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Assessing the Availability of Spatial Geothermal Information Using Business Tools and Exploratory Data Analysis

Agnieszka BIEDA[1], Agnieszka CIENCIAŁA[2], Kinga SZOPIŃSKA[3]* and *Peter BLISTAN[4]*

Authors' affiliations and addresses:
[1] AGH University of Krakow,
30 Mickiewicza Av., 30-059 Krakow, Poland
e-mail: agnieszka.bieda@agh.edu.pl

[2] Kielce University of Technology, 7 Tysiąclecia Państwa Av.,25-314 Kielce, Poland
e-mail: acienciala@tu.kielce.pl

[3] Bydgoszcz University of Science and Technology, 7 prof. S. Kaliskiego Av., 85-796 Bydgoszcz, Poland
e-mail: k.szopinska@pbs.edu.pl

[4] Technical University of Košice, Park Komenského 19, 040 01, Košice, Slovakia
e-mail: peter.blistan@tuke.sk

***Correspondence:**
Agnieszka Bieda
AGH University of Krakow,
30 Mickiewicza Av., 30-059 Krakow, Poland
tel.: +48 12 617 34 30
e-mail: agnieszka.bieda@agh.edu.pl

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Abstract
Geothermal energy is a renewable energy source that utilizes heat from the earth's core. Because of that, it is a reliable source of energy demonstrating great potential, which is still used to a small extent. Barriers to the wider use of geothermal energy include high investment costs, location constraints, and the quality of resources at various depths. Opposition from local communities is also a barrier. It results from low environmental awareness of geothermal opportunities, exacerbated by the lack of free access to good-quality geothermal spatial information. Therefore, the purpose of this study is to assess geothermal spatial information availability for selected geoportals using selected business tools and exploratory data analysis. The authors examined geoportals in terms of the information provided, the way it is presented, and the features available. They performed the assessment of their degree of similarity using competitive profile assessment, image graphs, cluster analysis, and affinity analysis. The research confirmed that the available spatial information is characterized by high variability, which indicates the lack of uniform rules for collecting, gathering, storing, and sharing geothermal data. The foregoing leads to information chaos, which can impede investors' investment decisions regarding implementing a geothermal installation on a property.

Keywords
renewable energy sources, geothermal energy, geoportal, competitive profile assessment, exploratory data analysis, image graphs, cluster analysis, affinity analysis.

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Introduction

Energy is a key resource necessary for economic growth and development (Vrijlandt et al., 2019). In addition to conventional (non-renewable) energy, societies have a number of renewable sources at their disposal that have significantly lower emissions and are thus safer for various components of the environment and human life than conventional solutions (Osinde et al., 2019). The growing importance of promoting the use of natural environmental resources is mainly due to the need to stop CO_2 emissions and reduce the greenhouse effect, which is justified by economic and environmental aspects (Janaszek and Kowalik, 2023). Geothermal energy is one of the renewable energy sources and uses heat from the earth's core. It is thus a reliable source of energy demonstrating great potential (Soltani et al., 2021a), which, according to Jolie et al. (2021), will reach 150 GWe of sustainable energy by 2050. Geothermal energy can be used to generate electricity (deep geothermal resources) or, using a heat pump system, for air conditioning and heating (shallow geothermal resources).

One of the main goals of climate and energy policy in the European Union is to increase the share of renewable energy in gross final energy consumption. This goal is confirmed by the provisions of Directive 2009/28/EC (Directive, 2009) and Directive 2018/2001 (Directive, 2018). Increasing the use of renewable energy resources is also driven by the desire to increase national energy security, affecting the proper functioning of the social, economic, environmental, and political spheres. Having considered the foregoing, but also because of growing environmental awareness, governments are beginning to recognize the need to increase the share of energy from geothermal sources in gross final energy consumption. For example, Poland, as an EU member state, has committed to at least a 23% share of renewable energy sources in gross final energy consumption by the end of 2030 (National, 2019). A similar situation applies to other countries. Despite these declarations and the high availability of geothermal resources, their use is still very low. According to Soltani et al. (2021b), the key barriers to the large-scale deployment of geothermal resources are high investment costs, locational constraints, the quality of resources at various depths, and opposition from local communities. The foregoing was also confirmed by other researchers (Vrijlandt et al., 2019; Mathiesen et al., 2020; Osinde et al., 2019; Jolie et al., 2021; Kovanič et al., 2023a; Kovanič et al., 2023b; Kovanič et al., 2024). In order to increase the use of geothermal resources, countries are taking numerous measures to support their potential users, e.g., subsidies for those citizens and local governments who want to use geothermal potential on their properties. In Denmark, for example, a research project (the GEOTHERM project, supported by the Danish Innovation Fund) defined geological, technical, and commercial obstacles to the use of geothermal resources. The project's main goal was to provide data and guidelines to ensure stable operation and implementation of commercially viable geothermal projects and to develop a business model for large-scale geothermal energy use (Mathiesen et al., 2020). The ThermoGIS workflow models were developed in the Netherlands (Vrijlandt et al., 2019). The model identifies the geothermal potential for the Netherlands and is intended to help solve problems with site selection for geothermal investments. It is supported by the government and private companies. In May 2022, the Polish government developed the "Multi-year Program for the Development of the use of Geothermal Resources in Poland" (Multi, 2021), in which the concept of developing and using geothermal energy until 2040, with an outlook to 2050, appeared. The document takes note of the potential of shallow geothermal energy and low-, medium- and high-temperature geothermal energy, energy storage, minimizing investment risks, and proposed legal changes. Issues addressed include conducting research, performing installations, and education and promotion. The Polish government also plans to increase funding for investment in geothermal resources. The cost of implementing the Program until 2050 was estimated at more than PLN 49 billion (Multi, 2021).

Education and promotion are extremely important in raising environmental awareness among the public, which can directly influence the increase in geothermal energy use. An important part of this effort is proper access to high-quality geothermal spatial information, which should be made available to the public in the form of geoportals. When constructing geoportals, it is necessary to use geo-information data, which allows for the introduction of standardized rules for collecting and archiving volumes that characterize the geothermal resource. GIS technology, combining digital maps of the analyzed area with relational databases, will also determine the land's geothermal potential, taking spatial variability in use, development, and geology into account. This seems to be the solution needed to increase the share of geothermal energy in gross final energy consumption. Having analyzed the above, **the purpose of this study is to assess geothermal spatial information availability for selected geoportals using selected business tools and exploratory data analysis.** Achieving this goal required identifying spatial geothermal information shared in each country (city) in the form of geoportals. Furthermore, it was necessary to carry out a quantitative assessment of selected geoportal features (their functionality) using the method of document analysis and critique and competitive profile assessment. The final step was to examine the similarities between the features found in the selected geoportals and attempt to aggregate the geoportals into homogeneous classes. The foregoing was done using a selected graphical technique (image graphs), cluster analysis (dendrogram), and affinity analysis. The analyses mentioned above were performed using Statistica software.

Methods of research

The purpose of the study was to identify existing geoportals in the field of geothermal energy, prepare a quantitative assessment of their features with a determination of the degree of feature similarity, and attempt to aggregate geoportals into homogeneous classes. In addition, the research will help select a geoportal with a competitive advantage. The detailed scope of the research stages is presented in Figure 1.

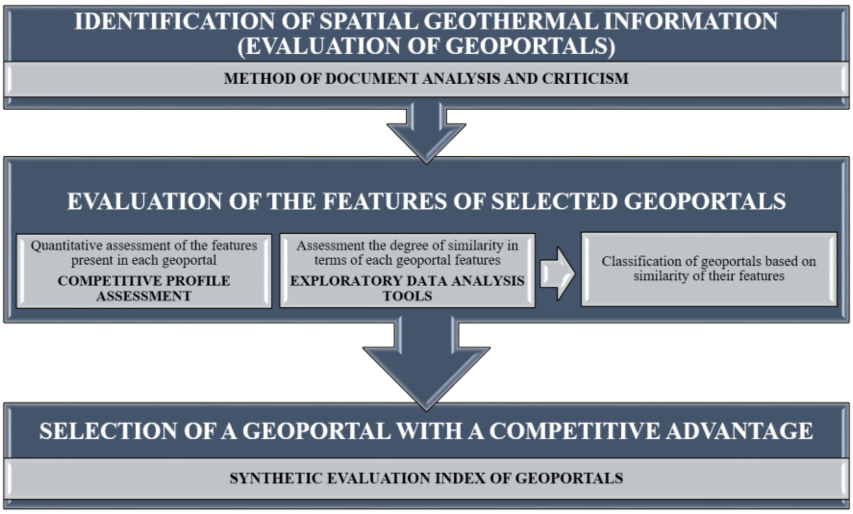


Fig. 1. Scheme of the research. Source: own study.

The identification of geoportals was done using the method of document analysis and critique. The selection of key competitors was guided by several criteria. First, portals that present geothermal information at different spatial scales (regional or local) and different geographic locations (e.g., operating on different continents) were selected. Secondly, portals presenting reliable information were chosen, i.e., portals recommended by public authorities. A quantitative assessment of the features of the selected geoportals was performed using competitive profile analysis. This method is derived from business analysis and is used to identify key competitors in the market (here: geoportals containing geothermal information). When performing a competitive profile assessment, it is necessary to identify key success factors, assign importance to them, and establish a synthetic rating index (Sohel et al., 2014; Bhattacharjee and Dey, 2015). The evaluation of success factors, or the evaluation of geoportal features, assumed that each feature (function) was equally important and each was an equal advantage. Hence, the competitive profile rating scale was "1" when the feature was available and "0" when the feature was not in the geoportal in question.

The similarity between geoportals, performed in relation to their individual features, was assessed using selected exploratory data analysis tools. After a detailed review of available solutions, graphical analysis techniques, cluster analysis, and affinity analysis were chosen for the study. All feature similarity analyses of the selected geoportals were performed using Statistica.

Pictorial charts were used in terms of the graphic analysis technique. These charts represent observations (geoportal features) in the form of multidimensional symbols. The basic idea behind this method is to take advantage of a person's ability to perceive complex relationships between multiple features (variables) as long as similar relationships between features exist for multiple objects (images). The essence of pictorial charts is the representation of individual cases in the form of graphic objects, where the values of variables are assigned to certain properties or dimensions of the object. The way to assign variables is to ensure that the overall appearance of the object best reflects the configuration of the values. Objects are visual representations of configurations of variable values that an observer can easily recognize. The analysis of pictorial charts consists of five stages: (i) selecting the order of variables to be analyzed; (ii) looking for potential regularities, such as similarities between groups of images, outliers, or links between different image features; (iii) identifying possible regularities with the variables affected by these regularities; (iv) reassigning variables to image features to verify the identified link structure; (v), checking and quantifying the identified structure or at least some aspects of it. The polygon method was used in the study in question. These are cyclic images in which the relative values of selected variables for each case are represented by slices of a circle (clockwise, starting at 12:00). The lengths of the section arms depend on the value of the feature they represent.

Cluster analysis involves several different classification algorithms, and its goal is to organize the observed data with an attempt to structure or group them in such a way that the degree of association between objects and objects belonging to the same group is as high as possible and as low as possible between objects from other groups. Cluster analysis can be used to detect structures in data without deriving an interpretation/explanation.

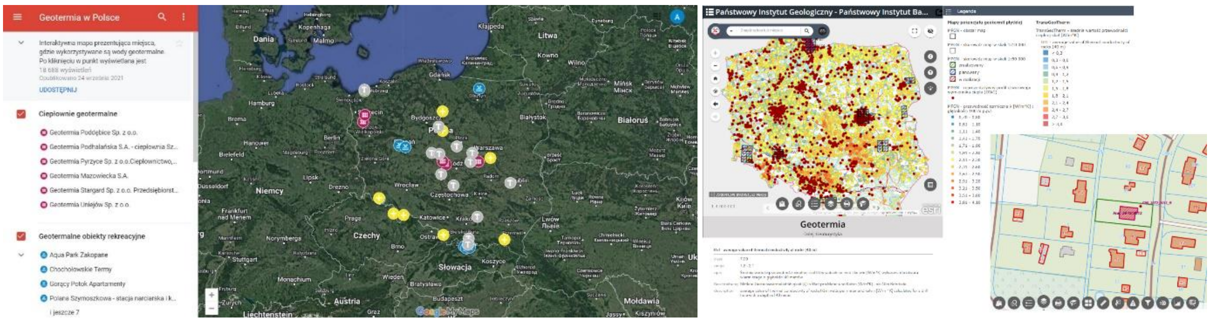
Cluster analysis can be divided into agglomeration, object and feature clustering (block clustering), and k-means clustering.

Affinity analysis is used to detect associations, or links or associations between specific values of categorical variables, in large data sets. Thanks to the use of an a priori algorithm (Han and Lakshmanan, 2001; Witten and Frank, 2000), it is possible to quickly process huge amounts of data in search of the aforementioned type of links, using predefined threshold values for their detection. This algorithm will not only automatically detect relationships that are valid but will also determine the partitioning degree for tables containing valid association rules.

The final stage of the research involved selecting a portal with a competitive advantage based on the calculated synthetic feature evaluation index of the selected geoportals and the results of feature similarity analyses.

Materials

As emphasized by Szalontai (2014), due to the increasing popularity of renewable energy sources, advancements in geographic information systems, and remote sensing methods, there are several possibilities for creating databases related to innovative alternative energy resources. Bieda and Cienciała (2021) point out that numerous maps or cadastres are currently available that provide information on the location and potential of renewable energy sources (RES). The authors indicate, however, that the literature on the subject rarely addresses the issue of geothermal cadastre. According to Meier (2020), geothermal energy is extracting heat from beneath the earth's surface, typically in the form of water or steam, to power electricity, heating, cooling, and other direct uses. The author highlights the fact that a significant amount of the world's geothermal energy potential lies within the Ring of Fire – the volcanoes around the Pacific Ocean. Hajto (2021) noted a meaningful increase in the global utilization of geothermal energy in 2015–2020. The author emphasized that the number of countries reporting geothermal electricity production has risen to 29 (including 11 in Europe). In contrast, the number of countries reporting the use of geothermal resources (among others, ground source heat pumps) has reached 88 (including 34 in Europe). China, Turkey, Japan, Iceland, Hungary, and New Zealand were the world leaders in terms of direct use of geothermal energy. For comparison, Page et al. (2010) noted that the USA generated the largest amount of geothermal energy than any other country in 2010 (four states had geothermal power plants – California, Nevada, Utah, and Hawaii). According to the authors, at the time, geothermal energy accounted for approximately a quarter of the electricity supply in the Philippines, making it the second largest consumer of this renewable resource in the world. The first geothermal power was developed in Italy (Larderello) in 1904. In contrast, Iceland is a pioneer in utilizing geothermal energy for space heating, with 25% of its electricity production coming from geothermal power facilities (Iceland, 2023). As pointed out by Bujakowski et al. (2020), in Poland, there are rich low-temperature geothermal resources that are adequate for district heating, balneotherapy, and recreation (Fig. 2a) (Map of Geothermal for Poland, 2023). Górecki et al. (2015) indicate that the most prospective geothermal province is the Polish Lowlands and Podhale area (Western Carpathians). The authors emphasize that the water in the aforementioned regions is characterized by temperatures exceeding 90 °C and significant discharge values from wells (reaching several hundred m^3/h). Another geospatial data set on geology in Poland is the Central Geological Database (CBDG). This resource operates in several subsystems, one of which is the map portal "CBDG CBDG Geology portal" (CBDG CBDG Geology portal, 2023). It includes maps of the potential for geothermal energy use in Poland (Figure 2b – left side) and spatial data of existing low-temperature geothermal installations (Figure 2b – right side). Geoportal allows for the location of land parcels where heat exchangers operate. It shows the number of holes, the well's depth and diameter, and the land's ordinate or installation date. Data on ground source heat pumps also contain data on the type of system used, power, and technical parameters (depth, length, design, type of working medium, etc.).



a) b)

Fig. 2. Spatial geothermal information in Poland: a) Map of Geothermal for Poland; b) CBDG Geology portal. Source: (Map of Geothermal for Poland, 2023; CBDG CBDG Geology portal, 2023).

In contrast, Slovakia is situated in a region of the world known for its abundance of geothermal resources, which, as stated by Kušnír (2011), are not being fully utilized. As indicated by the author, the largest source in Eastern Slovakia can be found near the city of Košice – in Ďurkov. The drawback of Slovakian sources lies in their low temperature, yet they are still viable for district heating or generating electricity.

Sadeghi and Khalajmasoumi (2015) note that although there is a vast amount of geothermal resources available, theoretically more than enough for the energy needs of humanity, only a very small percentage is actually used due to the fact that exploration involves a high degree of financial risk and uncertainty. Consequently, reliable exploration data on the geothermal potential are required. Elbarbary et al. (2022) emphasize that Geographic Information Systems (GIS) play a key role in integrating various types of thematic layers in larger regions and utilizing them to identify areas with high geothermal potential (Fig. 3) (Energieportal for Munich, 2023). Sadeghi and Khalajmasoumi (2015) confirm that the GIS methods can be applied to discriminate high-potential geothermal resources. According to them, a GIS provides computer-based mapping and integration of information for the management of data layers and decision-making based on combined geographical, geological, environmental, and other information layers to detect the best targets for more evaluation in future steps. They are crucial in identifying the spatial relationships between different pieces of evidence related to a particular phenomenon in such a way that a prediction can be made about its possible occurrence in the area of interest.

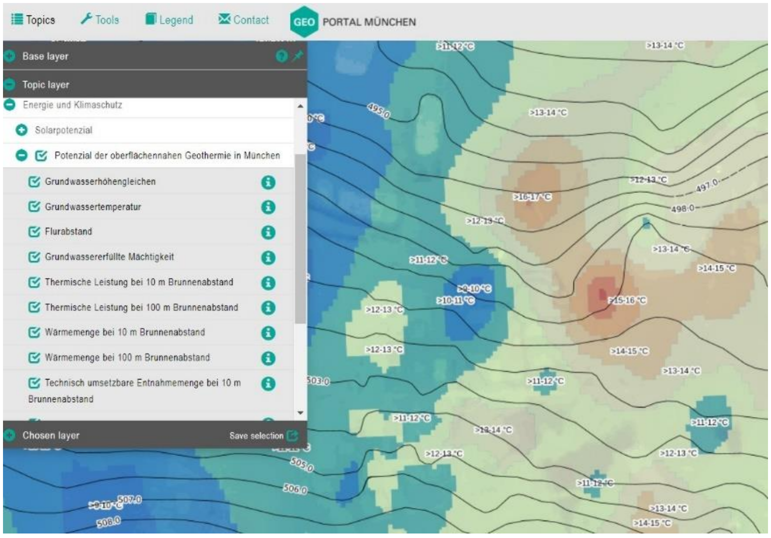


Fig. 3. Fragment of a map showing the groundwater situation, taking into account the basic parameters for the use of groundwater heat for Munich. Source: (Energieportal for Munich, 2023).

Currently, the primary method applied to predict geothermal favorable areas is based on geographic information system (GIS) software, combining multiple digital data layers and multi-criteria decision analysis (MCDA) (Meng et al., 2021; Abdel Zaher et al., 2018; Cambazoğlu et al., 2019). In their study, Coolbaugh et al. (2002) used GIS to integrate various types of geological, physical, and chemical data to predict where extensional geothermal systems are most likely to occur in Nevada. A map was produced based on the combination of seven evidence layers – Groundwater Chemistry, Young Volcanics, Groundwater Depth, Young Faults, and Other Evidence Layers, using logistic regression (The Gravity layer was omitted because of its high correlation with regional heat flux). Through their research, Yalcin and Gul (2017) employed the GIS-Based Multi-Criteria Decision Analysis Method (MCDA) to define geothermal potential areas. The Analytic Hierarchy Process (AHP) was applied in the decision analysis stage, and the pairwise comparison method was used to determine the relative weights of each criterion. According to the authors, the method has crucial benefits, such as the capability to explore existing and potential geothermal fields or achieve more controlled and accurate results by narrowing down the target area. Noorollahi et al. (2007) prepared a geothermal favorability map for Akita and Iwate in Northern Japan. To conduct the research, areas with appropriate thermal and geochemical conditions were identified, considering volcanic rocks, faults, and parameters related to active volcanism. Thermal suitable areas were chosen based on the heat flow and the temperature gradient, whereas geochemical suitable areas were determined by considering hot springs, fumaroles, and alteration zones. The authors state that 97% of existing geothermal wells are currently located within the first priority zone. Meanwhile, Yousefi et al. (2010) employed GIS to formulate a geothermal suitability map for Iran. The study integrated geological criteria (faults, volcanic rocks, and volcanic domes), geochemical criteria (hot springs alteration zones, mud pools), and geophysical criteria (shallow intrusive rocks). Subsequently, the authors proposed eighteen (18) promising areas within the country. In contrast, Soutullo et al. (2020) delineated geothermal resources for the needs of a platform developed for the Asturias region (along the Cantabrian coast in Spain). The estimation of average thermal conductivity relied on data derived from the National Geological Map (MAGNA). The calculation considered the conductivity assigned to each rock material according to tabular data prepared by the Institute for the Diversification and Saving of Energy of Spain. Utilizing a GIS model, Aboud et al. (2021) generated the first geothermal favorability map for Saudi Arabia, discerning the western region as more conducive to geothermal exploration. The GIS framework incorporated various geothermal datasets, including temperature profiles at different depths, heat flow measurements, geophysical parameters (seismic activity, Curie depths), and geological characteristics (faults, volcanic features, rock types, etc.). The authors emphasized that shallow Curie depths present a heightened potential for geothermal reservoirs, while the high geothermal gradient or high heat flow values indicate its average location. Similarly, Elbarbary et al. (2022) used GIS methodology to construct Africa's first regional-scale geothermal potential map. It was based on diverse datasets, including geothermal layers (hot springs and volcanoes), geological thematic layers (rock units and faults), and geophysical layers (heat flow derived from aeromagnetic data and seismicity). The authors employed a weighted overlay technique to generate the map. For the need to identify potential yet undiscovered geothermal resources on the island of Sicily (Italy), Trumpy et al. (2015) employed the Index Overlay method to prioritize favorable conditions. The researchers proposed a fully integrated analysis to classify the hydrothermal resources within regional reservoirs. They highlighted that the most relevant existing information regarding geothermal resources in Italy constituted deep temperature data from gas and oil exploration boreholes, coupled with chemical and physical information from wells and natural thermal springs. Conversely, Cambazoğlu et al. (2019) assessed the geothermal resource potential for the Gediz Graben in Western Anatolia, Turkey. Employing an ideal point methodology, The researchers introduced nine criteria layers into a GIS environment. These criteria included distance to cap rock units, Gutenberg-Richter b-value map, distance to faults and fault density, hot springs and graben center, night-time surface temperature, slope, and NDVI. Following the weighting of layers through the pairwise comparison method, the researchers utilized an ideal point methodology (Technique for Order Preference by Similarity to the Ideal Solution – TOPSIS) to rank geothermal favorability.

As outlined in the report issued by the Canadian Geothermal Energy Association (CanGEA, 2014), a standardized approach for evaluating and mapping geothermal potential using Enhanced Geothermal Systems is currently provided by The Global Protocol. Several portals worldwide are dedicated to planning energy policies, including geothermal energy, either at local, provincial, or national levels. Although the existing geothermal maps or cadastres vary in quality and sophistication, they share a common objective: to provide a preliminary overview of the suitability for geothermal energy utilization in specific locations. It is widely acknowledged that these maps serve as informative resources and do not substitute legally binding declarations or detailed investigation and planning conducted by specialized offices. The scope of the existing solutions also differs – from the settlement level to the province level and, in some instances, spans global perspectives. For example, the Geo-DH Map (Fig. 4) presents the geothermal potential assessment for fourteen countries: Italy, Bulgaria, Poland, Denmark, Germany, France, Netherlands, United Kingdom, Ireland, Slovakia, Czech Republic, Slovenia, Romania, and Hungary (Geo-DH, 2023). The system is based on current information in terms of heat demand and already operational district heating systems, as well as geological data.

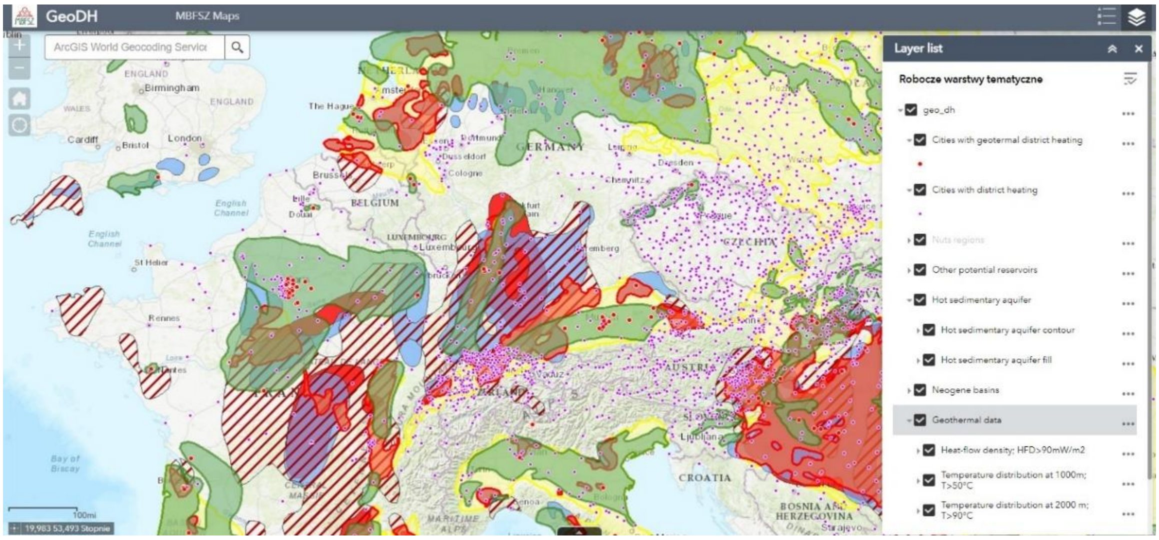


Fig. 4. Geo-DH Map. Source: (Geo-DH, 2023).

ThermoMap (Fig. 5) evaluates the very shallow geothermal potential (vSGP) by assessing the heat conductivity of unconsolidated underground layers up to a depth of 10m. It is specifically tailored for residents of the European Union, as well as scientists, designers, consulting engineers, and authorities. Its primary purpose is to provide a preliminary overview of, or in the case of specific test sites across Europe, more detailed data concerning the local geothermal conditions (ThermoMap, 2023).

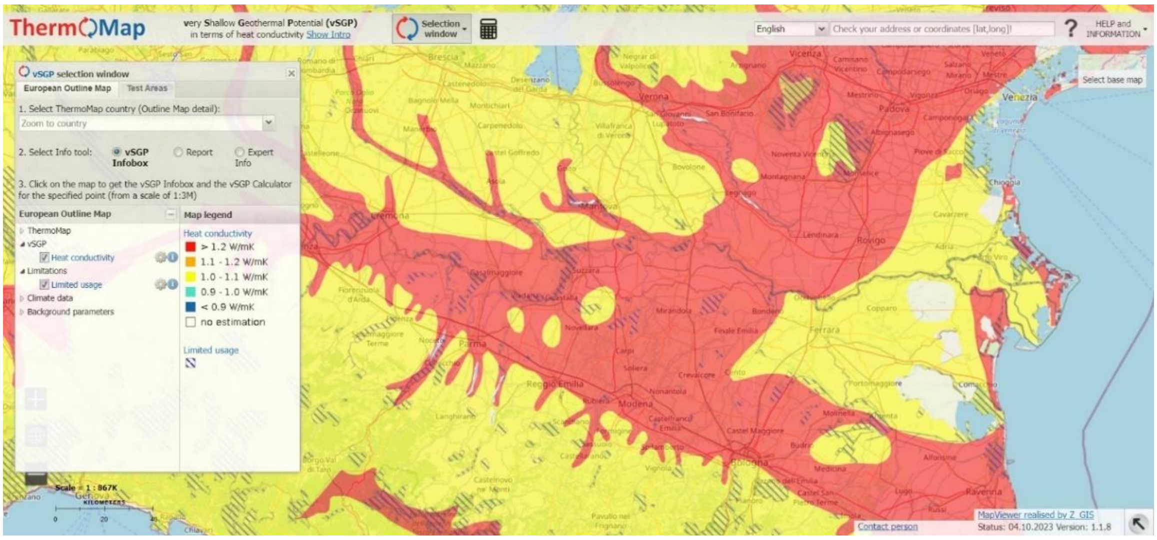


Fig. 5. ThermoMap. Source: (ThermoMap, 2023).

Conversely, the Global Geothermal Power Plant Map (Fig. 6) showcases the distribution of geothermal power plants worldwide. The service provides data on their name, country, the applied technology (Dry Steam, Binary or Flash plant), as well as the installed capacity (MW). It also includes power projects under development (Global Geothermal Power Plant Map, 2023).

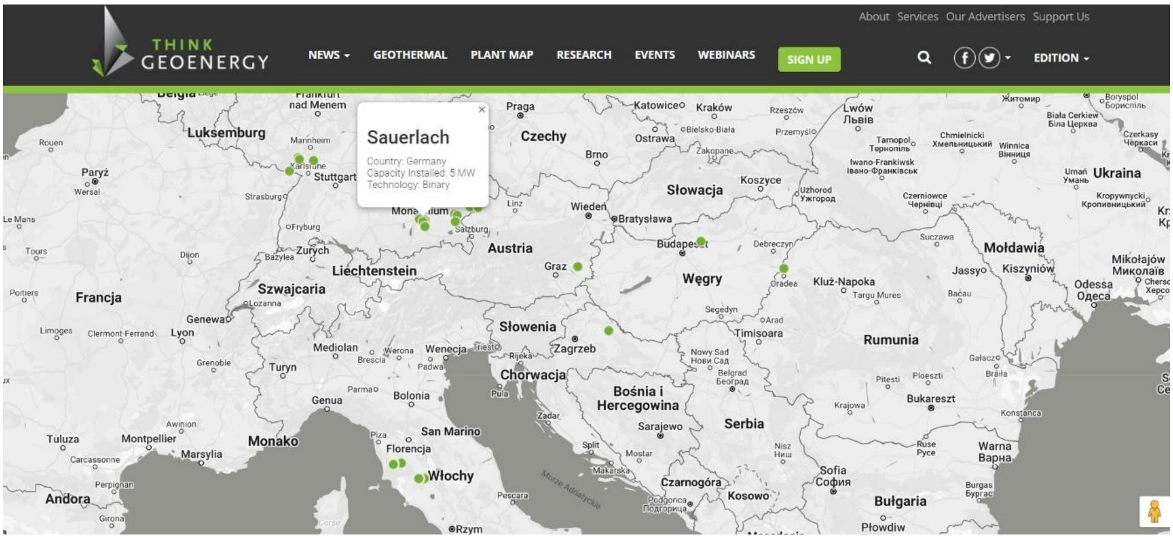


Fig. 6. Global Geothermal Power Plant Map. Source: (Global Geothermal Power Plant Map, 2023).

The Canadian National Geothermal Database (CNGD, 2023) provides maps, protocols, databases, and tools that may be used to assess geothermal resources for four provinces/territories: Alberta, Yukon, British Columbia, and Nunavut. The database stores data such as: temperature at depth, seismicity/microseismicity, permafrost data, heat flow, well logs, thermal conductivity, bottom hole temperatures (BHT), drill stem test (DST), porosity/permeability data, geophysical surveys, water chemistry, etc. As emphasized, it is relevant to all kinds of geothermal energy potential, including direct-use, hot sedimentary aquifer, hydrothermal, geopressure, geothermal fluids co-produced with gas and/or oil and minerals (mining), Enhanced Geothermal Systems (EGS), and more. The information stored includes historical data, as well as geothermal resource assessments provided by research organizations, universities, and publicly and privately funded geothermal exploration projects. All maps were prepared using Geographic Information Systems software (ArcMap 10.1) and are projected to the North American Datum 1983 (NAD83) coordinate system.

The Geothermal Information System for Germany (Fig.7) contains data from more than 30,000 boreholes. While primarily derived from oil and gas wells, the database also encompasses thermal, geothermal, mineral water, and mining wells. There are also hydraulic data (permeability and porosity), information on the hydrocarbon wells drilled in the former German Democratic Republic, temperature data, structural data from diverse map series, and contributions from project partners. The main framework of the system is rooted in 3D subsurface models. The map presents the distribution of geothermally suitable stratigraphic horizons and the location of nearby wells, showing both the lateral temperature distribution and the stratigraphy at a certain depth. The geothermal installations catalog provides information on deep geothermal systems in Germany, covering those currently in operation and those under construction. Notably, it does not encompass near-surface geothermal systems (Geothermal Information System for Germany, 2023).

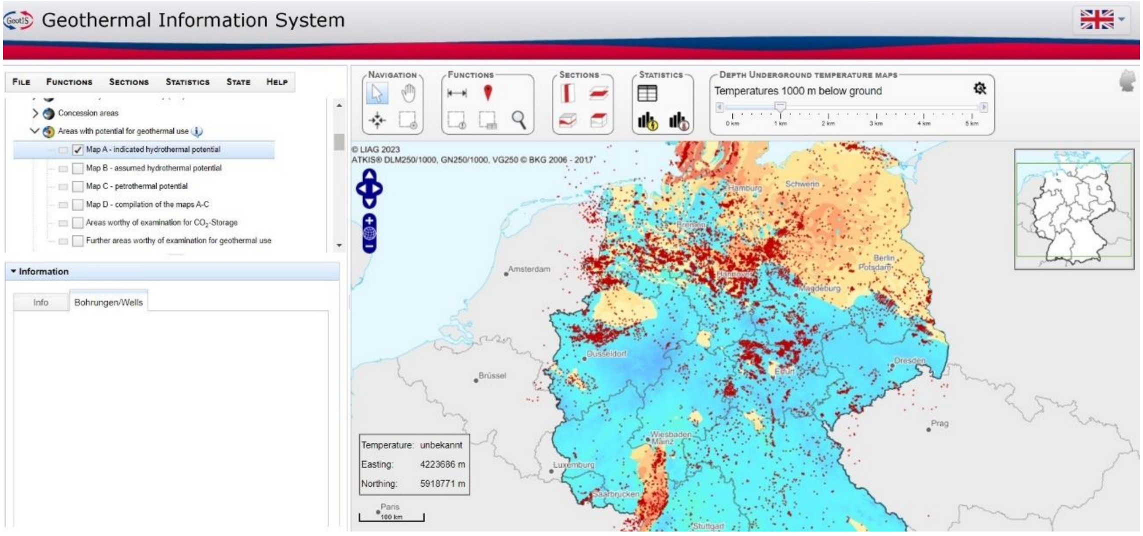


Fig. 7. Geothermal Information System for Germany. Source: (Geothermal Information System for Germany, 2023).

There are also country-specific portals on a regional and even local scale. Geothermies for France (Fig. 8) presents installations, related surface geothermal works on water tables and probes, and examples of surface geothermal energy operations (Geothermies for France, 2023). It also provides regional maps detailing surface geothermal resources, offering users insights into the characteristics of the local subsoil resource. It includes a thermal response test map as well. Users can use these maps to determine the regulatory classification – whether a chosen geothermal energy project of minimal importance falls within the green, orange, or red regulatory zone.

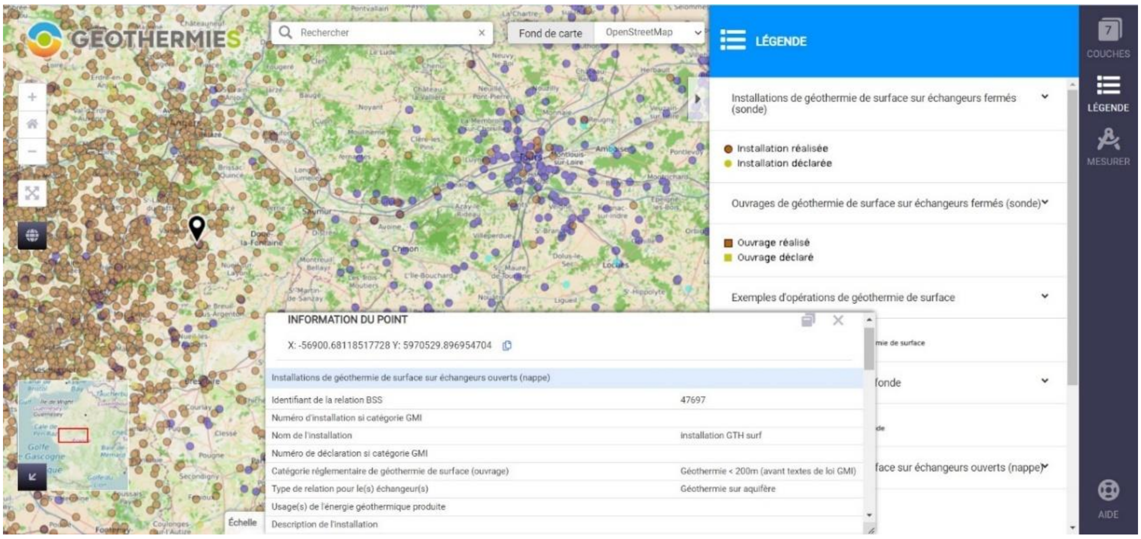


Fig. 8. View of the surface geothermal installations on closed exchangers (probe) and open exchangers (tablecloth) presented in Geothermies for France. Source: (Geothermies for France, 2023).

The Geothermal Information Platform for Hungary (Geothermal Information Platform for Hungary, 2023) (Fig. 9) represents Hungary's first digital platform dedicated to providing geological, hydrogeological, and geophysical data pertinent to the country's geothermal energy resources. The platform serves as a valuable resource for policymakers and national as well as international consortia intending to invest in geothermal projects in Hungary. It encompasses an interactive web map viewer that displays geothermal, geological, and other thematic maps, along with boreholes and related data. Additionally, the platform incorporates three modules (decision tree, risk mitigation, and benchmarking) to support project development. The maps presented are derived from regional geoscientific models, offering a large-scale preliminary overview of geothermal conditions. However, they cannot replace the detailed exploration required for specific project needs.

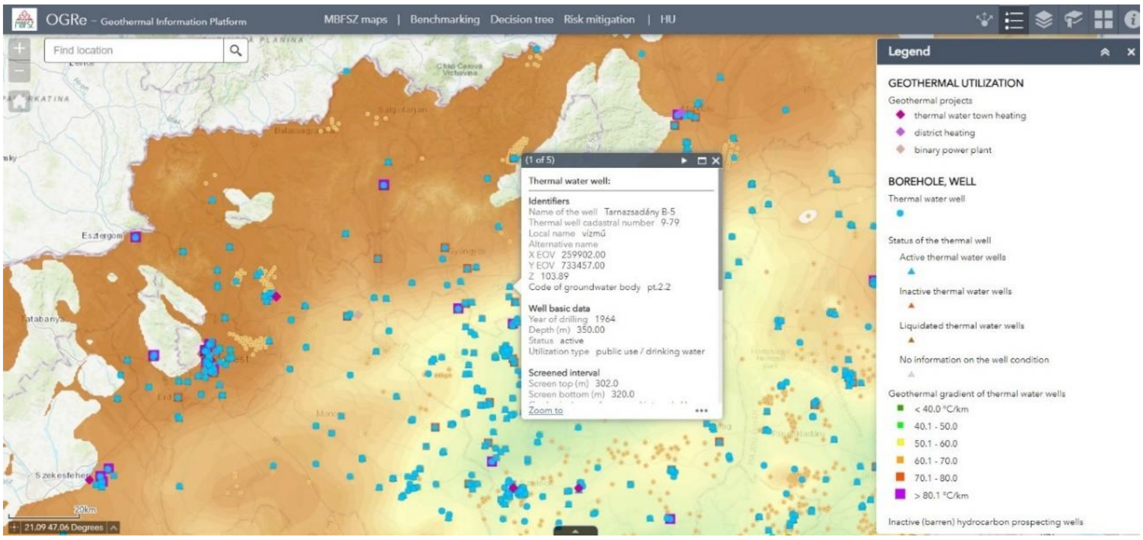


Fig. 9. View of geothermal utilization, borehole, wells, geological horizons, etc., available at Geothermal Information Platform for Hungary Source: (OGRe, 2023).

BdIGSCat – the Database of shallow geothermal energy installations in Catalonia (Spain) collects information on heat exchange systems using geothermal heat pumps, including the installations currently in operation, in project phases, and under construction (BdIGSCat, 2023). It offers an inventory of geothermal installations within the public sector, showing their location, system type, and thermal power. Conversely, the Interactive map of geothermal resources in the United States supplies large amounts of data related to geothermal energy in the United States (United States, 2023). Among others, the portal encompasses state geothermal maps, analyses of hot springs and wells in the Great Basin, data on geothermal potential for enhanced geothermal systems (EGS), insights into low-temperature geothermal resources, identification of hydrothermal sites, details on geothermal plants in operation and under development, transmission infrastructure, and well information, etc. There are also other layers, including volcanoes, major lakes and rivers, and environmental features (wilderness areas, brackish groundwater, wastewater, areas of critical environmental concern, etc.). For example, the Geothermal Information Layer for Oregon (Fig. 10) provides geolocation of geothermal wells and springs, as well as direct-use areas (Oregon, 2023).

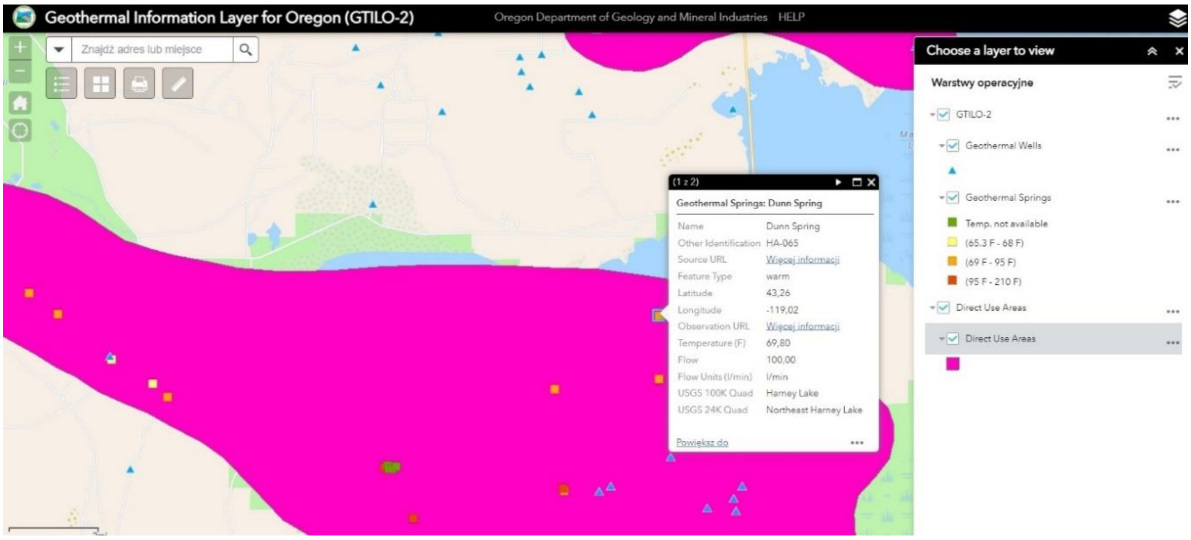


Fig. 10. View of data on one of the geothermal springs at the Geothermal Information Layer for Oregon. Source: (Oregon, 2023).

As pointed out, there are already over 1,800 systems for geothermal use in the city of Vienna (Geothermal Energy Potential Map of Wien, 2023) (Fig. 11). The wien.at city map provides an indicative overview of areas with favorable conditions for utilizing groundwater and near-surface geothermal energy. The data are derived from the knowledge provided by the Federal Geological Survey. To assess the geothermal capability of Vienna, the city's subsoil was categorized into geologically homogeneous areas, which were further translated into the potentials. The available layers include: thermal conductivity at depths of 0-30m, 0-100m, and 0-200m. Apart from its function as an information platform for citizens, the register of geothermal potential also serves as a tool for energy planning.

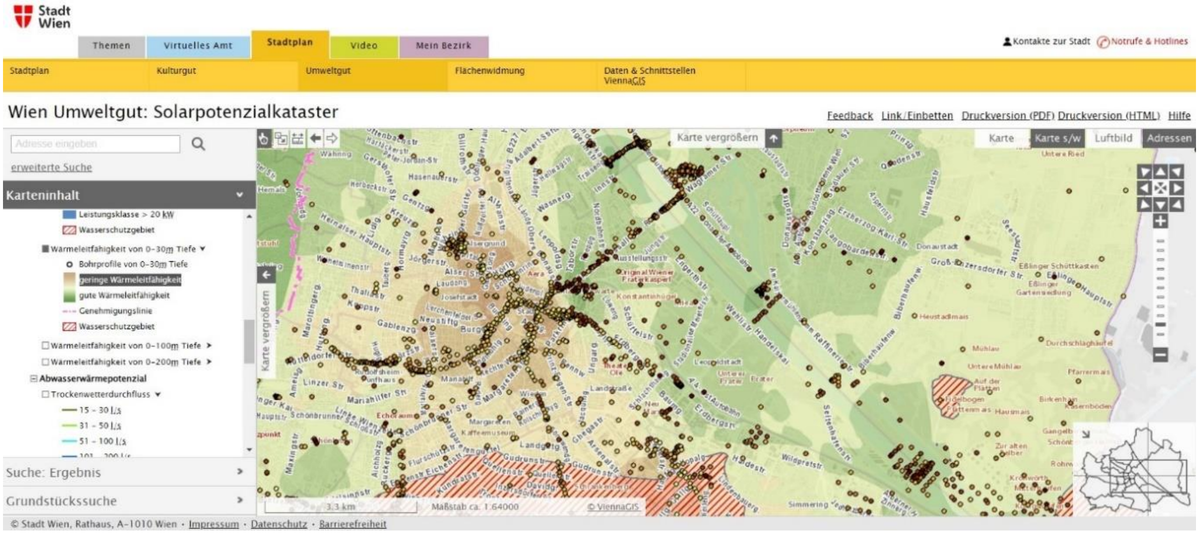


Fig. 11. Geothermal use for selected part of the city of Vienna. Source: (Geothermal Energy Potential Map of Wien, 2023).

Results

Using the method of document analysis and critique, the available map portals were analyzed, and 10 key competitors for a potential new geoportal with geothermal data were selected. These geoportals operate on various continents and in highly developed countries. Selected geoportals show data by region (e.g., Europe) or by city (e.g., Vienna). Each of these geoportals had an interface in English and was recommended by public authorities. After reviewing the features (functionalities) of the geoportals, their content was assessed in terms of the amount of data available (Figure 12, p. 11).

An assessment of competitors' strengths and weaknesses was made for a total of 70 features, which took into account geothermal data, the method they were presented, and available functions. It was assumed that each feature of the geoportal is equally important. Each was also treated as an equal advantage. The rating scale was: "1" when the feature was available and "0" when the feature was not in the geoportal (Dukaczewski and Bielecka, 2009; Siejka and Ślusarski, 2012; Siejka and Ślusarski, 2014; Bieda at al., 2016 As can be seen, the surveyed geoportals are characterized by different content of both geothermal data and the way they are presented (Figure 10). In most cases, a feature appeared in only one geoportal. This demonstrates the lack of a unified structure for the creation of geothermal spatial information and the lack of uniform rules for collecting, gathering, storing, and sharing data. Of the 70 emerging features, only 15 appeared in several geoportals. The most common features are: (i) the possibility of choosing background (e.g., base map, terrain model, satellite images, etc.), (ii) indication on orthophotomaps, Google Maps, topographical maps, Open street maps, etc., and (iii) presentation of location of geothermal wells, geothermal springs, etc. (features appeared in seven geoportals) and (iv) address/name of the geothermal installations (e.g., well), geothermal district heating (feature appeared in six geoportals). A detailed list of feature counts is presented in Table 1.

Global Geothermal Power Plant Map

- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.
- Presentation of location of geothermal wells, geothermal springs, etc.
- Address / name of the geothermal installations (f.e. well), geothermal district heating
- Installed geothermal capacity (approximately)
- Type of the installation / technology applied (binary / dry steam / single flash, etc.)

ThermoMap

- Bulk density
- Indicating zones of low / good thermal conductivity
- Showing calculated conductivity
- Range of heat conductivity
- Heat capacity
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Presenting further zones – water protection area, soil types, etc.
- Calculator of geothermal potential

GeoDH

- Heat-flow density
- Temperature distribution at 1000 m / 2000 m
- Presentation of location of geothermal wells, geothermal springs, etc.
- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.
- Address / name of the geothermal installations (f.e. well), geothermal district heating
- Coordinates – f.e. latitude, longitude of the site
- Installed geothermal capacity (approximately)
- Owner / consortium / operator, etc.

Geothermal Energy Potential Map of Wien

- Depth of thermal heat conductivity
- Indicating zones of low / good thermal conductivity
- Showing calculated conductivity
- Showing performance classes of thermal groundwater use
- Presentation of location of geothermal wells, geothermal springs, etc.
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.
- Presenting further zones - water protection area, soil types, etc.

Energieportal for Munich

- Showing groundwater levels (average low water level)
- Pointing groundwater temperature
- Indicating corridor distance (an average low water level)
- Containing data on groundwater filled thickness
- Presenting thermal power at selected distances from the well
- Showing amount of heat at selected distances from the well
- Presenting technically feasible withdrawal volume at selected distances from the well
- Indicating tertiary top contour lines (TOK) - representation of the elevations of the Tertiary upper edge
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.

Geothermal Information System for Germany

- Inlet / inflow depth
- Containing data on achievable / subserface / reservoir / wellhead temperature
- Annual production geothermal GWh/a
- Data on installed capacity
- Flow rate (Max, operating, water legislation)
- Presentation of location of geothermal wells, geothermal springs, etc.
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Presentation on graphs
- Address / name of the geothermal installations (f.e. well), geothermal district heating
- Coordinates – f.e. latitude, longitude of the site
- Total depth
- Installed geothermal capacity (approximately)
- Date/year of establish / drilling
- Concession area name / Department name
- Data on the state (under construction, operating)
- Primary use (thermal spa, district heating, potable water, etc.)
- Indicating areas worthy of investigation
- Indicating areas worthy of examination for CO_2-Storage
- Statistics
- Sections (horizontal / vertical)

Geothermal Information Layer for Oregon

- Presentation of location of geothermal wells, geothermal springs, etc.
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.
- Address / name of the geothermal installations (f.e. well), geothermal district heating
- Coordinates – f.e. latitude, longitude of the site
- Temperature (f.e. Outflow temperature, Bottom hole temperature)
- Flow
- Total MWe

Map of Geothermal for Poland

- Range of the Lower Cretaceous geothermal reservoir
- mmRange of the Lower Jurassic geothermal reservoir
- Presentation of location of geothermal wells, geothermal springs, etc.
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.
- Photos, hyperlink to site plan / satellite view / website, etc.
- Address / name of the geothermal installations (f.e. well), geothermal district heating
- Temperature (f.e. Outflow temperature, Bottom hole temperature)
- Method of use (e.g., district heating)
- Number of production holes
- Capacity of production holes
- Number of absorption boreholes
- Lithostratigraphy of the aquifer
- Mineralization of water
- Date / year of establish / drilling

Geothermies for France

- Coordinates – f.e. latitude, longitude of the site
- Type of the installation / technology applied (binary / dry steam / single flash, etc.)
- Type of relationship for the exchanger(s)
- Number of structures connected to the installation
- Total length of installed probes
- Date/year of establish / drilling
- Concession area name / Department name
- Data on the state (under construction, operating)

Geothermal Information Platform for Hungary

- Geothermal gradient of thermal water wells
- Presentation of location of geothermal wells, geothermal springs, etc.
- Possibility of choosing background (f.e. base map / terrain model, sattelite images, etc.)
- Indication on orthophotomaps / Google Map / topographical map / Open street map, etc.
- Address / name of the geothermal installations (f.e. well), geothermal district heating
- Code of groundwater body
- Coordinates – f.e. latitude, longitude of the site
- Height of the site
- Total depth
- Temperature (f.e. Outflow temperature, Bottom hole temperature)
- Type of the installation / technology applied (binary / dry steam / single flash, etc.)
- Outflow temperature (°C)
- Screen bottom (m)
- Geological age of screened interval
- Lithology of screened interval
- Date / year of establish / drilling
- Static water level (m)
- Dynamic water level (m)
- Max yield (l/min)
- Water type
- Total methane
- Relative methane

Fig. 12. Functionality of 10 selected geoportals

Table 1. Number of feature (functionality) repetitions in the surveyed geoportals. Source: own study.

Geoportal feature	Number of appearances of the feature in geoportals
Presentation of the location of geothermal wells, geothermal springs, etc. Possibility of choosing background (e.g., base map/terrain model, satellite images, etc.) Indication on orthophotomaps / Google Maps / topographical maps / Open street maps, etc.	7
Address / name of the geothermal installations (e.g., well), geothermal district heating	6
Coordinates – e.g., latitude, longitude of the site	5
Date / year of establishing / drilling	4
Temperature (e.g., Outflow temperature, Bottom hole temperature) Installed geothermal capacity (approximately) Type of the installation / technology applied (binary / dry steam / single flash, etc.)	3
Indicating zones of low/good thermal conductivity Showing calculated conductivity Total depth Concession area name / Department name Data on the state (under construction, operating) Presenting further zones - water protection area, soil types, etc.	2

Exploratory data analysis tools, including image graphs, cluster analysis, and affinity analysis, were used to compare features of geoportals. All analyses were performed in Statistica software. Pictorial charts have been used to take advantage of the human ability to automatically perceive visual similarity between analyzed objects (Lewicki et al., 1992). By using them, the features (functions) of each geoportal were represented as polygons (Fig. 13a). Each was created based on a circle divided into 70 slices (each slice corresponds to one attribute). The values of the variables are represented by the distances between the center of the graph and its edge (in the case under review, it is 1 or not shown on the graph). The features were plotted clockwise on the chart, starting at 12:00. As one can easily see, the vast majority of charts have the slices between the hours of 5:00 and 6:00 colored. The area presents features such as: (i) presentation of location of geothermal wells, geothermal springs, etc. – 7 geoportals; (ii) possibility of choosing background (e.g., base map / terrain model, satellite images, etc.) – 7 geoportals; (iii) indication on orthophotomaps / Google Maps / topographical maps / Open Street Maps, etc. – 7 geoportals; (iv) address / name of the geothermal installations (f.e. well), geothermal district heating – 6 geoportals; (v) coordinates – e.g., latitude, longitude of the site – 5 geoportals.

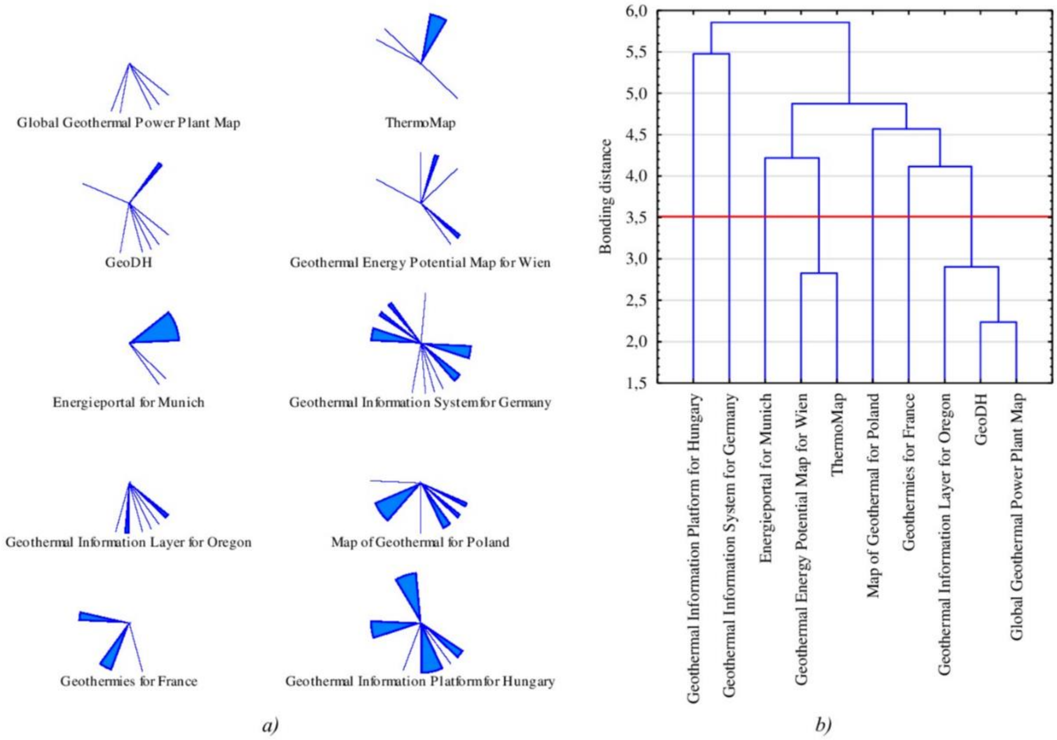


Fig. 13. Results of geoportal data exploratory analysis: a) graphical presentation of geoportal features; b) dendrogram classifying selected geoportals. Source: own study.

Cluster analysis was performed to see if individual geoportals, based on the similarity between them, could be grouped into classes. To carry it out, a dendrogram was plotted (Fig. 13b), which was created using Ward's data agglomeration method (Ward, 1963). The suggested cutoff level is between 2.24÷5.86. However, a plot of bond distances against clustering stages indicates that it should be 3.5. If the cutoff was close to 5.86, the analyzed geoportals would be divided into two clusters. The former would include studies for Hungary and Germany as a whole (containing the most, with 22 and 20 features analyzed, respectively), while the latter would include all others. If the cutoff is lower, the two top-rated geoportals will receive their own clusters due to their completely different content. The remaining geoportals, on the other hand, are further subdivided into sets of several elements. At a cutoff of 4.5, a portal for Poland starts constituting a separate cluster, in which 15 of the analyzed characteristics are presented. The geoportals for Munich and Vienna and ThermoMap, which contains data for most European countries (including those outside the EU), are then described as similar. An equivalent class (with a similar number of other features) would be created by geoportals for France, Oregon, as well as the Global Geothermal Power Plant Map (for most European countries) and Geo-DH (containing data from around the world). The cutoff level at 3.5 results in separate classes: (i) Geothermal Information Platform for Hungary; (ii) Geothermal Information System for Germany; (iii) Energieportal for Munich; (iv) Geothermal Energy Potential Map for Wien and ThermoMap; (v) Map of Geothermal for Poland; (vi) Geothermies for France; (vii) Global Geothermal Power Plant Map, Geo-DH and Geothermal Information Layer for Oregon.

On the other hand, affinity analysis, which is used to detect associations, that is, links or associations between specific values of categorical variables (Agrawal and Srikant, 1994), helped identify the features that most often co-occurred together in the analyzed geoportals. Its results, in the form of a network of association rules, are shown in Figure 14. The network was drawn under the assumptions that: (i) the analyzed feature will occur in at least 50% of geoportals (minimum support of the rule for the occurrence of a feature, i.e., "feature = 1"); (ii) minimum confidence (minimum certainty of the rule), i.e., the percentage of geoportals containing the analyzed rule in the set of those that meet the predecessor of the rule will be at least 50%; (iii) correlation, i.e., the impact of feature presence in a geoportal on the probability of the appearance of another feature in that geoportal being at least 50%. The values adopted resulted in the inclusion of only 4 features in the network that frequently occur together: (i) address / name of the geothermal installations (e.g., well), geothermal district heating; (ii) indication on orthophotomaps / Google Map / topographical map / Open street map, etc.; (iii) possibility of choosing background e.g., base map / terrain model, satellite images, etc.); (iv) presentation of location of geothermal wells, geothermal springs. These are the same features that were indicated as frequently occurring in the pictorial charts.

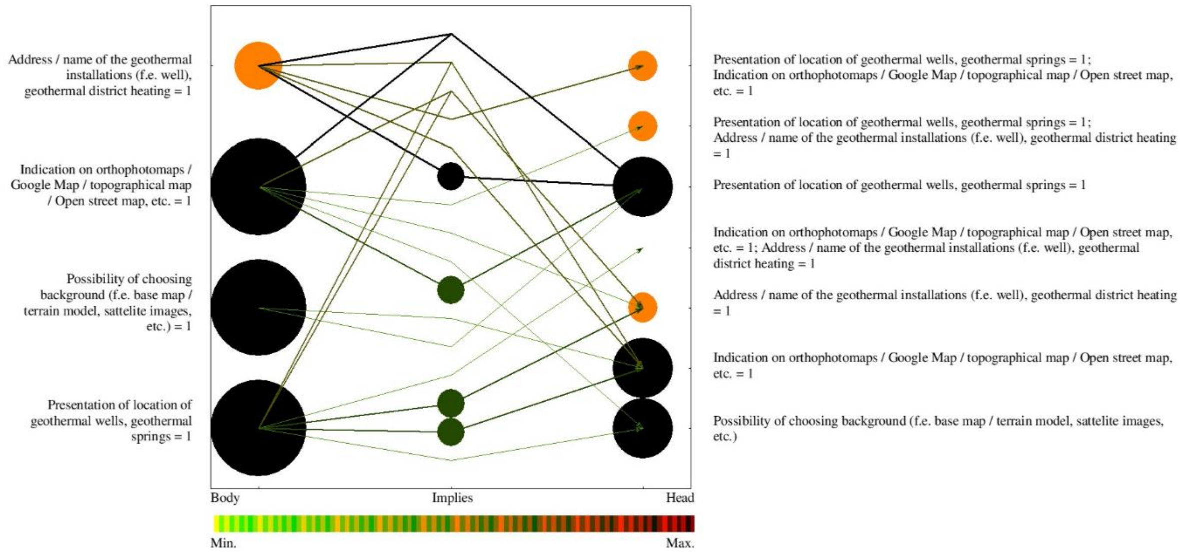


Fig. 14. Feature association rule network of selected geoportals. Source: own study.

After evaluating the features of geoportals and determining their degree of similarity, which became the starting point for categorizing the analyzed geothermal resource, a geoportal with a competitive advantage was selected. Its selection was helped by calculating a synthetic evaluation index ranging from 0 to 70 for each geoportal. It was determined by adding up the weighted scores of the individual characteristics. Each geoportal could have achieved a maximum synthetic evaluation index of 70 if it had all the defined features. Unfortunately, as can be seen, the surveyed geoportals are characterized by extremely high feature variability. The foregoing is confirmed by the calculated synthetic evaluation index (Figure 15). None of the surveyed geoportals achieved a 50% feature count. Only two of the 10 surveyed geoportals had feature counts of around 30%. These were the Geothermal Information Platform for Hungary with 22 features, and the Geothermal Information System for Germany with 20 features. Other geoportals obtained feature counts of about 10% (including: Map of Geothermal for Poland – 15 features, Energieportal for Munich – 10 features, 8 convergent features were obtained by geoportals: ThermoMap, Geo-DH, Geothermal Energy Potential Map of Wien, Geothermal Information Layer for

Oregon and Geothermies for France). Thus, it was found that Geothermal Information Platform for Hungary was the geoportal with a competitive advantage.

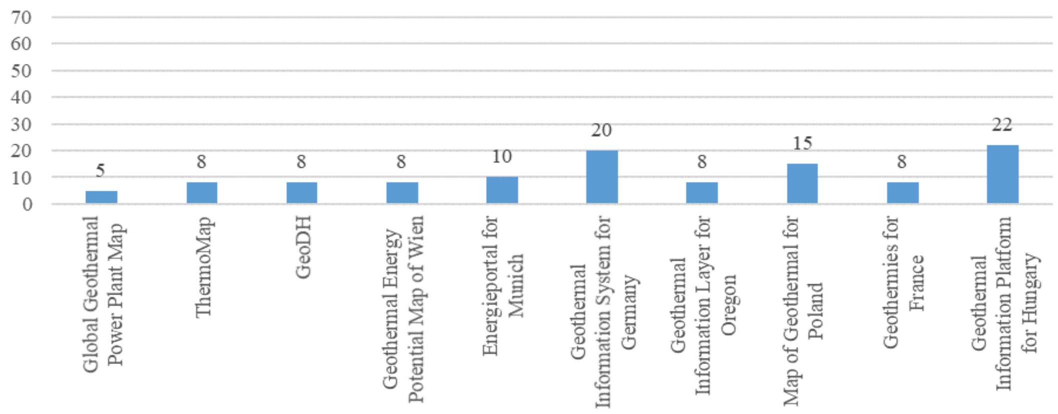


Fig. 15. Synthetic evaluation index of selected geoportals. Source: own study.

Discussion and conclusion

As emphasized in the literature, the potential of existing geothermal resources far surpasses humanity′s energy needs in theory. However, the practical utilization of these resources remains a challenge due to the significant financial risks and uncertainties associated with their exploration. Reliable data on geothermal potential are crucial for identifying highly promising zones and strategically planning energy policies at local, provincial, and national levels. This approach is instrumental in averting misguided investment decisions. Geographical Information Systems play a pivotal role in pinpointing favorable areas by integrating multiple digital data layers and employing multi-criteria decision analysis. While numerous maps and cadastres of renewable energy sources have already been implemented worldwide, geothermal cadastres are notably among the least frequently maintained. The existing solutions vary in quality and sophistication; however, they share a common goal – to provide a preliminary overview of the suitability of geothermal energy utilization in specific locations.

The paper prepares a content analysis of 10 geoportals that make geothermal spatial information available to the public. After a detailed analysis of their contents, it was found that each of them presents a different range of information. This is due to the lack of regulations on the procedures for collecting and sharing data, but most importantly, it is due to the lack of common regulations related to the topology of creating geothermal geoportals. Examples of "good practices" in this regard include geoportals presenting other environmental factors and threats, such as portals for strategic acoustic maps, which present the extent of different environmental noise type occurrences in a unified manner and with the use of a calculation and measurement algorithm, and implement the objectives of noise policy (Szopińska et al., 2022; Szopińska, 2017) or portals presenting air pollution, which provide data from air monitoring stations and are informative and educational (Szopińska et al., 2022). Another direction to eliminate the information chaos occurring with geothermal geoportals is to adopt the solution proposed by the team of Bieda and Cienciała (2021). The team proposed developing a renewable energy source cadastre (RES cadastre) based on the real estate cadastre. The RES cadastre should be an interoperable database system with reliable and legitimate information about sites. The application of the foregoing "best practice" principles could increase the use of geothermal energy, as reliable information provided in an understandable and accessible manner (e.g., in the form of a standardized geoportal) would improve environmental awareness among investors in terms of geothermal energy benefits.

Unfortunately, the analysis conducted with business methods and exploratory data analysis tools showed that as many as 70 features (functionalities) appear in the 10 surveyed geoportals that do not replicate between geoportals. Only two geoportals had 20 features in common. Most of the features appeared one at a time in geoportals. This means that the fragmentation of spatial information is very high. The foregoing made it significantly more difficult to conduct comparative analyses between geoportals. An attempt to divide the analyzed geoportals into subsets similar in terms of features and functionality did not yield the expected results. As a result of the cluster analysis, the 10 geoportals selected for analysis were divided into 7 classes, 5 of which contained only one element, while the other two contained 2 and 3 elements each. Thus, the degree of surveyed geoportal similarity was rated low. The Geothermal Information Platform for Hungary turned out to be a geoportal platform with a competitive advantage. Nevertheless, due to the discussed lack of similarity and significant fragmentation of features, standardization of geothermal spatial information should begin with the unification of the legal situation in the field of renewable energy sources and preparation of the procedure for developing geoportals. Only portals with an English interface were selected for the study. Arguably, such a study assumption may have constituted some limitations. The authors realize that they may have missed numerous valuable geoportals presented in national languages.

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