Introducing the Geothermal Suitability Map of Germany: A Tool for Assessing the National Potential for Shallow Geothermal Energy Utilisation

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ABSTRACT

Achieving net-zero emissions in Germany requires transforming the heating and cooling sector, which accounts for roughly 50% of national energy consumption and 90% of household energy use. A key aspect of the current energy transition strategy is the expansion of shallow geothermal energy (SGE), tapping into heat from depths of less than 400 meters via ground-source heat pump (GSHP) systems. However, progress is challenged by uneven availability of geoinformation, coupled with the inconsistent assessment of SGE potential across the country's 16 federal states.

This study is part of WärmeGut, an ongoing research project and data campaign aimed at standardising geothermal data and assessing the effective SGE potential in Germany. Here, we present a concept and workflow for developing nationwide standardised site-suitability maps for borehole heat exchangers, designed to address the significant variability in geological and hydrogeological systems, as well as the diverse legal frameworks governing SGE utilisation.

The site-suitability assessment, conducted in close collaboration with the State Geological Surveys of Germany, evaluates 40 parameters, which are related to geological and environmental conditions that may limit or prevent geothermal use. Criteria are grouped into four categories: i) conservation and environmental risk zones, (ii) regional subsurface geology, (iii) groundwater systems, and (iv) existing land use. More than 60 datasets - including geological maps, stratigraphic models, hydrogeological resources, 3D subsurface models, and environmental data - were compiled, reprocessed, and standardised using GIS tools. Three site-suitability classes were defined: (i) areas where GSHP installation is not permitted, (ii) areas with known usage restrictions, and (iii) areas without known usage restrictions. These are visualised using a traffic light colour scheme.

The resulting "traffic-light" map represents a pivotal step toward determining Germany's technical SGE potential. To date, approximately 55% of the investigated land shows no significant restrictions to SGE utilization, 38% faces usage limitations, and 7% is deemed unsuitable for BHE installation. These findings demonstrate that SGE may offers a viable and efficient solution for sustainable heating, including in regions with lower heat demand and limited district heating access. Overall, the "traffic-light" map provides a clear, consistent, and accessible tool for advancing GSHP deployment across the country.

1. INTRODUCTION

The heating and cooling sector (HCS) is one of the most demanding energy sectors in Europe, accounting for about 30% of total energy consumption and nearly 80% of energy output in individual households (Miocic et al., 2024). Particularly, cooling demand is projected to rise substantially by 2050, with residential consumption increasing by 750% (Munćan et al., 2024). Accordingly, the road to EU climate neutrality depends heavily on the successful implementation of an effective heat transition strategy.

Germany is likely one of the European countries where the HCS accounts for a particularly high share of national final energy consumption - 27% for space heating and 21% for process heat in 2023 - and represents nearly 90% of household energy use, corresponding to more than 560 terawatt-hours (TWh) (Umweltbundesamt, 2025). As of today, 55% of the energy used for heating and cooling derives from fossil fuels, comprising coal (0.5%), oil (18%), and natural gas (36.5%). The remaining share is split between electricity (21%), district heating (8%), and renewable energy sources (16%) such as waste heat and biomass, solar thermal energy, and geothermal energy. Although the share of renewable energy has grown significantly in the last two decades (Umweltbundesamt, 2025), a deeper transformation of the HCS is still underway to improve the chances of achieving net zero carbon emissions by 2045. One of the key pillars of Germany's energy transition strategy is expanding geothermal energy use (BMWK, 2022), including ground-source heat pumps (GSHPs) to tap into shallow geothermal potential, seen as pivotal for significantly reducing household reliance on non-renewable fuels.

Shallow geothermal energy (SGE), defined as the heat stored at depths between 0 and 400 meters (c.f. Haehnlein et al., 2010), is a proven and efficient alternative for sustainable heating (Ramos-Escudero et al., 2021; Miocic et al., 2024), particularly in areas with low heat demand and no access to district heating (Tissen et al., 2019; Walch et al., 2021). Unlike traditional water–air heat pump systems, which are sensitive to seasonal climate variability (Miocic & Krecher, 2022), the majority of GSHPs draw from stable subsurface temperatures found at depths greater than 15-20 meters. In Germany, temperatures can reach up to 30°C within the first 400 meters, following the local geothermal gradient (c.f., Agemar et al., 2012; 2013). Based on Born et al., (2022), SGE may enable the substitution of at least 75% of the energy demand in the HCS. Although this estimate requires further validation - being based solely on data from the federal state of North Rhine-Westphalia and not accounting for the considerable regional variability in regulations, as well as in the geological and hydrogeological subsurface conditions governing geothermal use across Germany (Ravidà et al., 2024) - it nonetheless provides a valuable indication of the pivotal role this resource could play in the heat transition. However, the expansion of SGE is hindered by inconsistent assessments of its theoretical, technical and economic potentials (*sensu* Rybach, 2015) as well as by the lack of standardised geoinformation. Existing data are often fragmented across state authorities (e.g., geological surveys, mining and nature conservation authorities), frequently difficult to access, and not directly comparable or scalable at the national level.

To address some of these challenges, the WärmeGut project was launched in 2022 with the aim of (1) compiling, standardising, and harmonising shallow geothermal geoinformation at the national level; (2) determining and mapping site-suitability for various geothermal applications within the first 400 meters depth; (3) assessing the technical potential of GSHPs; (4) closing the data accessibility gap by developing a comprehensive online tool integrated into GeotIS, Germany's established geothermal information system (Agemar et al., 2014). Altogether, these efforts aim to develop a platform and tools that support the heat transition nationwide.

This contribution focuses on one of the key aspects addressed within the WärmeGut project, namely data harmonisation, and presents the workflow for developing a standardised site-suitability map for various shallow geothermal systems, including borehole heat exchangers (BHEs), shallow geothermal well doublets, and geothermal collectors (Figure 1). As the project is still ongoing, only selected preliminary results for BHEs are presented here and should be considered as such.

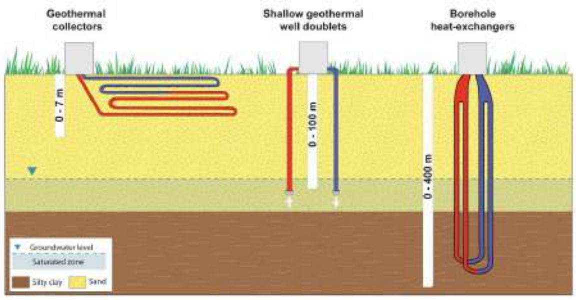


Figure 1: Simplified illustration of the three main configurations for SGE utilisation (Ravidà et al., 2024). The indicated depths correspond to the specific intervals investigated within the WärmeGut project. Image not in scale.

2. THE CONCEPT OF SITE-SUITABILITY

Geothermal suitability, or site-suitability, refers to the potential for harnessing SGE at a given location, based on the compatibility of GSHP systems with the prevailing regulatory framework as well as the local geological and hydrogeological conditions. Currently, some of the German federal states (Baden-Württemberg, Bavaria, Bremen, Hamburg, Hesse, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Thuringia) have developed regional site-suitability maps. However, the workflows and criteria used to define suitability classes vary significantly between states, complicating comparisons and hindering data integration. In contrast, this study aims to develop a workflow that enables a more consistent assessment of this parameter at a national scale.

To date, only a couple of projects in Europe have successfully implemented approaches to characterise geothermal suitability at such a large scale (cf. Goetzl et al., 2020; Pasquali et al., 2016). Among them, the Interreg Central Europe project GeoPLASMA-CE is particularly noteworthy for including six pilot areas in different European countries: Austria, Czech Republic, Germany, Poland, Slovakia and Slovenia (Hofmann et al., 2017). In GeoPLASMA-CE, geothermal suitability was determined by considering geological and geographical conditions known to pose challenges or risks to shallow geothermal installations. Specifically, seventeen installation criteria were included in the assessment, covering geological features (e.g., artesian aquifers, karst formations), risk factors (e.g., gas occurrences, flood-prone areas), and areas of public interest (e.g., water protection zones, nature reserves). Based on the presence of one or more conflicting conditions, the pilot regions were split into: areas where geothermal systems can generally be installed, areas requiring additional information and areas where GSHPs are generally not allowed.

The approach presented in this contribution builds upon the GeoPLASMA-CE concept by incorporating additional criteria to address the significant variability in geological and hydrogeological systems, as well as the diverse legal frameworks governing SGE utilisation across Germany (Somogyi et al., 2017; Ravidà et al., 2024). Additionally, frequent interaction and exchange with the Staatliche Geologische Dienste (SGD – the State Geological Surveys) and other environmental authorities form an integral part of our workflow.

3. CONFLICT CRITERIA FOR BOREHOLE HEAT EXCHANGERS

A total of 40 criteria were considered for assessing the suitability of BHEs, grouped into four categories: (i) conservation areas and environmental risk zones, (ii) geological features, (iii) groundwater systems, and (iv) land use restrictions (Fig. 2).

Conservation Areas and Environmental Risk Zones
Drinking water protection areas I and II
Qualitative curative spring water protection areas I and II
Drinking water protection III, III/A or III/1
Qualitative curative spring water protection areas III, III/A or III/1
Quantitative curative spring water protection areas A
Quantitative curative spring water protection areas B
Other drinking water protection areas
Other quantitative and qualitative curative spring water protection areas
Planned drinking water protection areas
Drinking water production areas
Other existing uses of groundwater
Coastal protection areas
Waterfront strips and floodplains
Flood risk areas
State-specific water laws
Landslide areas
Natural protection areas
National parks
Protected soils
Waterfront strips
Geological Features
Salt structures and salt-bearing rocks
Karst and sinkholes
Bedrock, fractured aquifers
Sulphate-bearing rocks
Highly permeable rocks
Fault zones
Swellable rocks (e.g. clay minerals)
Groundwater Systems
Glacial channels
Artesian
Aquifers in a pronounced storey structure
Deep aquifers
Salty groundwater, cement-corrosive groundwater
CO_2 and H_2S gas uprising
Ineffectiveness of protective covering layers
Depth-dependent, usable aquifers and limitations of drilling depth
Land Use Restrictions
Mining areas
Underground storages (e.g. radioactive waste, gas)
Oil and gas reservoirs and exploration areas
Contaminated sites: areas of soil contamination
Contaminated sites: areas of groundwater pollution

Figure 2: List of criteria employed to assess the site-suitability of BHEs.

The criteria were selected primarily based on the available guidelines for the use of SGE issued by various SGDs (e.g., Jensen et al., 2022; Obst et al., 2015; Rumohr et al., 2019) while also considering similar assessments available in the literature (Haehnlein et al., 2010; Hofmann et al., 2017; Dong et al., 2022).

3.1 Conservation and environmental risks

This category primarily includes water protection areas (Wasserschutzgebiete – WSG), namely areas which are subject to special regulations aimed at safeguarding groundwater from harmful substances and other hazards. Aquifers in these zones are often designated for drinking water supply or curative springs. According to the national water resource act (Wasserhaushaltsgesetz [WHG], 2009), any use of the ground and subsurface is strictly prohibited within a 10-meter radius of production wells (WSG Zone I), as well as within the distance where pathogenic microorganisms, bacteria, or pollutants could reach the well in less than 50 days (WSG Zone II) (Fig. 3). Beyond these zones - within the broader catchment area (e.g., Zone IIIA and IIB) and aquifers designated for other purposes - regional regulations define the conditions for SGE exploitation.

This category also includes areas subject to specific surface geomorphological risks, such as coastal zones, floodplains, flood-prone areas, landslide-prone regions, and riparian buffer zones (Fig. 2). Additionally, it covers soils requiring special protection, as well as natural reserves and national parks designated for the protection of nature and landscapes under the Federal Nature Conservation Act (Bundesnaturschutzgesetz, [BNatSchG], 2009).

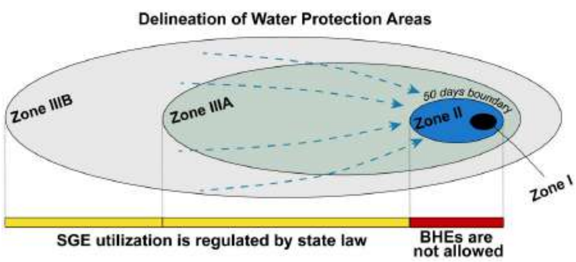


Figure 3: Conceptual definition of water protection areas. Zones I and II are located closest to the production wells and are generally unsuitable for the utilization of SGE. In contrast, in many federal states, the installation of BHEs is largely permitted at greater distanced from extraction wells (e.g., Zone III), provided that specific technical safety measures are implemented.

3.2 Geological criteria

Various geological features, occurring at depths between 0 and 400 meters, may limit or hinder SGE utilisation or compromise the long-term performance of GSHPs. Examples include shallow diapirs and salt structures, where interactions between seepage water or groundwater and easily soluble rocks can trigger the formation of cavities or loosened zones, posing significant challenges during drilling operations (Jensen et al., 2022). Similar considerations apply to existing karst features such as sinkholes and dolines, which may cause subsidence or instability. Anhydrite-bearing formations also represent a critical concern: when exposed to water, anhydrite transforms into gypsum, a reaction accompanied by a volume increase of up to 60% (Cooper, 2020). The swelling can cause local uplift, disrupt geothermal system functionality, and endanger nearby infrastructure (c.f. Sass & Burbaum, 2012). Additionally, regions defined by rocks with highly variable hydraulic properties, such as fractured reservoirs, and regions with swellable claystones are included in the assessment.

3.3 Groundwater system-related criteria

This category encompasses various hydrogeological criteria aimed at preserving the natural equilibrium of groundwater systems and minimising the risk of contaminant migration. For example, the presence of artesian or multi-storey aquifers at a given site may hinder or limit GSHPs installation, as drilling operations could create unintended hydraulic connections between otherwise separate aquifers. Similarly, site-specific depth restrictions may apply to BHE installations to prevent drilling into deep reservoirs.

Other criteria in this category relate to the presence of highly saline groundwater or groundwater containing potentially harmful gases (e.g., carbon dioxide, hydrogen sulphide, or methane) within multiphase aquifer systems.

3.4 Existing land uses

Existing land uses delineate areas where the installation of BHEs may conflict with already established human activities, particularly those involving the exploitation of other subsurface resources. These include mining zones, licensed areas for hydrocarbon extraction, and subsurface regions designated for storage purposes, such as gas reservoirs or radioactive waste disposal sites.

Additionally, this category covers areas where past human activities have led to deep soil and groundwater contamination. In such cases, geothermal drilling may interfere with existing containment measures or even trigger the spread of contaminants.

4. WORKFLOW

The development of a harmonised suitability map for Germany involves several steps, beginning with the assessment of the relative importance of conflict criteria across the sixteen federal states, followed by data compilation, processing, and mapping. Each step is carried out in close coordination with the SGD of the respective states. A brief overview of the workflow is provided below.

4.1 Populating the criteria catalogue

The relative importance of all 40 criteria was assessed across the 16 federal states. Each criterion was classified into one of five categories based on its influence on BHE installation (Figure 4):

i. Strong restriction – The criterion generally prohibits BHE installation at the site.

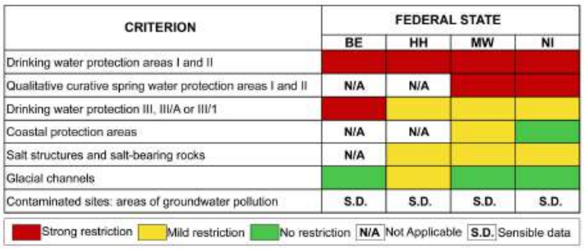
ii. Mild restriction – The criterion allows BHE installation but imposes specific depth limitations, technical requirements, or necessitates further site-specific investigations.

iii. No restrictions – The criterion generally does not affect BHE installation.

iv. Not applicable – The criterion is not relevant for assessing BHE suitability in the specific state, or corresponding geoinformation is currently unavailable.

v. Sensitive data – The criterion may affect BHE suitability, but the related data cannot be disclosed.

The initial version of the criteria catalogue was based on existing geothermal guidelines (e.g., Jensen et al., 2022; Obst et al., 2015; Rumohr et al., 2019) and was subsequently refined in close consultation with the SGDs and relevant environmental authorities.



CRITERION	FEDERAL STATE			
	BE	HH	MW	NI
Drinking water protection areas I and II				
Qualitative curative spring water protection areas I and II	N/A	N/A		
Drinking water protection III, III/A or III/1				
Coastal protection areas	N/A	N/A		
Salt structures and salt-bearing rocks	N/A			
Glacial channels				
Contaminated sites: areas of groundwater pollution	S.D.	S.D.	S.D.	S.D.

Figure 4: Excerpt of the catalogue showcasing the relevance of specific criteria among federal states. BE – Berlin; HH – Hamburg; MW - Mecklenburg–Western Pomerania; NI – Lower Saxony.

4.2 Data compilation

Over 60 existing layers are compiled, reprocessed and integrated via ArcGIS Pro (version 3.4), and its built-in functionalities. Data sources primarily include freely accessible online databases provided through the geoportals of the SGDs and the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe - BGR). The datasets comprise, for example, existing suitability maps, layers showcasing the distribution of artesian aquifers and saline groundwater, the location of mining areas, curative and water protection zones, the distribution of sulphate-bearing rocks, and other relevant geological and hydrogeological features (Figure 2). In some cases, non-publicly available datasets were provided directly by the competent authorities. Additional geoinformation was extracted, for instance, from existing 3D models, such as the distribution of salt structures in the North German Basin, derived from the BGR's TUNB model (von Goerne et al., 2024).

4.3 Data processing

All compiled layers from different sources are systematically reprocessed by assigning a new set of standardised attributes, based on the key criteria they represent and their relevance for BHEs site-suitability. Accordingly, a new layer is created for each relevant conflict criterion in every federal state. This step is central to the harmonisation process, as input data often differ significantly in structure and descriptive properties. Implementing a unified attribute scheme ensures a consistent representation of suitability across all states.

All newly generated layers are clipped to the respective federal state boundaries to eliminate duplicated information or invalid assessments across borders. Polygons within each layer sharing the same properties are then organised into multiparts to remove redundancies. Where point-based geoinformation exists in the original data sources, it is converted into polygon features. Finally, rivers and lakes are erased from the maps, as these areas are, by default, considered unsuitable for BHE installation.

4.4 The "traffic-light" map

Based on the conflict criteria assessment, the geothermal suitability for GSHPs is classified into three main categories, visualised using a traffic-light colour scheme (Figure 5): red indicates areas where the installation of GSHPs is not permitted; yellow denotes areas with known technical restrictions or depth limitations; and green highlights regions where no areal restrictions are known.

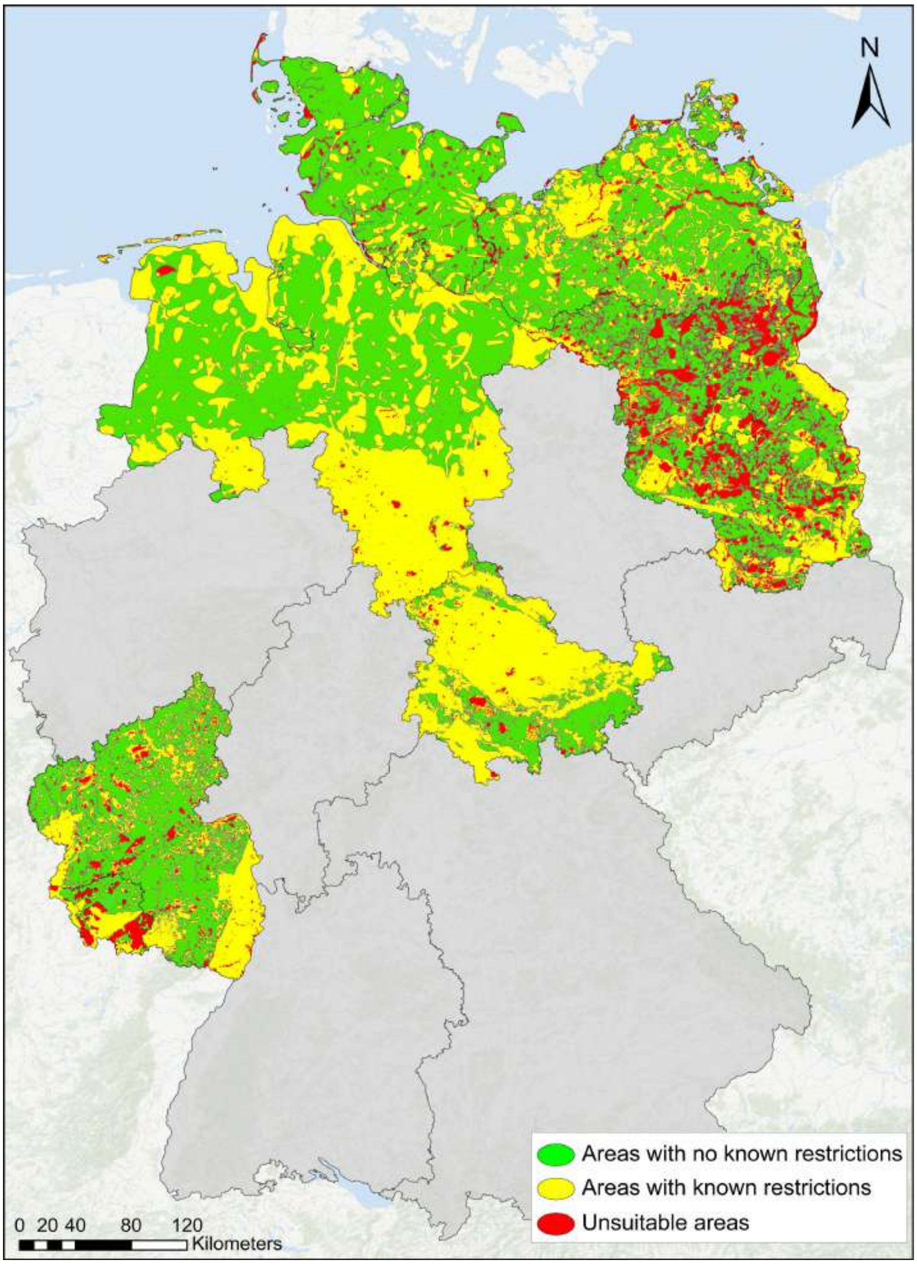


Figure 5: Site-suitability ("traffic-light") maps for SGE utilization via borehole heat exchangers in ten out of sixteen German federal states.

The completed maps for each federal state are gradually published on GeotIS following final review and approval by the respective competent authority. Within GeotIS, the so-called “traffic-light” maps are supported by a range of information retrieval tools and additional resources designed to enhance and streamline its practical use (Figure 6). These include, for instance, a modal window that appears with each user interaction and displays key information such as the suitability class, reasons for restrictions, and links to the specific geothermal and geological portals of the relevant state authority. Additionally, the portal provides a clear explanation of the suitability map, along with detailed information about the underlying data sources.

5. RESULTS AND DISCUSSION

5.1 Area-distribution of suitability classes

Ten out of the sixteen federal states of Germany are shown here with their site-suitability, or “traffic-light,” maps (Figures 5 and 6). Among these are states for which this represents the first-ever regional suitability assessment, including Berlin, Brandenburg, Mecklenburg–Western Pomerania, Saarland, and Schleswig-Holstein. For the remaining states - Bremen, Hamburg, Lower Saxony, Rhineland-Palatinate, and Thuringia - the suitability maps developed in this study can be considered either extensions of existing maps or, in some cases, more detailed representations aligned with a national standard.

Approximately 7% of the covered territory is considered unsuitable for BHE installation, corresponding to about 10,736.8 km² out of 154,184.4 km². Restrictions or conditions potentially limiting SGE utilisation were identified across roughly 40% of the investigated area (61,683.9 km²), represented in yellow in Figure 5. Due to overlapping conflict criteria, about 2.3% (3,480 km²) of this area coincides with zones already deemed unsuitable. Areas with no known restrictions, shown in green, account for approximately 55.3% of the territory.

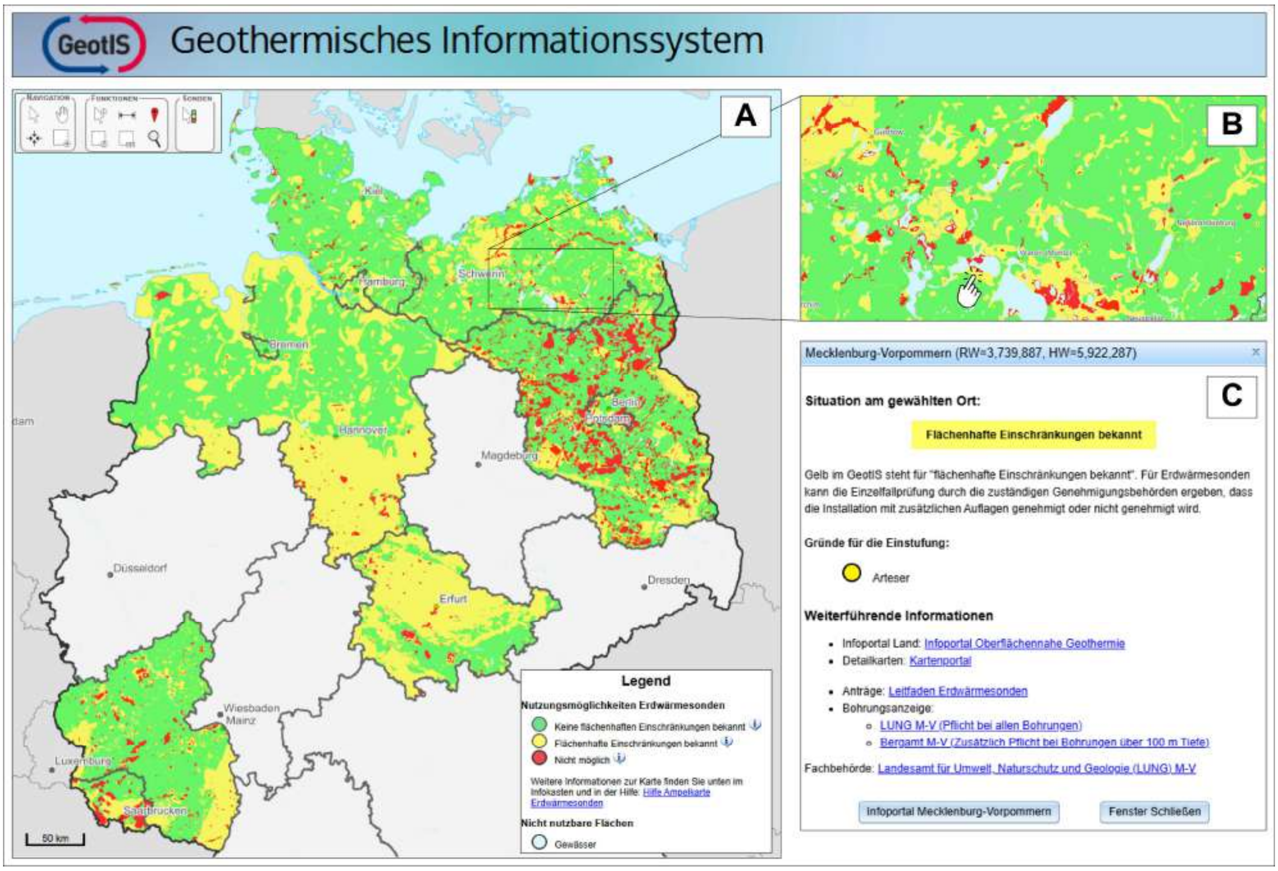


Figure 6: “Traffic-light” map in GeotIS. (A) Overview of the ten federal states covered in this study. (B) Example at higher magnification. The cursor indicates the coordinates selected to activate the modal window. C) Modal pop-up window displaying the specific suitability class of the selected area, the reasons for any restrictions, and links to further information, including the geoportal of the competent state authority. Currently, the map and its associated information retrieval tools are available in German only.

However, significant differences exist at the level of individual federal states, as illustrated in Figure 7. For instance, in Bremen, Hamburg, and Lower Saxony, less than 2% of the area is classified as unsuitable for SGE, corresponding to approximately 0.8 km², 8.8 km², and 558.5 km², respectively. In these states, restrictions mainly stem from the presence of drinking water and curative spring water protection zones I and II. In contrast, about 24.9% of Saarland, equivalent to roughly 636.4 km², is deemed unsuitable for the installation of BHEs. In this case, even extended water protection zones (e.g., zone III) are considered strong conflict criteria. Beyond water protection areas, unsuitable regions also correspond to national parks and/or nature reserves, particularly in Mecklenburg–Western Pomerania, Berlin, Brandenburg, and Schleswig-Holstein. In other states, the influence of nature conservation areas on the suitability is not yet systematically addressed in the regional guidelines or appears to be assessed case-by-case by the permit authorities.

The distribution of areas with known restrictions also varies significantly across the federal states, ranging from 18.4% (2,814.9 km²) in Schleswig-Holstein to 64.4% (453.2 km²) in Hamburg and 68.8% (11,102.8 km²) in Thuringia. A major factor driving this regional variability is the presence and extent of specific geological and hydrogeological risk features. For instance, in the North German Basin, Quaternary glacial deposits and Tertiary claystones and sandstones dominate the first 400 meters of depth (Scheck & Bayer, 1999; Manhenke et al., 2001). Geological hazards in this region are primarily associated with the uprising of shallow diapiric structures originating from the deeper Permian Zechstein strata (Scheck et al., 2002; Paul, 2014). These features cover less than 2% of the area in Lower Saxony, Mecklenburg–Western Pomerania, Hamburg, and Schleswig-Holstein, but exceed 20% in Bremen. Additionally, glacial channels deeply incising into Tertiary formations can significantly limit geothermal installation due to the increased risk of hydraulic connections between aquifers at different depths (Manhenke et al., 2001). In Hamburg, this criterion affects about 341.4 km², equivalent to roughly 45% of the federal state's surface.

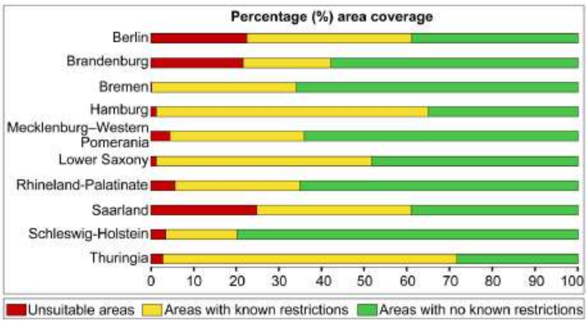


Figure 7: Distribution of suitability classes by percentage area coverage.

Southward, where Mesozoic-Palaeozoic sedimentary units and crystalline rocks are stacked and juxtaposed at shallower depths, both the extent and diversity of (hydro-)geological risks increase. Common features include aquifers with a pronounced layered structure, covering up to 9.9% (1,602.8 km²) of Thuringia and 12.7% (2,516 km²) of Rhineland-Palatinate. Other prevalent risks are associated with the presence of artesian aquifers, which affect about 4% of the territory in Brandenburg, as well as karst features, dolines, and suberosion processes, impacting approximately 12.5% of the territory in Thuringia.

Within the "existing land uses" category, the most significant areal restriction is linked to areas with active or historical mining activities, which together span 5,363.5 km², corresponding to about 3.5% of the total investigated area.

5.2 Considerations for the SGE usage potential

Although still under development and currently limited to BHEs, the "traffic-light" map for geothermal suitability already offers valuable insights into the potential use of shallow geothermal energy resources in Germany. Among the mapped states, the share of areas where BHEs can be installed without usage restrictions ranges from 28.3% in Thuringia to 79.8% in Schleswig-Holstein (Figure 7) and reaches 55.3% across the entire study area. According to the very rough geothermal potential estimate included in Bonn et al. (2022), approximately half of the German territory may be available for unrestricted SGE exploitation. Furthermore, with the implementation of additional technical measures, a basic coverage rate of up to 75% could be achieved nationwide. Although our study does not yet include all federal states, the preliminary results for the extent of regions without known restrictions are remarkably similar. Conversely, regions with identified technical restrictions and limitations account for approximately 37.7% of the investigated area. Accordingly, the preliminary maximum theoretical suitability coverage for BHEs can reach 93%, at least within the federal states included in the present study.

Nonetheless, despite the level of detail achieved in this study, certain factors that may limit suitability have not yet been incorporated into the "traffic-light" map. For example, contaminated sites, albeit listed in the original criteria catalogue (Figure 2), were not represented in the majority of the federal states due to their classification as sensitive information (Figure 4) and thus are not publicly accessible. Similarly, underground infrastructures (e.g., subway systems, tunnels, sewer networks, underground parking) common in urban areas were not considered, either due to unavailable data or the absence of regulatory integration into geothermal guidelines. In some cases, critical geoinformation required to map specific conflict criteria is still missing or under acquisition. As a result, green areas may, in reality, cover a smaller portion of the territory than currently depicted. Moreover, other potential restrictions, such as additional natural conservation areas not initially included, may also exist. All these factors could reduce the total area suitable for SGE exploitation.

It is also important to emphasise that the "traffic-light" maps alone do not represent the effective geothermal potential, neither the theoretical potential (i.e., the physically available thermal energy within a given ground volume; Rybach, 2015; Bayer et al., 2019) nor the technical potential (i.e., the technically extractable heat considering built environment constraints and thermal interference; Miocic et al., 2024). Both types of potential would require a far broader evaluation of parameters, including thermo-hydraulic properties at specific depths (e.g., thermal conductivity, heat capacity, subsurface temperature), local heat demand, building thermal characteristics, building plot features, and technical installation details such as BHE number, depth, and spacing (Walch et al., 2021; Miocic et al., 2024). Nonetheless, the regional suitability assessment presented here serves as a fundamental input for subsequent estimations of technical and developable geothermal potential at a site.

6. FINAL REMARKS

In this contribution, we introduced a novel workflow for determining and mapping site-suitability for ground-source heat pump (GSHP) systems, specifically borehole heat exchangers (BHEs), to support the exploitation of shallow geothermal energy (SGE) in Germany. The main novelty of this work lies in the creation of the first nationwide standardised geothermal suitability map, which is also the first of its kind at this scale in Europe. The map addresses and overcomes the longstanding challenges of uneven geothermal geoinformation availability and inconsistent assessment methodologies across the country's 16 federal states.

To ensure national applicability, the workflow was designed to account for a comprehensive range of factors that may hinder or limit GSHP installation, including geological, hydrogeological, environmental, and land-use-related restrictions. These are represented by 40 conflict criteria, whose assessment is largely governed by state-specific regulations and varies from federal state to federal state. A distinguishing aspect of our approach is that the assessment of conflict criteria was carried out in close collaboration with all of State Geological Surveys of Germany, significantly enhancing both its accuracy and legitimacy.

Site suitability is visualized using a traffic-light color scheme, where red indicates areas unsuitable for the installation of BHEs, yellow marks areas with known restrictions, and green represents areas with no known limitations. The maps of ten federal states are presented in this study, namely Berlin, Brandenburg, Bremen, Hamburg, Lower Saxony, Mecklenburg–Western Pomerania, Rhineland-Palatinate, Saarland, Schleswig-Holstein, and Thuringia. Among them, only about 7% of the mapped territory is classified as unsuitable for SGE exploitation, while approximately 55% shows no restrictions. The remaining 38% are subject to specific usage conditions, such as depth limitations, technical requirements during drilling and/or operation, or require further site-specific investigations. These findings highlight the broad viability of SGE as a sustainable heating solution, particularly in regions with limited access to district heating or relatively low heat demand. However, the coverage of areas deemed unsuitable varies significantly at the regional level (from 0.2% in Bremen to 24.9% in Saarland) reflecting the differing abundance and assessment of conservation and environmental risks. Similarly, the extent of areas with known restrictions ranges from 16.8% to 68.8% across states, largely due to geological variability within the first 400 meters of depth. In particular, the contrasting distribution of Cenozoic versus Mesozoic–Paleozoic lithology and their associated risk factors play a major role in the observed differences between northern and central/southern Germany.

As part of the WärmeGut project, this study supports the strategic expansion of geothermal energy use in Germany. The resulting suitability, or "traffic-light" map, is not only nationally consistent, but it also stands for ease of understanding and accessibility, being already available via the GeotIS geoportal. These qualities make it a valuable tool for supporting the heat transition, enabling clearer identification of SGE opportunities, and helping bridge existing information gaps. In the long term, the "traffic-light" map is expected to become a central reference and informative tool to assist the planning and design of GSHP systems across the country.

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Additional information about the WärmeGut project is available at www.waermegut.de, while the GeotIS web portal can be accessed at www.geotis.de.

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