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De-risking database for Hot Sedimentary Aquifers

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ABSTRACT

At the COP26 Summit in 2021, the world's largest greenhouse gas emitting nations have committed to Net Zero or carbon neutrality targets between the years 2045 to 2060. In parallel, there is an increasing investment in geothermal energy technology to diversify the power mix and decarbonise energy generation. Hot Sedimentary Aquifers (HSAs) are underdeveloped geothermal resources with plenty of renewable heat and investment potential. These large and hydraulically conductive groundwater systems, typically occurring in large sedimentary basin settings away from more conventional geothermal resources in fault zones or volcanic regions. They are hot enough and have sufficient productivity to provide significant low-carbon resources for heating or electricity generation, and often need no or limited well stimulation reducing public acceptance challenges. However, due to subsurface uncertainty and key information gaps there can be an unpalatable level of risk associated with delivery of HSA projects. This paper introduces a new database that captures publicly available information for 45 successful and failed HSA exploration and energy generation projects, enabling a robust assessment of predictive parameters for de-risking prospective HSA developments. The database enables comparison of factors within specific sedimentary basins (e.g., specific to the geological setting of a basin), between nations (e.g., specific to the regulatory regime), and location-independent technical aspects (e.g., drilling technology). We summarise findings from the first phase of data collection, encompassing a suite of project information such as reservoir properties and exploration and operation encountered risks. Case studies are discussed from the UK, the Netherlands, Denmark and Poland and preliminary recommendations for best practice in both HSA project development and data curation are presented.

1. INTRODUCTION

Geothermal energy is an important contribution to diversification of power and heat mix away from fossil fuels in many countries. The geothermal potential of Hot Sedimentary Aquifers (HSAs) has gained great interest in the last 20 years. HSAs are conduction-dominated hydrothermal systems in permeable sedimentary strata at depths of more than 200m and down to 4km (Gillepsie et al., 2013). In contrast to hot dry rock systems, HSAs do not usually require significant well stimulation to establish economically sustainable production rates. Temperatures of geothermal wells that currently produce from HSA usually range from 20°C to 80°C and the hot water produced is suitable for heating applications or occasionally electricity generation when the resource temperature exceeds 100°C. The heat from hydrothermal systems can be exploited via several types of well systems, in accordance with reservoir properties, project strategy and environmental regulations. A so-called "doublet system" includes a production well that extracts hot water and an injection well that re-injects cooled water back into the geothermal reservoir to maintain reservoir pressure or comply with local environmental regulations. Geothermal well systems utilising a single borehole (i.e. that pumps and discharges water) are rarer, with thermally spent water discharged to local water course or into the sea, such as at Southampton, UK (Downing et al., 1984). This configuration was especially selected for old (1970s, 1980s and 1990s) projects but its use is now restricted (or not permitted anymore) in many countries for environmental reasons e.g. high levels of TDS (salinity) or other constituents (Finster et al., 2015). A so-called "triplet" well configuration involves either two production wells and an injection well, such as at Fresnes, France or a single producer with two injection wells such as at Champigny-sur-Marne, France. Sometimes, other configurations such as "quadruplet" or "quintet" systems can be used depending on the thermal properties of the geothermal system exploited.

Countries that have potential HSA resources differ in their strategy of geothermal resource exploitation. The Netherlands has developed many HSA projects since the 2000s, especially in the West Netherlands Basin (Mijnlieff, 2020). The uptake of HSA geothermal projects was fuelled by the rise in gas prices and the crucial need for decarbonised energies. Indeed, the theoretical potential for direct use of geothermal energy in the Netherlands is substantial, at around 90,000 PetaJoule of heat in place (HIP) in the major reservoirs in Permian, Lower Triassic and Lower Cretaceous sandstones (Van Heekeren and Bakema, 2015). Italy is the global birthplace of geothermal industry with the first extraction of boric acid from volcanic mud using geyser steam that took place Larderello in 1880. In contrast to the Netherlands, since the 1900s, the country has mainly focused on exploring hot dry rock systems for electricity generation. One of the reasons for the very low growth of geothermal production for direct uses of the heat in Italy is the lack of effective support schemes and regulation (Manzella et al., 2019).

In addition to economic or legislative boundary conditions, the understanding of properties of the geothermal resource (or uncertainty thereof) is a major factor that facilitates uptake of geothermal development. Those uncertainties, together with financial and technical risks, and paucity of data, increase the risk exposure of projects and contribute to stakeholder reluctance to invest in HSA developments. If not mitigated, such risks can lead to the closure of a well, the abandonment of a geothermal project or a change in the purpose of the well.

Here we present a comprehensive assessment of currently operational and past HSA projects to highlight the most important predictive parameters for success, inform risk mitigation strategies and encourage the development of HSA technology.

2. METHODS

2.1 Systematic Literature Review

A systematic literature review synthesises the current state of knowledge in a specific field, by aggregating data systematically collected from peer-reviewed and grey literature (Figure 1). By examining pertinent literature, this research method allows an understanding of the scope and depth of the field studied as well as identification of research gaps and developing new theories (Xiao and Watson, 2019). Stewart (2004) defined a good review as comprehensive, fully referenced, selective, relevant, balanced, critical, analytical and a synthesis of key themes and ideas.

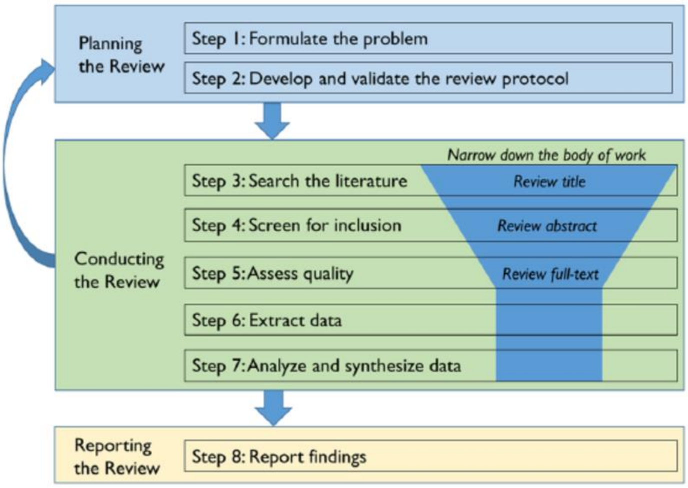

Figure 1: Process of a systematic literature review (from Xiao and Watson, 2019)

An initial HSA de-risking database was constructed using information from various sources (including online databases, research publications and websites). At the time of writing, it covers four countries: the UK, the Netherlands, Poland, and Denmark.

2.1.1 Various Data Sources

The identification and screening process is presented in Figure 2 and is adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocols (Moher et al., 2010; Nguyen et al., 2019). For each search term, the first 10 pages of each utilized search engine were investigated.

Databases were found using search terms in Google including the name of the country investigated as well as keywords such as "geothermal database", "public geothermal data" or "online dataset geothermal projects" "geological survey" (Figure 2). The number of results differed according to the country investigated.

Research articles were searched through search engines like Google, Google Scholar, university or private libraries, in scientific journals and research databases. The search words used included "hot sedimentary aquifer projects", "geothermal energy" "geothermal projects" "geothermal sedimentary projects" together with the name of the country studied. Only articles and abstracts that contained specified keywords and that were properly addressing the research objectives were selected to be further studied (Figure 2).

In the absence of project-related publications or reports, websites could represent a useful data source and can contain borehole reports and details on existing projects that will not be found anywhere else online. The search words are the same than for research articles but using Google. Websites can be projects, such as the trans-European PERFORM project (https://www.geothermperform.eu) whose main objectives are to improve geothermal plant performance, lower operational expenses and extend the lifetime of infrastructure, by combining data collection, predictive modelling, innovative technology development and in-situ validation. Some operators also publicly share data about their power or heat plants on their website. The screening process for website selection is detailed in Figure 2.

Overall, the systematic review process took between one day and one week per country. Most of the time, a second review was performed afterwards, to gain more details for a specific project or well discovered during the first assessment. Specific search words including the name of a well (ex: "PNA-GT-02"), a project (ex: "Thisted"), parameters such as "porosity" or" depth" as well as the words "well report", "project", "final report" or "production test" were then used in Google and Google Scholar. A single key data collection source for all projects cannot be highlighted, as each country has its own political, regulatory and economic circumstances. However, a new trend is materialising in the last decade, with increased nations planning to massively invest in geothermal energy and therefore providing a wide access to the actual state of play of the technology and existing projects. The World Geothermal Congress (WGC) also created in 1995 the "country update" category of papers for the same purpose, that provides an up-to-date review of the geothermal development of a country (Krieger et al., 2022). In WGC 2000 and 2005, 72 countries have reported projects utilising geothermal energy for direct-heat applications or power generation (Lund, 2009), against 88 reports for WGC 2020 (Rumberg, 2020). However, Lund (2009) indicated that not all countries submit regular updates to the WGC, with at least 5 countries that develop geothermal projects for direct heating purposes not included in the Proceedings for WGC 2005.

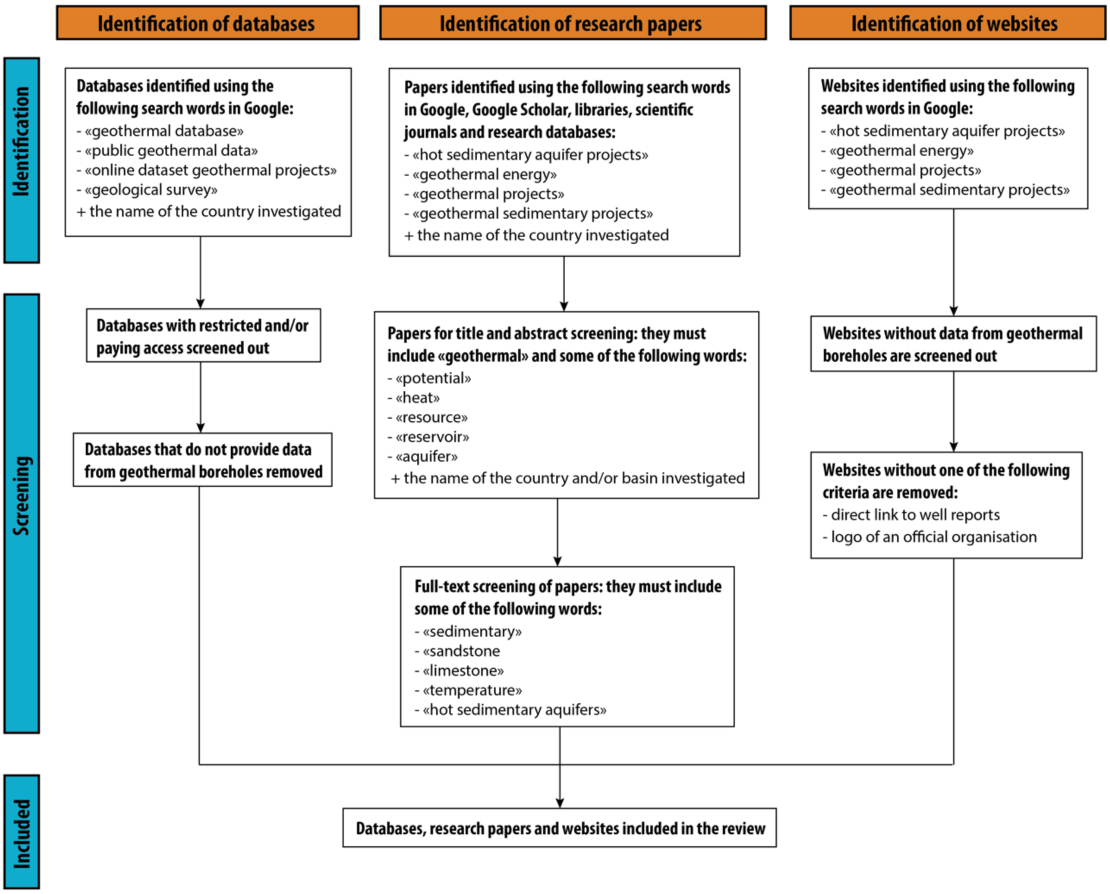

Figure 2: PRISMA flowchart of databases, research papers and website selection for the systematic literature review

2.1.2 A Country-Dependent Approach

Dataset availability is often related to the regulatory regime of a nation and these are dissimilar between the four countries studies in this paper. The methodology applied was therefore somewhat different for each country.

In the Netherlands, the geological survey (TNO) manages an open access database for geothermal projects which encompasses many parameters. General data such as the name and the starting date of the project, the number of wells, and the system type and use of the project are also commonly specified in Dutch scientific papers. Overall, the research process for this nation data was relatively simple and many data were found in a short amount of time.

Poland and Denmark have been more complicated countries to investigate for HSA data. Polish and Danish databases do not provide many geothermal data and information was mainly collected through Google Scholar and Google. However, it took much more time and search words including the name of the wells investigated + "well report" had to be used to obtain further details for the projects. In a third phase, search words were typed in Polish and Danish which increased the number of results.

Data research for HSA projects of the UK mostly involved scientific articles. The latter were found without difficulty using the search words specified in the previous section. Data provided is usually very detailed with parameters for each geothermal resource or reservoir. Although the British Geological Survey has an online database including energy and water datasets, the data can only be displayed in map viewers, which makes aggregating the data very time-consuming.

2.1.3 Data Quality Appraisal

Assessment of data quality is an integral part of a systematic literature review and was performed throughout the entire process. Quality assessment implies checking that the values stored are correct, that there is no erroneous information and evaluation of the quality of the data sources. Most of the data collected comes from either well reports or published papers, and the information provided is therefore considered to be trustworthy. However, a few data could only be found in websites conducting an inventory of currently operational geothermal plants in a given country, with details on some parameters such as well depths, temperature and target formation. Even if only websites that are part of an official organization and/or displayed links to official project or well reports were selected during the systematic literature review process, the information provided is not entirely reliable. In several research papers and reports some variables are only provided as a range of values, which lowers their precision. For instance, a geothermal well drilled in 1981 in Larne, Northern Ireland, gave a porosity range from 15% to 25% for the target Sherwood Sandstone reservoir (Busby, 2014). Such ranges make any comparison or conclusion difficult and reduce data quality as they can only be included in the database as a mean (porosity of 20% for this example). Overall, around 7% of the numerical values of the hydrogeological dataset was reported as a range. Moreover, many boreholes have been drilled several decades ago when drilling, logging and testing techniques were not as advanced as more recent example, resulting in higher chances of inaccurate results and technical issues.

2.2 HSA Database

The HSA de-risking database encompasses a range of parameters that have been classified into four main categories: (1) general project information; (2) geological setting data; (3) hydrogeological property data; and (4) any risks encountered during the project (Figure 3). 36 parameters have been selected to describe each geothermal project as comprehensively as possible.

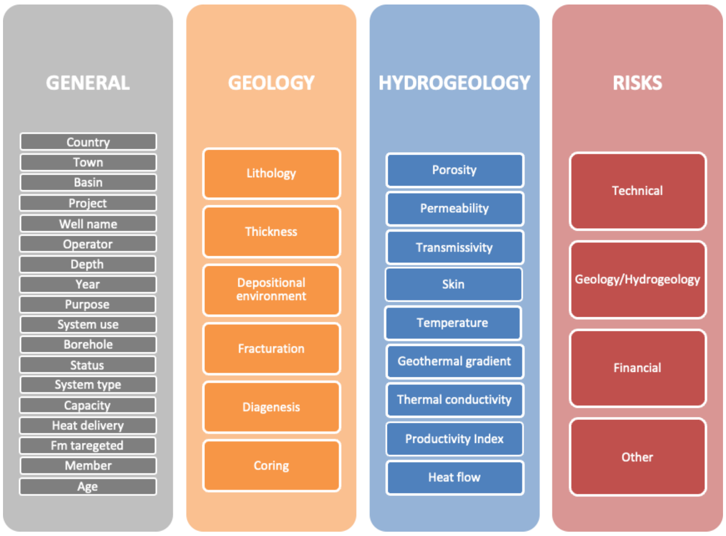

Figure 3: Listing of main parameters researched for each HSA project

General information includes typical variables found for each project, regardless of the field, such as project name, year(s) active, country, host sedimentary basin and targeted geological formation, and drilled borehole data (e.g. depth, name, status, system use, capacity). Within the geology category, parameters assessed included reservoir lithology, thickness (gross and net), and any information related to diagenesis and structural evolution. Collated reservoir information incorporates a suite of fluid and heat flow properties, all of which are strongly corelated with one of three key parameters: porosity, permeability and reservoir temperature. The last category gathers the diverse types of risks that can be faced when conducting a geothermal project. In most cases, risk is related to technical aspects, geological or petrophysical parameters, or project financing.

3. RESULTS AND DISCUSSION

3.1 Data availability and reporting

Interesting findings regarding availability were discovered during the systematic literature review process. The type of data and reports available strongly depends on the country, often driven by regulatory regime. In the Netherlands, the institution of the Mining Law in 2003 considerably improved the availability of information. Since 2003, all geothermal and oil and gas operators are required to publish geological and production data online in an open access database (www.nlog.nl) within 5 years of acquisition rather than 10 years as it was previously the case (Kombrink et al., 2012). The database, managed by the Geological Survey of the Netherlands (TNO) on the behalf of the Ministry of Economic Affairs and Climate, holds various data types such as 2D and 3D seismic lines, licences, oil and gas fields and borehole data. For most Dutch geothermal boreholes, the online database provides well reports, well test results, lithological logs and occasionally descriptions of core or cutting samples. The database access is public, free of charge and detailed. However, only raw data like lithological logs must be published in the online database, while interpreted data such as well tests are exempt from the rule. Developers only have to publish data several years after acquisition, and therefore the database is not fully up to date. The projects completed in the range 2018-2022 are not yet available online as it appears that companies and operators usually wait until the end of the embargo period (i.e., 5 years after acquisition) to publish the data. In old wells, regardless of the country, many petrophysical parameters were not evaluated and very little well or production test data is typically available. Consequently, both recent (2018 and after) and old (1960-1990) projects can lack published data. The Netherlands appears to be the exception when it comes to freely accessible geothermal data repositories, operators in most countries are not required by law to publish project related results.

The Croatian Hydrocarbon Agency (AZU) also provides a free of charge access to reports of Croatian geothermal wells, seismic data, and GIS data through the Croatian Geothermal Virtual Data Room (VDR). However, the VDR is a controlled-access database: it is available for investors only and access is not provided for academic purposes.

In the UK, the British Geological Survey (BGS) retains a wide range of general geoscience data, through datasets, borehole reports and map viewers of the whole nation. However, the available information is not as detailed (i.e. with exact values for many parameters) as the Dutch database as not all reports (and thus data) can be accessed online. The same observation can be applied to both Danish and Polish geothermal databases that usually only provide general data, such as project and well name, depth, coordinates, and drilling date.

Information on geothermal wells drilled in the UK is conventionally published in research articles, most of the time by way of the BGS. Detailed data is usually provided, with parameters for each geothermal resource or reservoir, and information accuracy can be tested by cross-checking multiple articles. The abundance of geological variables in UK papers could be explained by a political desire to facilitate access to data in order to develop HSA projects.

Danish and Polish research papers provide a good overview of existing plants and projects with common parameters included, such as reservoir temperature and total depth of the well, but they do not always specify petrophysical data like porosity or permeability, which are critical for the assessment of a geothermal aquifer. The same observations can be applied to the Netherlands, where a number of scientific articles listing existing hot sedimentary aquifer projects and potential targets can be found, but without details regarding the related geological and reservoir parameters.

Nevertheless, it should be noted that not all projects targeting HSAs were included into the database. As previously stated, there are only little data available on very recent projects, so it was decided to not incorporate any borehole (1) drilled after 2018 and (2) that does not include basic project information (i.e. name, system type, depth, year). Moreover, this study was focused on deep sedimentary reservoirs only, thus shallow technologies such as ground source heat pumps (GSHP) or flooded mine workings are not covered. Aquifer Thermal Energy Storage (ATES) systems were not included either, but as an emergent technology they could represent, if hot and deep enough, an excellent opportunity to enrich the database in the future.

3.2 Development of Geothermal Energy Technology

The database currently includes 88 geothermal boreholes associated with HSAs in the UK, the Netherlands, Denmark and Poland. These boreholes are from a total of 45 HSA projects: one borehole can reach several target aquifers and one project may involve a doublet or triplet (or more) system of boreholes. Fifty-three (60%) of the boreholes were drilled in the Netherlands, 19% in Poland while the other countries represent approximately the same percentage of wells, with 9% for the UK and 11% for Denmark. However, as outlined in the previous section, none of these borehole records have data for every variable, leading to gaps in the database.

The types of wells systems utilised in the compiled HSA projects are reported in Figure 4. More than half of the wells (56%) exploit the reservoir via a doublet or a double-doublet (quadruplet) system, 31% use a single well system and the triplet configuration is utilised in only four projects (9%). A geothermal project in the Carpathian (Poland) is currently exploiting a sedimentary aquifer using a quintet system including two injectors and three producers. The septet borehole system (Figure 4) will be used in another Polish system, that is currently extracting heat using a triplet but whose project assumes the production of four new geothermal wells in the coming years (Cloudzynska, 2019).

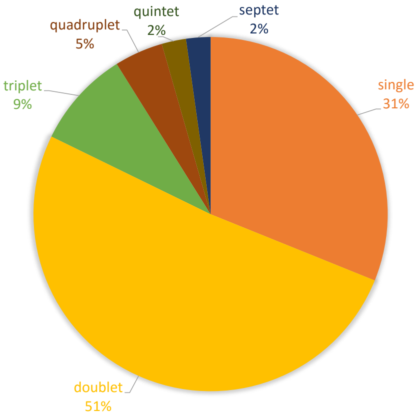

Figure 4: Proportion of borehole system types used in database-included projects

The variation in technical approach in each country can be assessed by looking at the difference between the number of new boreholes versus the number of new projects. The total number of HSA projects increased through time, with almost twice as many new projects developed throughout 2011-2019 than during the previous decade (Figure 5). However, each country shows different progress during the last 50 years with a much greater increase in projects in the Netherlands than any other country.

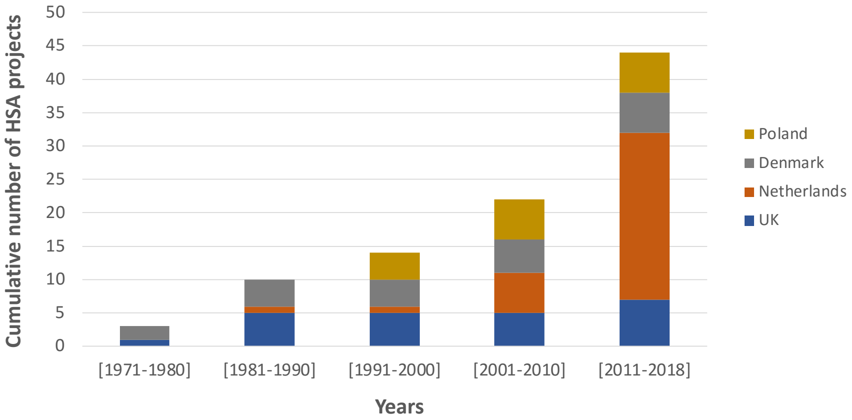

Figure 5: Cumulative number of HSA projects per 10-year interval, including projects that are currently running and shut projects.

In the Netherlands, the first exploration well for geothermal development (Asten-2) was drilled in 1987 in the in the Roer Valley Graben (Kombrink et al., 2012). Dufour and Heederik (2019) suggested that a large amount of natural gas reserves proven in 1986-1987 as well as a lack of support and cooperation between oil companies and the government slowed down geothermal energy development. The legislative framework to explore geothermal energy was unclear due to lack of knowledge and experience of permitting and licencing. Since the end of the 1990s, especially following the Kyoto protocol (1997), geothermal energy received a renewed interest in the Netherlands and steps were taken to create a pertinent legislation (Lokhorst and Wong, 2008). Figure 5 shows that 4 projects were initiated between 2001 and 2010 while only the Asten project pre-dates this period. The emergence of new techniques such as basin modelling, 3D seismic interpretation and subsurface temperature assessments kickstarted a series of studies to estimate geothermal resources (Kombrink et al., 2012). In the middle of the 2000s, high gas prices as well as the pressing need to reduce CO_2 emissions further convinced Dutch authorities and companies of the need to invest in geothermal energy. The number of exploration licenses considerably increased in subsequent years with 93 applications by August 2011, most of them in the West Netherlands Basin (Kombrink et al., 2012). By January 2019, the Netherlands counted 51 exploration licences and 12 production licences. Between 2011 and 2018, the Netherlands have experienced the fastest development of geothermal energy in Europe. Willems and Nick (2019) suggest that geothermal production from the Lower Cretaceous reservoirs could cover up to 20% of heat demand in Zuid-Holland province by 2050. The results from our study show the same trend with only Asten-2 starting in the 1980s and the 1990s, then almost four times more projects between 2011-2018 than 2001-2010 (Figure 5). This pattern is seen in all exploited reservoir units: Lower Cretaceous, Carboniferous and Lower Permian aquifers.

Figure 6 illustrates the evolution of the number of new HSA wells (first bar for each decade), compared to the evolution of the number of new HSA projects since the 1970s (second bar for each decade), giving a ratio of the number of wells per project throughout the decades. The ratio of single to multi-well systems has evolved with time in the Netherlands, with twice as many boreholes as projects between 2011 and 2019 (Figure 6). This feature can probably be explained by increased use of doublet systems with producer and injector wells. However, Willems and Nick (2019) suggest that Dutch doublet deployment has not been efficient and predict that only 1% of potential heat within Lower Cretaceous aquifers will be recovered within 30 years. They also state that individual operators develop individual doublet systems which focus on small and decentralised heat grid demands (such as greenhouse agriculture), while a regional coordinated approach, matching up wider scale and interlinked heat demand, could increase potential heat recovery by several orders of magnitude.

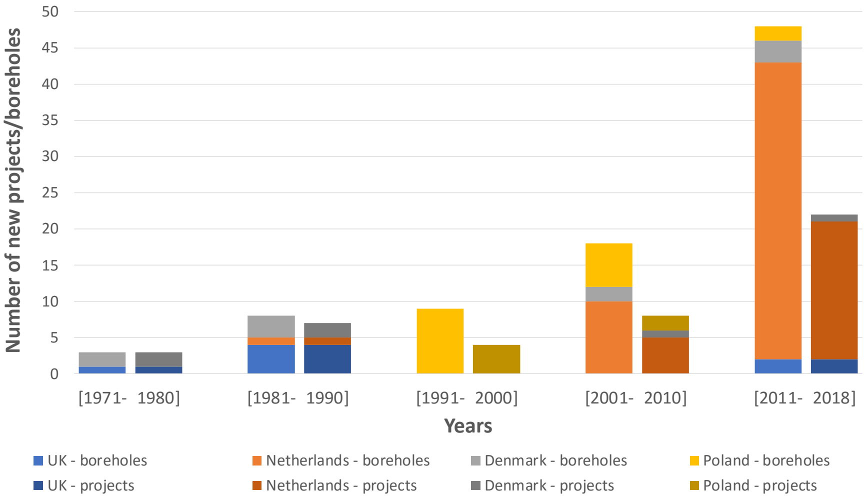

Figure 6: Evolution of the number of new HSA boreholes compared to the number of new HSA projects per 10-year interval. UK is in shades of blue, the Netherlands in shades of orange, Denmark in shades of grey and Poland in shades of yellow. Lighter shades are fore boreholes while darker shades relate to projects

In the UK, the government and the European Commission funded the Geothermal Energy Program following the increase in oil prices between 1977 and 1994 to assess the potential of British HSA resources (Downing and Gray, 1986). Four deep geothermal boreholes were drilled but by the end of the 17-year Program, the only commercial use occurred at Southampton to provide heat to a district heating scheme (Barker et al., 2000). In 2004, the UK became a net-importer of energy due to the decline of the North Sea hydrocarbon production. As fossil fuel supply became restricted and more expensive and the drivers for decarbonization became stronger in the 2000s, geothermal exploration efforts were made to diversify the UK power mix and develop geothermal energy for direct use applications (Busby, 2010). Aforementioned developments and technological drilling advances enhanced the case for exploitation of HSA resources in the UK (Busby, 2014). However, the Southampton District Energy Scheme remains the only deep commercial geothermal project in the UK to date. The borehole was drilled in 1987 to a depth of 1.827 km and is targeting Triassic Sandstones. The Southampton borehole was located at a coastal site so the brine could be discharged directly to the sea and no reinjection borehole was required (Barker et al., 2000). Since then, most new boreholes drilled in the UK have been for demonstration or exploration purposes, resulting in a UK borehole to project ratio of 1:1 (Figure 6). The number of HSA related boreholes peaked in the 1980s (n = 5), with no new wells in the 1990s or 2000s, and two new projects in the 2010s. With a total of one active project (and another one only used for research purposes), the UK lags behind the other countries in the present study in the development of HSAs.

Denmark hosts a large geothermal potential, with estimated HSA resources sufficient to cover household heating supplies for more than 100 years (Sørensen et al., 1998). Since the mid-1990s, the Danish government has focused on low-CO_2 producing heating sources and increased fossil fuel taxes (Mahler and Magtengaard, 2005), leading to increased development of renewable energies. The target is to reach 100% renewable energy by 2050 with a specific focus in some regions such as the Copenhagen area, which holds a substantial geothermal potential and should be carbon-neutral by 2025 (Mathiesen et al., 2010). Technological improvements in the 2000s increased the interest in aquifers with good porosity and permeability properties and high productivity (Nielsen et al., 2004). Figure 6 shows that since the 2000s, there is around twice as many boreholes as HSA projects reported in Denmark (Figure 6), meaning that Danish geothermal systems are mainly doublets plus three single wells. The number of Danish HSA projects increased from beginning of the 1970s to the end of the 1980s (Figures 5 and 6). This trend slowed in the 1990s but resumed from the 2000s and will likely continue in the following decade. Despite those encouraging results, only a fraction of the Danish geothermal resources is being exploited at present, with only six projects reported in this study. Indeed, there are very few options for risk hedging and the regulation for shallow plants is still complex even though it is currently being revised (Røgen et al., 2015).

In Poland, four HSA projects were initiated in the 1990s and two in the 2000s, and development of new projects has since stagnated (Figure 6). However, several Polish projects developed their well systems in the 2010s to meet the ever-increasing heat demand. For example, a new producer well was drilled in 2013 in the Podhale geothermal project that was first initiated in 1992 (Sliwa et al., 2021). Slow growth of new projects is mainly due to a lack of financial support as well as economic and legal barriers (Sowizdzal, 2018). The Central Fund for Water Management and Environment Protection provided financial support for geothermal investments and, as a result, 30 applications were submitted in 2016 (Sowizdzal, 2018). Furthermore, many positive decisions on financing new research drillings for geothermal were issued at the end of the 2010s, and therefore around 10 new geothermal wells are expected in the coming years (Kępińska, 2019). Polish geothermal exploitation has so far focused on small scale heating applications such as space heating, balneotherapy, or bathing (Sowizdzal, 2018). Technology has evolved over the decades: vertical geothermal boreholes made of steel pipes have been gradually replaced by directional wells (Sliwa et al., 2021). Furthermore, many geothermal or former oil wells were reconstructed over the years and may have both prevented the closing of some projects and allow for the lifetime extension of others (Bujakowski et al., 2020). Overall, there is not a widely used well system in Poland. Conversely, they are exploiting HSA utilizing a wide range of systems (single, triplet, quadruplet, quintet, septet) (Figure 6).

3.3 Causes of Failure in HSA Projects

The data analysis showed that HSA projects are subject to four dominant types of risk during geothermal development (Table 1).

Risk	Details
Technical	Well integrity issues: corrosion, formation damage, clogging, wellbore deviation
Geology/Hydrogeology	Changing groundwater chemistry, ground deformation, fault reactivation, aquifer uncertainties, temperature colder than expected, low petrophysical values, insufficient water flow or productivity or injectivity, water pollution, induced seismicity
Financial	Lack of funding, bankrupt, project not commercially attractive, insufficient number of subscribers
Other	No demand for the water nearby, wrong decisions, timing, scheduling

Table 1: Detailed classification of the 4 types of risks catalogued in the database: drilling, geology and hydrogeology, financial and any other risk

A project is defined as failed when at least one of the risks cannot be mitigated leading to abandonment of the project and/or a change in the purpose of the wells. For example, a project drilled for heating purposes that failed to flow water to surface or shows an unexpected low permeability, that is now used for research purposes is considered as having failed. just like a project abandoned because of a well that experienced corrosion deposits, or due to a lack of funding. A project can be abandoned due to one of several of the risks listed in Table 1. Amongst the 45 projects gathered in the database, 40% experienced at least one failure. The proportion of failed HSA projects varies between the UK, Denmark, Poland and the Netherlands (Figure 7). The highest failure rate of all countries is observed in the UK, with six out of eight projects that either are no longer active or never launched. These projects were drilled for research purposes (n=7) or to provide heat to a district heating scheme (n=3). Denmark shows a success rate of 66% with only two out of six projects that experienced at least one issue. 40% of Dutch projects experienced some form of failure, while Poland shows 100% success: none of the six HSA projects that were launched in Poland experienced a single failure. Technological improvements for geothermal energy in Poland such as well reconstructions that have been undertaken in the 1990s, 2000s and 2010s on abandoned or damaged boreholes (Bujakowski et al., 2020), or lack of reporting of failed projects could explain the success rate.

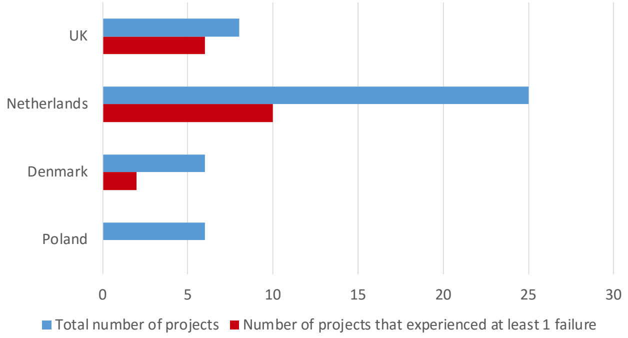

Figure 7: Total number of HSA projects (blue) versus the number of projects experiencing 1 or more failure during project development (red), for each country assessed

4. CONCLUSION

Hot sedimentary aquifers (HSA) have significant potential to provide a low-carbon heat source, but projects must cope with a large number of uncertainties and risks. A database was created to capture key information from HSA-related projects in four countries: the UK, the Netherlands, Denmark, and Poland. The database includes information gathered from 88 boreholes, with the number of recorded parameters for each borehole or project ranging from 11 to 28. Preliminary analysis shows interesting trends regarding the type of borehole systems used for HSA development: each country has its most common system type that highly depends on both technical evolutions as well as the legal framework in place. 51% of the 45 HSA projects employ a doublet system with an injector and a producer. On the other hand, a single well configuration was selected in 31% of the projects (mainly old or/and exploration wells) versus 9% for a triplet system. Regarding project successes, 18 of them experienced one or more failures during their development with a substantial difference in success rate for each country studied.

This paper presents the initial findings of the HSA database development. Future work will expand the geographical reach of the database, expand on the number of factors that may have influenced failure, as well as examining different modes of project failure. Learning from project failure will ensure a rapid roll-out of this exciting new technology to help meet decarbonisation targets and secure energy supplies.

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