbox is based on the latest release of the Hotmaps toolbox (see https://www.hotmaps.eu/map) from 2020 and consists of two main parts:

- A GIS-based Graphic User Interface for data visualization.
- Two tools: a Gamebook and a calculation module, named Geophires. (**It is important to note that other tools will be added in the future for shallow geothermal potential assessment**).

The Gamebook is used for the first movers in the field to get insight into geothermal-based district heating systems. It can also be used for strategy developers to get insights into a region's geothermal-based district heating systems.

On the other hand, GEOPHIRES is a calculation module designed to support technical and economic decision-making in the geothermal sector. It caters to the needs of experts with geothermal expertise by integrating engineering models for reservoirs, wellbores, and surface plant facilities of a geothermal plant with an economic model. This combination allows for estimates of capital costs, operation and maintenance expenses, lifetime energy production, and the overall levelized cost of energy.

For a complete description of the decision support toolbox, please refer to the D3.1, White book of the spatial dataset-related toolbox.

To visualize the datasets in the toolbox or perform calculations on the provided datasets, it is necessary to integrate them into a database (see Data Management Plan, D1.5). For smooth integration of the data into the database, specific structures and rules are defined to automate the process.

This section outlines the required instructions for data preparation, primarily derived from the Hotmaps Guideline for data upload on GitLab (Appendix 2).

1. Data publication

Following the Data Management Plan (D1.5) and the FAIR principles (Findable, Accessible, Interoperable, Reusable), SAPHEA recommends that all project partners and dataset owners publish their datasets and obtain a DOI (Digital Object Identifier). This step is essential for ensuring proper attribution, enhancing visibility, and supporting the long-term accessibility of geoscientific data for future research and development.

SAPHEA has successfully facilitated the collection and publication of over ten pan-European datasets. The organization actively encourages its partners to make their open datasets available to the public. Publishing these datasets with a Digital Object Identifier (DOI) is a simple yet effective way to enhance data integration, promote reproducibility, and increase the accessibility of geoscientific data within the geothermal sector and related scientific communities.

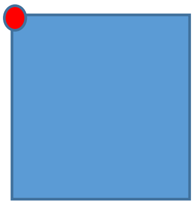
2. Data harmonization and integration

For a given parameter, there may be multiple datasets from different sources, such as various case studies. To create a unified dataset, these diverse sources must be harmonized into a coherent whole. This process involves standardizing each component dataset to ensure consistency in file format, GIS resolution, units of measurement, and other relevant standards. The result is a seamless, integrated dataset that is suitable for analysis and application.

According to the Hotmaps guidelines (Appendix 2), the data should be harmonized and integrated into SAPHEA's GitLab (Appendix 1) as follows:

1. **Repository Structure**: Each data repository on GitLab requires a unique, lowercase name with alphanumeric characters, a README.md file for metadata, a datapackage.json file for detailed descriptions, and a data folder for storing datasets.
2. **Data Formats and Projection Standards**:
    - **Raster Data**: GeoTIFF format is mandatory, with EPSG:3035 as the projection system. Specific compression settings are advised to optimize file size.
        1. All the raster data sets should have a raster origin (top-left corner) with X and Y coordinates as a factor of 100. E.g., X=5565400, Y=4365500. If the initial raster file does not follow this, then it should be resampled (e.g., using ArcGIS, QGIS, Python, R, etc.)

(X, Y) = (5565400, 4365500)



    - **Vector Data**: Provided in GeoJSON format with EPSG:3035 or CSV format with additional columns on NUTS or LAU code.
    - **Tabular Data**: Stored in CSV format, often linked to geographic data via NUTS/LAU codes.
3. **Data Packaging and Metadata**: The datapackage.json file encapsulates metadata for machine and human readability. Templates are available for different data types (raster, vector, tabular), and guidelines cover required fields like projection, transformation factors, and file descriptions.
4. **Licensing and Source Attribution**: Each dataset should include clear licensing information, contributor details, and source references to maintain transparency and data reusability.

This structured approach ensures interoperability, quality control, and compliance with European data standards, aiding in accurate energy mapping and analysis.

Catalogue of collected datasets

This chapter provides a comprehensive overview of the catalogue of datasets collected to support geothermal resource characterization and underground thermal energy storage planning. In alignment with Task 2.3, the objective is to compile geoscientific datasets that will offer crucial input for investment decision-making and strategic planning in geothermal energy projects. The dataset catalogue is available on the project's GitLab, serving as a digital annexe. The link to the digital annexe can be found at the end of this report (Appendix 1).

The collected datasets serve two primary purposes. First, they will provide critical geoscientific inputs to the WP3 decision-support toolbox, aiding in analyses and planning for geothermal applications. Second, these datasets will be integrated, when possible, into the project's map viewer to facilitate visualization and spatial analysis of geothermal resources across various regions. To ensure compatibility and ease of use, dedicated workflows (Task 2.4) have been developed to harmonize the data and prepare it for use in both the Geophires calculation tool and the Graphic User Interface.

Once completed, the catalogue will be submitted to EuroGeoSurveys (https://eurogeosurveys.org/) for publication within the European Geological Data Infrastructure (EGDI) (https://www.europe-geology.eu/). This will enhance the accessibility and utility of these geothermal datasets, supporting ongoing research and development in geothermal energy.

1. Publicly accessible spatial pan-European datasets

During the data acquisition phase, the research team conducted a comprehensive evaluation of pan-European geospatial data sources relevant to geothermal energy applications. Although a broad array of datasets was reviewed, many were deemed unsuitable for the project's objectives due to limitations such as inadequate spatial resolution, restricted public accessibility, and a lack of content specifically tailored to geothermal energy planning. While the complete catalogue of pan-European datasets is excluded from this report due to its extensive size, it is available in the digital annexe provided in Appendix 1.

Following this evaluation, a refined selection process was implemented to identify the datasets most appropriate for assessing the potential of various geo-HC scenarios described in D2.2 (see Table 1).

A key outcome of this initiative was the publication of over ten new pan-European datasets, which were previously unavailable, and their release as publicly accessible resources. These datasets are highlighted in the GeoDH project and the Atlas of Geothermal Resources in Europe section of this report.

Both tables mentioned are freely available for download via the project's GitLab repository (Appendix 1) and the SAPHEA market uptake hub (https://www.saphea.eu/).

Table 1: Publicly accessible pan-European datasets usable for the potential assessment of the different geo-DHC scenarios of the D2.2.

Classification	Content	Database	Description	Data license type	Geothermal scenario usage	Depth of usage	Type of assesment
Geodesy	Elevation	NASA Earthdata	Topographic data (30-m resolution digital elevation models)	CC BY 4.0	Borehole heat exchanger	Middle deep	Quantitative
GeoHazards	Landslide risk	ESDAC	European Landslide Susceptibility Map version 2 (ELSUS v2)	Unknown	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
GeoHazards	Earthquake risk	EFEHR	Web platform of the European Facilities for Earthquake Hazard and Risk (EFEHR)	CC BY 4.0	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
Geology	Depth of aquifer	EGDI	Link to EGDI map-viewer provides pan-European data on groundwater resources	CC BY 4.0	Groundwater open loop system	Shallow	Qualitative and Quantitative
Geology	Aquifer types	EGDI	Link to EGDI map-viewer provides pan-European data on groundwater resources	CC BY 4.0	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
Geology	Groundwater storage	EGDI	Link to EGDI map-viewer provides pan-European data on groundwater resources	CC BY 4.0	Groundwater open loop system HT-ATES + deep geothermal	Shallow to deep	Qualitative and Quantitative
Geology	Hot sedimentary aquifer and neogene basins location	Zenodo	Location data of hot sedimentary aquifers and Neogene basins in EU	CC BY 4.0	Hydro-geothermal HT-ATES + deep geothermal	Middle deep to deep	Qualitative
Groundwater	Thickness of saturated layer	EGDI	Link to EGDI map-viewer provides pan-European data on groundwater resources	CC BY 4.0	Groundwater open loop system	Shallow	Qualitative and Quantitative
Groundwater	Transmissivity	EGDI	Link to EGDI map-viewer provides pan-European data on groundwater resources	CC BY 4.0	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
Groundwater	Surface water	GSWE	Global Surface Water map	Copernicus Regulation	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
HydroGeology	Aquifer location	BGR/IHME	International Hydrogeological Map of Europe, scale 1:1 500 000 (IHME1500)	Unknown	Groundwater open loop system	Shallow	Qualitative
HydroGeology	Permeability and porosity	GLHYMPS 2.0	Shallow and deep permeability and porosity values for various types of consolidated and unconsolidated sediments	CC BY 4.0	Groundwater open loop system Borehole Heat Exchanger Hydro-geothermal HT-ATES + deep geothermal Petro-geothermal	Shallow to very deep	Qualitative and Quantitative
Land Use	European protected sites	European Environment Agency	Maps of protected sites in Europe: Natura 2000, Emerald sites and Nationally designated areas (CDDA)	CC BY 4.0	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
Land Use	Mining sites	PANGAEA	Polygons covering the extents of active mining sites worldwide	CC BY 4.0	Groundwater open loop system Borehole heat exchanger	Shallow to middle deep	Qualitative and Quantitative
Thermodynamic	Heat flow density	Zenodo	Areas in Europe where the Heat Flow Density is greater than 90 mW/m²	CC BY 4.0	Borehole Heat Exchanger HT-ATES + deep geothermal Petro-geothermal	Middle deep to very deep	Qualitative
Thermodynamic	Subsurface temperature	EAGE	3D temperature model of the European crust and sedimentary basins	Unknown	Hydro-geothermal HT-ATES + deep geothermal Petro-geothermal	Middle deep to very deep	Qualitative and Quantitative
Thermodynamic	Temperature isolines at depth	Zenodo	Pan-European dataset of subsurface temperature isolines at 1000 m and 2000 m depth	CC BY 4.0	Hydro-geothermal HT-ATES + deep geothermal Petro-geothermal	Middle deep to very deep	Qualitative and Quantitative
Thermodynamic	Temperature distribution at depth	Zenodo	Temperature distribution at depth in Europe, specifically areas with temperatures exceeding 50°C at 1000m depth and 90°C at 2000m depth	CC BY 4.0	Hydro-geothermal HT-ATES + deep geothermal Petro-geothermal	Deep to very deep	Qualitative and Quantitative

Data from the GeoDH project

The GeoDH (Geothermal District Heating) project, which concluded in 2014, promoted geothermal district heating systems in Europe by addressing barriers, raising awareness, and training stakeholders (http://geodh.eu/). Among all the data of the GeoDH project, SAPHEA collected and helped publish nine pan-European datasets. Those datasets are now publicly accessible on Zenodo through four data publications (Table 2, Figure 1).

Table 2: Details of the GeoDH project data published thanks to SAPHEA and available on Zenodo.

Type of data	Format	Description	File number	DOI
Cities using Geothermal and/or conventional District Heating	shp	Location of cities across Europe that use Geothermal and/or conventional District Heating.	2	10.5281/zenodo.14044090
Geological areas of interest for Geothermal District Heating	shp	Location of hot sedimentary aquifers and Neogene basins.	4	10.5281/zenodo.14044110
Heat flow density contours	shp	Areas where the heat flow density is greater than 90mW/m².	1	10.5281/zenodo.14044108
Temperature distribution at depth	shp	Areas with temperatures exceeding 50°C at 1000m depth and 90°C at 2000m depth.	2	10.5281/zenodo.14044103

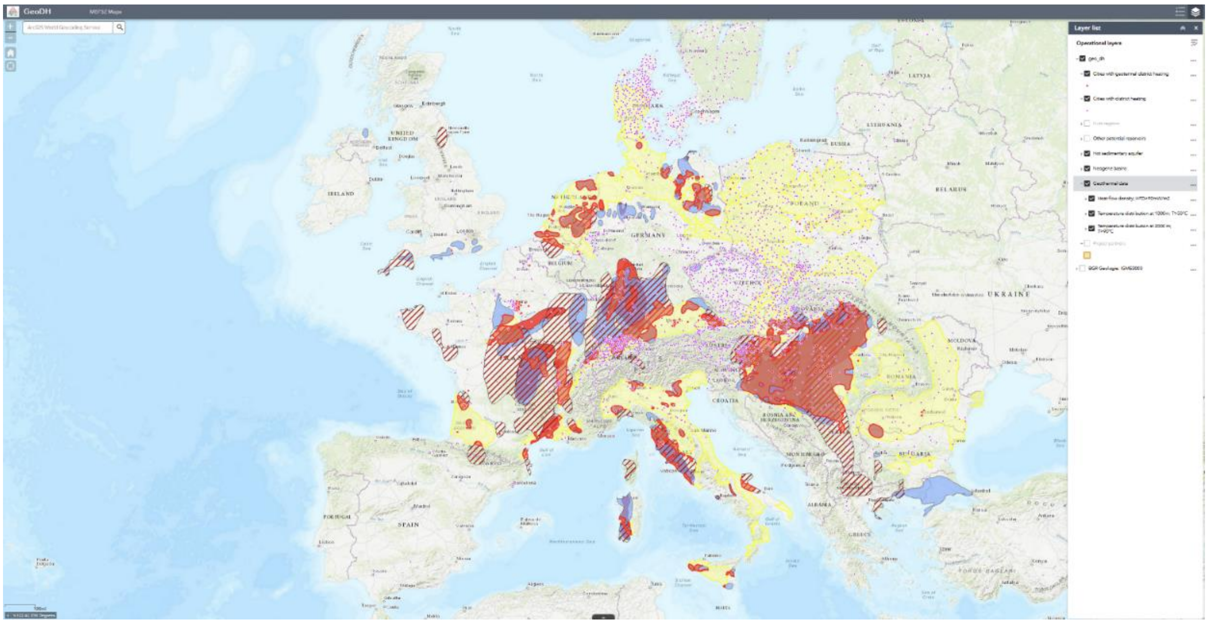


Figure 1: Map visualization of the GeoDH data.

Data from the Atlas of Geothermal Resources in Europe

The *Atlas of Geothermal Resources in Europe* (Hurter and Haenel, 2002) is a comprehensive resource funded by the European Commission, offering detailed maps and assessments of geothermal potential across European countries. Developed through collaboration among geothermal experts, it provides a unified view of Europe's geothermal resources, serving as a valuable tool for policymakers, researchers, and industry professionals. By identifying promising areas for geothermal exploration, the atlas supports the growth of sustainable energy sources, contributing to Europe's goals of expanding renewable energy use and reducing carbon emissions.

Among all the data of the *Atlas of Geothermal Resources in Europe*, SAPHEA collected and helped publish two pan-European datasets. Those datasets are now publicly accessible on Zenodo through one data publication (Table 3, Figure 2).

Table 3: Details of the data from the Atlas of Geothermal Resources in Europe published thanks to SAPHEA and available on Zenodo.

Type of data	Format	Description	File number	DOI
Temperature isolines at a certain depth	Geopackage	Digitizations of isotherms at 1000 meters and 2000 meters depth.	2	10.5281/zenodo.13799306

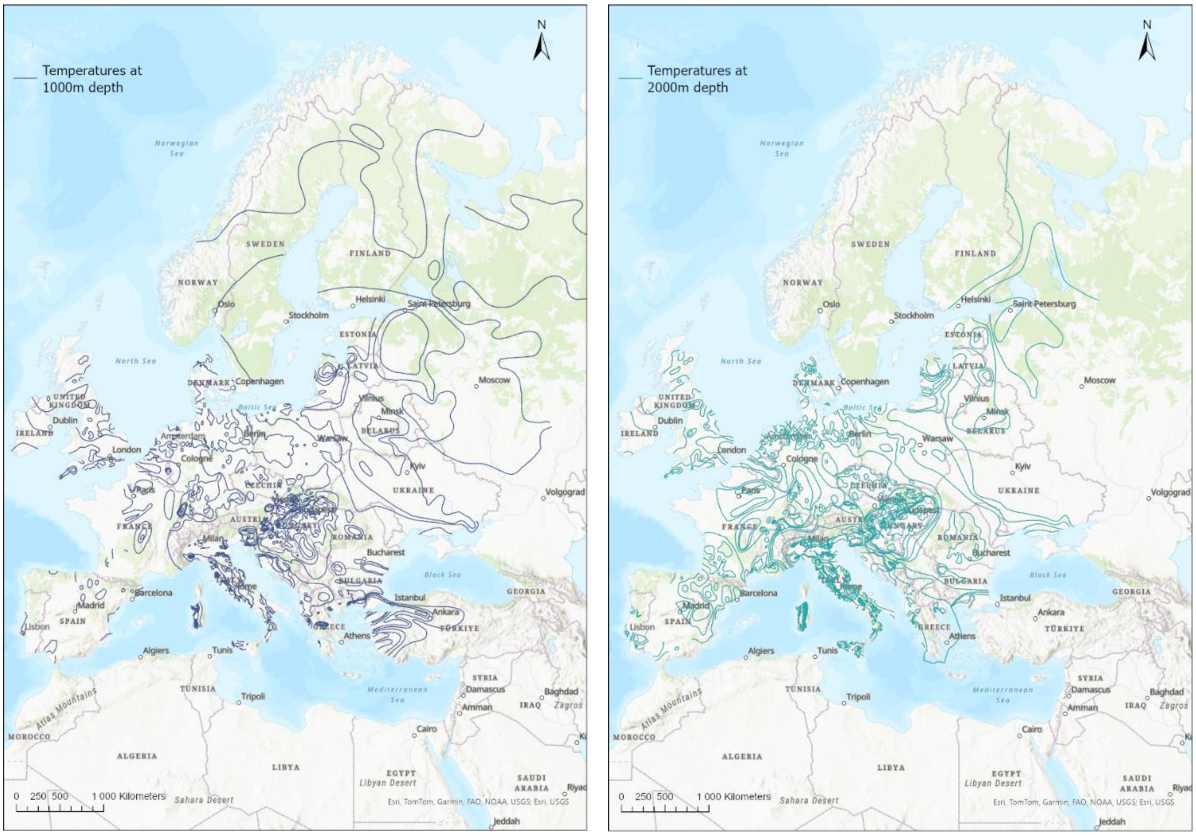


Figure 2: Map visualization of the data from the Atlas of Geothermal Resources in Europe.

2. Local and case study datasets

Alongside the collection of pan-European datasets, the team also worked on local data collection in collaboration with our partner countries. These local datasets are divided into two groups:

- Regional/Local data for the Graphical User Interface.
- Case study data to feed the techno-economic decision support tool: Geophires.

Regional/Local data by country for visualization

Germany

The local data from Germany used for visualization consists of 5 datasets from Bavaria (Table 4). An example is displayed in Figure 3 showing the discharge temperature distribution of the Malm-Reservoir.

Table 4: Data collected from Germany.

Type of data	Format	Resolution	Units	Description
Production Volume Flux zones	shp	-	l/s	Malm reservoir discharge values for probabilities p10, p25, p50, p75, p90 (https://zenodo.org/records/14004200)
Production Temperature distribution	tif	50x50	°C	Discharge temperature distribution of the Malm reservoir (https://zenodo.org/records/14003451)
Potential of groundwater heat pump use	tif	100x100 m	kW	Geological dataset providing energy potential data on shallow open-loop groundwater systems.
Potential of borehole heat exchanger use	tif	100x100 m	kW	Geological dataset providing energy potential data on shallow closed-loop systems (BHE).
Potential of horizontal collector use	tif	100x100 m	kW	Geological dataset providing energy potential data on shallow closed-loop systems (Horizontal Collectors).

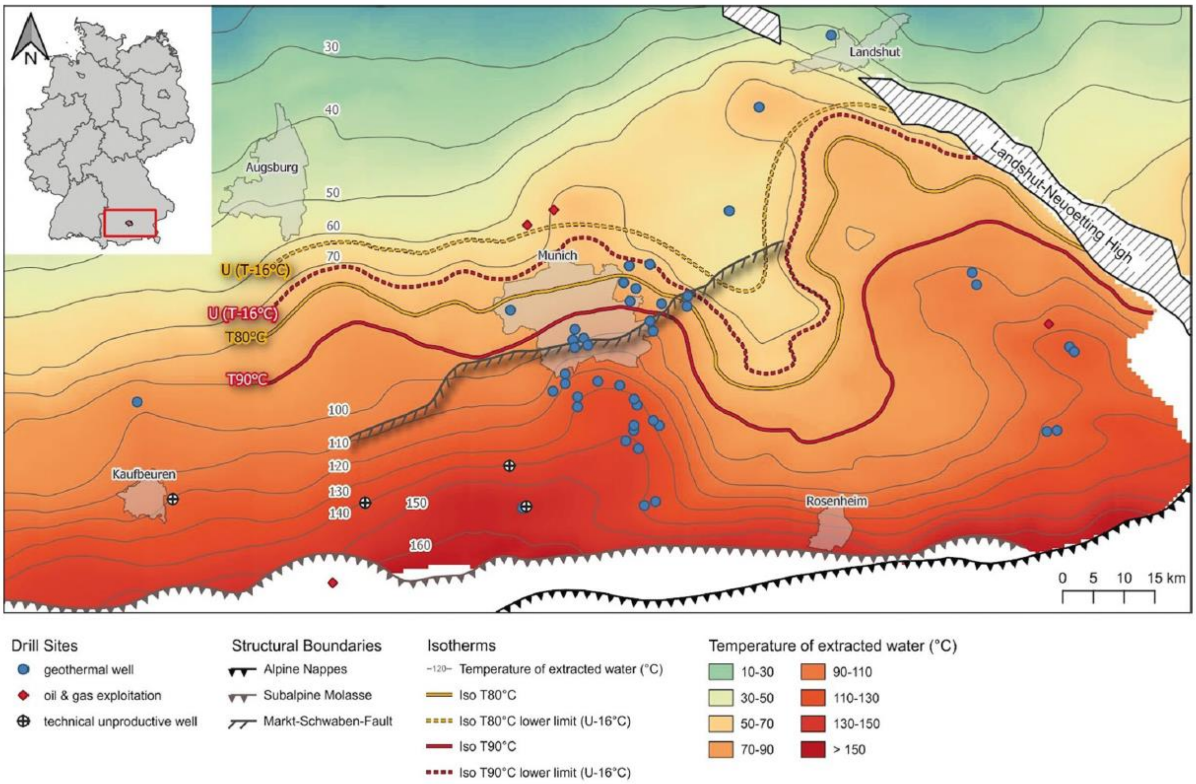


Figure 3: Discharge temperature distribution of the Malm reservoir.

Poland

The local data from Poland used for visualization consists of 22 datasets from Krakow (Table 5: Data collected from Poland). An example is displayed in Figure 4.

Table 5: Data collected from Poland (area of Krakow).

Type of data	Format	Resolution	Units	Description
Topographic map	raster		m a.s.l.	DEM model for Krakow area
Thermal conductivity	raster	50m	W/(m*K)	Average thermal conductivity over a range of up to 50 m
Thermal conductivity	raster	50m	W/(m*K)	Average thermal conductivity over a range of up to 100 m
Thermal conductivity	raster	50m	W/(m*K)	Average thermal conductivity over a range of up to 150 m
Thermal conductivity	raster	50m	W/(m*K)	Average thermal conductivity over a range of up to 200 m
Temperature map	raster	50m	°C	Average temperature up to 50 m
Temperature map	raster	50m	°C	Average temperature up to 100 m
Temperature map	raster	50m	°C	Average temperature up to 150 m
Temperature map	raster	50m	°C	Average temperature up to 200 m
Structural map	ASCII Grid (ZMap+)	250m	m a.s.l.	Structural map of the Upper Jurassic formation

Thickness map	ASCII Grid (ZMap+)	250m	M	Thickness map of the Upper Jurassic formation
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the top of the Upper Jurassic formation
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the base of the Upper Jurassic formation
Structural map	ASCII Grid (ZMap+)	250m	m a.s.l.	Structural map of the Lower Carboniferous & Upper Devonian formation
Thickness map	ASCII Grid (ZMap+)	250m	M	Thickness map of the Lower Carboniferous & Upper Devonian formation
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the top of the Lower Carboniferous & Upper Devonian formation
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the base of the Lower Carboniferous & Upper Devonian formation
Structural map	ASCII Grid (ZMap+)	250m	m a.s.l.	Structural map of the Lower Devonian formation
Thickness map	ASCII Grid (ZMap+)	250m	M	Thickness map of the Lower Devonian formation
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the top of the Lower Devonian formation
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the base of the Lower Devonian formation
Structural map	ASCII Grid (ZMap+)	250m	m a.s.l.	Structural map of the Cambrian & Precambrian (undivided) formation - the Basement
Temperature map	ASCII Grid (ZMap+)	250m	°C	Temperature map at the top of the Cambrian & Precambrian (undivided) formation - the Basement

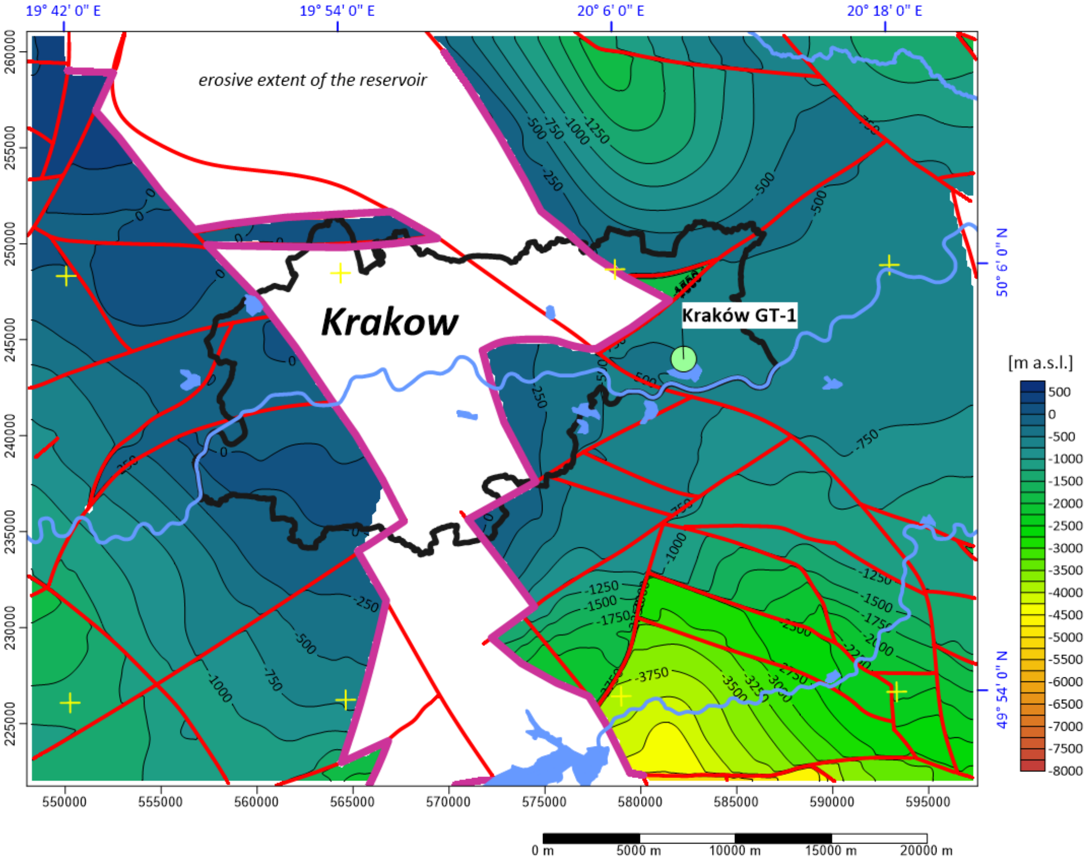


Figure 4: Structural map of the top of Lower Carboniferous & Upper Devonian (carbonates) - the potential geothermal reservoir in Krakow, along with the location of the planned Krakow GT-1 geothermal borehole (red lines – main faults).

Austria

The local data from Austria used for visualization consists of 8 datasets from across the country (Table 6). An example is displayed in Figure 5.

Table 6: Data collected from Austria.

Type of data	Format	Resolution	Units	Description
Geothermal reservoir polygons	shp			Contours of geological formations in which at least one borehole has proven the presence of thermal water and is suitable for geothermal energy
Reservoir temperature range	excel		°C	Temperature range of the geothermal reservoirs
Reservoir depth range	excel		m	Depth range of the geothermal reservoirs
Reservoir porosity	excel		%	Porosity range of the geothermal reservoirs
Reservoir permeability	excel		mD	Permeability range of the geothermal reservoirs
Reservoir salinity	excel		g/l	Fluid salinity range of the geothermal reservoirs
Reservoir transmissivity	excel		m²/s	Transmissivity range of the geothermal reservoirs
Reservoir hydraulic conductivity	excel		m/s	Hydraulic conductivity range of the geothermal reservoirs

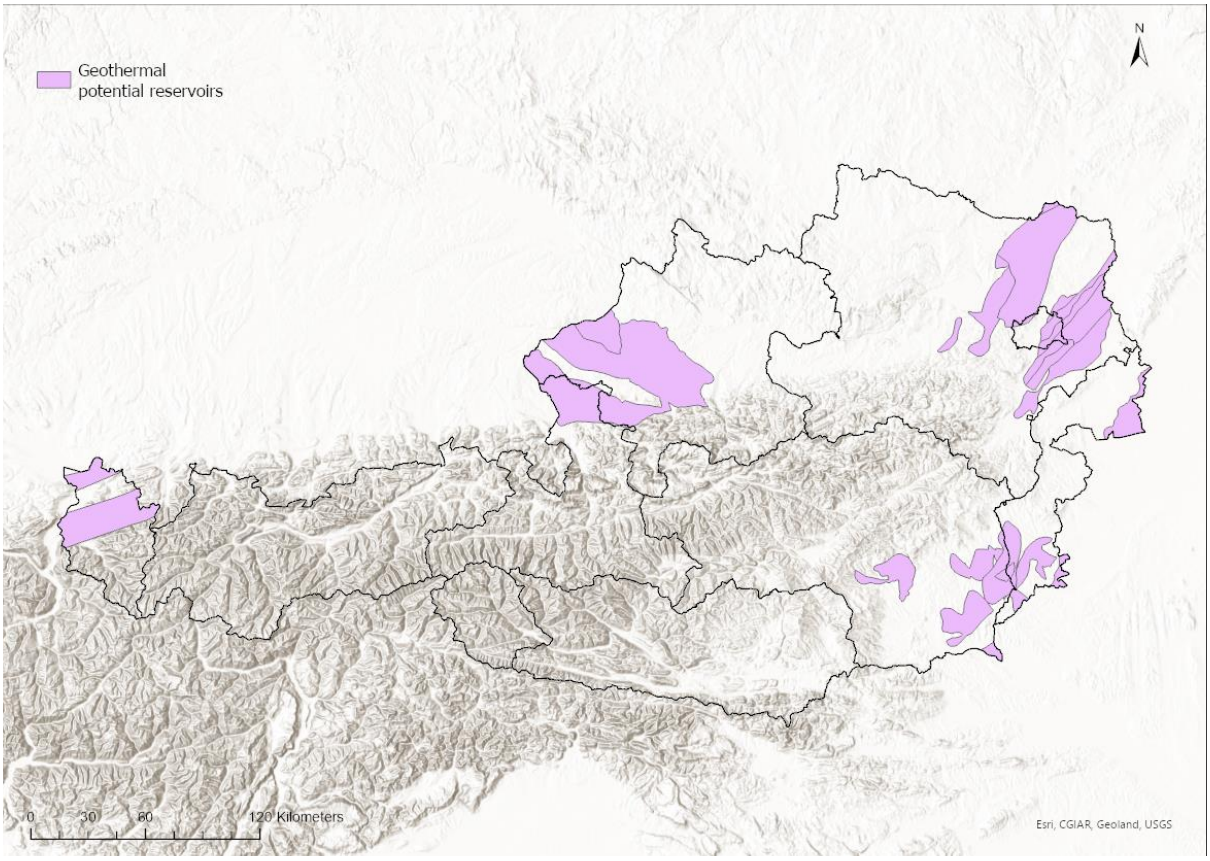


Figure 5: Contours of the geothermal potential reservoirs of Austria.

Case study data for Geophires

Six case studies have been selected across six different partner countries:

- Aarhus in Denmark
- Cornwall in the UK
- Krakow in Poland
- Nizza Montferrato in Italy
- Vienna in Austria
- Munich in Germany

For each of these case studies, the following parameters list was collected to feed the Geophires tool:

Main parameters:

- **Reservoir Depth**: Depth of the reservoir (unit: km)
- **Number of segments**: Number of segments from surface to reservoir depth with specific geothermal gradient (allowable values: [1, 2, 3, 4]).
- **Gradient 1**: Geothermal gradient in segment 1 (unit: °C/km)
- **Gradient 2**: Geothermal gradient in segment 2 (unit: °C/km)
  - It is possible to provide up to 4 different gradients
- **Thickness 1**: Thickness of segment 1 (unit: km)
- **Thickness 2**: Thickness of segment 2 (unit: km)
  - It is possible to provide up to three thicknesses (the last one will be calculated based on the reservoir depth)
- **Production Flow Rate per Well**: Geofluid flow rate per production well (unit: kg/s)
- **Injectivity Index**: Injectivity index is defined as the ratio of injection well flow rate over injection well outflow pressure drop (unit: kg/sec/bar)
- **Productivity Index**: The productivity index is defined as the ratio of production well flow rate over production well inflow pressure drop (unit: kg/sec/bar)
- **Injection Temperature**: Constant geofluid injection temperature at injection wellhead (unit: °C)
- **Utilization Factor**: Ratio of the time the plant is running in normal production in 1 year (allowable value range: [0.1,1])
- **Plant Lifetime**: System lifetime (unit: years)
- **Discount Rate**: Discount rate used in the Standard Levelized Cost Model (allowable value range: [0.1,1])

Other optional parameters:

- **Production Well Diameter**: Inner diameter of production wellbore (assumed constant along the wellbore) (unit: inches)
- **Injection Well Diameter**: Inner diameter of injection wellbore (assumed constant along the wellbore) (unit: inches)
- **Reservoir Volume**: Geothermal reservoir volume (unit: m^3)
- **Reservoir Density**: Constant and uniform reservoir density (unit: kg/m^3)
- **Reservoir Heat Capacity**: Constant and uniform reservoir heat capacity (unit: J/kg/K)
- **Reservoir Thermal Conductivity**: Constant and uniform reservoir thermal conductivity (unit: W/m/K)
- **Circulation Pump Efficiency**: Specify the overall efficiency of the injection and production well pumps (allowable value range: [0.1,1])
- **Surface Temperature**: Surface temperature used for calculating bottom-hole temperature (with geothermal gradient and reservoir depth) (unit: °C)

- **Ambient Temperature**: Ambient (or dead-state) temperature used for calculating power plant utilisation efficiency (unit: °C)
- **End-Use Efficiency Factor**: End-Use Efficiency Factor (allowable value range: [0.1,1])
- **Electricity Rate**: Price of electricity to calculate pumping costs (unit: €/kWh)
- **Cost Adjustment Factors**: Multipliers can be used to adjust the built-in cost calculations, with an allowable value range of [0, 10]. Separate adjustment factors can be applied to all the cost categories listed below. It is recommended to provide these factors after receiving the initial results. Additionally, you can supply absolute cost values for the categories mentioned below, which allows you to bypass the model's cost calculation and the adjustment factors for those specific categories.
- **Reservoir Stimulation Capital Cost**: Total reservoir stimulation capital cost (unit: M€/year)
- **Surface Plant Capital Cost**: Total surface plant capital cost (unit: M€/year)
- **Field Gathering System Capital Cost**: Total field gathering system capital cost (unit: M€/year)
- **Exploration Capital Cost**: Total exploration capital cost (unit: M€/year)
- **Wellfield O&M Cost**: Total annual wellfield O&M cost (unit: M€/year)
- **Surface Plant O&M Cost**: Total annual surface plant O&M cost (unit: M€/year)
- **Water Cost**: Total annual make-up water cost (unit: M€/year)

Due to publication restrictions, specific values for each country's parameters are not included here. However, you can request the parameter list for a specific country by directly contacting the individual responsible for the case study.

Methodology for Geothermal Scenario Assessment

Parameters and information needed for a geothermal energy feasibility study or potential assessment linked to defined Scenarios (in D2.2)

In this description, the main task is to support the assessment of the heat resource potential. Therefore, the difference in the scenarios regarding the grids (mainly their operation temperature) is only of minor importance. Due to this, the scenarios are here summarized regarding their similar underground source type:

(1) groundwater with lower temperatures – shallow aquifers

(2) conventional borehole heat exchanger – shallow to middle deep underground

(3) groundwater/fluids with higher temperature - deeper aquifers

(4) high-temperature Aquifer Thermal Energy Storage – middle deep underground

(5) advanced/enhanced geothermal systems – deeper underground

In each of the five categories, the information and parameters for a feasibility and potential assessment are mostly equal, and methodologies to conduct the assessment are similar.

An assessment of geothermal energy potential or pre-feasibility can be categorized in different ways due to their levels of detail. The most significant difference is between a qualitative and quantitative assessment. Qualitative assessments mainly show if the underground is suitable for the use of geothermal energy regarding a specific geothermal technology (displayed here as the scenarios in the catalogue). They give “only” coarse information on the suitability and can be used as a proxy for energy planning. The qualitative assessment shows how many areas are suitable for geothermal energy and can therefore contribute to the development of energy strategies on a broader scale. At a regional or local level, for instance, in municipalities, the heat energy transition is practically conducted. This is where real actions and measures are implemented due to comprehensive heat energy planning. Therefore, a potential assessment should be conducted quantitatively to show how much heat energy demand can be met by geothermal energy and to compare the energy provided by geothermal sources with the potential of other heat technologies. For a quantitative assessment, much more detailed information is mandatory, ideally at a fine scale, although theoretically, it can also be conducted on a large scale. However, depending on the resolution of the datasets used, the significance of the derived values must be carefully evaluated. Nevertheless, within the framework of an assessment using available (open-access) datasets on a pan-European scale, a quantitative assessment is not feasible due to coarse-scale information. Even a qualitative assessment requires careful validation.

In the presented description of information and parameters needed for geothermal energy potential assessments, respectively pre-feasibility studies, the information/parameters are classified due to the minimum information that is needed for a **qualitative assessment (QL)** and/or a **quantitative assessment (QN).**

For all scenario sets, restricted areas must be considered that limit the spatial potential. Therefore, special areas, like protected areas or natural risk zones, should be checked for an assessment. They usually have specific individual regulations defined by ordinance, decree, or other legal instruments. In the INTERREG GRETA project (D2.3.1) the zones were grouped into four sources of regulations. It is appropriate to check whether these regulations preclude drilling, excavating, reinjecting, or other operations required for geothermal energy (Table 7).

Table 7: General example of cross-connections between special areas and different sectors. Ten special areas are identified in 4 different sectors' documents in this example. More cross-connections can be found. (Source: Greta project D 2.3.1).

	Special areas	Source of regulations
1.	Drinking water protection areas	I. Regulations for the protection areas of water resources intended for human consumption
2.	Riparian, waterside and coastal land	II. Regulations of the water management and management schemes & Objectives and provisions of the water management plans
3.	Nature protected areas for water dependent ecosystems	
4.	Contaminated areas	
5.	Protection areas of other water uses (mineral, thermal, process water,…)	
6.	Areas of interaction with other installations and water rights	
7.	Areas of permanent or temporary impact on water regime or status	
8.	Flood and erosion areas	III. Natural hazard prevention plans / natural risk zones
9.	Landslide areas	
10.	Areas designated for underground storage facilities for gas, oil or chemicals,…	IV. Mining rights, mineral resources management plans

These restricted areas must be excluded from the assessed geothermal energy potential, depending on the data availability and provided knowledge.

Based on the defined scenario sets above the information/parameters for geothermal potential assessment are described in the following.

Scenario Set 1

B 01 Shallow geothermal & Free cooling - DC Network (aquifer)
B 02 Groundwater + decentral LTHP - LT Network
B 05 Groundwater + central HP - MT/HT Network
C 01 Basic + LT ATES + LT/MTHP- LT/MT Network

The first set of scenarios focuses on the thermal use of groundwater through open-loop systems in shallower aquifers. To conduct a feasibility analysis, it is essential to provide a detailed description of the aquifer used as a heat source. First, we need to assess the usable volume of the aquifer, which includes the spatial extent and thickness of the aquifer, as well as its hydraulic properties. Additionally, information regarding groundwater temperature and hydrochemistry is also vital. Important parameters for the assessment are summarized in Table 8.

Table 8: Information and parameter description needed for geothermal energy potential assessment and pre-feasibility analysis for scenario set 1.

Information/ Parameter	Unit	Description	Classification of Assessment
Spatial Extent of the Aquifer (SEA)	-	Practically, hydrogeological boundaries define the spatial extent of an aquifer. This means that the regarded geological horizon must have a reasonable hydraulic conductivity, and the boundaries of such aquifer are generally defined by less permeable geological conditions. Due to the permeability/hydraulic conductivity geological horizons are classified into aquifers (high hydraulic conductivity) and aquitards (low hydraulic conductivity). According to DIN 18130-1 (applies to unconsolidated rock), a possible limit value between low conductive and high conductive geological horizons would be approximately 10^{-6} m/s. All classified aquifers have a theoretical geothermal energy potential for scenario set 1, despite there being significant differences in the permeability.	QL/QN
Depth to the Aquifer (DtA)	[m]	The depth from the surface to the aquifer generally determines whether the aquifer is classified as a shallow aquifer or a middle deep to deep aquifer. In the scenario set 1, only shallow aquifers are considered, but there is no universally agreed-upon definition of "shallow." Shallow geothermal systems are typically defined to a depth of 400 meters below the surface, but in practice, shallow aquifers used for thermal purposes are usually not deeper than about 60 to 100 meters. It is important to note that there is a gradual transition between shallow and middle-deep aquifers. It is also advisable to consider the groundwater temperature of the aquifer in this	QL/QN

		context. The scenario set 1 is designed for lower source temperatures (< 30°C), which are associated with shallow depths. The Depth to Aquifer (DtA) is also crucial in determining the depth required for drilling a well. This can be used in quantitative potential assessments. For this aspect see also the description of the Groundwater Table Distance to the Surface (GTDtS).	
Aquifer Thickness (AT)	[m]	The aquifer thickness is defined as the thickness of the geological horizon designated as the aquifer (see above). It is determined by the top and bottom boundaries of this geological horizon. The overlying and underlying horizons typically have significantly lower permeability (caprock).	QL/QN
Saturated Aquifer Thickness (SAT) - Groundwater Table	[m] - [m a.SL]	The Saturated Aquifer Thickness is defined by the AT but is limited to the part, which is filled with groundwater. Hence, the thickness of the unsaturated zone within the aquifer is subtracted from AT. Therefore, information about the groundwater table level is necessary. SAT is mainly of interest to shallow aquifers because many of them are unconfined. It must be considered that the groundwater table is a dynamic parameter and can significantly fluctuate over time, especially in shallow aquifers. Hence, the SAT can be just used as an average value or minimum /maximum value. In the case of confined aquifers, the SAT is equal to the AT.	QN
Groundwater Table Distance to the Surface (GTDtS)	[m]	Generally, the distance of the groundwater table to the surface defines how deep you must minimally drill for a well. In confined aquifers, this is equal to DtA. A high GTDtS can cause higher drilling costs. Depending on the size of the system, this can lead to economically unfavourable conditions for the implementation. The knowledge about GTDtS is also of importance for a detailed quantitative potential assessment integrating technical/regulation issues. Because by the injection in an open loop system, an impounding at the injection well must be considered. In the case of a small GTDtS, the impounding can lead to flooding or can negatively impact buildings and is regulated by water administration. Furthermore, it is essential to take artesian conditions into account. This may influence the assessment of geothermal potential, impact safe drilling conditions, and further maintenance of the installation, including injection pressure, etc.	QN
Hydraulic Conductivity/Permeability (HC/P)	[m/s]/ [m^2]	The hydraulic conductivity/permeability is a sensitive parameter defining the aquifer productivity and is mandatory for a QN assessment. HC/P defines if a geological horizon is defined as an aquifer (see description SEA). As the HC/P is a sensitive parameter, a detailed QN assessment must have high-resolution information.	QN

Hydraulic Gradient (HG)	[%]	The hydraulic gradient contributes (among AT and HC/P) to the groundwater velocity. The parameter is used in some QN potential assessment methodologies.	QN
Hydrochemical Conditions (HChem)	e.g. [mg/l]	Knowledge about the hydrochemical conditions is crucial due to some negative effects on open loop systems e.g. clogging and corrosion. Particularly thresholds for iron and manganese as well as oxygen are important to assess to interpret the suitability of an aquifer for geothermal energy open loop systems. It is worth noticing that water treatment options exist to install also successful operations in harsh hydrochemical conditions. However, these systems are not very common and increase the installation cost significantly, hence, they are mostly used for larger systems.	QL/QN
Groundwater temperature (GT)	[°C]	The groundwater temperature is needed to assess the efficiency of an open loop system. Hence, it is not crucial for a general QL assessment but beneficial for a QN assessment. However, some thresholds are important for the potential assessment. In the case of using groundwater for cooling the temperature for the warmer injection into the aquifer is mostly regulated, resp. Limited by the water authority. Therefore, the knowledge of maximum allowed injection temperatures in the regarded area along with the in-situ groundwater temperature is necessary to assess the suitability for cooling systems. The minimum groundwater temperature can be also a technical limit for the utilization of open-loop systems for heating.	QN
Restricted Areas (RA)	[m^2]	Mainly due to regulations and risk prevention, geothermal energy implementations are restricted in specific areas. Table 7 shows exemplarily such areas. Generally, the information about these areas is provided by the administration at different levels. The main specific areas are water protection zones, contaminated sites, natural hazard zones (landslides, flood areas), geological risk zones (karstic areas, artesian areas), etc. Some of this information, like water protection zones, should be used for a QL assessment if the data is available. For a QN assessment, the restricted areas should be considered as detailed as possible, especially on a regional and local scale.	QL/QN

Methodology to assess the potential of Scenario Set 1

Qualitative

Minimal information for a basic QL assessment should be the SEA (assuming that the definition of "aquifer" includes favourable hydraulic conditions), average AT, and DtA. Additionally, Restricted Areas (RA) should be identified. It would be beneficial if also the hydrochemistry conditions were known.

These parameters can be determined using publicly available maps and data on local hydrogeological conditions. On an ideal basis, this information has already been analyzed and compiled in an accessible data set or map. One example on a regional scale is the potential map of the Bavarian Environment Agency (Bayerisches Landesamt für Umwelt -LfU, 2024: https://www.karten.energieatlas.bayern.de), which shows the general suitable areas for the use of shallow geothermal open loop systems in quaternary horizons (Figure 6). As described in the next paragraph, these designated areas have already been analyzed for suitability using quantitative parameters.

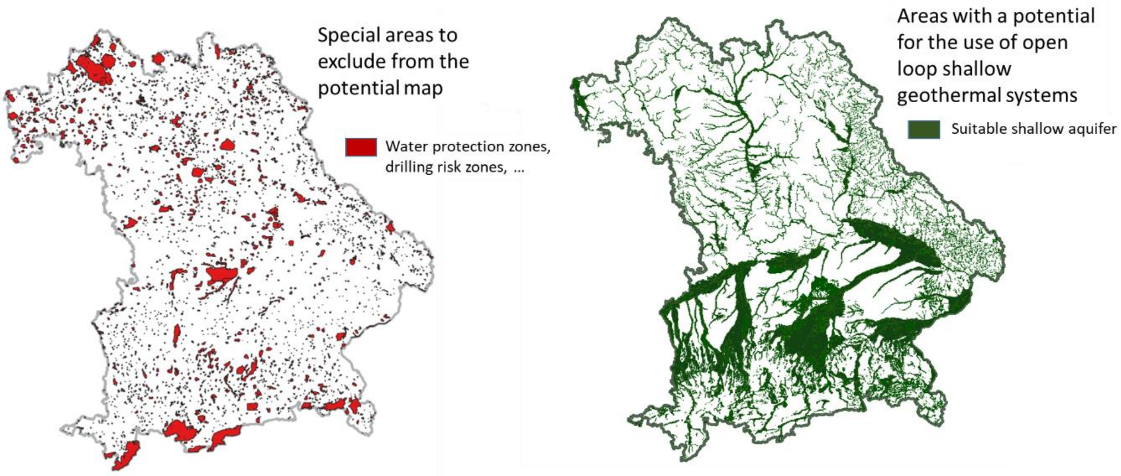


Figure 6: Map of special areas, which must be excluded from the potential map (left) and suitable areas for the use of shallow groundwater systems (right) (Bayerisches Landesamt für Umwelt (2024)).

Quantitative

For a QN assessment based on the methodology used for the potential quantification, several more parameters must be included.

One example of those methodologies is the TAP method (Boettcher et al., 2019). Here, the parameters SEA, SAT, GTDtS, HC, HG, and RA are used. Additionally, technical parameters are predefined, like the distance between production and injection well (here 10 m for small systems and 100 m for large systems) to avoid thermal interaction between the wells. This distinction (small and large distance between the wells) is necessary because the quantified shallow geothermal potential is dependent on the volume flux you can produce out of an aquifer and inject it back without a thermal breakthrough. If the distance between the wells is large more groundwater can circulate without a thermal breakthrough resulting in a higher potential at one location. Besides the pumping rate, the thermal breakthrough is dependent on the hydraulic parameters of HC, HG, and AT. Additionally, regulations from the water authority are considered. Therefore, the water table at the injection well must be more than half a meter below the surface to avoid flooding (GTDtS necessary) and the withdrawal at the production well should decrease the water table by only about 1/3 of the AT. With this method, the technical volume flux production rate of an aquifer is calculated (Figure 7). Using this information, you can further calculate the geothermal potential by adding the common temperature spreading considering GT. Below there is a practice example for this QN-assessment method for the Munich case study (Figure 8).

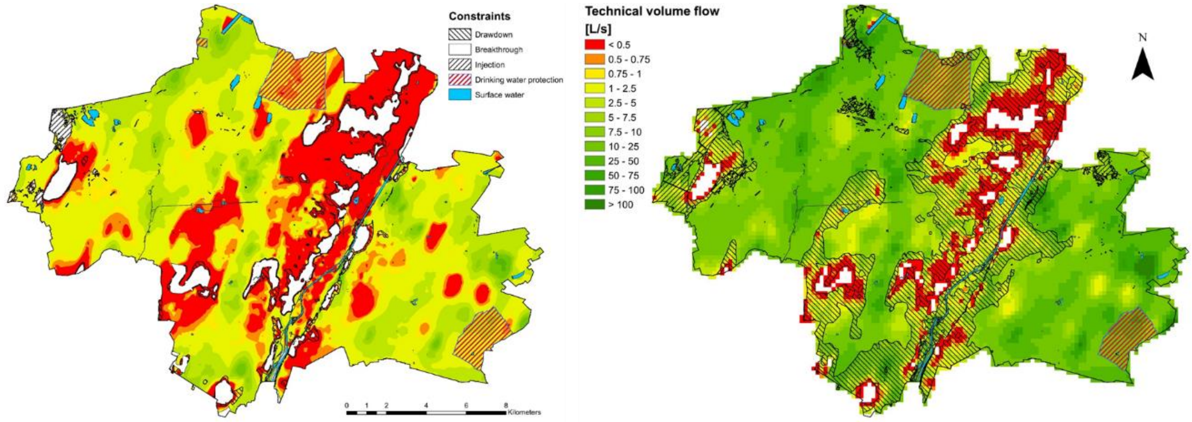


Figure 7: Example of a QN assessment for scenario set 1 using the TAP methodology in the Munich case study. Left: Technical volume flux production rate for good doublets with a 10 m distance (small systems); right: Technical volume flux production rate for good doublets with a 100 m distance (large systems) (Boettcher et al. 2019).

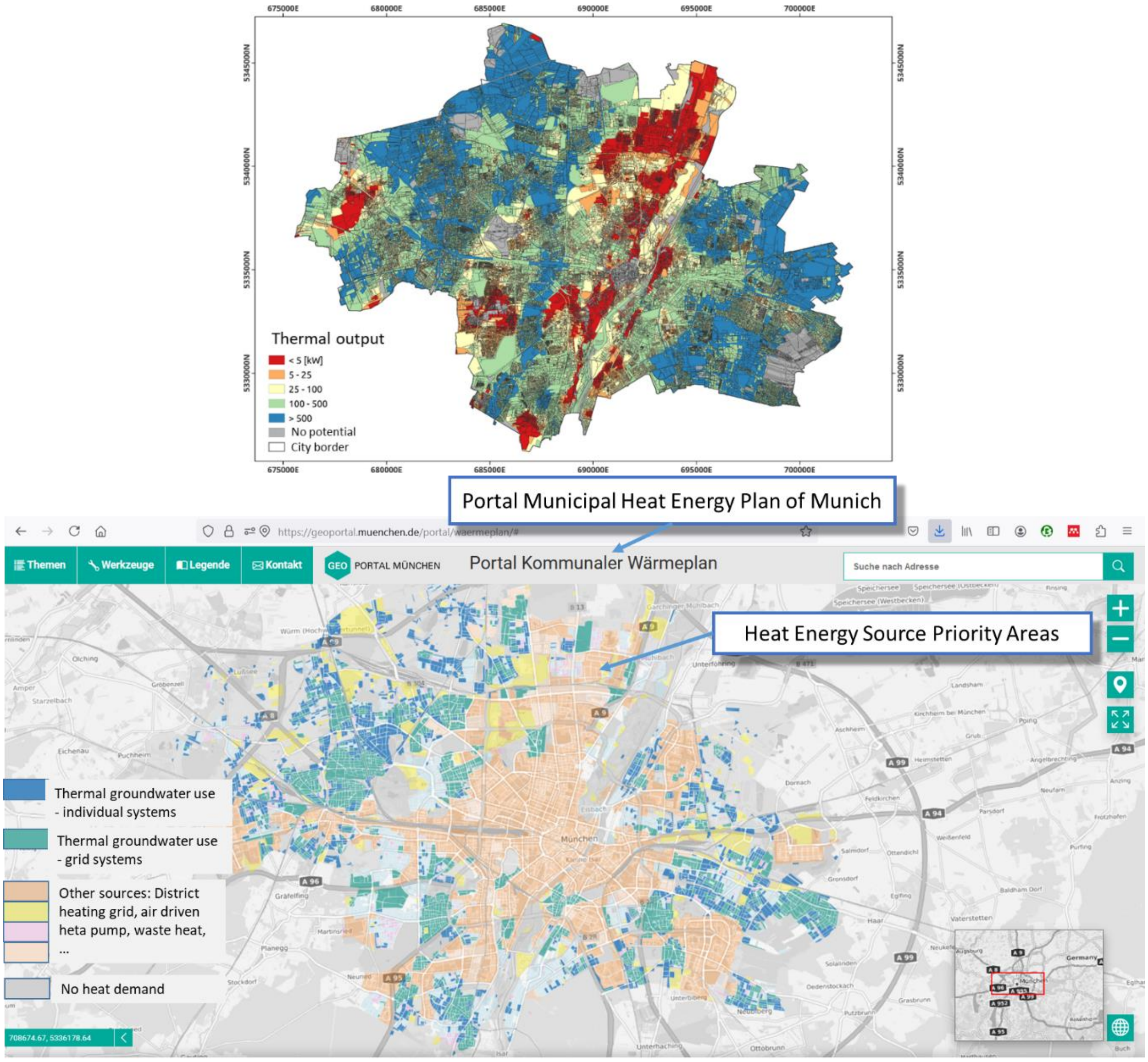
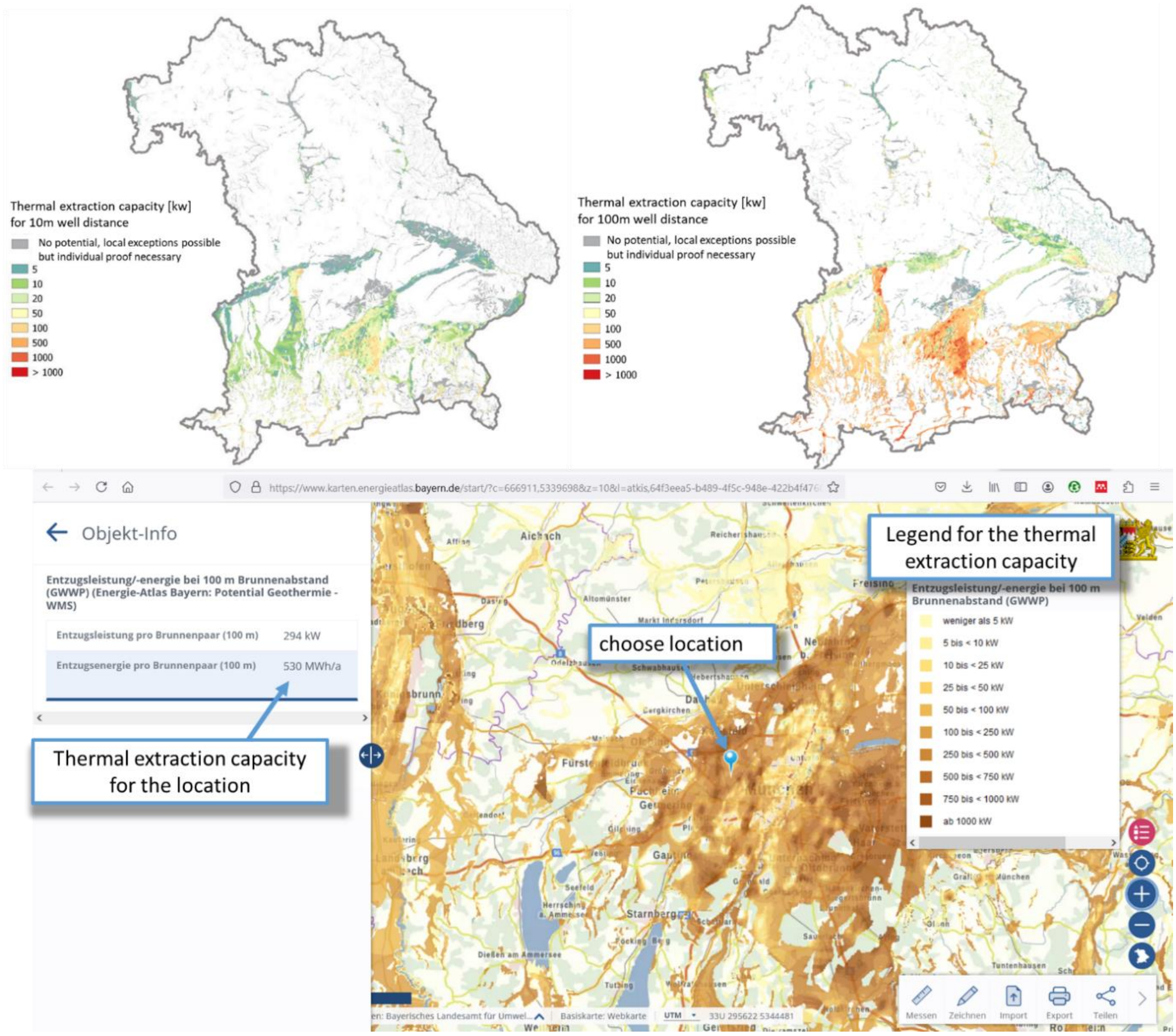


Figure 8: Top: QN assessment in the Munich case study for scenario set 1 regarding the thermal use of groundwater for heating. Here, the good doublet distance is set to a possible maximum at an available parcel (Boettcher et al. 2019); Bottom: Integration of the potential assessment into the municipal heat energy plan (https://geoportal.muenchen.de/portal/waermeplan/).

As seen in Figure 9, the TAP methodology has furthermore been expanded to a broader scale compromising the State of Bavaria through the “Energieatlas Bayern” (Energy Atlas Bavaria: https://www.karten.energieatlas.bayern.de) giving a basis for qualitative and also first quantitative assessment.



Entzugsleistung/-energie bei 100 m Brunnenabstand (GWWP) (Energie-Atlas Bayern: Potential Geothermie - WMS)

Entzugsleistung pro Brunnenpaar (100 m)	294 kW
Entzugsenergie pro Brunnenpaar (100 m)	530 MWh/a

Figure 9: Bavaria-wide extraction capacity [kW] for groundwater heat pumps. Top left: Well spacing 10m, top right: well spacing 100m, bottom: individual information for a specific location using the web portal (Bayerisches Landesamt für Umwelt, 2024, https://www.karten.energieatlas.bayern.de).

Available Information/Data on the European Level for an Assessment of Scenario Set 1

The quantity and quality of data for the quantitative assessment of shallow open-loop systems are generally considered to be high. The expertise lies primarily within the regional (water) authorities. Some of this data is available at larger scales in Europe, some of higher quality, some of lower quality. To consolidate the data for a quantitative assessment on a pan-European scale, analogous to Energieatlas Bayern, much more regional data of higher quality is needed. Currently, accessible pan-European data usable for assessments of shallow open loop systems are listed in Table 9.

Data is widely available for SEA, DtA, AT, and SAT through publicly accessible EGDI (European Geological Data Infrastructure) and BGR (Bundesanstalt für Geowissenschaften und Rohstoffe, Germany) databases. Including information on RA, available and accessible through up to six different databases, a fully qualitative assessment is possible without taking hydrochemical conditions (HChem) into account. Data on HC/P can be used and respectively calculated through two publicly accessible datasets. For GTDtS, HG, and GT no direct pan-European data is available. However, HG can be interpolated through available elevation models including local information on GH and GTDtS. Overall, much more high-quality regional data is needed for a detailed quantitative analysis.

Table 9: Publicly accessible pan-European datasets for potential assessment of scenario set 1.

Dataset	URL	Scenario parameter	Suitable for assessment
International Hydrogeological Map of Europe (IHME) BGR, aquifer types	BGR - Projects - IHME1500 - International Hydrogeological Map of Europe 1:1,500,000	SEA	QL
European Geothermal Database Infrastructure (EGDI), aquifer types	EGDI (v1.6)	SEA	QL/QN
European Geothermal Database Infrastructure (EGDI), groundwater storage	EGDI (v1.6)	SEA, SAT, AT	QL/QN
European Geothermal Database Infrastructure (EGDI), thickness of the saturated layer	EGDI (v1.6)	SAT	QL/QN
European Geothermal Database Infrastructure (EGDI), Depth of Aquifer	EGDI (v1.6)	DtA	QL/QN
Global Hydrogeology MaPS 2.0 (GLHYMPS 2.0) global permeability of unconsolidated and consolidated Earth	https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU	HC/P	QN
European Geothermal Database Infrastructure (EGDI), transmissivity of prime aquifers	EGDI (v1.6)	HC/P	QN
PANGAEA database, Global-scale mining areas	https://doi.pangaea.de/10.1594/PANGAEA.910894	RA	QL/QN
Surface water map	https://global-surface-water.appspot.com/download	RA	QL/QN
ESDAC database, landslide map	https://esdac.jrc.ec.europa.eu/content/european-landslide-susceptibility-map-elsus-v2	RA	QL/QN
EFEHR database, Earthquake risk	https://eu-risk.eucentre.it/	RA	QL/QN

European Environment Agency (EEA) database, European protected sites	https://www.eea.europa.eu/en/analysis/maps-and-charts/european-protected-areas-1	RA	QL/QN
EEA database, Nature reserve	https://www.eea.europa.eu/data-and-maps/explore-interactive-maps/european-protected-areas-1	RA	QL/QN

Scenario Set 2

B 06 BHE + central HTHP/BTES
B 07 BHE + decentralized LTHP - LT Network- MT/HT Network

Scenario set 2 represents the use of borehole heat exchangers for shallow and middle-deep installations. For the assessment of a potential or feasibility analysis, the underground conditions such as thermal conductivity and underground temperature for the relevant drillable geological horizons are important. Important parameters for a potential assessment are described in Table 10.

Table 10: Information and parameter description needed for geothermal energy potential assessment and pre-feasibility analysis for scenario set 2.

Information/ Parameter	Unit	Further Description	Classification of assessment
Geological Horizons (GH)	-	Practically, knowledge of the geological horizons for the definition of TC and HCap as well as hydrogeological boundaries defines the spatial extent of potential aquifers (SEA).	QL
Thermal Conductivity (TC)	[W/mK]	Thermal Conductivity is a key parameter for closed-loop systems and the extractable energy from the underground. The TC is rock-specific and depends on the water saturation of the rocks (see description of SAT and GTL). Data for TC can be derived from rock measurements and literature data and can be linked to GH. Geological surveys/environmental agencies often provide spatially distributed information for the thermal conductivity of specific rock types on regional/local levels. This parameter is crucial for QL and QN assessment.	QL/QN
Heat Capacity (HCap)	[J/m³K]	Heat capacity is a crucial parameter to evaluate thermal storage potential such as BTES. HCap is rock specific and depends on the water saturation since water has significant HCap (4.2 MJ/m³K) compared to air (1 kJ/m³K) and solid particles (2 MJ/m³K). For a QN assessment of BTES, this parameter is crucial.	QN
Geological Horizon Thickness (GHT)	[m]	The thickness of the GH is used to estimate the integrated, averaged TC over the depth. For instance, to estimate a depth-dependent TC for a specific drilling depth, GHT and TC of the specific GH are necessary. For a QN assessment, this information is recommended.	QN
Groundwater Table Distance to the Surface (GTDtS)	[m] - [m a.SL]	The groundwater table level helps distinguish between unsaturated and saturated zones underground. Understanding the saturated zone is crucial for scenario set 2 for two main reasons: it typically has higher thermal conductivity (TC) due to water-filled pores, and the convection process in aquifers can improve borehole heat exchanger efficiency. To assess these potential benefits, it's important to know the groundwater table level, referred to as the SAT (see the SAT description for scenario set 1), and to have information about the local aquifers.	QN

Underground Temperature (T)/ Temperature Gradient (TG)	[°C] [K/m]	The temperature of the underground is an essential parameter to estimate the efficiency of a borehole heat exchanger and is mandatory for a QN assessment. Geological surveys or Environmental Agencies often provide information about the underground temperature or a temperature gradient on a regional/local scale. For a rough estimation, also an average temperature gradient can be used. For shallow boreholes (e.g. < 150 m) normally a single value of undisturbed subsurface ground temperature is used.	QL/QN
Hydraulic Gradient (HG)	[%]	The hydraulic gradient contributes to the groundwater velocity and flow direction, which controls the thermal recovery of BTES systems. For a QN assessment of BTES, this parameter is crucial.	QN
Hydraulic Conductivity/Permeability (HC/P)	[m/s]/ [m2]	The hydraulic conductivity/permeability is a sensitive parameter defining the aquifer productivity and is mandatory for a QN assessment of both BHE and BTES. It is crucial for a detailed QN assessment.	QN
Restricted Areas (RA)	[m^2]	Mainly due to regulations and risk prevention, geothermal energy implementations are restricted in specific areas. Table 7 shows exemplarily such areas. Generally, the information about these areas is provided by the administration at different levels. The main specific areas are water protection zones, contaminated sites, natural hazard zones (landslides, flood areas), geological risk zones (karstic areas, artesian areas), etc. Some of this information, like water protection zones, should be used for a QL assessment if the data is available. For a QN assessment, the restricted areas should be considered as detailed as possible, especially on a regional and local scale.	QL/QN

Methodology to assess the potential of Scenario Set 2

Qualitative

Minimal information for a basic QL assessment should be the GH, average subsurface temperature T, and average thermal conductivity TC. Additionally, Restricted Areas should be identified. It would be beneficial if also the hydrogeological conditions were known for better estimation of BTES potential.

A designation of potential areas for the usage of shallow BHE is currently being developed in the “WärmeGut” project, a geothermal energy campaign funded by the Federal Ministry of Economics and Climate Protection (BMWK), to tap the potential of shallow geothermal energy. With the involvement of the state geological services of Germany, data gaps will be closed through extensive data processing to provide uniform traffic light maps for possible area restrictions on the usage of shallow geothermal BHE throughout Germany. These maps will be publicly accessible through GeotIS (geothermal information system for Germany: https://www.geotis.de), developed by the Leibniz Institute for Applied Geophysics (LIAG), and will give a basis for a qualitative area assessment of shallow BHE (Figure 10).

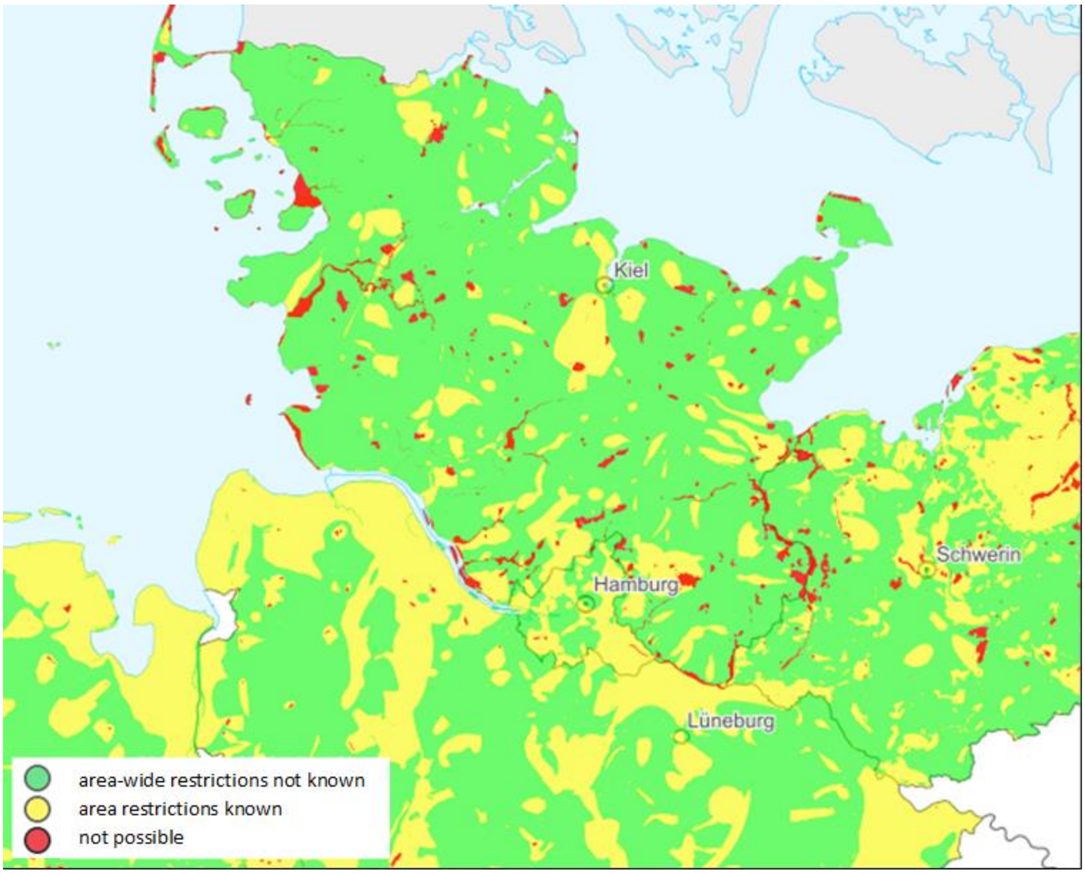
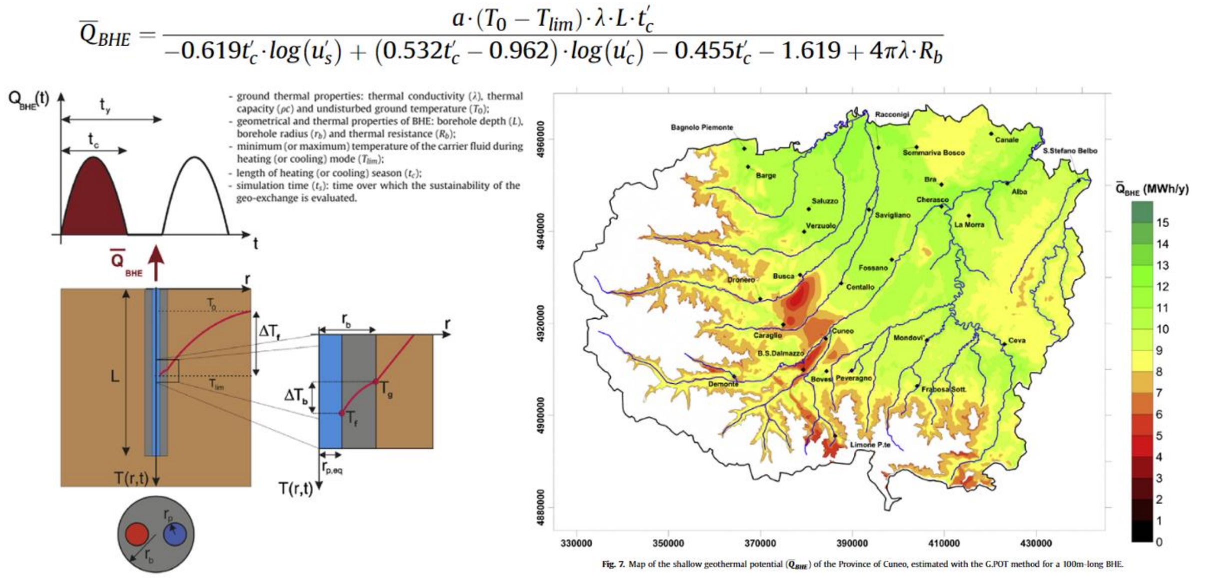


Figure 10: Traffic light map of northern Germany regarding the possible usage of shallow BHE (changed after GeotIS, 2024: https://www.geotis.de).

Quantitative

For a QN assessment, several more parameters must be included.

One example of these methodologies is the G.POT methodology (Casasso and Sethi, 2016), aiming to define the amount of extractable energy of a 100-m borehole heat exchanger drilled in the Cuneo Province (NW Italy). Here, the geological parameters GH, T, and TC are used together with engineering data such as BHE configuration and depth, borehole thermal resistance, and heating season length (Figure 11). Other parameters such as GHT, GTL, HG, HC, and HCap are important for more in-depth BHE calculation and BTES potential evaluation. Other methodologies are described and discussed in Bayer et al. (2019).



$$\overline{Q}_{BHE} = \frac{a \cdot (T_0 - T_{lim}) \cdot \lambda \cdot L \cdot t'_c}{-0.619t'_c \cdot log(u'_s) + (0.532t'_c - 0.962) \cdot log(u'_c) - 0.455t'_c - 1.619 + 4\pi\lambda \cdot R_b}$$

- ground thermal properties: thermal conductivity (λ), thermal capacity (ρc) and undisturbed ground temperature (T_0);
- geometrical and thermal properties of BHE: borehole depth (L), borehole radius (r_b) and thermal resistance (R_b);
- minimum (or maximum) temperature of the carrier fluid during heating (or cooling) mode (T_{lim});
- length of heating (or cooling) season (t_c);
- simulation time (t_s): time over which the sustainability of the geo-exchange is evaluated.

Fig. 7. Map of the shallow geothermal potential ($\overline{Q}_{BHE}$) of the Province of Cuneo, estimated with the G.POT method for a 100m-long BHE.

Figure 11: QN assessment in the Cuneo Province (NW Italy) as an example for scenario set 2 regarding BHE. The result is an amount of annual extractable thermal energy (MWh/y) by a 100-m BHE.

Another example is VDI 4640, a guideline from the Association of German Engineers (VDI, 2010) that addresses the thermal use of the subsurface, particularly shallow closed systems. VDI 4640 serves as a fundamental method for estimating the quantitative potential in the initial planning phase. First, GH, GHT, GTL, and thermal properties of the subsurface TC and HCap, are determined. In addition to geological parameters, the heat demand (e.g., full load hours) and the type of use (heating and/or cooling) must be defined. Based on these parameters, VDI 4640 defines extraction rates per meter of BHE (W/m) to ensure a consistently reliable functionality of the system, from which the required probe depth and the number of probes can be calculated.

The methodology for designing geothermal probes in this guideline is based on several assumptions: Maximum heating capacity:30 kW, Intended BHE depth: 50 to 200 m, Maximum of 5 approximately equally long BHE, No thermal interaction expected with other geothermal systems in the immediate vicinity, Minimum probe spacing of 6 m and no deviation from the linear arrangement, cooling capacity: max. 75% of the heating capacity, Annual full-load hours for cooling: max. 300 h/a.

Even though the assumptions are very limiting, the VDI methodology serves as a fundamental assessment of the quantitative potential and provides the basis for further preliminary investigations, such as (Geo-)Thermal-Response-Tests.

As an example of a QN assessment using a VDI-based methodology the regional analysis for Bavaria is presented in the following (Figure 12). The above-described VDI methodology was used but adapted e.g. to use more than five BHEs at one ground and limited to the allowed drilling depth. Additionally, technical regulations are integrated into the assessment like the distance of the BHEs from buildings and neighbourhood areas. The analysis is conducted by using TC (derived from GH/GHT in combination with laboratory and field tests of TC and GTDtS), T, and RA (Bayerisches Landesamt für Umwelt-LFU, 2024; https://www.energieatlas.bayern.de/).

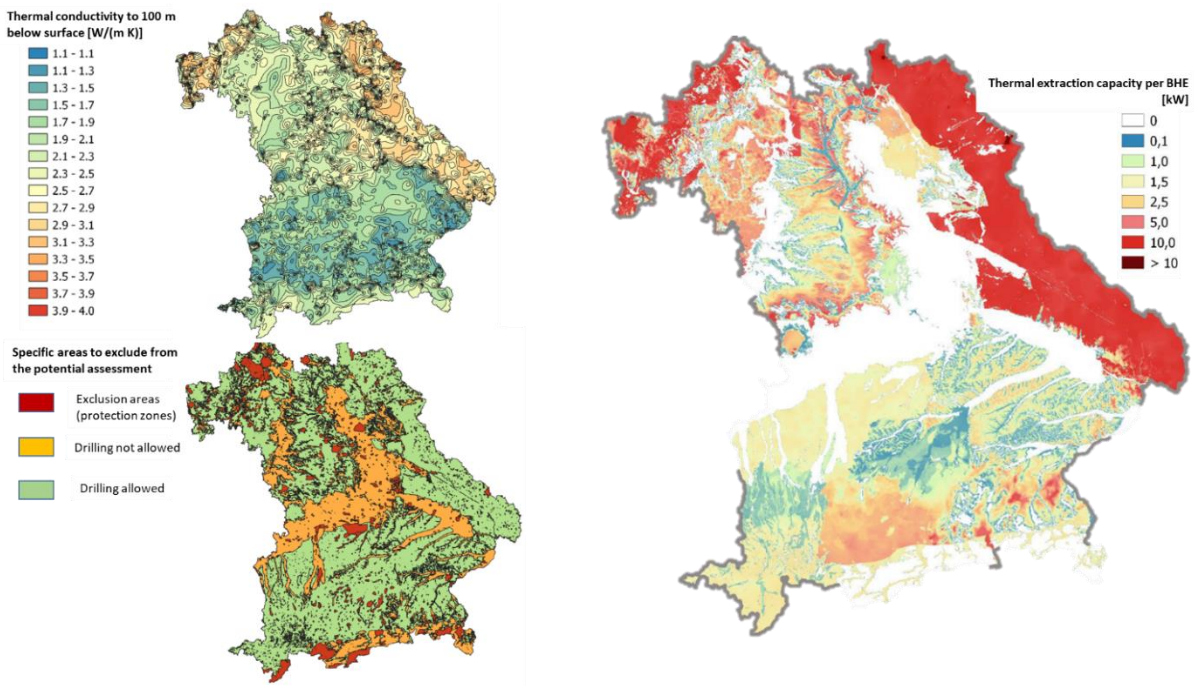


Figure 12: Quantitative Potential Assessment for the region of Bavaria based on an adopted VDI methodology (Bayerisches Landesamt für Umwelt, 2024).

Available Information/Data on the European Level for an assessment for Scenario Set 2

Crucial parameters for BHE and BTES potential quantification of scenario set 2 are not directly available at a pan-European scale. However, some available geological and hydrogeological data can be used to estimate these parameters with a good level of accuracy. Additionally, to the scenario set 1, publicly accessible pan-European input datasets important for scenario set 2 cover GH, GHT, as well as HC/P, ranges for local formations. Furthermore, the datasets can be used to assign TC and HCap values to the defined GH analogous to Dalla Santa et al. (2020), VDI 4640, or similar. This is mainly surficial information that can however be used for early-stage evaluations (Table 11).

Furthermore, topographic and climatic datasets can be used to infer the undisturbed subsurface temperature for T/TG via empirical relationships such as Signorelli and Kohl (2004). Digital elevation models can also be used to infer HG values locally, assuming a certain value of GTDtS.

Again, local profound geological and hydrogeological information is important for more detailed analysis.

Table 11: Publicly accessible pan-European datasets for potential assessment of scenario set 2.

Dataset	URL	Scenario parameter	Suitable for assessment
European Geothermal Database Infrastructure (EGDI), aquifer types	EGDI (v1.6)	GH, GHT	QL
Geothermal District Heating (GeoDH), heat flow density	https://zenodo.org/records/14044108	TC	QL
Global Hydrogeology MaPS 2.0 (GLHYMPS 2.0) global permeability of unconsolidated and consolidated Earth	https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU	HC/P	QN
European Geothermal Database Infrastructure (EGDI), transmissivity of prime aquifers	EGDI (v1.6)	HC/P	QN
Temperature and precipitation gridded data	https://cds.climate.copernicus.eu/datasets/insitu-gridded-observations-global-and-regional?tab=overview	calc. T/TG	QN
Topographic data (30-m resolution digital elevation models)	30-Meter SRTM Elevation Data Downloader	calc. T/TG	QN
PANGAEA database, Global-scale mining areas	https://doi.pangaea.de/10.1594/PANGAEA.910894	RA	QL/QN
Surface water map	https://global-surface-water.appspot.com/download	RA	QL/QN
ESDAC database, landslide map	https://esdac.jrc.ec.europa.eu/content/european-landslide-susceptibility-map-elsus-v2	RA	QL/QN
EFEHR database, Earthquake risk	https://eu-risk.eucentre.it/	RA	QL/QN
European Environment Agency (EEA) database, European protected sites	https://www.eea.europa.eu/en/analysis/maps-and-charts/european-protected-areas-1	RA	QL/QN
EEA database, Nature reserve	https://www.eea.europa.eu/data-and-maps/explore-interactive-maps/european-protected-areas-1	RA	QL/QN

Scenario Set 3

B 03	**Hydrothermal Direct Use- HT Network**
B 04	**Hydrothermal Direct Use - MT Network**
C 02	**Hydrothermal + HTHP - MT/HT Network**
C 03	**Hydrothermal + Sorption Chiller - DC Network**

Scenario set 3 represents the hydro-geothermal use. It can be described as a reservoir (geological horizon) having a relevant permeability to provide a significant fluid volume with a suitable (high) temperature (in the scenario catalogue defined by larger than 30 °C). The latter is the main difference between scenario set 1 and is generally linked to a higher depth but there is a seamless transition to the scenario set 1. Important parameters for a potential assessment are described in Table 12.

Table 12: Information and parameter description needed for geothermal energy potential assessment and pre-feasibility analysis for scenario set 3.

Information/ Parameter	Unit	Further Description	Classification of assessment
Spatial Extent of the Reservoir (SER)	-	Comparable to the scenario set 1, hydrogeological boundaries define the spatial extent of a reservoir for hydrothermal use. This means that the regarded geological horizon must have a reasonable permeability, and the boundaries of such reservoir are generally defined by less permeable geological conditions.	QL/QN
Reservoir thickness (RT)	[m]	The reservoir thickness is defined as the thickness of the geological horizons building up the reservoir and is derived by the boundary top and bottom surface of the geological horizons. The overlaying and underlying horizons normally a significantly different permeability and less fluid productivity, which is comparable with AT in the scenario set 1.	QL/QN
Permeability (P)	[m^2]	The permeability is a parameter defining the volume flux productivity and is mandatory for a QN assessment. Together with the rock temperature, P defines if a geological horizon represents a reservoir (see description SER). As P is a sensitive parameter for productivity, a detailed QN assessment must have high-resolution information. In a reservoir built by interbedded strata, the net gross permeability can be used for the interpretation of the productivity.	QL/QN
Porosity (PO)	[%]	In many cases, information about the permeability of a reservoir is not available. Because of the relationship between Porosity and Permeability (Poro-Perm), PO can be used as a “Proxy”-parameter for an interpretation of the volume flux productivity. Analog to P also with PO-values the “Netto Gross” Porosity can be assessed in interbedded strata.	QL/QN
Underground Temperature (T)/ Temperature Gradient (TG)	[°C] [K/m]	The temperature of the underground is an essential parameter to estimate the efficiency of hydrothermal use and is mandatory for a QN assessment. Geological surveys or environmental agencies often provide information about the underground temperature or a temperature gradient on a regional/local scale. For a rough estimation, also an average temperature gradient can be used.	QL/QN

Methodology to assess the potential of Scenario Set 3

Qualitative

The qualitative assessment of scenarios in set 3 is essentially constrained to regions where hydrothermal potential is proven or assumed. The extent of these regions is known through the operation of existing hydrothermal plants, exploratory drilling through f.e. oil and gas exploration, or assumed through seismic tests, modelling, and regional geological knowledge. The crucial parameter for QL assessment is therefore SER, T, respectively, TG.

The extent of regions consisting of hydrothermal reservoirs, as well as Temperatures can be obtained from consolidated, digitized maps, as seen in Figure 13, or web portals such as GeotIS (https://www.geotis.de).

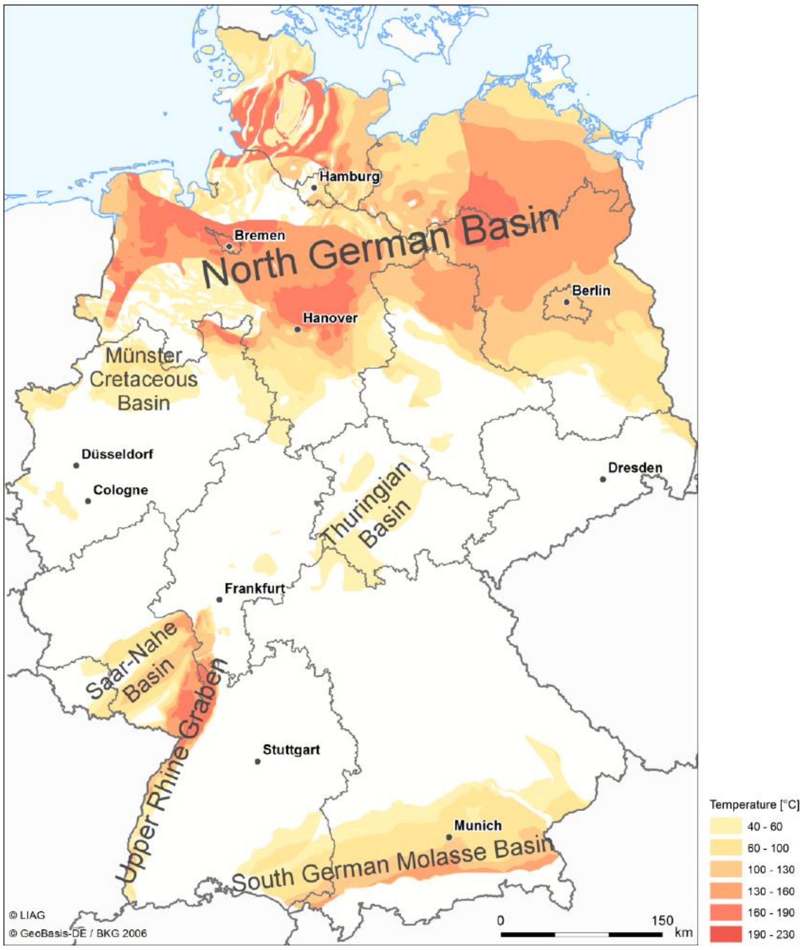


Figure 13: Known and assumed hydrothermal reservoirs in Germany (Agemar et al., 2014).

Quantitative

For the quantitative assessment of hydrothermal systems information on the spatial extent of the reservoir (SER), reservoir thickness (AT), permeability (P), porosity (PO), underground temperature (T), and temperature gradient (TG) is mandatory. Essentially, the hydrothermal potential is defined by the geothermal productivity of a borehole, which corresponds to the extractable thermal power. This is determined by the flow rate of thermal water through the borehole and the production temperature (respectively T, TG). The distribution of production temperature and flow rate is controlled by the characteristics of the reservoir (P, PO). Based on these parameters, the hydrothermal potential is calculated.

In the context of the Masterplan Geothermie Bayern 2020 (Molar-Cruz et al., 2022, https://geothermie-allianz.de/wp-content/uploads/2022/09/Gutachten-Masterplan-Geothermie-Bayern.pdf), the hydrothermal potential of the Bavarian Molasse Basin was quantitatively analysed. Here, the Malm reservoir forms a fractured karst-pore aquifer with generally high thermal water availability. The used methodology is primarily based on the creation of an isothermal map, which is cross-checked with the production temperatures of existing geothermal plants in the Molasse Basin, which together with the spatial extent of the reservoir and its thickness (SER, RT) forms the basis for temperature predictions of the reservoir. The estimation of flow rates is carried out through hydraulic zoning of the reservoir based on permeability and porosity. Additionally, the dependence of the flow rate on pressure drawdown could be described using known productivity indices, allowing further insights into reservoir hydraulics.

From the overall interpretation of the data, the reservoir was divided into areas with suitable production temperatures (Figure 14) and similar hydraulic properties, as can be seen in Figure 15.

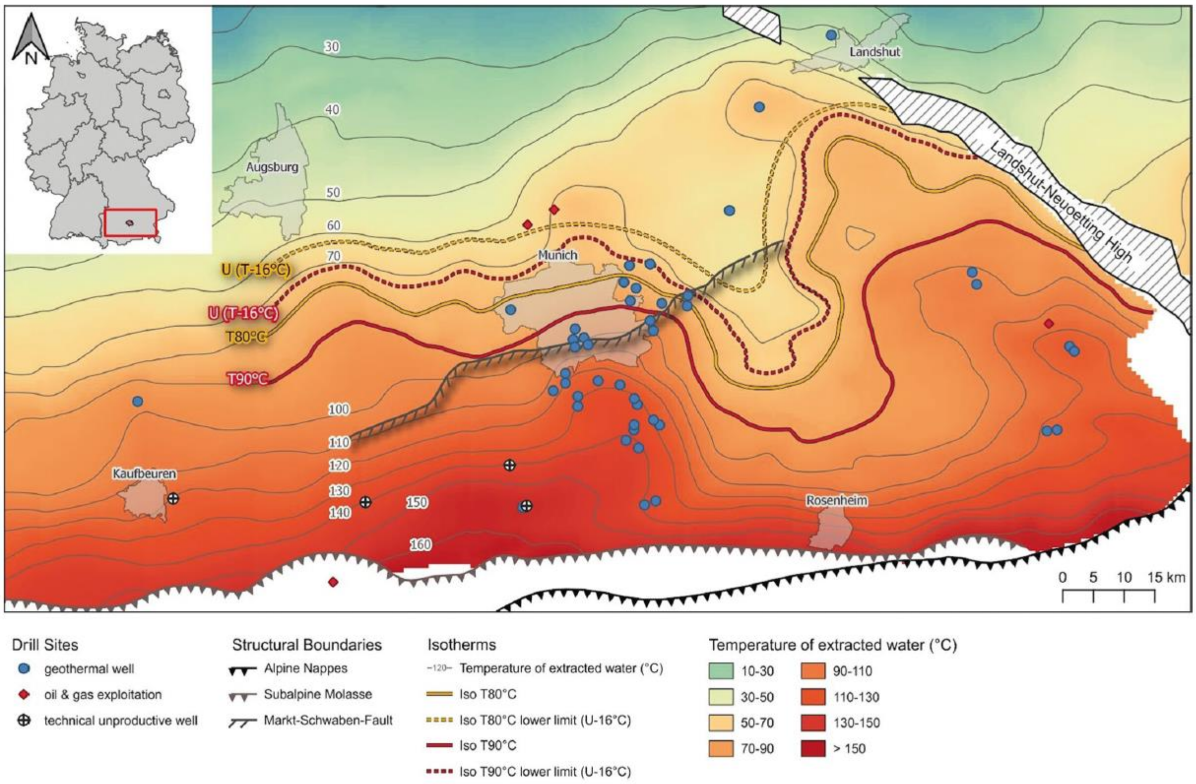


Figure 14: Estimated production temperature prognosis for the Upper Jurassic reservoir in the Bavarian Molasse Basin assessed by a correlation of production temperatures and temperatures at the top of the reservoir taken from the GeotIS - platform (www.geotis.de). This correlation shows residuals up to 16 °C between the production temperatures and the temperature on the top of the Upper Jurassic Reservoir. South of the 80 °C (resp. 90 °C) isotherm shown, there is a relatively high probability of producing a temperature of 80 °C (resp. 90 °C) and higher. North of it, it is expected that this production temperature will not be reached anymore. In the range between the respective isotherm and the limit isotherm U(T-16°C), however, there is a small probability of reaching 80 °C (resp. 90 °C) due to the uncertainty of the temperature forecast. (Zosseder et al., 2022).

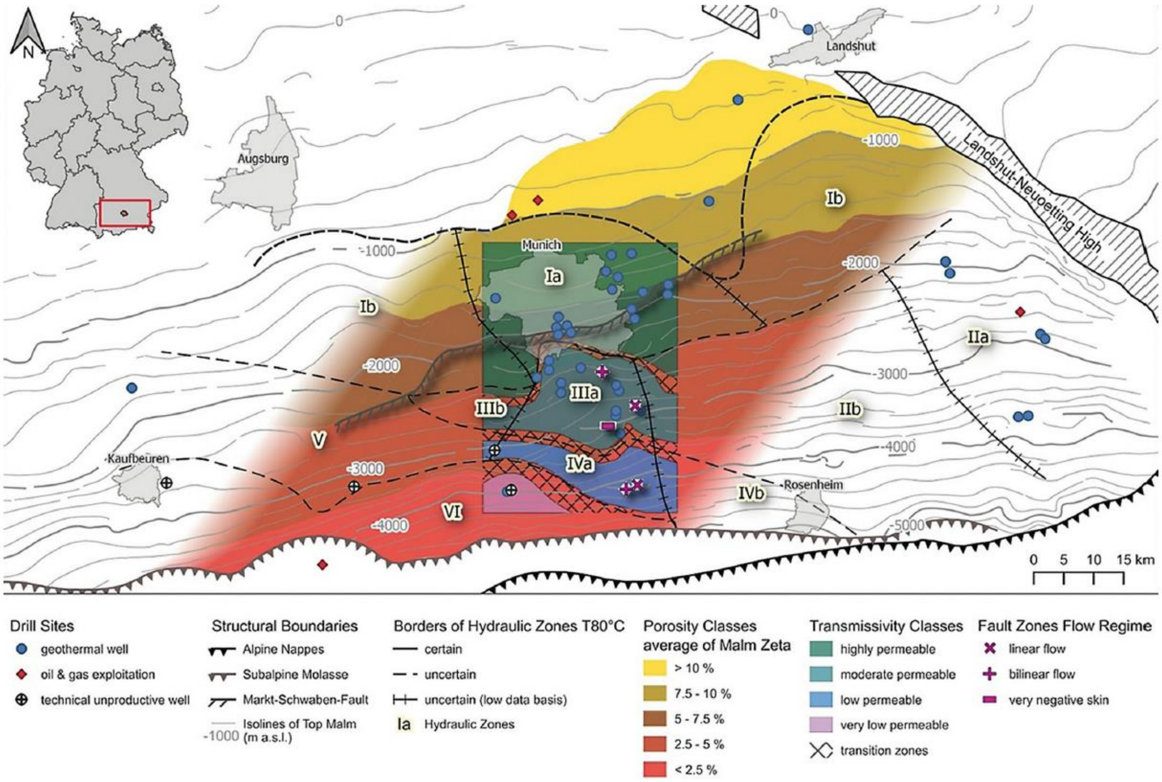


Figure 15: Displayed i) permeability (accordingly transmissivity) and flow zone regimes derived from hydraulic test analyses, ii) average matrix porosity distribution, derived from laboratory tests and borehole geophysical analyses. The limitation of the spatial parameter distribution is caused by the limited available database. The displayed hydraulic zones represent different production rate ranges, derived from the described parameter distributions by known production rates of the existing geothermal wells. The zones are classified with the following production rate ranges and estimated averages: Zone Ia,b – 75 to 180 l/s, 90 l/s; Zone II a – 65 to 180 l/s, 90 l/s; Zone II b – 65 to 180 l/s, 80 l/s; Zone III a, b – 40 to 150 l/s, 80 l/s; Zone IV a,b – 40 to 60 l/s, 50 l/s; Zone V – 5 to 50 l/s, 15 l/s, Zone VI – 0 to 10 l/s, 5 l/s The differentiation of zones in separate zones a and b is due to an increase of uncertainty. In such b-areas, the database is even more limited and the estimated production rate ranges are very uncertain (Zosseder et al., 2022).

Furthermore, to calculate the energy potential, the spatial extent of the reservoir was divided into hexagons with an area of 7.8 m², considered the minimum utilization field for a doublet system. Interference between systems is guaranteed for a usage period of 25-30 years. Based on a minimum production temperature of 90°C and an injection temperature of 50°C, the technical potential is calculated (Figure 16). In further studies, the techno-economic parameters of development have been used to calculate the production costs for the hexagons.

Overall, the applied methodology represents a quantitative assessment of high quality and serves as an essential foundation for heat planning and the integration of geothermal energy into district heating networks.

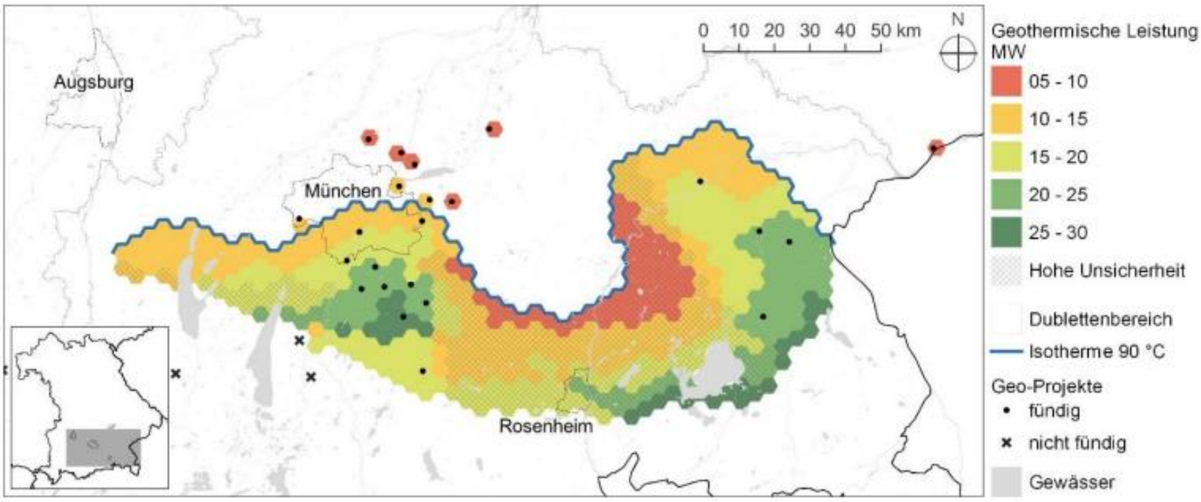


Figure 16: Hydrothermal Potential of the Malm-Reservoir in the Bavarian Molasse Basin (Molar-Cruz et al., 2022).

Available Information/Data on the European Level for an assessment for Scenario Set 3

The extent of proven and assumed hydrothermal potential areas across Europe are mapped mostly country-wide, in Figure 13. The specific information on each hydrothermal reservoir is locally known. Nevertheless, consolidated pan-European digitized maps are rare. A qualitative overview is available through the GeoDH project (http://geodh.eu/), which includes potential reservoirs for hydrothermal systems throughout Europe (SER).

For rough quantitative assessments, pan-European data for P, PO, and T/TG is publicly accessible and listed in Table 13 below. However, analogous to scenario sets 1 and 2, locally available data of higher resolution is needed for a more detailed analysis.

Table 13: Publicly accessible pan-European datasets for potential assessment of scenario set 3

Dataset	URL	Scenario parameter	Suitable for assessment
Geothermal District Heating (GeoDH), hydrothermal reservoir map	https://zenodo.org/records/14044110	SER	QL
Geothermal District Heating (GeoDH), temperature distribution	https://zenodo.org/records/14044103	T/TG	QL/QN
Subsurface temperature isolines at 1000 m and 2000 m depth	https://zenodo.org/records/13799306	T/TG	QL/QN
EarthDoc database, temperature model	https://www.earthdoc.org	T/TG	QL/QN
Global Hydrogeology MaPS 2.0 (GLHYMPS 2.0) global permeability of unconsolidated and consolidated Earth	https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU	P, PO	QL/QN

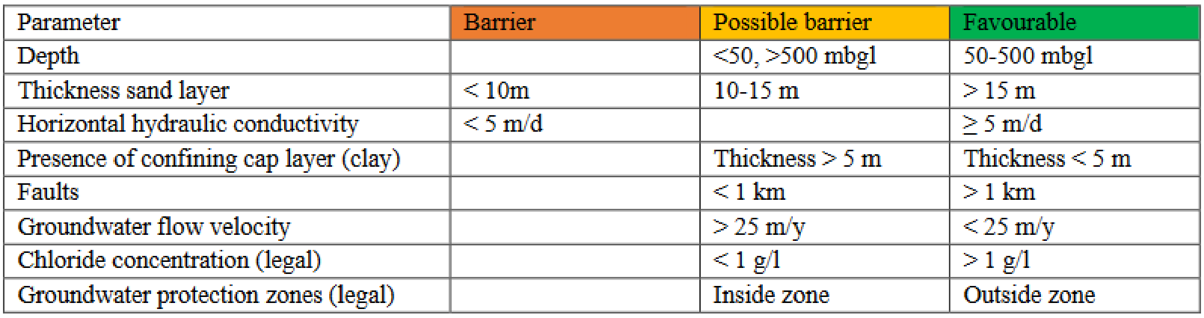
Scenario Set 4

F 01 Basic + HT-ATES – MT/HT Network

Scenario set 4 uses High-Temperature ATES (Aquifer Thermal Energy Storage, temperature typically about 90°C) in combination with conventional deep geothermal and a district heating grid. The choice to use ATES is driven by the need to address the seasonal mismatch between heat supply and demand. During the summer, excess heat from diverse sources (geothermal, solar panel or industry) is stored in the aquifer and then used during peak demand in winter. A "typical" ATES can cover a peak demand of about 5 – 10 MW of heating power. A problem intrinsic to all storage technologies is the loss of energy. For an ATES, this means that the temperature during heat extraction will always be lower than the temperature level during the storage phase. To overcome this issue, the ATES at the Delft University campus, Netherlands is supplying a secondary heating grid on a lower temperature level during winter when the energy demand is peaking (Bloemendal et al., 2020). Another possibility is to associate a heat pump with the HT-ATES system to achieve the higher temperatures required for the main heating grid.

Analogous to Scenario Set 3, critical inputs include the aquifer's depth, thickness, porosity, permeability, and underground temperature, all of which influence heat storage and losses. Additionally, the presence of a confining cap layer and faults as well as the Groundwater flow velocity and Groundwater chemistry are important parameters. Dinkelman and Bergen (2022) proposed certain threshold values (Table 14) that they used for the creation of national potential maps (QL assessment) for The Netherlands. Groundwater chemistry and thermal properties are also important for preventing scaling and optimising energy retention. While similar parameters are needed as in scenario set 3, the reversed flow direction in HT-ATES operations makes injectivity and water chemistry even more critical. The natural water flow rate should be sufficiently low to ensure effective storage, and both surface and downhole equipment must be designed to handle both high temperature and periodic use of wells for both injection and production. Important parameters for a potential assessment are described in Table 15.

Table 14: Subsurface criteria for creating the national potential maps, including legal criteria (for The Netherlands; taken from Dinkelman & Bergen, 2022).



Parameter	Barrier	Possible barrier	Favourable
Depth		<50, >500 mbgl	50-500 mbgl
Thickness sand layer	< 10m	10-15 m	> 15 m
Horizontal hydraulic conductivity	< 5 m/d		≥ 5 m/d
Presence of confining cap layer (clay)		Thickness > 5 m	Thickness < 5 m
Faults		< 1 km	> 1 km
Groundwater flow velocity		> 25 m/y	< 25 m/y
Chloride concentration (legal)		< 1 g/l	> 1 g/l
Groundwater protection zones (legal)		Inside zone	Outside zone

Table 15: Information and parameter description needed for geothermal energy potential assessment and pre-feasibility analysis for scenario set 4.

Information/ Parameter	Unit	Further Description	Classification of assessment
Spatial Extent of the Reservoir (SER)	-	Comparable to the scenario set 1, hydrogeological boundaries define the spatial extent of a reservoir for hydrothermal use. This means that the regarded geological horizon must have a reasonable permeability, and the boundaries of such reservoir are generally defined by less permeable geological conditions.	QL/QN
Reservoir thickness (RT)	[m]	The reservoir thickness is defined as the thickness of the geological horizons building up the reservoir and is derived by the boundary top and bottom surface of the geological horizons. The overlaying and underlaying horizons normally a significantly different permeability and less fluid productivity.	QL/QN
Geological Horizons (GH)	-	Practically, knowledge of the geological horizons for hydrogeological boundaries defines the spatial extent of potential aquifers (SEA) and different permeability (P).	QL
Permeability (P)	[m^2]	The permeability is a parameter defining the volume flux productivity and is mandatory for a QN assessment. Analogous to scenario 3, P defines if a geological horizon represents a reservoir (see description SEA). As the P is a sensitive parameter for productivity, a detailed QN assessment must have high-resolution information. In a reservoir built by interbedded strata, the “Netto Gross” Permeability can be used for the interpretation of productivity.	QL/QN
Porosity (PO)	[%]	In many cases, information about the permeability of a reservoir is not available. Because of the relationship between Porosity and Permeability (Poro-Perm), PO can be used as a “Proxy”-parameter for an interpretation of the volume flux productivity. Analog to P also with PO-values the “Netto Gross” Porosity can be assessed in interbedded strata.	QN
Underground Temperature (T)/ Temperature Gradient (TG)	[°C] [K/m]	In contrast to scenario 3, the optimal initial temperature of the reservoir is subjected to different considerations. Typical storage temperatures are in the order of 30 - 60°C above the initial reservoir temperature. As temperature correlates with depth, shallower reservoirs often mean cheaper in terms of drilling and pumping costs but might be subjected to increased clogging issues if injection temperatures strongly differ from the reservoir temperature.	
Heat Capacity (HCap)	[J/m3K]	The heat capacity parameter for HT-ATES refers to the ability of the aquifer materials (both the water and the geological storage formations and caprock) to store heat. This parameter is crucial for determining how much thermal energy can be stored and subsequently retrieved from the system.	QN
Thermal Conductivity (TC)	[W/mK]	The thermal conductivity parameter for HT-ATES is a measure of how well heat can be transferred through the aquifer materials, including both the geological	QN

		formations (+caprock) and the water within the aquifer. This parameter is critical for understanding the rate at which heat is transferred to and from the storage medium, which directly impacts the efficiency of heat storage and recovery in HT-ATES systems.	
Hydrochemical Conditions (HChem)	[mg/l] [g/m^3]	Groundwater chemistry refers to the composition of the water in the aquifer, which affects scaling, corrosion, and overall system efficiency. Key factors include salinity, pH, and the concentrations of ions like chloride and bicarbonate. Temperature changes due to HT-ATES at anoxic conditions can lead to chemistry changes in underground chemistry and the mobilization process of specific substances (e.g. arsenic compounds).	QN

Step for assessing the potential of the Scenario Set 4 (HT-ATES Integration)

1) Identification of regions with seasonal heat imbalance

Begin by identifying regions where there is a significant heat surplus during the summer and high heat demand during the winter. These regions are prime candidates for HT-ATES, as they can benefit from storing excess heat generated in the warmer months for use during colder periods.

2) Screening for suitable aquifers

Next, screen for aquifers that are at a suitable depth for HT-ATES implementation (comparable with procedures for scenario set 3), ensuring that the aquifer depth is appropriate for storing high-temperature water. Consider the competitive use of aquifers, particularly those used for drinking water, and prioritize those with minimal interference with other critical water sources.

3) Geological parameter assessment

Conduct a detailed assessment of the geological characteristics of the selected aquifers. This includes evaluating:

- SER & RT: Ensure the aquifer is deep enough to store heat efficiently and extensive enough to meet the storage demands. Verify the lateral continuity of the aquifer to ensure consistent storage capacity across the region. Faults or Fractures: Identify any significant faults or fractures that could lead to unwanted heat dissipation.
- P/PO: Assess the aquifer's permeability to determine how easily water can flow through the system.
- GH: Analyse the stratigraphy to understand the layering within the aquifer, ensuring the presence of impermeable layers that prevent heat loss.

4) Groundwater chemistry Analysis (HChem)

Groundwater chemistry is important in the design and operation of HT-ATES systems, as it directly influences the long-term performance, durability, and efficiency of the storage process. Risks of corrosion, scaling and/or clogging of the wells are directly linked to the pH, salinity and concentration of carbonate minerals (Oerlemans, et al., 2022).

5) Qualitative Screening Enhancement

Build upon the qualitative screening by integrating the geological and chemical data collected. Use this information to refine the selection of aquifers and prioritize those that show the greatest potential for efficient and safe HT-ATES implementation.

6) Storage Temperature Demand Assessment

Determine the required storage temperatures based on the specific needs of the district heating networks in the target region and compare them to the underground temperature (T). The storage temperature should be high enough to meet winter heating demands but within the operational limits of the HT-ATES system.

7) Estimation of ATES Size

Estimate the size of the HT-ATES system based on historical, current, or planned ATES projects, which typically store between 8-30 GWh of heat per heating season. Use these benchmarks to gauge the storage capacity needed for the scenario set 4 implementations.

Available Information/Data on the European Level for an assessment for Scenario Set 4

Accessible pan-European datasets for scenario set 4 are listed in Table 16.

Table 16: Publicly accessible pan-European datasets for potential assessment of scenario set 4.

Dataset	URL	Scenario parameter	Suitable for assessment
Geothermal District Heating (GeoDH), hydrothermal reservoir map	https://zenodo.org/records/14044110 -	SER	QL
Geothermal District Heating (GeoDH), heat flow density	https://zenodo.org/records/14044108	TC	QL
European Geothermal Database Infrastructure (EGDI), groundwater storage	EGDI (v1.6)	SER	QL/QN
Geothermal District Heating (GeoDH), temperature distribution	https://zenodo.org/records/14044103	T/TG	QL/QN
Subsurface temperature isolines at 1000 m and 2000 m depth	https://zenodo.org/records/13799306	T/TG	QL/QN
EarthDoc database, temperature model	https://www.earthdoc.org	T/TG	QL/QN
Global Hydrogeology MaPS 2.0 (GLHYMPS 2.0) global permeability of unconsolidated and consolidated Earth	https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU	P, PO	QL/QN

Scenario Set 5

F 02 **Advanced Geothermal Systems (AGS)**
F 03 **Enhanced geothermal system (EGS)**
F 04 **Deep BHE + HTHP – MT/HT Network**

Scenario set 5 represents petro-geothermal use. In general, it could be used anywhere but is expected to be implemented where no aquifer is available for hydro-geothermal use. F02 and F04 are closed-loop systems, whereas F03 use a certain porosity in the underground, which must be enhanced so that fluid as heat transfer media can be circulated. Important parameters for a potential assessment are described in Table 17.

Table 17: Information and parameter description needed for geothermal energy potential assessment and pre-feasibility analysis for scenario set 5.

Information/ Parameter	Unit	Further Description	Classification of assessment
Geological Horizons	-	The deep rock formations accessed by AGS (**F02**) may be sedimentary rocks or, ideally, even deeper, and thus hotter crystalline rock formations. In contrast to a traditional geothermal system, a closed-loop system uses a working fluid that circulates with a designed flow rate. In this sense, the system is independent of permeability, greatly reducing the exploration risk. Advances in drilling technology have led to the consideration of such closed-loop systems for the development of deeper (higher temperature) geothermal resources. For **F02 t**arget rock formations must be characterised with laterally contiguous stratigraphy in clastic or carbonate rock. Boreholes documenting must enter basement – non-permeable competent rock, by 5 km TVD. Moreover, the reservoir rocks must have strength and integrity (e.g. no intersection of faulted/fractured or dissolution cavity-type zones). Areas characterized by a young, active seismic are excluded.	QL/QN
Thermal Conductivity (TC)	[W/mK]	TC is an important parameter for deep closed-loop systems and the extractable energy from the underground. The TC in AGS (**F02**) in contrast to shallow geothermal use - linked to **Scenario Set 2,** does not depend on the water saturation of the rocks because, by design, AGS (**F02**) are in dry, consolidated rocks. Data for the TC can be derived from rock measurements and literature data, however, be aware that the literature TC data on a deep geological profile is rather poor. Geological surveys/ environmental agencies often provided spatially distributed information for the thermal conductivity of the specific rock types on regional/local levels. This parameter is crucial for QL and QN assessment. The Enhanced geothermal system (EGS) refers to F03, also known as the Hot Dry Rock method (HDR) or Hot Fractured Rock (HFR), harnesses geothermal heat from the Earth's depths, typically between 3 to 6km, residing within low permeability rocks or even deeper. The higher the rock TC, the better the renewability of the geothermal resources.	QL/QN

Underground Temperature (T)/ Temperature Gradient (TG)	[°C] [K/m]	High-temperature gradient (>0.03 K/m). The temperature of the underground is an essential parameter to estimate the efficiency of AGS/EGS/HDR systems and is mandatory for a QN assessment.	QN
Permeability (P)	[m^2]	In contrast to a traditional geothermal energy system, a closed-loop system **F02** (AGS) uses a working fluid that circulates with a designed flow rate. In this sense the system is independent of permeability, greatly reducing the exploration risk. The lower the target rock permeability, the better. In **F03** (EGS) the permeability of the reservoir rocks can be enhanced by hydro-shearing, pumping high-pressure water down an injection well into naturally fractured rock. The injection increases the fluid pressure in the rock, triggering shear events that expand pre-existing cracks and enhance the site's permeability. The initial permeability should be low (<3mD) - the lower the better, whilst finally, after enhancement treatments, we strive to obtain the highest possible controlled permeability (the higher target rock permeability, the better).	QN
Porosity (PO)	[%]	In **F02** (AGS) the requirement of high reservoir integrity imposes a very low rock porosity value, the lower - the better. In general, EGS (**F03**) refers usually to reservoirs designed to produce thermal energy from low-conductivity or low-porosity geothermal resources. However, the exact porosity values can differ based on factors such as rock type, depth, and temperature, especially when considering EGS Hydrothermal systems, which consider the operation of systems where rock porosity reaches 15-25%. The most suitable rock type for EGS is typically granite or other crystalline basement rock. Based on the literature the effective porosity in EGS (**F03**) should not exceed 3% (the lower the better).	QN
Reservoir thickness (RT)	[m]	The reservoir thickness must ensure sufficient rocks' volume for heat accumulation supplied to the geothermal system. For example, the bottom thickness limits for AGS (**F02**) are about 40 m (EAVOR). Based on the literature the reservoir thickness in EGS (**F03**) should be greater than approximately 200m.	QN
Stress field (SF)	-	The four main types of stress are typical: Compression: stress which causes a rock to squeeze or push against another rock. Tension: stress which occurs when rock pulls apart or gets longer; Shear Stress: stress which occurs when tectonic plates move past each other causing the rock to twist or change shape and Fault: break in the rock. In EGS (**F03**), the stress field plays a critical role in reservoir behaviour and performance. The in-situ stress state is essential for understanding how fractures and faults behave within the geothermal reservoir. The stress field is estimated using techniques such as borehole measurements, seismic data, and numerical simulations. The stress field influences fracture orientation, propagation, and closure. Fractures tend to align with the direction of maximum horizontal stress. Hydraulic fracturing (stimulation) aims to create fractures that intersect the stress field favourably for fluid flow and heat exchange. Since in AGS (**F02**), the stability of the exchanger system is crucial, the stress field should be low. Thus, the systems are located outside tectonically active zones, fault zones etc.	QL/QN

Methodology to assess the potential of Scenario Set 5

Qualitative criteria determining technology applications:

Advanced geothermal systems (AGS) consider a variety of engineered systems to produce geothermal energy. These systems primarily vary based on the length and geometry of the closed-loop wells placed in the subsurface but can also vary in the materials used in well construction and the working fluid used. Two common designs of closed-loop geothermal systems are the U-tube (e.g., *Eavor-Loop*) and the tube-in-tube (e.g., *GreenFire's GreenLoop*).

1) Identification of areas suitable for the application of technology (site location)

The geological conditions required for GreenFire's GreenLoop technology are not publicly disclosed. However, based on the general principles it should be assumed that the conditions are like those of borehole heat exchanger installations. To ensure high efficiency, the best conditions for location include:

- Areas with high-temperature geothermal resources in volcanic zones are preferred;
- Favourable rock types include granites, basalts, and compact igneous rocks, which can retain heat effectively.

In the case of *Eavor-Loop* Solutions, the installation location should meet some quality criteria, including geological assessment (deep structure and tectonics) should be considered. The most important are:

1) Geological parameter assessment:
    - Deep geological structure analysis: analysis of lithological profile aimed at the indication of competent rocks. The site should have stable formations (compact limestones, dolomites, metamorphic rocks, etc.) to minimize risks like subsidence or seismic activity, with favourable rock types for efficient heat exchange (high TC values). Eavor-Loop solutions work in both sedimentary and igneous, metamorphic basement rocks (Eavor-Loop 1.0 (TRL8) or Eavor-Loop 2.0 (TRL3)).
    - Deep-tectonic analysis: preferable areas without active tectonics, outside earthquake areas, crustal stress zones and active faults that can influence subsurface borehole heat exchanger geometry or even cause its destruction;
    - The research should be supported by geophysical methods, including 2-3D seismic;
    - 3D geological modelling can give an advantage;
    - Regional geothermal gradient assessment: site location should be in a favourable geothermal gradient area, as higher gradients indicate the potential for more efficient heat extraction;
2) Technical considerations:
    - In the case of Eavor Solutions, it is required to be certain that the rock in the radiator section can be properly sealed.
3) Surface infrastructure screening
    - Proximity to existing infrastructure, such as roads, power lines, heating networks and facilities – can significantly reduce development costs and facilitate easier access for maintenance and operation.

Eavor-Loop technology is highly scalable, as it does not rely on high-temperature volcanic areas, permeable aquifers, or hydrothermal flow capacity. This scalability allows for the use of standardised, repeatable drilling solutions, enabling expansion without the constraints of scarce resources or high-risk exploration.

The capacity of individual *Eavor-Loop* systems typically ranges from 5 MW to 20 MW per installation, though scaling the technology further is possible as it is still being optimised. Multiple loops could be combined to create larger power plants with capacities reaching 100 MW or more.

Enhanced Geothermal Systems (EGS) require specific geological conditions. Environmental and social factors should also be considered. Key qualitative criteria include:

1) Geological parameter assessment:
    - Preferring areas of high-temperature gradient: the rock formation must be sufficiently hot to generate a significant amount of heat;
    - Permeability: the rock formation should finally have some degree of permeability to allow fluid circulation through it. This can be either naturally occurring permeability or induced permeability created through hydraulic fracturing;
    - Rock stability: the rock formation must be stable enough to withstand the pressure and temperature conditions created by the geothermal system;
    - Absence of faults: Major faults or fractures can create pathways for fluid to escape, potentially reducing the efficiency of the geothermal system. However natural faults may also be considered as a part of the system, but first, they should have been properly studied;
    - Fresh water availability: necessary for the system to ensure fluid circulation and function the system effectively.

Other minor but also important factors determining the EGS location are resistance to water saturation (especially resistivity to swelling = low clay content), susceptibility to massive fracturing, and lack or very weak inflow of groundwater into the EGS system.

2) Environmental and Social Factors:
    - Seismic risk assessment: the location should have a low seismic risk to minimize the potential for induced earthquakes;
    - Groundwater resources: the project should avoid interfering with valuable groundwater resources;
    - Land use and public acceptance: the location should be compatible with land use plans and have support from local communities.

Quantitative Screening Enhancement

By integrating geological, technical, and environmental factors, we can refine the selection of AGS/EGS locations and target rocks, prioritizing those with the highest potential for successful implementation. In quantitative analysis, the following steps should be considered:

1) Temperature gradient assessment: determines the optimal drilling depth, the most suitable drilling technology, and the accessibility of the geothermal resource.
   The scope of application of Eavor-Loop for various purposes depending on the geothermal gradient is shown in Table 18.

Table 18: Temperature gradient criteria conditioning the use of Eavor-Loop for different applications (Eavor, 2022)

Technology	Heating	Colling	Power
EL1.0	> 25°C/km	> 30°C/km	> 45°C/km
EL2.0	> 20°C/km	> 25°C/km	> 40°C/km > 25°C/km (Germany)

2) Indication of competent rock (stratigraphy, lithology) in the geological profile for applications of the appropriate Eavol-Loop solutions.
3) Selection of the technology: quantitative analysis of the temperature gradient and qualitative analysis of the geological profile allows for the selection of competent rocks, their depths and, consequently, the determination type of technology to be used (EL1.0, EL2.0) following Table 19.

Table 19: Scope of different Eavor-Loop technological solutions depending on the lithology of the target rock formation (Eavor, 2022)

Parameter	Eavor-Lite	Eavor-Loop 1.0	Eavor-Loop 2.0
Angle X	90°	90°	160-180°
Rock type	Sedimentary	Sedimentary	Igneous, Metamorphic

4) 3D Geological and parametric model preparation: aim at the integration of available data for further resource and risk assessment and uncertainty analysis.
5) Estimation of the resource:

   In the EGS system, the methodology relies mostly on the assessment of the volume mass of rocks and accompanying fluids (heat in place—HIP), along with the estimation of temperature and other parameters. Apart from HIP technical and economic potential should also be estimated. Technical potential assessment includes, among others, the estimation of the recoverable fraction (recovery factor) of reserves suitable for utilization from a technical point of view. The current use of EGS technology indicates that most projects are aimed at electricity generation rather than the production of heat. Waste heat can be used for heating purposes when the heat consumer market is nearby. The resource assessment methodology is complex and can be found among the other in Van Wees et al. (2011). The specific resource assessment methodology for AGS remains undisclosed, it likely involves evaluating the heat content of the rock mass, the feasibility of efficient heat extraction based on petrophysical and thermal parameters, and the system's overall heat recovery efficiency.

6) Numerical simulation of the system: conduct numerical simulations to model the performance of the AGS/EGS system. These simulations should:
   - Determine the size and geometry of the subsurface part of the system: borehole requirements to ensure heat/cold demand;
   - Assess system efficiency: evaluate how effectively the system can release heat for the specific heating network demand;
   - Integration into DHN: simulate the integration of the AGS/EGS into the existing district heating network to identify potential efficiencies and challenges.

Enhanced Geothermal Systems (**EGS**) are still in the early stages of large-scale development in Europe, though several projects are aiming to advance the technology. The capacity of typical EGS installations in Europe tends to be in the single-digit to low double-digit megawatt (MW) range, but larger projects are being planned as the technology matures. Most EGS projects in Europe have capacities between 1 MW and 20 MW. Larger, experimental, and pilot plants aim to eventually reach 50 MW or more, but many are still in the demonstration or early development phases. Example: Soultz-sous-Forêts EGS Project (France)

An example of **EGS** projects in Europe are:

- Soultz-sous-Forêts project located in Alsace, France, Upper Rhine Graben region. Capacity: c.a. 1.7 MWel. Initially designed as a research site, it has been in operation since the early 2000s;
- Insheim Geothermal Plant (Germany). Capacity: Around 4.8 MWel (in the Palatinate region). This project uses a combination of EGS and conventional geothermal technologies, providing a template for expanding EGS use.
- Landau Geothermal Plant (Germany). Capacity: approximately 3 MWe;
- United Downs Deep Geothermal Power (UK). Planned capacity: Up to 10 MWel. The UK's first geothermal power project is located in Cornwall, which aims to demonstrate the potential of deep geothermal technology, including EGS methods.

Since **AGS (F02)** projects are still emerging, typical capacities are smaller but scalable. The following capacity ranges are seen in early AGS deployments in Europe:

- Pilot Projects: 1 MW to 5 MWe. These are demonstration or pilot projects designed to prove the viability of the technology in various conditions.
- Commercial Projects: 5 MW to 20 MWe. An example is the first commercial project in Geretstried, Germany (Bavaria). At the Geretsried facility, the Eavor-Loop boasts approximately 8.2 MWe and a thermal capacity of 64 MWth, providing enough power for nearly 32,000 households in the region. The geothermal plant is on track to be producing energy by 2024 and will reach its full capacity in 2026.

The capacity of **AGS** (Eavor Loop) depends on factors like the depth of the loop, the geological conditions, and the specific site. The company's goal is to make these systems scalable so that multiple loops can be combined to create larger power plants with capacities reaching 100 MW or more by connecting several loops.

Available Information/Data on the European Level for an assessment for scenario set 5

Accessible pan-European datasets for scenario set 5 are listed in Table 20.

Table 20: Publicly accessible pan-European datasets for potential assessment of scenario set 5

Dataset	URL	Scenario parameter	Suitable for assessment
Geothermal District Heating (GeoDH), heat flow density	https://zenodo.org/records/14044108	TC	QL
Geothermal District Heating (GeoDH), temperature distribution	https://zenodo.org/records/14044103	T/TG	QL/QN
Subsurface temperature isolines at 1000 m and 2000 m depth	https://zenodo.org/records/13799306	T/TG	QL/QN
EarthDoc database, temperature model	https://www.earthdoc.org	T/TG	QL/QN
Global Hydrogeology MaPS 2.0 (GLHYMPS 2.0) global permeability of unconsolidated and consolidated Earth	https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU	P, PO	QL/QN

References

Agemar, T., Weber, J., Schulz, R. (2014): Deep Geothermal Energy Production in Germany. – Energies 7, p. 4397-4416; doi:10.3390/en7074397.

Bayerisches Landesamt für Umwelt (LfU) (2024): Bayernweite, räumlich detaillierte Bestimmung des umsetzbaren Potenzials der oberflächennahen Geothermie zur Einbindung in den Energie-Atlas Bayern. (Bavaria-wide, spatially detailed determination of the realisable potential of near-surface geothermal energy for integration into the Energy Atlas of Bavaria):https://www.cee.ed.tum.de/fileadmin/w00cbe/hydro/Pictures/pic_projects/EnergieAtlas/EAB_Abschlussbericht_final_20240408.pdf.

Bayer, P., Attard, G., Blum, P., Menberg, K. (2019): The geothermal potential of cities. Renewable and Sustainable Energy Reviews, Volume 106: p 17-30. https://doi.org/10.1016/j.rser.2019.02.019.

Bloemendal, M., Vardon, P. J., Medema, A., Snelleman, S., Marif, K., Beernink, S., van Veldhuizen, F., Pijnenborg, M., Sudintas, G., & van Oort, T. (2020): *HT-ATES at the TU Delft campus: Feasibility study*. Delft University of Technology and ENGIE. https://projecten.topsectorenergie.nl/storage/app/uploads/public/60d/4e3/a23/60d4e3a23cc94359031598.pdf.

Böttcher, F., Casasso, A., Götzl, G., Zosseder, K. (2019): TAP - Thermal aquifer Potential: A quantitative method to assess the spatial potential for the thermal use of groundwater. Renewable Energy, 142, 85-95. https://doi.org/10.1016/j.renene.2019.04.086.

Casasso, A. Sethi, R. (2026): G. POT, A quantitative method for the assessment and mapping of the shallow geothermal potential, Energy 106: p. 765-773.

Dinkelman, D. and van Bergen, F. (2022): Evaluation of the countrywide potential for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Netherlands, in: European Geothermal Congress, 2022.

Eavor, 2022: The World's Environmental Cooling Challenges & How Eavor Can Help. Eavor YouTube Channel. https://youtu.be/iOdFysHkAnc.

EU-Alpine Space Project GRETA “Near-surface Geothermal Energy in the Territory of the Alpine Space” (2018): Deliverable D2.3.1 – Harmonized guidelines for legal and technological procedures.

European Commission: Directorate-General for Research and Innovation, Hurter, S., & Haenel, R. (2002): *Atlas of geothermal resources in Europe*, (S.Hurter, editor, R.Haenel, editor) Publications Office.

Molar-Cruz, A., Maximilian F. Keim, M. F., Schifflechner, C., Loewer, M., Zosseder, K., Drews, M., Wieland, C., Hamacher, T. (2022): Techno-economic optimization of large-scale deep geothermal district heating systems with long-distance heat transport. Vol. 267, Energy Conversion and Management, https://doi.org/10.1016/j.enconman.2022.115906.

Oerlemans, P., Drijver, B., Koenen, M., Koornneef, J., Dinkelman, D., Bos, W. & Godschalk, B. (2022): First field results on the technical risks and effectiveness of mitigation measures for the full scale HT-ATES demonstration project in Middenmeer, in: European Geothermal Congress, 2022.

Van Wees, J.D.; Boxem, T.; Calcagno, P.; Lacasse, L.; Manzella, A., 2011: A Resource Assessment Protocol for GEO-ELEC. A Living Document Produced by the GEO-ELEC Project, 1–18. Available online: http://www.geoelec.eu/wp-content/uploads/2012/04/GEOELEC_RESOURCE-ASSESMENTPROTOCOL_v-16-dec-2011.pdf.

VDI- Verein Deutscher Ingenieure e.V. (2010): Thermal use of the underground Fundamentals, approvals, environmental aspects.

Zosseder, K., Pfrang, D., Schölderle, F., Bohnsack, D., Konrad, F. (2022): Characterisation of the upper Jurassic geothermal reservoir in the South German Molasse Basin as basis for a potential assessment to foster the geothermal installation development – Results from the joint research project Geothermal Alliance Bavaria. Geomechanics and Tunnelling 15, No. 1, pp. 17–24. https://doi.org/10.1002/geot.202100087.

Appendix 1: Catalogue of datasets, digital annexe

SAPHEAS's GitLab serves as a digital annexe:

https://gitlab.com/saphea-h2020

Appendix 2: Hotmaps guidelines

The Hotmaps guidelines PDF file is saved below. To open the file, double-click on the image below. If it doesn't work, please use the following URL: https://wiki.hotmaps.eu/uploads/Hotmaps_Data-upload-on-Gitlab_2017-12-04_V4.pdf.

hotmaps_guidelines.pdf