Global database of hot sedimentary aquifer geothermal projects: De-risking future projects by determining key success and failure criteria in the development of a valuable low-carbon energy resource

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Abstract

Hot sedimentary aquifers (HSAs) have huge potential for low-carbon energy supply but remain a relatively untapped resource. For example, HSAs could meet 100 years of UK national heat demand. The main technical barriers to HSA deployment are subsurface risks and associated well completion requirement. Numerous studies and policies have attempted to tackle these hurdles, but the sluggish implementation of HSA projects underscores the need for a deeper understanding of what works and what does not. Embracing a "learning from failure" ethos, we compiled a comprehensive database of key performance indicators (KPIs) through a systematic review of publicly available information from 256 HSA projects across eight countries where data were widely available: Australia, Croatia, Denmark, France, Germany, Poland, the Netherlands, and the UK. This database encompasses project specifics, borehole details, geological and hydrogeological parameters, associated risks, and mitigation strategies. Analysis reveals that 26% of HSA projects failed, mainly due to geological and hydrogeological (39% of all reasons), financial (26%) and technical (25%) issues. Mitigation or remediation strategies were implemented by 24% of both failed and running projects, resulting in a general decrease in failure rate over time. Successful projects emphasise the importance of robust pre-drilling site characterisation and ongoing system monitoring. We recommend the adoption of international standards for geothermal play classification and data reporting to enhance appraisal of HSA prospects. By quantifying KPIs for project failure and success, we hope to derisk and inform better budgeting of HSA endeavours, thereby bolstering the success and viability of future HSA projects.

1 Introduction

The energy sector is responsible for 35% of global emissions (Bruckner et al., 2014). In 2022, the share of renewable energy in the fossil fuel dominated global energy mix (electricity, transport, and heating) was 12.3% (Renewables share of total energy supply in the Net Zero Scenario, 2010-2030, 2023). To achieve effective decarbonisation of energy systems, a rapid transition to renewable technologies is required. Unlike other intermittent renewable options, geothermal can produce largely weather-independent low-carbon energy for multiple applications such as baseload power generation and heating of buildings, greenhouses, and heat for industrial processes. With a technical potential of 200 GWe for power and 5000 GWt for heat generation (IPCC, 2011), geothermal energy could supply c. 8% of global power needs and service 17% of the world's population (IPCC, 2007). Geothermal energy produces negligible greenhouse gas emissions (McCay et al., 2019), the comparative land occupancy of a power plant is very low (7.5 km2/TWh, McDonald et al., 2009), and the global average levelised cost for this energy (USD 71/MWh) is competitive against already widely adopted renewable energy options like offshore wind (USD 84/MWh) and solar PV (USD 57/MWh) (IRENA, 2021).

Various parameters are used to categorise geothermal systems e.g., depth, temperature, enthalpy, heat transport mechanism, rock type, geology, resource extraction technology or the environmental-socio-economic viability of a project. The geothermal community lacks a common definition and boundaries for each category, except the latter that is internationally agreed via the United Nation Framework Classification for Resources (UNFC) group (Falcone and Conti, 2019). However, this scheme is only relevant for the sustainable management of geothermal resources and does not fit in this study. The introduction of multiple classifications that are not recognised as international standards (Breede et al., 2015) creates confusion which may be contributing to the slow uptake of geothermal development. This paper focuses on a category of geothermal plays called hot sedimentary aquifers (HSAs). The definition of HSAs found in the literature can be ambiguous, so HSAs are identified here as large, conduction-dominated reservoirs found in sedimentary basins. HSAs must be hot enough and have sufficient productivity to constitute a potential geothermal resource (Gillespie et al., 2013); Busby, 2014; Comerford et al., 2018). Stimulation techniques are typically not required due to the targeted completion of wellbores into zones of comparatively high primary or secondary permeability (Huddlestone-Holmes and Hayward, 2011), but they might be applied to some HSA boreholes to increase the near-wellbore permeability, especially in carbonate reservoirs. Some countries use the alternative term hydrothermal systems, although this is not restricted to HSAs and can encompass other geothermal resource types such as volcanic plays or fault systems, as long as the hot water is produced from naturally occurring water-bearing structures (Moeck, 2014; Breede et al., 2015; Huddlestone-Holmes and Hayward, 2011;Acksel et al., 2022).

Based on the literature for HSAs and deep geothermal energy, we define HSAs as having minimum temperatures of 20°C (Gillespie et al., 2013) and depths of 200 m below ground level (mbgl) (Banks, 2012; AFPG, 2023). These are the shallowest and coolest thresholds found in the literature for HSA or deep geothermal systems. The 200 m cut-off is also used by various countries for energy and water regulations (Tinti et al., 2016; SEPA, 2016; Tsagarakis et al., 2020). HSAs are especially suitable for heating applications, but the water produced can be used for electricity generation when reservoir temperature and average ambient surface temperature difference is sufficient, e.g. ≥ 90°C in temperate climate regions (Kabeyi, 2019). In 2018, 50% of global energy consumption was for heating (IEA, 2019), implying that HSA systems could have a considerable impact in the future energy provision of many countries. In the UK, HSA heat in place (HIP) has been conservatively estimated at 55,834 to 91,112 TWh (Busby, 2014) which if used solely for heat could meet 100 years of current UK demand (OFGEM, 2016). HSAs usually have lower development costs than other geothermal systems thanks to shallower drilling targets, higher borehole flow rates, and use of proven and conventional technology (Barnett, 2009). One of the main barriers for HSA development is related to geological uncertainties. Assessing subsurface thermal resources up to several kilometres below ground can be challenging as the understanding of aquifer properties mainly comes from surface and near-surface data (Gillespie et al., 2013). Information gaps are usually found in rock property, geological, geophysical and borehole data (Witter et al., 2019). These uncertainties, together with financial, technical, and policy concerns, significantly enhance project risk exposure and lead to stakeholder reluctance to invest in HSAs (Gehringer and Loksha, 2012). If not mitigated or addressed, these risks can result in the abandonment of geothermal projects.

Failures can be taken as learning opportunities as is common aviation, amongst other industrial sectors (Syed, 2015). However, in the geothermal industry, reporting failures is not a common practice. In this paper, we present an assessment of operational and closed projects targeting HSAs in eight countries to identify the most important predictive parameters and gaps that must be addressed to de-risk future HSA prospects. We examine the most common reasons for project failure, and we highlight that organisational learning from failures is key to the improvement of the geothermal sector.

2 Methodology

2.1 Systematic literature review methodology

A database of hot sedimentary aquifer heat and power projects was built using a systematic literature review approach to examine the key performance indicators (KPIs) associated with successful and unsuccessful projects. A systematic literature review synthetises the current state of knowledge on a topic by methodically compiling information from peer-reviewed and (high quality) grey literature. This research methodology enables the comprehension of the breadth and depth of the area under study, the development of new hypotheses and the identification of research gaps (Xiao and Watson, 2019). The HSA database covers eight countries: Australia, Croatia, Denmark, France, Germany, Poland, the Netherlands, and the UK. Figure 1 describes the identification and screening process, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Moher et al., 2010; Nguyen et al., 2019). Data were collected from three sources: online databases, research publications and websites. In this work, 'project' refers to a single commercial or research project that may have drilled one or more boreholes, as well as any associated thermal demand. For each country investigated, HSA projects or boreholes were identified during the initial evaluation and screened for more information. More in-depth research was sometimes needed to find out the failure causes of a project: search terms entered into Google and Google Scholar included the name of a project (e.g., "Asten"), name of a borehole (e.g., "GPNE1"), parameters (e.g., "porosity" or "depth"), together with "borehole report", "project", "final report", production test", "closure", or "failure". Only already processed data were included in the database, e.g. we did not compute petrophysical variables (porosity, permeability) from well logs when applicable. Projects initiated after 2022 or without sufficient information such as project name, location or depth were not considered. Initial results for Denmark, the Netherlands, the UK, and Poland were presented in Brémaud et al. (2023): this paper describes results from an extension of the database into Australia, Croatia, France and Germany, and more in-depth analysis of previously explored countries. Other countries were investigated – Spain, Italy, Hungary, Switzerland, Turkey, China, and Algeria – but they were not included in the database due to a lack of publicly available information, reporting or no existing/past HSA projects. The main data collection sources for each project are different, not least because each nation has its own political, legal and economic circumstances.

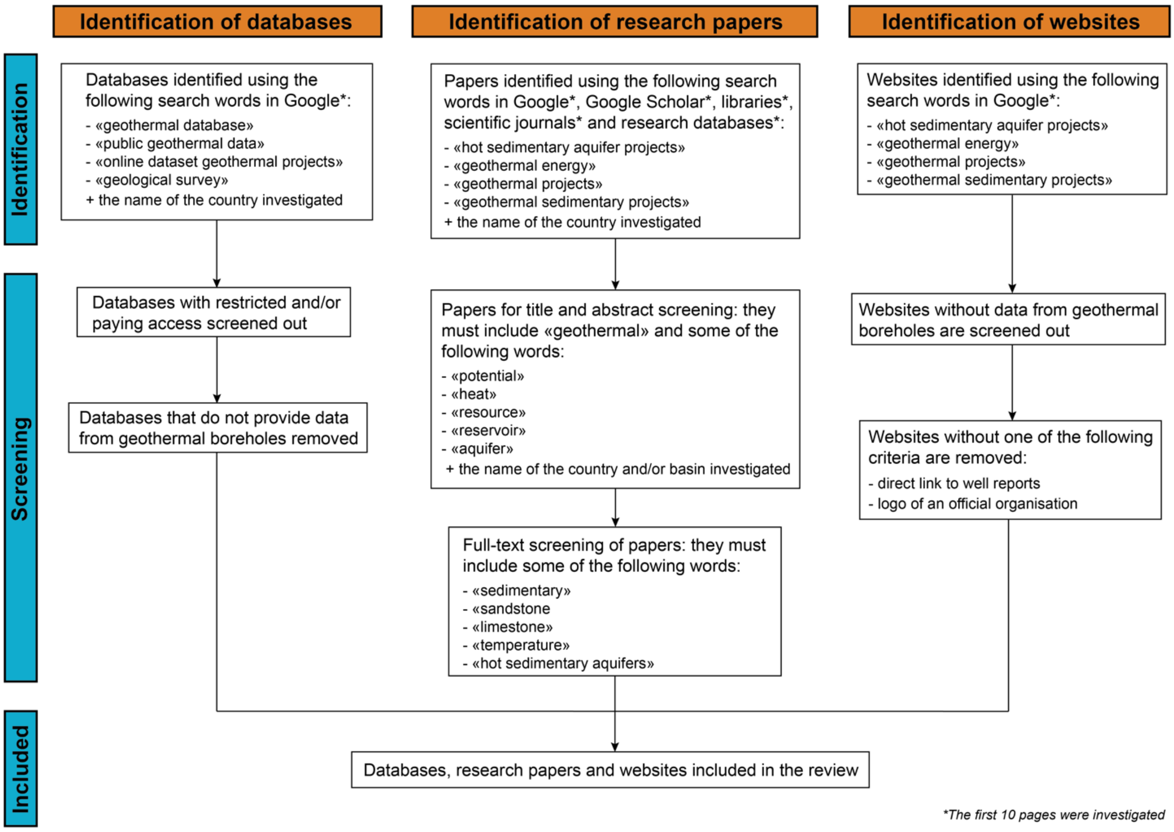


Figure 1: Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flowchart (Moher et al., 2010) of databases, research papers and websites selection for the systematic literature review.

Data collection was also facilitated by various members of the geothermal community who provided access to restricted-access databases and internal reports, shared their datasets, and reviewed some parts of the HSA database. This was especially true for French, Australian, Dutch, and German geothermal projects.

A systematic literature review requires data quality assessment to evaluate the veracity of data sources and ensure information accuracy. Data collated from published articles, end-of-borehole reports or national geothermal databases are considered the most reliable. Occasionally, detailed information on specific projects was only available on websites that inventoried geothermal projects in one or more countries, which are subject to uncertain quality control measures, so it is acknowledged that these datasets may contain transcribing or other reporting errors. A higher likelihood of erroneous results arises from boreholes drilled decades ago, when drilling, logging, and testing techniques were less advanced than today.

2.2 Structure of the hot sedimentary aquifers database

The HSA database considers a wide range of project and borehole characteristics, and 57 parameters were chosen to describe the project characteristics as accurately as possible. The variables were organised into separate categories (Brémaud et al., 2023): (1) general information on the project/borehole; (2) geology variables; (3) hydrogeological data; (4) risks associated with the project/borehole, and (5) mitigation and remediation measures. Table 1 summarises the information collected in the database fields.

Some numerical variables are only provided as a range in publications and reports. Should it happen, the range is recorded in the database, and the median is used for data analysis (Brémaud et al., 2023). For example, Biernat (1993) provided effective porosity and permeability values of respectively 10–30% and 900–1300mD for the Jurassic sandstone reservoir of the Pyrzyce heating plant. In total, 2% of the numerical values of the geological and hydrogeological database parameters were reported only as a range.

Table 1

Description of fields for each category of the HSA database

Fields	Description
(1) General	
Project	
Country	Name of the country investigated
Town	Name of the (nearest) town where the borehole is drilled/planned to be drilled
Basin	Name of the geological basin drilled/planned to be drilled
Project/System	Name of the geothermal project or system
Operator	Name of the organisation/company that is developing the geothermal project
System use	Specific use of the heat produced, e.g., district heating, greenhouse heating
General system use	Broad use of the heat produced, i.e., power only, heat only, research, heat and power, other
System type	Type of borehole system used in the project, i.e., single borehole, doublet, triplet (etc.)
Heat Capacity (kW)	Heat generated or planned by the geothermal project
Power Capacity (kW)	Power generated or planned by the geothermal project
Water disposal	When applicable, network where the pumped water is discharged
Status	Current (2022) status of the project, e.g., active, closed

Outcome	Current (2022) result of the project, e.g., success, failure
Borehole	
Borehole short name	Name of the geothermal borehole
Year	Completion year of the borehole
Closure Year	Year of closure or suspension of the borehole
Total MD (km)	Measured depth of the borehole, i.e. the total length of the wellbore measured along its length
Total TVD (km)	True vertical depth of the borehole, i.e. absolute vertical distance between the rotary table and the end of the wellbore
Target MD (km)	Measured depth of the reservoir, i.e. the length of the wellbore until the middle of the reservoir, measured along its length
Target TVD (km)	True vertical depth of the reservoir, i.e. absolute vertical distance between the rotary table and the mid-reservoir
Coring	Specifies whether cores were collected from the borehole or no (Y/N)
Borehole drilled	Specifies whether a borehole was drilled or not (Y/N). Some of the projects included are in development, or were stopped before the drilling phase
Borehole trajectory	Trajectory of the borehole, i.e., vertical or deviated
Borehole type	Type of borehole, i.e., injector or producer
Flow rate (l/s)	Water flow rate of the borehole
Stimulation	When applicable, specifies which stimulation type was performed in the borehole
Number of sidetracks	When applicable, specifies how many sidetracks were drilled
Target formation/group name	Formation or group name of the reservoir rocks
Member	Member name of the reservoir rocks
(2) Geology	
Age	Age of the reservoir rocks
Lithology	Lithology of the reservoir rocks
Gross aquifer thickness (m)	Total thickness of the reservoir
Net aquifer thickness (m)	Net reservoir interval, i.e. part of the reservoir that has been identified as having a useful capability to store fluids and allow them to flow (Worthington, 2010)

Depositional environment	Depositional environment of the reservoir rocks
Fracturing/Faulting	Specifies any information regarding fractures/faults nearby the borehole
Diagenesis	Specifies any information on reservoir diagenesis
(3) Hydrogeology	
Porosity	Porosity of the reservoir
Permeability (mD)	Permeability of the reservoir
Transmissivity (Dm)	Transmissivity of the reservoir
Skin factor	Skin factor (positive or negative), i.e. region of increased or decreased permeability around the wellbore. Geothermal borehole producing water typically display a negative skin factor (Rutagarama, 2012)
Geothermal gradient (°C/km)	Geothermal gradient in the vicinity of the borehole
Target temperature (°C)	Temperature of the reservoir
Productivity index (m3/h/bar)	Productivity index of the reservoir
Thermal conductivity (Wm-1K-1)	Thermal conductivity of the reservoir
Heat flow (mWm-2)	Heat flow of the reservoir
(4) Risks	
Technical	Problems associated with the technology or processes used in the geothermal project
Geology/Hydrogeology	Issues related to the geological or hydrogeological parameters of the reservoir
Financial	Challenges on the management or allocation of financial resources for a geothermal project
Social	Geothermal risks that are linked to public concerns or interest
Policy	Matters associated with policies and regulations for geothermal projects
(5) Mitigation and remediation	
Sidetracks	Drilling of sidetrack boreholes
Old doublet replaced	Replace an old doublet borehole system with a new one

New borehole added to the project	Add a new borehole to the existing borehole configuration
Refurbishment/improvement work	Perform refurbishment or improvement work on the installations
Back-up reservoir layer	Foresee a fall-back reservoir target in case of issues with the first one
Stimulation	Stimulation or workover of a geothermal borehole
Change in the system use	Modify the planned system use of the geothermal hot water

The "general" section contains essential information about a geothermal project and the borehole(s) drilled, e.g. title, location, timeline, status, capacity, purpose, and the geological formation(s) reached. We distinguished between parameters associated with boreholes (e.g. borehole name, trajectory or type) and fields specific to projects (e.g. capacity, status, outcome). For the purpose of this research, failure is defined as follows: At least one of the risks occurs, cannot be mitigated, and leads to the abandonment of a project during its planned lifetime. Regarding research projects, a project is said to have succeeded when only drilled to investigating the geothermal potential of a reservoir and collect data such as temperature gradients or rock cores. If a research borehole aims to demonstrate a favourable productivity and the geothermal reservoir does not meet expectations, it is here classified as a failure. The "geology" and "hydrogeology" categories encompass variables related to the reservoir properties, structure, composition as well as heat and fluid flow properties. The former subclass includes the thickness and lithology of the rocks targeted and provides information regarding potential fault structures or geochemical alteration processes within or near the borehole. Key components of the "hydrogeology" group are typically petrophysical and thermal properties such as productivity, flow rate, porosity, temperature, thermal conductivity, or permeability; all derived from latest available data (e.g. well-tests or production data). The "risks" category encapsulates the potential technical, economic, and socio-political risks faced by projects. Examples of each risk are presented in Table 2.

Table 2

Detailed classification of the five types of risks catalogued in the database: technical, geology and hydrogeology, financial, social, and policy risks

Risk Category	Examples
Technical	casing/tubing issues, poor condition of the bore, failure of the pumping equipment
Geology/Hydrogeology	Ground deformation, subsidence, fault reactivation, induced seismicity, borehole integrity issues (corrosion, formation damaged, clogging, scaling), aquifer uncertainties, low petrophysical and thermal values, changing or unfavourable groundwater chemistry

Financial	Lack of funding, bankruptcy, not commercially attractive, insufficient number of subscribers, no use of the water nearby
Social	Local communities against the project
Policy	Lack of support by the authorities, wrong decisions, expiration of the drilling permit, environmental awareness, political choices

The "mitigation and remediation" category captures planned interventions for particular project conditions or remediation measures to improve project performance.

3 Results

Although the HSA database contains information from 57 parameters on collated projects, it must be underlined that none of the projects report data for all variables in the public domain. Some installations do not provide any data on first-order variables such as the borehole depth, or any information related to the geothermal reservoir, i.e. geological or reservoir parameters. Thus, almost 34% of database cells are blank, rising to 56% for geology and hydrogeology values.

The database collates information on 256 projects targeting HSAs in seven European countries: Croatia, Denmark, France, Germany, Poland, the Netherlands, and the UK; plus, Australia. The target aquifer can be produced using various borehole systems (e.g., single, doublet or more boreholes), and some boreholes are producing from several geothermal reservoirs. Therefore, from these 256 projects, a total of 464 boreholes and 51 unique target reservoirs from 477 total data entries are reported in the database. 202 boreholes (44%) were drilled in France, followed by Germany (n=88, 19%), Australia (n=64, 14%) and the Netherlands (n=53, 11%). The remaining countries each represent < 6% of the total number of boreholes: 5% (n=22) from Croatia, 4% (n=17) from Poland, and 2% from Denmark (n=10) and the UK (n=8). The results and variables presented in this paper will thus be influenced by the prevalence of French projects.

Over half of the projects (56%) use a doublet system configuration, i.e., with a producer and an injection borehole. Around one third (30%) use a single borehole, and the thermally spent water is discharged into surface watercourses (32%) (e.g., rivers, streams), ponds (11%), or the sea (2%); transferred to local water network after treatment (21%) or used for agricultural purposes (3%). A triplet configuration is utilised in 18 projects (7%) and can entail two producers and one injector (57%), or one producer with two injectors (43%), primarily based on the project requirements for reservoir productivity. The remaining projects use more advanced borehole designs, such as four or five boreholes, and two of them are produced through a septet and a sextet (0.4%).

3.1 Growth of geothermal exploitation over time

Figure 2 shows the number of new boreholes (first/lighter bar) and the number of new projects (second/darker and stipple bar) since the 1890s. Only nine projects (corresponding to ten boreholes) were initiated in Australia, Germany and later in France up to 1960. Seven boreholes were artesian, and the hot water is, or was, typically being used for pools and spas. The two remaining boreholes were former oil boreholes drilled in France. The 1960s saw an 11-fold increase in new projects until the end of the 1980s (n = 103), mostly due to developments in France (n=81). The first geothermal projects in the Netherlands, Croatia, UK and Denmark were also initiated in 1960–1990. This slowed down in the 1990s with only 19 new projects, although this decade shows a significant increase in new projects in Australia, Germany, Croatia and the first four HSA projects in Poland. The number of new projects increased again in the 2000s (n=30) and 2010s (n=82), a high proportion of them being initiated in the Netherlands, France, Germany, and to a lesser extent in Australia.

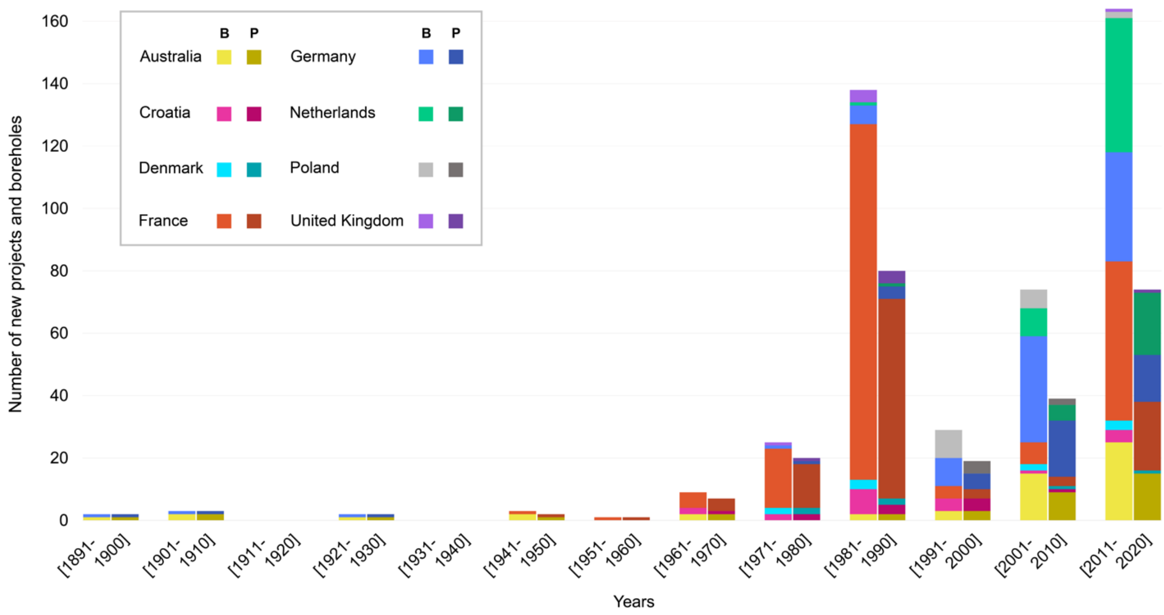


Figure 2: Number of new HSA boreholes (first, lighter column) and new HSA projects (second, darker column) per 10 year interval since 1891 for Australia (yellow), Croatia (pink), Denmark (turquoise blue), France (orange), Germany (neon blue), the Netherlands (green), Poland (grey) and the UK (purple). The increase in the ratio of boreholes (B) to projects (P) indicates a greater use of multi-borehole systems.

Most pre-1961 projects were single borehole systems, and the number of multi-borehole systems has increased with time (Fig.2). Countries such as France, Germany, the Netherlands, Poland and Australia show an evolution from around one borehole per project at the onset of geothermal energy development, to twice as many boreholes as projects as the industry matured and environmental regulations were established, especially regarding water disposal. This trend is seen to a lesser extent in Denmark, indicating a greater prevalence of single borehole systems. The evolution of borehole configuration in Croatia does not show a clear trend in the ratio of boreholes/projects. Though it has a comparatively small number of total projects (n = 6), the UK stands out with a borehole-to-project ratio of 1:1 for each decade, i.e., every one of the 6 UK projects to-date has pursued a single borehole strategy.

3.2 Geological and reservoir parameters

Sixteen parameters depicting the geological characteristics and behaviour of the reservoirs have been included in the HSA database. Figure 3 overlays collated information from HSA boreholes for which basin, lithology, porosity and permeability data were available (179 data points, representing 38% of the total data entries). The two main lithologies shown in Fig.3 are limestone (70%) and sandstone (28%), followed by mixed reservoirs made of claystone and sandstone (2%) or limestone and sandstone (1%). Data are also clustered depending on the 14 geological basins where the boreholes were drilled. The sandstone domain (yellow ellipse in Fig.3) shows an extensive range of permeability versus porosity values (permeability: 1–104 mD and porosity: 8%–38%), largely due to six outlying data points from a borehole in the West Netherlands Basin (purple data points with porosity >20% in Fig.3). In 1987, the first Dutch geothermal borehole was drilled in Asten (the Netherlands) to assess the productivity of six Lower Cenozoic reservoirs for heat applications. Following low transmissivity results, the borehole was eventually abandoned (Mijnlieff, 2020). Limestone reservoirs (green ellipse in Fig.3) have significantly tighter ranges in values (permeability 102 to 104 mD; porosity 4%–24%). 99% (n=124) of the limestone data points come from the Dogger reservoir of the Paris basin (green triangles in Fig.3) and the remaining limestone data point (yellow triangle in Fig.3) corresponds to a borehole drilled in the Carpathian Basin. The black dotted line distinguishes between EGS porosity/permeability domains that require hydraulic stimulation to run (below the line), and those where stimulation is not often used for enhancing permeability (Moeck, 2014). All data points but two are located above the black dotted line. The two points located below the threshold are boreholes initiated in the Otway Basin (Australia) and the Himmerland Graben (the Netherlands) that failed due to unfavourable reservoir conditions.

Figure 3 underlines a lack of available petrophysical data. 48% (n=14) of the basins in the database (n=27) are not represented in Fig. 3 as no information was available. Only 3 of these 14 basins show more than 3 data points. Limited data from German (1%), Australian (3%) and Croatian (0%) projects are represented, while most Danish (90%) and French (64%) projects have available petrophysical information. This trend is similar for all geological and hydrogeological parameters, with relatively little information available. Reservoir parameters such as productivity index, thermal conductivity and heat flow only contain values for 13%, 1.2% and 1.2% of the HSA database entries respectively.

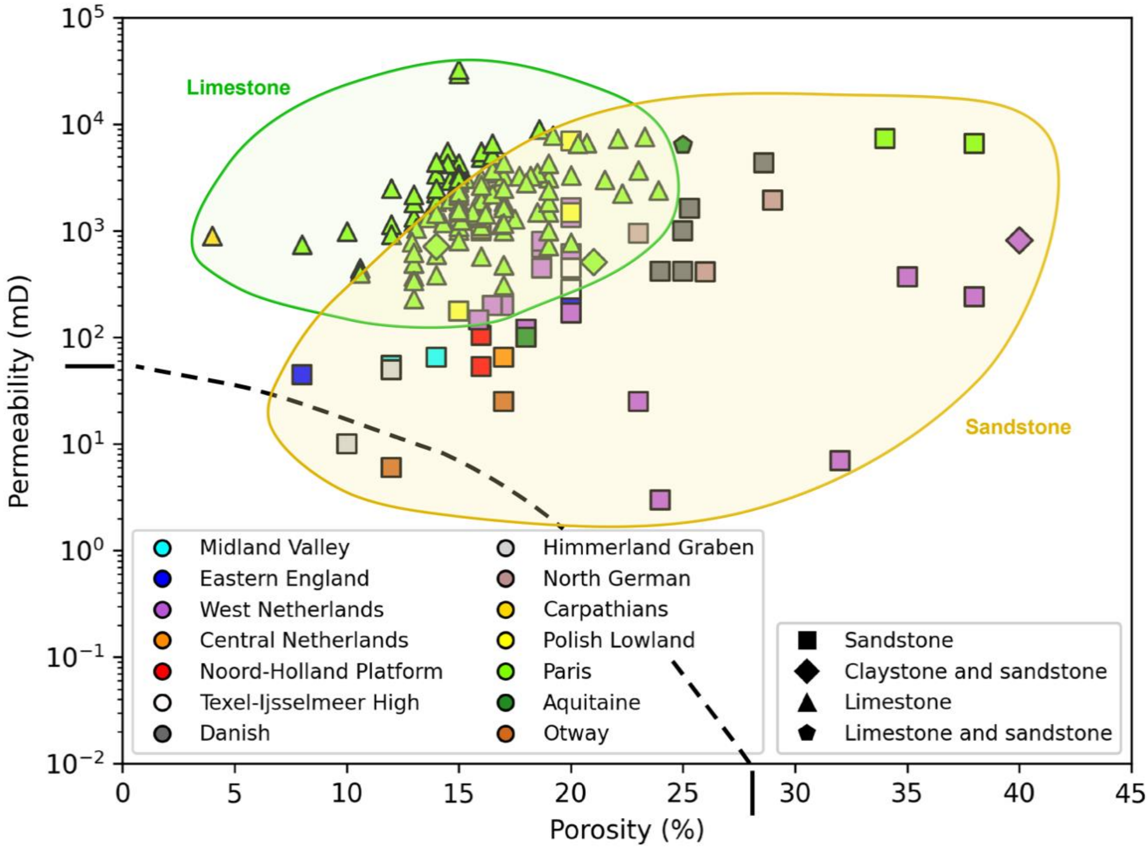


Figure 3: Porosity and permeability of various geothermal reservoirs. Porosity/permeability domains characteristic for different reservoir rock types: limestone (green ellipse) and sandstone (yellow ellipse) have been drawn from the data. According to Moeck (2014), the domain below the black dotted line classifies as EGS and therefore requires technical enhancement for producing hot water. The shapes and colours of data points

3.3 Unsuccessful hot sedimentary aquifer projects

Information on failure reporting or analysis was not usually available from operator reports or project stakeholders themselves, but instead was collected from other sources, for instance newspaper reports. Amongst the 256 projects in the database, 26% (n=67) were unsuccessful due to at least one failure, and 11% piled up several issues. The proportion of failed HSA projects varies for each country (Fig.4). The highest failure rate was observed in Danish projects (67%). UK projects also experienced a high rate of failure with five out of eight projects (63%) that are either no longer active or were never launched. However, this number must be put into perspective as five of these projects were drilled for research purposes with a failure rate of 60%. In comparison, Poland shows a 100% success rate (n=6). The Netherlands, Croatia, France and Australia experienced between 24% and 29% project failures, with 22 projects in France that experienced 2 or more diverse problems. Germany had the second lowest rate of failure (13%). Yet it should be noted that not all basins in individual nations have the same success rate. All HSA projects initiated in the Perth Basin (n=15) in Western Australia are still running (as of 2022) while Eromanga Basin projects show a failure rate of 87.5%. This difference in success rate is likely due to diverse uses of the hot water: the Perth Basin is a mature and well-studied area for geothermal heat production, while the main aim of the HSA projects drilled in the Eromanga Basin is to generate electricity through deeper wells at relatively low temperatures (with regards to electricity production), i.e. 80 to 100°C (Pujol et al., 2015).

It is likely that there is a reporting bias, i.e., an under-reporting of failed projects (Dawson and Dawson, 2018), unless there are regulatory reporting requirements as is the case in the Netherlands (see discussion section). Therefore, these numbers should be taken in context.

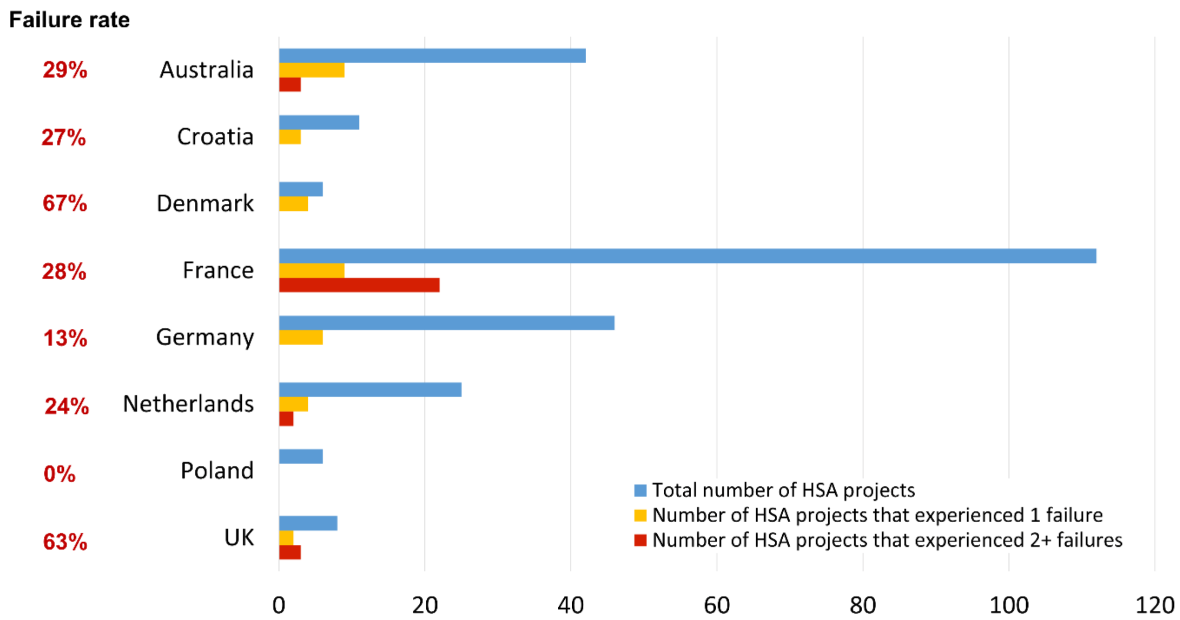


Figure 4: Total number of HSA projects (blue) versus the number of HSA projects that experienced one (yellow) or more (red) failures, for each country assessed.

Figure 5(a) illustrates the three main reasons for closure or suspension of the 67 failed projects: (i) issues with assessment of geological and/or reservoir properties (39%); (ii) financial decisions (26%); and (iii) technical problems on/in the borehole (25%). Policy decisions (7%) are the remaining reason behind the failure of HSA projects, and 4 projects (3%) did not communicate the causes. No social concerns led to the closure of any of the HSA projects collated (Table 1, Fig.5). Most problems encountered in the geological and hydrogeological category are related to chemical degradation of the borehole or unfavourable reservoir parameters (Table 2). The proportion of failure causes is different for each country (Fig.5(b)). Project failures from France is due to a blend of financial, technical and geological and hydrogeological reasons. Geological and hydrogeological issues prevail for Danish, Dutch, British and German failures, while HSA failures in Croatia and Australia are dominated by financial aspects and policy respectively. Unknown failure reasons are greatest for Germany (17%) and Denmark (25%), but this is likely linked to the small number of projects involved (respectively n=6 and n=4).

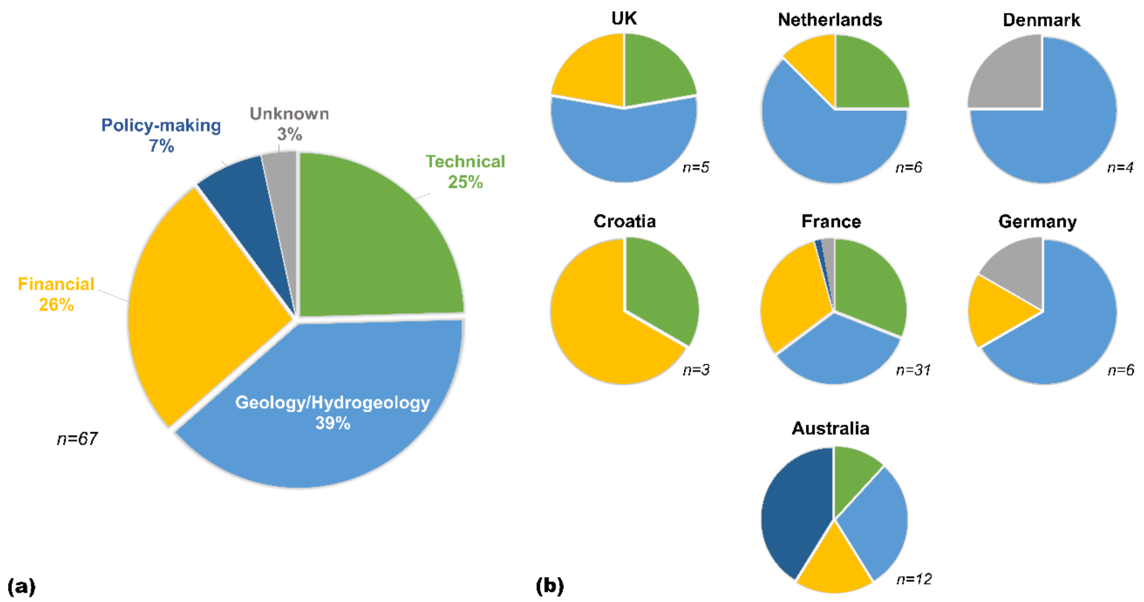


Figure 5: Failure categories of unsuccessful HSA projects (a) for the full database and (b) for each of the countries.

Assessing causes of failure during different stages of the project lifecycle is essential. The initial development phase encompasses all project steps from resource exploration to drilling and borehole completion, and when applicable, plant construction and commissioning. The operational phase starts once the system is commissioned and includes reservoir monitoring and operational maintenance until project completion and decommissioning. The three main failure classes display a high percentage of failure during the operational phase, i.e., 72% for the geology and hydrogeology group, and respectively 83% and 84% for the technical and financial categories (Fig.6). Policy is the only exception, with 63% (n=5) of policy-related project failures occurring during the development phase. This is mainly related to a project initiated in 2017 in Winton (Queensland, Australia) to provide 310 kWe to the city and that became the first Australian geothermal power plant in 25 years (Ballesteros et al., 2019).However, the plant never delivered power due to commissioning issues and was shut down. The problems encountered by the Winton project influenced cessation of four nearby projects. Bulloo Shire Council Mayor declared that "all the news that we were getting out of Winton was that it wasn't working yet, to lay off, so we did that" (O'Neal, 2022).

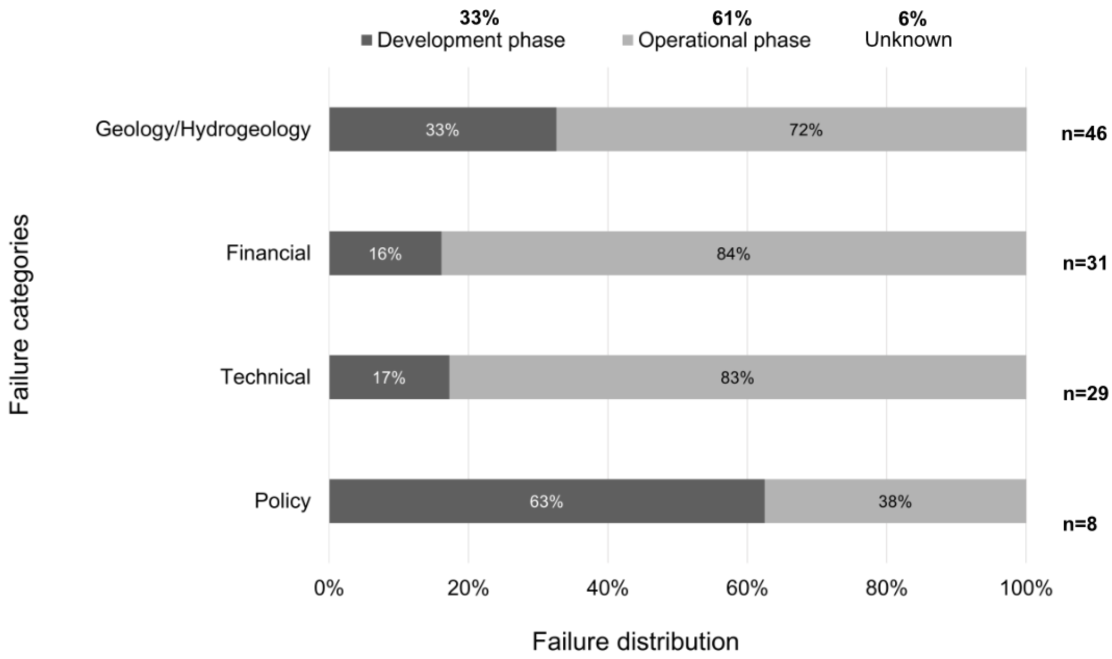


Figure 6: Distribution of failures per risk category and project phase.

3.4 Mitigation and remediation strategies

More than half of all projects (n = 136), including both active and closed projects, have implemented strategies to mitigate encountered risks. Utilised strategies are grouped into seven categories (Table 1; Fig.7). The main approaches applied are stimulation on the borehole (59%), the use of sidetrack boreholes (14%) and refurbishment and/or improvement work on one or several boreholes (9%).

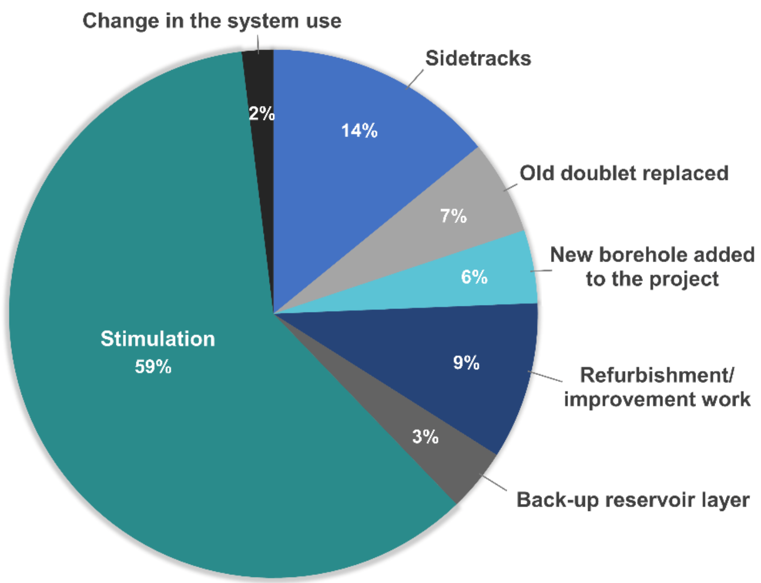


Figure 7: Distribution of the seven mitigation and remediation strategies identified.

In contrast to hot dry rock systems, HSAs do not necessarily require borehole stimulation. However, 94 projects (37%) required acidizing to establish economically sustainable production rates, and two projects in the Upper Rhine Graben also undertook hydraulic fracturing. Acid stimulation is frequently used in carbonate reservoirs for increasing the permeability and therefore improving the productivity of a borehole by dissolving acid-soluble minerals in the rock matrix. This method has been widely employed in two major geothermal reservoirs included in this study: the Dogger limestones of the Paris Basin (France) (n=75) and the Malm limestones of the Bavarian Molasse Basin (Germany) (n=18). Acidizing was successfully used to increase the yield of 14 boreholes drilled nearby Munich as some of them are only a few kilometres apart (Schumacher and Schulz, 2013). The acidizing stimulation technique has also been designed to cope with borehole damage (Ungemach et al., 2009; Hoefner et al., 1987; McLeod, 1984). In total, 59% of the projects that implemented risk mitigation or remediation measures have used borehole stimulation (Fig.7).

A sidetrack is a secondary borehole drilled from the original as an offshoot (Richardson and Neymeyer, 2013), and is usually completed following technical difficulties, to bypass unusable sections of the borehole, or to explore other geological layers nearby. 22 projects (9%) reported in the database required a sidetrack to be drilled, and 60% of sidetracked boreholes have been drilled in the Netherlands, most following technical issues in the original borehole.

Figure 8 presents the distribution per country of all projects that carried out risk mitigation and remediation strategies compared to those which were active in 2022 and the total number of projects. Poland represents only 3% of projects that performed mitigation or remediation, but had the highest rate of implementation, with reconstruction work undertaken on boreholes that were damaged or decommissioned in 4 out of 6 projects (67%). In these cases, borehole refurbishment work was assessed to be a more cost-effective option than drilling new boreholes (Bujakowski et al., 2020). Other projects in western Europe and Australia also performed improvement work or repairs on geothermal boreholes to fix damaged casing, replace broken pieces, address clogging or changing the submersible pump (Lopez et al., 2010; Dufour and Heederik, 2019; (Stuke, 2019).

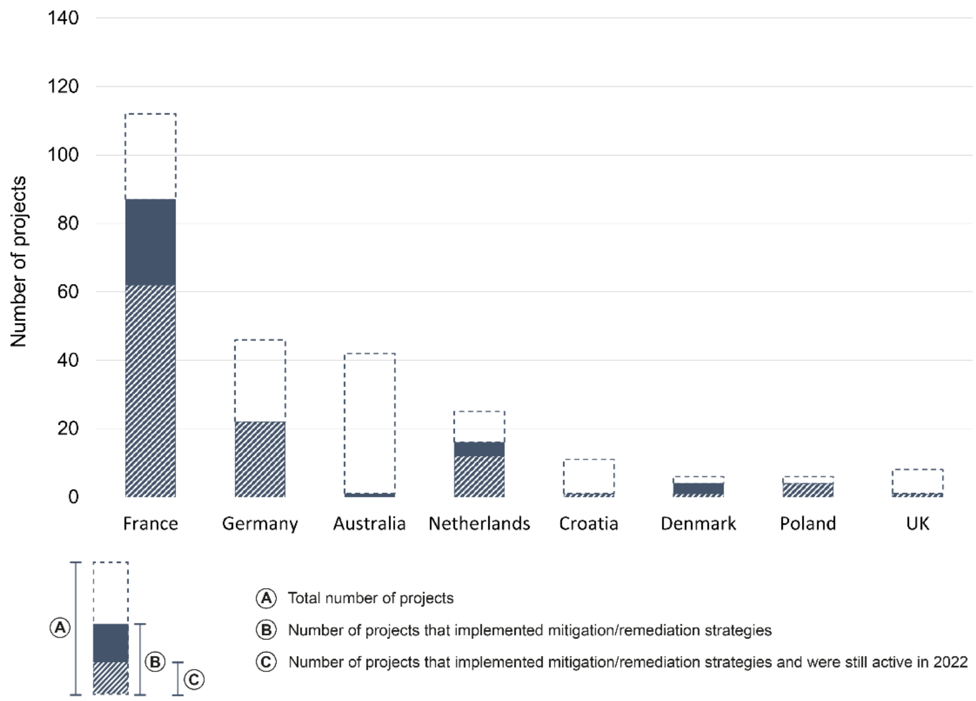


Figure 8: Distribution of (C) the projects that implemented mitigation or remediation strategies and are still active today, compared to (B) all the projects that applied those methods, compared to (A) all running and closed HSA projects, per country investigated.

Remediation measures can also involve a renewal of operations: for instance, adding a borehole to the current system (6% of all strategies, Fig.7) or decommissioning and replacing a geothermal doublet that has reached its planned lifetime (7%, Fig.7) that would provide heat to the same (or a bigger) district heating network. Both strategies have been mostly performed in France, with a share of 71% for the first and 100% for the second approach. In the Paris Basin, nine projects were renewed from 1989–2018 by completely replacing the original doublet. Indeed, the operating permits were for a duration of between 15 and 30 years (Hamm et al., 2019) and completion of new doublets were required to: (1) build more efficient and durable geothermal systems with subhorizontal drilling (Ungemach et al., 2019) (2) limit corrosion by using composite materials (Boissavy et al., 2020); (3) increase heat production (ADEME, 2012, Boissavy et al., 2020); or (4) extend the heating network (ADEME, 2012). For three projects, geothermal installation renewal was carried out in two phases: a new borehole is drilled and used as a doublet with the best performing original borehole, and several years later a new second borehole is drilled and the original borehole system is decommissioned (ADEME, 2012). Since 2008, five doublet installations targeting the Dogger limestones in the Paris Basin have drilled a new producer borehole to increase their heat production and are now operating as triplet systems with two producers and one injector (Lopez et al., 2010).

Defining back-up reservoir layers (3% on Fig.7) is a strategy especially implemented by French geothermal companies to reduce the risks, simplify, and speed up the decision-making in case of problems encountered with the first geological target. Issues are typically linked to the reservoir itself, e.g., the layer could not be found, or the aquifer has less favourable reservoir properties (productivity, flow rate, permeability) than expected. Two HSA projects in the Netherlands and Denmark also had primary and back-up geothermal targets.

When facing technical, geological or economic difficulties, one way to resume or continue exploiting the subsurface geothermal resource is by changing the purpose of the boreholes. This has been done in three projects: two in Germany and one in the UK (Fig.7). The Science Central project in Newcastle-Upon-Tyne, UK was initiated in 2011 and includes a 1.8 km deep borehole. The transmissivity of the target Fell Sandstone aquifer was too low to provide space heating for local buildings, as initially planned (Younger et al., 2016). However, this project was not seen by the operators as a failure because it proved that the resource was there. The borehole has since been transitioned to a geothermal research site. Newcastle City Council's director of investment and development said that: "It was really exploratory and in essence it has achieved everything that was set out [...] about understanding geothermal heat at a 2km depth" (Proctor, 2022). Bruchsal and Unterhaching geothermal projects in Germany both faced economic difficulties after more than a decade of operation. The Bruchsal doublet was drilled in the Upper Rhine Graben in 1987 and initially suppled heat to a district heating scheme. In the 1990s, both boreholes were stopped following oil prices drops (Herzberger et al., 2010). Energy policies were fundamentally modified in the early 2000s with the renewable energy act (EEG) that came into force (Gründinger, 2017). The Bruchsal project was eventually revitalised, and boreholes were recommissioned in 2003 to provide 500 kWe (Herzberger et al., 2010). In Unterhaching (Bavarian Molasse Basin), the geothermal power plant was built in 2004 to supply power and heat to the city. However, electricity generation was not cost-effective, leading to a change in project purpose. Since 2017, the plant solely delivers district heating to c. 7,000 households (Richter, 2018).

These examples demonstrate the utility of risk mitigation and remediation measures to overcome prospective HSA project failure. Amongst all HSA projects in the database that acted to reduce risks, 76% were still active in 2022 (Fig.8) although the results are dissimilar for each country. Croatia, Germany, Poland and the UK show a 100% rate, followed by the Netherlands and France with respectively 75% and 71%, and Denmark and Australia fall behind with 25% and 0%. Of the 24% projects that eventually failed, only one of 33 (3%) failed for a reason related to the implemented risk mitigation strategy. The Sønderborg project (Denmark), drilled in 2013, did not find its initial Bunter Sandstone target reservoir, so opted for a backup completion into the Gassum Formation at a c. 1km shallower depth. This option allowed the system to deliver district heating for five years. However, the plant never ran as planned due to technical issues in the injection borehole. Fine sand entered the injector and acted as a plug: the system (especially the screen) was initially designed for a deeper and more porous reservoir. In 2018, long-term decreasing injectivity and difficulties in injecting the water back into the reservoir meant the operators eventually closed the geothermal installations (Berg Badstue Pedersen, 2020).

4 Discussion

4.1 Evolution of energy regulations

Geothermal energy can be classified as a relatively new or unexploited energy source when comparing current exploitation to global potential: in 2023, geothermal accounted for a negligible share (0.5%) of global renewable-based energy generation (IRENA and IGA, 2023) but it has the potential to meet more than 3% of electricity demand and c. 5% of heating and cooling demand by 2050 (Craig and Gavin, 2018). Geothermal energy development goes together with an evolution of energy regulations, but this change is innately linked with the state of play of geothermal technology in each country. No specific legal regulation has yet been implemented for most investigated nations to set guidelines for the geothermal sector.

Poland lacks any geothermal regulation, despite geothermal being recognised as the renewable energy with the highest technical potential (Szalewska, 2021). Thus, shallow and deep geothermal energy are subject to six different laws, although Szalewska (2021) states that the complexity of the legal framework is not a limiting factor for the development of geothermal energy in Poland.

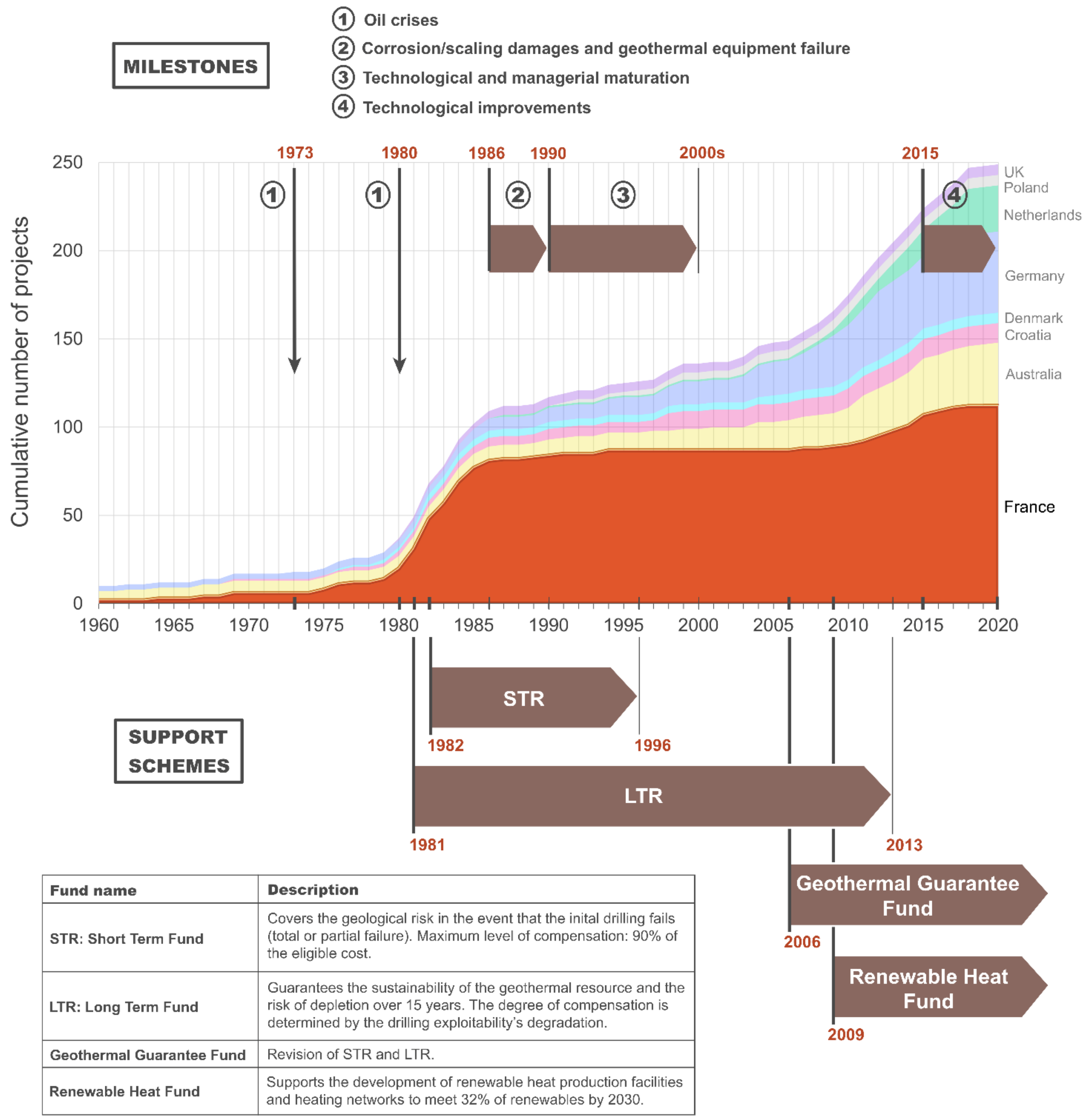
As of 2023, the UK has no legal acknowledgement of geothermal resources and “the absence of a coordinating body for the geothermal application process is seen by stakeholders as a barrier to faster roll out of geothermal projects, and many [of them] have found the regulatory requirements for deep geothermal projects to be somewhat difficult or extremely difficult” (Abesser et al., 2023). This could explain the limited geothermal development in the UK compared to other countries, with only 8 HSA projects identified as of 2022.

In Germany, the exploitation of subsurface heat is regulated by the "Bundesberggesetz" (Federal Mining Act), which covers various aspects of mining activities, including geothermal energy extraction. The Federal Ministry for Economic Affairs and Climate Protection oversees mining activities and energy policies at the federal level. Germany is divided into 16 federal states, each with its specific regulations and authorities governing geothermal energy and subsurface heat production. At the local level, municipalities and districts may have their own zoning regulations and permits that apply to geothermal projects. The current trend is to harmonise and simplify regulations while also strengthening environmental impact monitoring (Stemmle et al., 2024). The evolution of the regulations has a direct impact in the geothermal development in Germany with an increase in number of projects and boreholes throughout the last two decades (Fig.2).

The growth of the geothermal sector is also inherently correlated with the use of the subsurface by other industries. An intensive expansion of the coal industry caused the failure of two HSA projects in Australia (Fig.5(b)). In the 1950s, two boreholes in the Gippsland Basin (Victoria State) were used to process water in paper manufacturing, but regional coal mining activities caused substantial dewatering that led to decommissioning of several geothermal installations in the area (King et al., 1987). In 1989, the Mulka power plant, the first geothermal Organic Rankine Cycle (ORC) plant designed and built in Australia, was shut down after only three years of operation because the land was bought as a mining lease (Popovsky, 2013).

Oil price fluctuations have significantly impacted the geothermal market, as evidenced by the repercussions of the 1973 oil crisis. This is particularly clear in France, where in the 1970s HSA projects were shut down during the operational phase (Fig.6). The drop in oil prices, technical difficulties and corrosion issues encountered by those geothermal installations in the 1980s and the 1990s (Laplaige et al., 2000) ultimately led to the closure of 21 projects (8% of total projects) in the Paris basin. Early Dogger aquifer geothermal projects faced considerable sulphide mineral scaling problems, with plant operators needing more expertise to face resulting technical and financial issues (Laplaige et al., 2000). Since the 2000s, the rate of failure decreased seven-fold in the Paris Basin, with only three projects (12.5% of projects in the Paris Basin) closed following an issue. Corrosion and scaling phenomena have been controlled thanks to technological improvements (Lopez et al., 2010), and geothermal stakeholders have gained experience throughout the decades.

Since the 1980s and following several energy crises (Fig.9), the French geothermal market also considerably benefited from several insurance and risk mitigation schemes that helped limit financial risk and reassure potential investors. Two complementary mechanisms, i.e., short-term risk (STR) and long-term risk (LTR) insurance, were implemented to cover geological risks during the rise of geothermal district heating in France (Fig.2, Fig.9). The STR covered total or partial failure of the first borehole drilled. Success or failure are there based on a temperature/flow rate zone. Simultaneously, the LTR was focused on long-term exploitation, especially covering the risks related to the degradation of the installations and the reservoir exploitability (Boissavy and Laplaige, 2018). This success story inspired other European countries to set up their governmental funds for supporting the launching of geothermal heating projects: in 2010, the Netherlands introduced a government guarantee scheme on drilling risks, followed by the Stimulation Sustainable Energy production scheme two years later (Mijnlieff et al., 2013) that facilitated completion of 43 geothermal boreholes (Fig.2). These schemes were critical for the advancement of deep geothermal in the Netherlands (Boissavy and Laplaige, 2018).



Fund name	Description
STR: Short Term Fund	Covers the geological risk in the event that the inital drilling fails (total or partial failure). Maximum level of compensation: 90% of the eligible cost.
LTR: Long Term Fund	Guarantees the sustainability of the geothermal resource and the risk of depletion over 15 years. The degree of compensation is determined by the drilling exploitability's degradation.
Geothermal Guarantee Fund	Revision of STR and LTR.
Renewable Heat Fund	Supports the development of renewable heat production facilities and heating networks to meet 32% of renewables by 2030.

Figure 9: Risk mitigation and HSA market development in France since the 1960s.

4.2 Lessons learned from mitigation/remediation measures and failures in hot sedimentary aquifer plays

Building a "learning from failure" culture requires operators to report consistently and perform detailed failure analysis to ensure the proper lessons are learned (Edmondson, 2011). However, this is not a common practice in the geothermal industry, and HSA projects included in this study do not often reveal details on encountered issues. Without a mechanism for reporting, there is limited opportunity for future projects to learn from previous failures. The analysis of the main failure modes for the compiled HSA projects clearly shows that geology and hydrogeology account for the highest proportion of the failure causes (Fig.5). Indeed, the profitability of a geothermal project is mainly threatened by the resource (i.e. subsurface conditions and geological structure) risk (Deinhardt et al., 2021). As shown in Fig.10, the costs of geological studies to assess resource potential and test drilling are usually very high for the developer. The development cost of a geothermal project is usually between 4.5 M USD and 5.5 M USD per installed megawatt (DiPippo, 2016) and drilling expenditures in hydrothermal power projects typically account for 25%–50% of CAPEX costs (Tester et al., 2006). However, as geothermal development stages progress, a greater understanding of the field characteristics is reached, reducing the risk (in theory). In Fig.10, we highlight a higher number of failures (and therefore risks) during the operational phase (61%) than during the development phase (33%) (Fig.10, Fig.6). Figure 10 is based on Gehringer and Loksha (2012) who displayed a very low risk at the end of the development phase (blue curve in Fig.10), and seemingly no additional cost for the operational phase. This may be because they decided to mostly focus on the development stage, while we included both in our study, or because we include another 12 years of data. Throughout this work, we also showed that assessing the risks and acting prior to any major failure is an efficient lever to preventing the closure of HSA installations. Such measures were applied in 63 projects (25% of total projects) and 80% of these projects remained active in 2022. An adequate installation (both surface and borehole) of monitoring can significantly improve the understanding of the system. It also helps to avoid potential failures through renovation or improvement work on the geothermal installations (22% of all measures), or decisions to be taken based on reservoir changes (add another borehole, 10%; replace a doublet, 13%; change the system use of the heat, 5%). Atkins (2013) provided insights gleaned from various geothermal projects and especially stated that borehole monitoring and management are of key importance.

The HSA database shows that geological and hydrogeological data are significantly lacking, either not measured or not reported by geothermal operators. This significant gap of crucial data might encourage developers or governments to invest more in exploratory geological studies at the early development stage of a geothermal project or region to limit any issues linked with reservoir and geological aspects. It should also encourage operators to carry out regular monitoring to avoid borehole integrity issues such as clogging or corrosion, and technical problems with the installations.

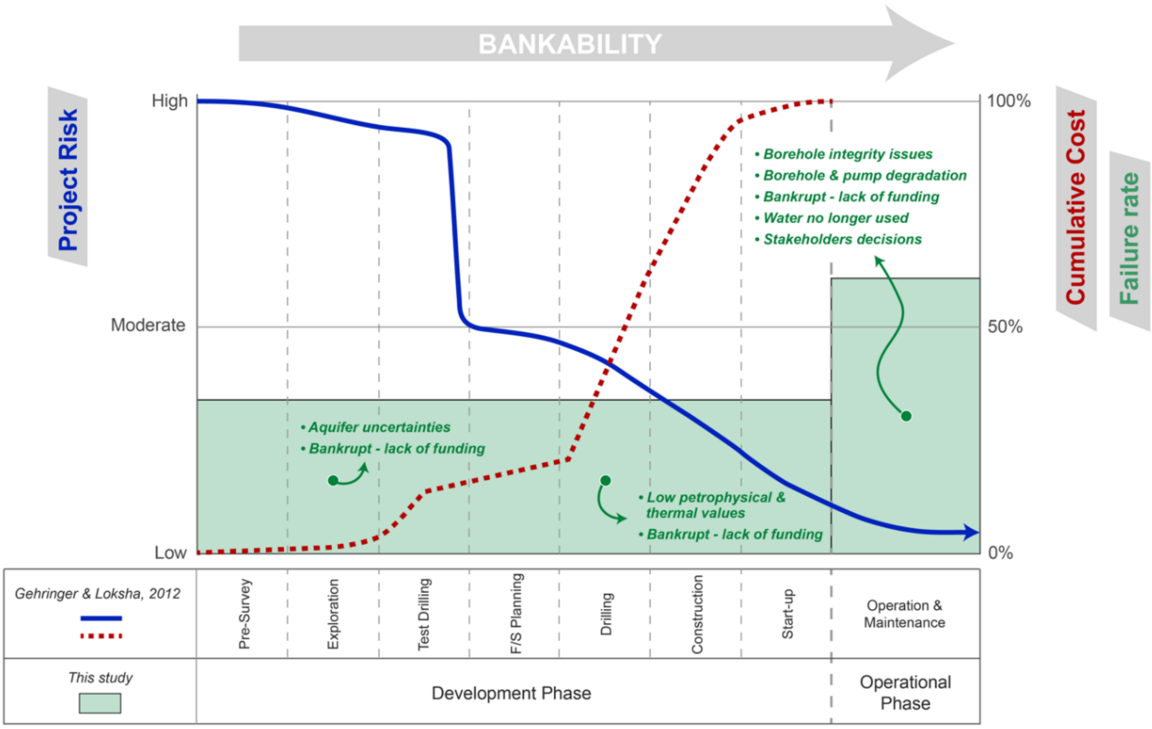


Figure 10: Geothermal Project Cost, Risk Profile and Failure Rate at various stages of development and operational phases. Project risk and cost profiles (blue and dashed red lines respectively) are from Gehringer and Loksha (2012). Failure rate and reasons (green) are findings from this study.

However, although huge progress has been made in surface and subsurface exploration technologies, prognoses of the depth of a reservoir, its properties (porosity, permeability, temperature, flow rates, etc.) as well as the output from a geothermal borehole remain uncertain until the first borehole is drilled. There are similar challenges in the hydrocarbon industry, though the returns on geothermal investment are comparatively small, making risk more economically unpalatable and therefore more likely to result in project termination (Gehringer and Loksha, 2012). Cumulative costs for exploration and test drilling can account for up to 15% of the overall capital cost, for a near-halving from high to moderate project risk (Fig.10; Gehringer and Loksha, 2012). Due to these uncertainties, funders sometimes lack the risk appetite for becoming involved in such investments (Climate Investment Funds, 2014). Balancing the probability of success against the cost of failure is key to reach the best expected outcome (Gehringer and Loksha, 2012). Success stories such as the maturation of French know-how during the early stages of geothermal energy can also be used as a model for helping other countries grow their geothermal sector.

None of the 256 projects in the HSA database has raised project-stopping public concerns (Fig.6). There can be a variety of reasons that can negatively influence public appetite for geothermal developments: project location (Carr-Cornish and Romanach, 2014; Edelstein and Kleese, 1995), distrust between parties involved (Willems et al., 2020), and fears over induced seismicity. The latter is partially a legacy of failed enhanced geothermal system (EGS) projects which have demonstrably triggered earthquakes and caused damage to surface infrastructure (e.g., Burnside et al., 2019 ; Edwards et al., 2015; Trutnevyte and Wiemer, 2017; Westaway and Burnside, 2019). Triggered seismicity at EGS projects has apparently had little negative influence on public opinion of HSA projects, but it is crucial that prospective operators ensure full and transparent dialogue with local stakeholders to outline prospective project risks and mitigations.

4.3 Geothermal data collection and availability

Reporting standards, data availability and type are highly variable depending on historic timing and national location of geothermal project. Amongst countries investigated in this study, France and the Netherlands stand out by providing open or on-demand, free of charge access to a national database that integrates widely ranging data and knowledge on heat or electricity production from geothermal resources.

In the Netherlands, geophysical, borehole and production/injection data are supplied to the Geological Survey of the Netherlands (TNO) and made publicly available online (www.nlog.nl) no more than five years after acquisition (Kombrink et al., 2012). This mandate to make data available came out from the 2003 Mining Law. Published information includes seismic data, production and injection data, field and production licences of developed fields, maps and models, and core and borehole data. The online database usually provides a wide range of data for reported boreholes: original end-of-borehole reports, lithological logs, well-test reports and sometimes water analysis and reports on palynology and diagenesis evolution (TNO, 2023).

In France, the “Système de bancarisation et de suivi des opérations de géothermie de basse énergie en France métropolitaine” (SYBASE) Project has been in operation since 2018 and includes data and knowledge on geothermal boreholes across mainland France. It has been developed from the previous 2002 “Dogger base” database which recorded information on geothermal installations targeting the Dogger limestone aquifer in the Ile-de-France region. Unlike the Dutch geothermal database, the full SYBASE database access is restricted to government administration organisations, Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME, the French agency for ecological transition), and licenced subsurface engineering consultancies. Public access is provided to limited data (e.g. technical information on the boreholes and targeted reservoir, temperature and sometimes transmissivity) through the “Geothermie Perspectives” website (Hamm et al., 2019). We have been given access to the full geothermal database as an exception for this study, which includes end-of-well reports, sometimes combined with geological and production test reports.

To a lesser extent, Germany and some Australian states also grant access to geothermal databases. Germany has been moving towards a more open data policy, especially with the Geologie Datengesetz (Geology Data Act), which came into effect on June 30, 2020. This new law replaces the 1934 Repositories Act (Lagerstättengesetz, LagerstG) and governs tasks related to geological mapping at both the federal and state levels. It focuses on making geological data accessible to the public, particularly datasets older than ten years. Despite the positive intentions of the law, its practical implementation has faced challenges. This is mainly due to limited financial resources available to the responsible institutions, making it difficult to efficiently manage the workload required to comply with the law's provisions (personal communication, 2022). GeotIS (www.geotis.de) is the information system that provides knowledge on the use and potential of geothermal energy in Germany via a map interface. It is based on data from boreholes (geothermal, oil and gas, mining) and porosity, permeability, temperature and structural data processed into 3D subsurface models (GeotIS, 2023). A table compiling all geothermal installations plus specific information for each operation can also be accessed. However, no raw report has been provided, and reservoir data are missing. The situation in Australia differs from state to state. For example in South Australia, all open source geothermal exploration data is available on the SARIG (https://map.sarig.sa.gov.au/); it includes well completion reports, company exploration reports, geophysical surveys and other raw and interpreted geoscientific data. In other states such as Western Australia, availability of data varies. For direct-use projects, only limited data is available in the public domain. Well Completion Reports and Exploration activity reports for projects undertaken under the Petroleum and Geothermal Energy Resources Act 1967 is available on WAPIMS (https://wapims.dmp.wa.gov.au/wapims) in a database containing primarily oil and gas data that is only released sometime after the exploration works takes place for confidentiality reasons. The earliest release date for the well's basic data and reports is two years from the end of the activity. Release provisions for basic survey's data can vary according to survey type, permit type, and commercial intent (exclusivity). The earliest release is three years from the end of the activity. Confidentiality periods of up to 15 years may apply. Most recently however, the Department of Mine and Environmental Regulation started compiling geothermal-specific database as part of its Carbon Dioxide Geological Storage Atlas project (https://wapims.dmp.wa.gov.au/WAPIMS/Search/CO2StorageAtlas).

Accessing relevant information for nations with no central data repository or open-access geothermal data requirements is much more challenging. The Agencija Za Ugljikovodike (AZU, Croatian Hydrocarbon Agency) does hold a free-of-charge geothermal database with access to all borehole reports, seismic and GIS data of geothermal operations in Croatia (AZU, 2023); however, the Croatian Geothermal Virtual Data Room (VDR) is only available to collaborators of Croatian university-led research or potential investors. HSA data from Croatia, Denmark, Poland, the UK and, to a certain extent, Australia (direct-use projects in Western Australia) were mainly retrieved from research publications and reports, although these often lack details and typically only provide an overview of current and past projects. However, a new trend is emerging in the last decade, with more countries planning to invest in geothermal energy resulting in more data becoming available, which in turn enables a better understanding of the state of play of the technology.

In addition to significant challenges with data availability and accessibility, the geothermal industry also lacks common definitions on reported as well as a misalignment of collection methodologies between various geothermal organisations. Such issues, especially regarding industry data (e.g., capacity or production variables) at a global scale, lead to misunderstandings and uncertainties in the resulting geothermal values conveyed (Krieger et al., 2022). Our analysis is based on the hot sedimentary aquifer definition previously specified: large and conduction-dominated sedimentary reservoirs of depths ≥ 200m and temperatures ≥ 20°C with elevated heat flow and sufficient productivity to constitute a potential geothermal resource. The outcomes of this study would be impacted by the alteration of geological, temperature and depth thresholds. An explicit definition of an international standard for classifying such geothermal plays, and to a wider extent all geothermal systems would remove ambiguities, greatly enhance appraisal of potential HSA prospects, and promote worldwide opportunities for geothermal resource development.

5 Conclusion

In this paper, we present the Hot Sedimentary Aquifer database which captures data from 256 geothermal projects across 19 sedimentary basins in eight countries (Australia, Croatia, Denmark, France, Germany, Poland, the Netherlands, and the UK). Information was collated using a systematic literature review approach and classified in various categories. The following points are key lessons for the sector:

- 26% (n = 67) of the projects of the HSA database have failed and 39% of these failures are related to geological or hydrogeological factors. Financial and technical issues are responsible for 26% and 25%, respectively, of unsuccessful projects. This emphasises the importance of site characterisation prior to drilling to limit geological and reservoir risks, borehole monitoring and technological improvements to effectively manage geochemical and technical issues, and widespread application of risk insurances.

- 24% (n=61) of HSA projects implemented remediation or mitigation techniques to reduce the chances of failure, which proved useful as 80% of these 61 projects were active as of 2022. The main measures were the drilling of sidetrack boreholes (32%) and renovation and/or improvement work on the geothermal installations (22%). Poland stands out from other studied countries by using risk reduction measures in 67% of its projects.

- The database does not hold values for all projects and variables, with nearly 34% of the data missing. In particular, 56% of geological and hydrogeological values are lacking, whereas these variables are responsible for almost 40% of failed projects. This exposes the poor accessibility of geothermal data and reporting globally. Similarly to Dickinson and Ireland (2023), we argue that better data availability is key for a proper risk assessment of HSA projects and more broadly the expansion of geothermal energy worldwide.

- Reported values, including success rates and data availability, vary considerably across countries and over time; mainly driven by (i) regulatory regimes, such as proper law-making to make energy data publicly available and encourage geothermal development, and (ii) technological evolution, such as drilling techniques and corrosion reduction measures. The development of hot sedimentary aquifers requires consistent support to companies, primarily through financial schemes to limit the risks. Therefore, risk mitigation schemes that were implemented in France since the 1980s considerably contributed to the development of renewable energies and even inspired other countries, such as the Netherlands, to set up their fund.

We explored the accessibility of HSA project information across the world. Ultimately, HSA database construction was limited by lack of open access data for countries outwith the eight mentioned above. Although we consider the database broadly representative of all HSA projects, analytical outcomes may be influenced by additional data from other countries. Therefore, the database could be improved with new countries and extra parameters such as drilling technology, borehole design or total project cost. For the HSA to optimise learning opportunities from previous project successes and failures, we recommend that nations/organisations follow the example of France and the Netherlands, plus Australia and Germany to a lesser extent (state-dependent regulations) which have set the standard for governmental policies, data reporting and have thriving HSA industries as a result.

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