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Potential Study for Future Heat Supply in NRW (G): Geothermal potential analyses for greenfield exploration areas

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INTRODUCTION

The federal state of North Rhine-Westphalia (NRW) in Germany is well known for its centuries-long mining tradition. In its deeper subsurface, it hosts extensive sedimentary deposits that could potentially be utilized for hydrothermal geothermal energy production. These primarily include carbonates of Devonian, Carboniferous, and Cretaceous age, as well as unconsolidated sediments from the Tertiary. Due to intensive lignite and hard coal mining activities, the geological subsurface down to the coal-bearing strata - particularly in the Rhenish mining area and the Ruhr district - is considered well explored. In contrast, comparatively little is known about the deeper-lying potential hydrothermal reservoirs, as these were of no economic relevance in the past (e.g., for hydrocarbons). Consequently, NRW can currently be classified as a greenfield exploration area with respect to hydrothermal geothermal energy. To date, no implementation projects for hydrothermal utilization have been realized.

In recent years, however, initial exploration activities have been initiated by local energy providers, the Geological Survey of North Rhine-Westphalia (GD NRW), and research institutions such as the Fraunhofer IEG. In 2024, the Ministry of Economic Affairs, Industry, Climate Action and Energy (MWIKE NRW) presented the 'Masterplan Geothermie' (Geothermal Master Plan), a strategy to accelerate geothermal development, accompanied by a clear political commitment to make geothermal energy widely accessible in NRW. This framework includes a comprehensive exploration program under which the GD NRW, commissioned by MWIKE NRW, is tasked with carrying out seismic surveys and exploration drilling as part of state-level investigations. Another key instrument is the funding program 'progres.nrw' – Risk Mitigation for Hydrothermal Geothermal Energy, which supports preliminary exploration activities by external investors. In parallel with the Geothermal Master Plan, the State Agency for Nature, Environment and Climate of NRW (LANUK NRW), in cooperation with Fraunhofer IEG, conducted the Study on the Future Heat Supply in NRW (short: NRW Heat Study). The NRW Heat Study provides a statewide quantitative assessment of medium- and deep hydrothermal potentials in NRW, for the first time. The methods applied and the results of this potential assessment are presented here, including outlook on ongoing medium to deep geothermal projects.

1 HYDROTHERMAL RESERVOIRS IN NORTH RHINE-WESTPHALIA

In North Rhine-Westphalia (NRW), carbonates are currently regarded as the most promising hydrothermal reservoir. These include Upper Cretaceous limestones, platform carbonates ('Kohlenkalk') from the Lower Carboniferous, Dinantium, and Devonian 'Massenkalk', consisting of massive carbonate deposits. They occur widely in northern, central, and western parts of NRW to depths of up to 6000 meters approximately, being further present in parts of Belgium and the Netherlands. These carbonates can be utilized for the extraction of thermal waters due to both primary permeability (interconnected pore space) and secondary permeability (karstification, fracture networks). As a result of compaction and diagenetic processes, multiple tectonic overprints, and partial dolomitization, they might exhibit, particularly within major fault zones, hypogenic paleokarst features as well as pronounced fracture systems and fracture networks, providing excellent transmissivities for thermal waters, Moeck (2014); Müller et al. (2023); Ritzmann et al. (2022); Lippert et al. 2022; Jüstel et al. (2024).

In addition, in the Tertiary, unconsolidated sediments of silt to sand (e.g. the 'Cologne' and 'Grafenberg' Formations of the Oligocene), embedded in clay layers, are of particular interest. These occur in the western part of NRW at depths of up to approximately 1700 meters. They form highly productive porous aquifers which have been extensively investigated due to lignite open-pit mining in the Rhenish mining area. Figure 1 illustrates a

typical subsurface profile in western NRW, showing the distribution of mentioned reservoir formations. The interpretation is based on the evaluation of 2D seismic data from the survey 'Lower Rhine' carried out by the GD NRW.

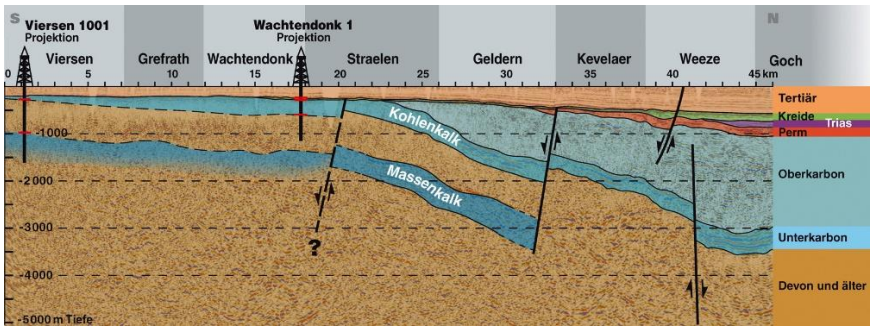


Figure 1. Representation of the subsurface profile in western NRW based on the evaluation of the 2D seismic data from the survey 'Lower Rhine', GD NRW (2025).

More potential reservoir formations in NRW could gain interest in the future, such as sandstones and carbonates of Jurassic, Triassic, and Permian age. However, these were not considered in the NRW Heat Study due to insufficient data availability at time of conduction.

2 QUANTIFICATION OF HYDROTHERMAL POTENTIALS IN NRW

Within the framework of the NRW Heat Study, hydrothermal geothermal potentials for direct thermal water use were determined, splitting the potentials into two depth intervals: Firstly, medium-depth geothermal energy at depths between 400 to 1500 meters TVD. Secondly, deep geothermal energy at depths between 1500 to 5000 meters TVD, Energieatlas (2024). Information on depth and thickness of the four considered reservoirs (Tertiary, carbonates from the Cretaceous, Lower Carboniferous and Devonian) is based on geological models provided by the Geological Survey of North Rhine-Westphalia (GD NRW) for the NRW Heat Study.

2.1 Methods of Potential Assessment

For the NRW Heat Study, we emphasized the importance of consideration of different methods for geothermal potential estimation methods, specifically, firstly, stochastic geothermal doublet performance calculations, and secondly, volumetric quantifications of the heat in place method by Muffler and Cataldi (1978). A detailed overview of these two potential estimation methods and their relevance, including a statistical comparison on the resulting regional, spatial output is conducted by Benoit et al. (2025).

For potential estimations in the NRW Heat Study, only stochastic geothermal doublet performance calculations were selected by LANUK NRW, due to the choice of restricting results to a geothermal doublet as plant type. Hence, in this case, this method was favoured as it allows for the inclusion of technical parameters of a geothermal plant installation consisting of a hydrothermal doublet with one production and one injection well. As a result, potential hydrothermal utilizations can be represented more realistically, and statements about technical potentials might be delivered more comprehensible to policymakers and public.

The potential assessment assumes that a hypothetical hydrothermal doublet requires a representative area (here, a conservative approach of 9 km^2) to avoid hydraulic interference between neighbouring doublets. To represent this spatially, a 3 × 3 km grid was applied across the entire state of NRW. For each grid cell, the hydrothermal potential was calculated for both all four reservoirs (figure 2), splitting medium-depth and deep geothermal, and using the tool DoubletCalc for stochastic calculations, Benoit et al. (2025). DoubletCalc developed by TNO, Mijnlieff et al. (2014), is designed for analytical calculation of the thermal output of geothermal doublets. Input parameters include geological reservoir properties such as depth, thickness, permeability, salinity, net-to-gross ratio, and temperature gradient as well as technical factors such as casing configuration, doublet design, and pump specifications. With a Monte Carlo-based approach it allows to quantitatively determine theoretical extractable thermal energy from one doublet in megawatt (MW) by giving probability distributions (e.g., P90, P50, P10). Figure 2 summarizes the calculation logic applied in this study. In the NRW Heat Study, the doublet calc Monte Carlo calculation is performed for each reservoir in every grid cell individually. If multiple potential reservoirs are present within one grid cell, the energetically most favourable reservoir is selected for each of the two depth intervals (medium-depth and deep geothermal energy) Benoit et al. (2025).

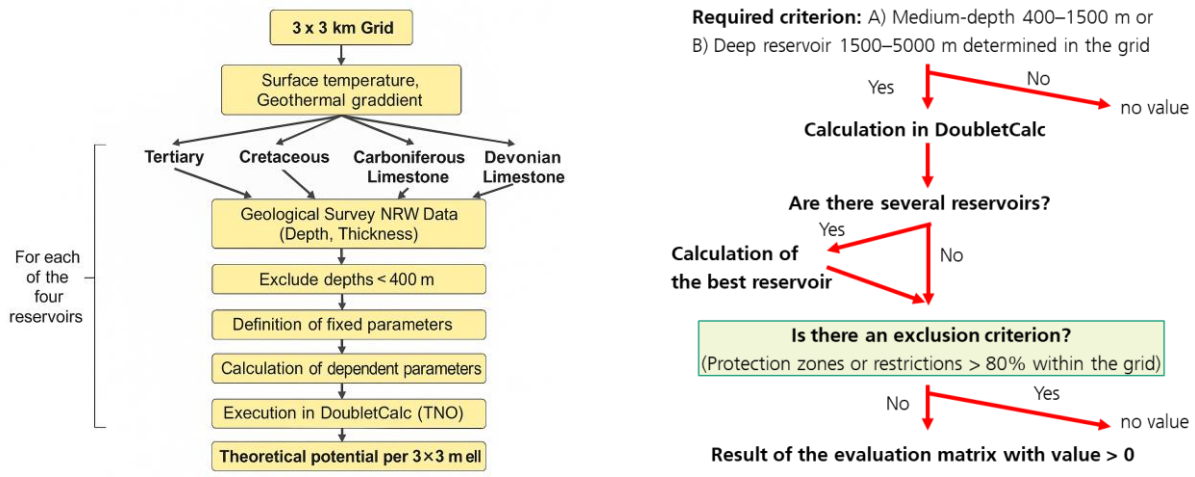


Figure 2. Workflow in the NRW Heat Study for the stochastic assessment of hydrothermal geothermal potential (left), and for the evaluation matrix on those potentials (right).

2.2 Results of Potential Assessment

Figure 3 and 4 show the results of the hydrothermal potential assessment for medium-depth and deep geothermal energy in North Rhine-Westphalia (NRW) for the P50 probability case.

For medium-depth geothermal energy, selecting the highest performance value per grid cell yields in NRW a theoretical total capacity of 5246 MW and a theoretical annual heat production of 31.5 TWh (assuming 6000 operating hours per year as a conservative average estimate). The identified potentials are mainly associated with Tertiary sediments in the western part of NRW (Lower Rhine area) and with Cretaceous carbonates in the northern part of NRW (Münsterland Cretaceous Basin). Both reservoir types predominantly occur within the medium-depth range.

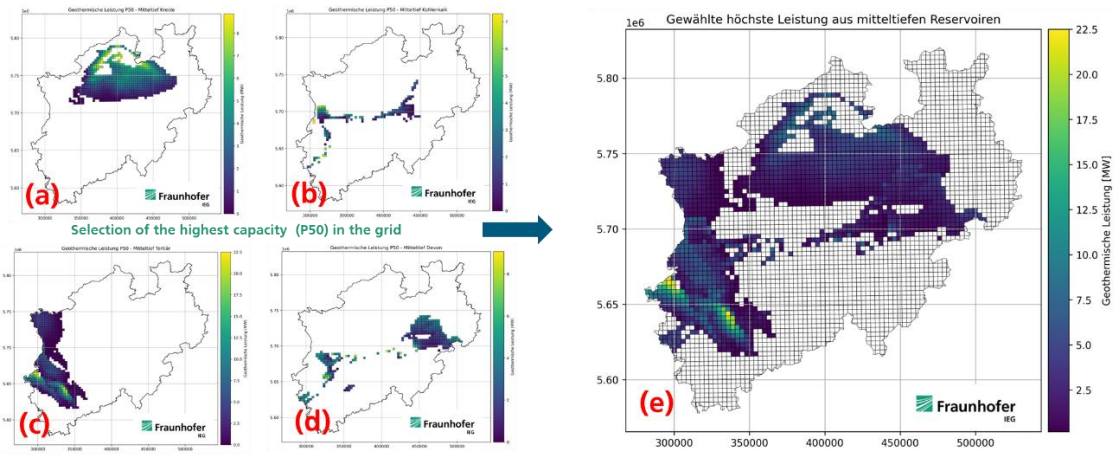


Figure 3. Theoretical geothermal potential (MW) of medium-depth hydrothermal reservoirs (400 – 1500 m) in P50 case; (a) potential of Cretaceous carbonates; (b) potential of Carboniferous carbonates; (c) potential of Tertiary sediments; d) potential of Devonian carbonates; (e) selection of highest potential per grid, Energieatlas (2024).

For deep geothermal energy, selecting the highest performance value per grid cell results in NRW in a theoretical total capacity of 17240 MW and a theoretical annual heat production of 103.4 TWh (assuming 6000 operating hours per year). The capacity is significantly higher than that of medium-depth geothermal energy, primarily because greater depths and higher reservoir temperatures allow for higher extraction rates from the doublets. The identified potentials are mainly derived from Carboniferous and Devonian carbonates located in the central, western, and northern parts of NRW. Carbonate reservoirs at depths between 5000 - 6000 m were illustrated informally (in brown shading).

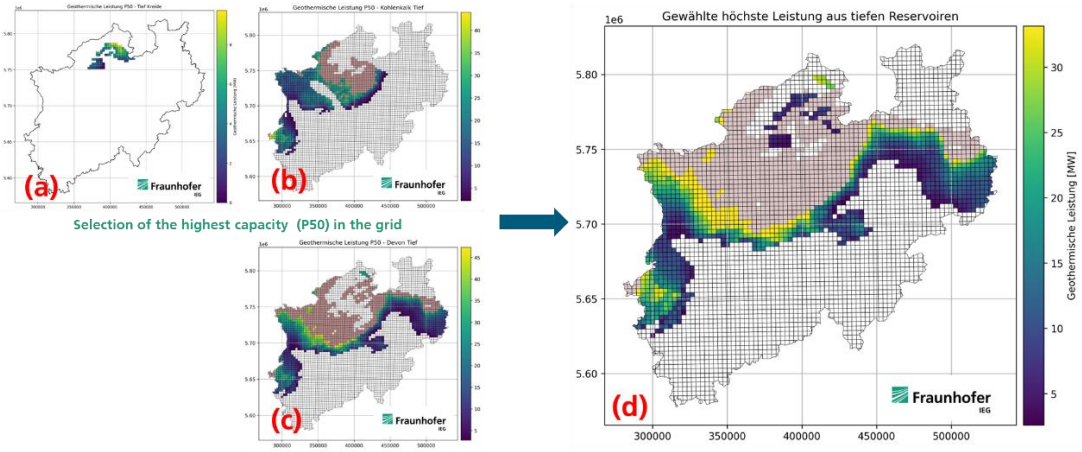


Figure 4. Theoretical geothermal potential (MW) of deep hydrothermal reservoirs (1500 – 5000 m) in P50 case; (a) potential of Cretaceous carbonates; (b) potential of Carboniferous carbonates; (c) potential of Devonian carbonates; (d) selection of highest potential per grid, Energieatlas (2024).

To make the results easily understandable to the public, as a next step, the potential results are included in an evaluation matrix, where surface and subsurface criteria influence the final matrix result. This matrix result should give an easy overview whether a specific location on map is highly suitable to implement geothermal energy as heat source in the future. The results of the geothermal evaluation matrix are accessible in the interactive geo-data platform, Energieatlas (2024), open source.

To present reliable results which policymakers can work with, in a final step, the calculated theoretical geothermal potential is minimized by an uncertainty factor. The final resulting number shall give an estimate or a prediction on the technical applicability of geothermal power and its respective estimated sum. The uncertainty factor in this study was determined following the GPOS method proposed by Lochem (2021), which accounts for the probability and uncertainty of various influencing parameters such as the presence, permeability, and hydrochemical suitability of the reservoir for geothermal utilization. Based on this approach, an uncertainty range of 0.1–0.2 was derived for deep geothermal energy, and a range of 0.2–0.4 for medium-depth geothermal energy. For deep geothermal, the percentage is half as high compared to medium-depth, due to its lower exploration activity and higher data uncertainty in NRW. Taking these into account, and assuming 6000 operating hours per year, the resulting technical applicability and utilization potential for North Rhine-Westphalia amounts to 6.3 – 12.6 TWh/a for medium-depth geothermal energy, and 10.3 – 20.7 TWh/a for deep geothermal energy.

3 CONCLUSION AND OUTLOOK

With the calculation approaches of the NRW Heat Study , a statewide quantitative assessment of medium-deep to deep-hydrothermal geothermal potential has been carried out for North Rhine-Westphalia (NRW) for the first time. Within the framework of the NRW Heat Study, conducted by LANUK NRW, a total heat demand of 163.4 TWh/a is projected for the year 2045 for the state NRW, of which 135 TWh/a will be required for space heating and domestic hot water, while additional 28.4 TWh/a for process heat of up to 200 °C, Energieatlas (2024). Based on the technical applicability and utilization potential of geothermal doublets determined above, medium-depth geothermal energy could supply approximately 3.5 – 7 %, and deep geothermal energy 6 – 12 %, of NRW's projected heat demand in 2045.

Geothermal potentials determined in this study can serve as an initial foundation for municipal heat planning. In particular, local energy suppliers and municipalities can use these results to conduct preliminary assessments on whether medium-depth or deep geothermal energy as heat source may be feasible within their respective administrative or supply areas. The first step in this process should include pre-feasibility and feasibility studies, which can be used to validate and further refine the results presented here.

Regardless of this, numerous exploration activities (seismic surveys and/or exploration wells) related to the utilization of hydrothermal geothermal energy have already been carried out or are currently in preparation in NRW. In addition to the state-level exploration programs conducted by the GD NRW, the following projects, among others, can be mentioned: Geothermal paper drying in Hagen, Greenhouse heating in Straelen, Geothermal District heating supply for the municipal utilities of Münster, Düsseldorf, Duisburg, Aachen,

Mülheim, Oberhausen and Wuppertal as well as the Fraunhofer Field Scale Laboratory for Geothermal Energy Rhineland.

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follow the scientific format, e.g. Verma and Pruess (1976).