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Risk Analysis of High-Temperature Aquifer Thermal Energy Storage (HT-ATES)

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Abstract

The storage of heat in aquifers, also referred to as Aquifer Thermal Energy Storage (ATES), bears a high potential to bridge the seasonal gap between periods of highest thermal energy demand and supply. With storage temperatures higher than 50 °C, High-Temperature (HT) ATES is capable to facilitate the integration of (non-)renewable heat sources into complex energy systems. While the complexity of ATES technology is positively correlated to the required storage temperature, HT-ATES faces multidisciplinary challenges and risks impeding a rapid market uptake worldwide. Therefore, the aim of this study is to provide an overview and analysis of these risks of HT-ATES to facilitate global technology adoption. Risk are identified considering experiences of past HT-ATES projects and analyzed by ATES and geothermal energy experts. An online survey among 38 international experts revealed that technical risks are expected to be less critical than legal, social and organizational risks. This is confirmed by the lessons learned from past HT-ATES projects, where high heat recovery values were achieved, and technical feasibility was demonstrated. Although HT-ATES is less flexible than competing technologies such as pits or buffer tanks, the main problems encountered are attributed to a loss of the heat source and fluctuating or decreasing heating demands. Considering that a HT-ATES system has a lifetime of more than 30 years, it is cru-

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cial to develop energy concepts which take into account the conditions both for heat sources and heat sinks. Finally, a site-specific risk analysis for HT-ATES in the city of Hamburg revealed that some risks strongly depend on local boundary conditions. A project-specific risk management is therefore indispensable and should be addressed in future research and project developments.

Keywords: High-Temperature Aquifer Thermal Energy Storage, ATES, Risk Analysis

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Abbreviations

ATES, Aquifer Thermal Energy Storage; CAPEX, Capital costs; CHP, Combined Heat and Power; DH, District Heating; ECES, Energy Conservation through Energy Storage; DOE, Department of Energy; HT, High Temperature; HVAC, Heating, Ventilation, and Air Conditioning; IEA, International Energy Agency; INL, Idaho National Laboratory; LT, Low Temperature; OP, Occurrence Probability; OPEX, Operational costs; RBS, Risk Breakdown Structure; R&D, Research and Development; RHC, Renewable Heating and Cooling; SV, Severity; UC, Uncertainty; UTES, Underground Thermal Energy Storage;

1. Introduction

Most governments have undertaken to reduce greenhouse gas emissions to prevent the worst effects of global warming. While the majority of efforts are focusing on electricity production, the share of renewable energies in the heating and cooling sector is stagnating at around 10% (REN21, 2019). In addition, with rising prosperity, human well-being in buildings including thermal and air comfort is gaining significantly more importance (Cuce et al., 2017, 2019). Thus, energy saving technologies are becoming increasingly popular over the last decades (Sher et al., 2019). Considering that around 50% of the global energy consumption is attributed to the thermal energy sector (REN21, 2016), climate change mitigation strategies must be reconsidered and should also include renewable heating and cooling (RHC) solutions. The challenge of integrating renewable technologies into the thermal energy sector is that demand for heating or cooling does not coincide with RHC supply in most cases. Underground thermal energy storage (UTES) is considered as promising technology to bridge this seasonal demand-supply gap (Dincer & Rosen, 2011). However, artificial storage tanks are highly space-intensive and hence, hardly suitable to store significant amounts of energy in an urban environment. In contrast, the storage of temperatures below 25 °C in shallow aquifers (LT-ATES) is characterized by high storage capacities, but not compatible with other renewable technologies (solar, biomass, geothermal) or industrial heat waste (Fleuchaus et al., 2018). Depending on the type of application, solar thermal collectors, for instance, are characterized by a large range of operating temperatures, which particularly exceed 100 °C (Danesharzarian et al., 2018) enabling higher storage temperatures and, therefore, requiring greater storage depths. High-Temperature Aquifer Thermal Energy Storage (HT-ATES) (> 50 °C), in contrast, has the potential to cost-efficiently store large energy volumes at high temperatures.

There is a 50-year historical development of HT-ATES. First research experiments were initiated by the Storage program of the International Energy Agency (IEA) to tackle increasing fuel prices after the big oil crises in North America and Europe in the early 1970s (Sanner, 2001). However, with decreasing oil and gas prices in the following decades, alternative heating technologies such as HT-ATES became less attractive and research and development

(R&D) activity in the field of geothermal energy focused on power generation. Consequently, even though promising results were achieved at several demonstration projects, HT-ATES still has not tapped significant energy markets (Fleuchaus et al., 2018). While renewable heating and cooling was neglected by significant climate change mitigation strategies in the past, many scientist now appeal for a prioritization of the decarbonization of the thermal energy sector (REN21, 2016, 2019). Consequently, HT-ATES is moving back into the scientific focus and several projects were recently initiated, particularly in Central Europe (Section 3).

In order to establish HT-ATES as a key technology in the energy transition, future demonstration plants should strive to proof technical reliability to build up trust among investors, politicians and the population. However, compared to other renewable technologies, the storage of heat in the subsurface is associated with multidisciplinary and complex risks. Thus, a comprehensive risk management should be an integral part of any project to develop site-specific risk mitigation strategies. Despite its importance, risk management in HT-ATES has not been addressed by past research activities, yet. Risk related research was focusing on direct geothermal utilization, addressing only specific risks such as induced seismicity (Trutnevyte & Azevedo, 2018; Mignan et al., 2015; Trutnevyte & Wiemer, 2017; Knoblauch & Trutnevyte, 2018), exploration risks (Siler et al., 2017; Robertson-Tait et al., 2015) or well integrity (Southon, 2005; McVeigh et al., 2007; Lentsch & Schubert, 2013). This was also stated by Lohne et al. (2016b), who reviewed 54 studies in the course of the project „EU Horizon 2020 GeoWell". They concluded that most studies focus on geological and financial risks, whereas environmental, social or legal risks as well as risk-management strategies are hardly ever considered. Even though risk assessment is often applied in practice (Lohne et al., 2016a), current literature still lacks research focusing on holistic risk assessment approaches. So far, no attempt was made to identify and assess all potential risks of geothermal and in particular HT-ATES projects.

The objective of this study is, therefore, to foster technology adoption by obtaining a deeper understanding of risks in HT-ATES and establishing a risk assessment framework for risk management and mitigation for future projects. To meet these objectives, risks of HT-ATES are identified based on a review of the past and current HT-ATES activities. The identified risks are qualitatively analyzed by means of an online survey among experts in geothermal energy. This generic analysis is complemented by a project-specific risk analysis of a HT-ATES project in the city of Hamburg to analyze the impact of local and site-specific risks. The outcome of this study will not only serve as a first basis for a project-specific, holistic risk mitigation strategy, but also create an awareness for the importance of risk management in HT-ATES.

2. Methods

2.1. High-Temperature Aquifer Thermal Energy Storage

The basic principle of ATES was described by numerous studies (Schaetzle et al., 1980; Dickinson et al., 2009; Bloemendal, 2018) and is illustrated in Fig, 1. ATES systems consist of at least one groundwater well-doublet. In summer, groundwater is abstracted from the „cold“ well, charged with surplus heat from renewable or non-renewable sources and injected into the „warm“ well. The pump direction is reversed in winter to recover the injected heat from the warm well. Over time, various concepts and designs have developed. These concepts are differentiated based on several characteristics, such as the storage depth, the storage temperature, the system design (mono- or multi-well) or the energy source and consumer (Fleuchaus et al., 2018). The key distinction is based on the storage temperature. Low-temperature (LT) ATES systems are characterized by a maximum injection temperature of 25 °C. They are mainly applied in buildings with a balanced heating and cooling demand and usually a heat pump is used to meet the required temperature level of the heating system of the associated building. While LT-ATES can also be used for cooling purpose, the technology is due to the low temperature level mainly restricted to the refurbished/new building sector. By contrast, HT-ATES systems allow storage temperatures up to 100 °C. While LT systems store the residual thermal energy of the heating and cooling process, heat sources and sinks of HT-ATES are independent from each other. Potential excess heat sources are various types of renewable energies (solar, geothermal, biomass, power to heat, incineration plants) or waste heat from industry. Due to higher storage temperatures, HT-ATES is afflicted to certain difficulties from a technical, financial and legal aspects, and hence they are much less

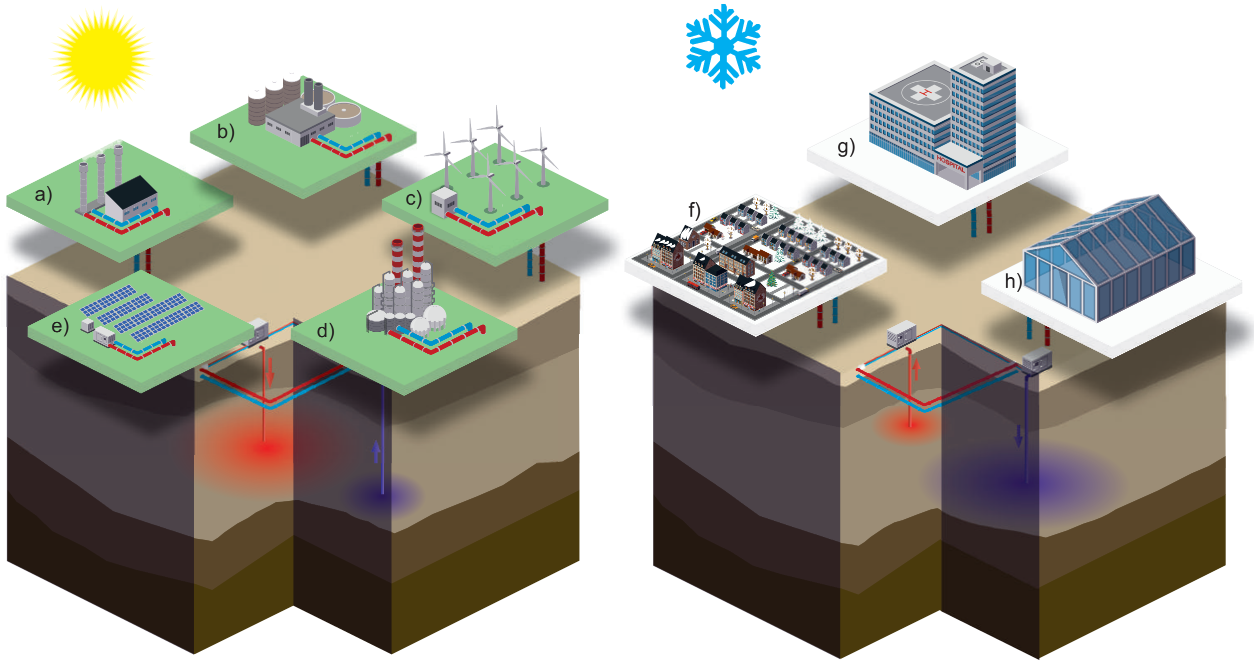

Figure 1: Basic principle of HT-ATES. In summer, the aquifer is charged with surplus heat from (non-)renewable energy sources such as geothermal (a), biomass (b), power-to-heat (c), industrial heat waste (d) or solar (e). The stored heat is recovered in winter to supply district heating (DH) systems (f), large building complexes (g) or industrial applications such as greenhouses (h).

widespread compared to LT ATES systems (Fleuchaus et al., 2018).

Since this study is focusing on HT-ATES, we consider only ATES with a storage temperature above a certain temperature threshold. However, different threshold values between LT- and HT-ATES are defined in the literature. Drijver (2011), Drijver et al. (2012) and Kallesøe & Vangkilde-Pedersen (2019) distinguish between LT (< 30 °C), mid-temperature (MT) (30-60 °C) and HT- (> 60 °C) ATES. In contrast, other authors define HT-ATES with a storage temperature above 50 °C (Bakema et al., 1995; Jenne, 1990; Sanner et al., 2003; Zeghici et al., 2014; Andersson & Sellberg, 1992). This discrepancy can be explained as follows: from a legal point of view, the temperature levels are stipulated by the maximum allowed injection (T_{Max}) temperature, which is defined by national or regional legal guidelines. For most European countries, T_{Max} varies between 18 and 25 °C (Hähnlein et al., 2010, 2013). Additionally, higher storage temperatures do not only trigger geochemical reactions and affect groundwater characteristics (density, viscosity), but also highly affect the choice of materials or components. For instance, water treatment to prevent scaling, clogging or corrosion is usually not required at temperatures below 50 °C (Kallesøe & Vangkilde-Pedersen, 2019). Additionally, higher storage temperatures trigger geochemical reactions and also affect the physical groundwater characteristics by increasing density and decreasing viscosity. The difference of density and viscosity between the injected warm and the ambient cold water causes buoyancy flow and therefore mixing of the different water temperatures reducing the recovery factor (Buscheck et al., 1983; Drijver et al., 2012). According to Doughty et al. (1982), buoyancy flow is fostered by temperatures above 60 °C. However, below 60 °C and temperature changes below 10 K, these effects are typically negligible (Hecht-Méndez et al., 2010). Finally, the threshold can also be established considering the requirements of the demand. However, the required temperature of the heating system strongly depends on the DH grid, the energy standards of buildings as well as the requirement of the heat pump. In this study, the definition established in Annex 12 of the Energy Conservation through Energy Storage (ECES) of the IEA is followed, where the minimum storage loading temperature is set to 50 °C.

2.2. Definition of risk management

Risk is defined by ISO-31000-2018 as an effect of uncertainty on objectives and is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence ISO 31000 (2012). The central pillar of the risk management process is the risk assessment comprising of risk identification, analysis and evaluation (Fig. 2). Risk identification includes finding, recognizing and describing potential risks ensuring that all risks and lessons learned from past projects are considered in the risk management process (Michelez et al., 2010). All sources of risk associated with the project objectives should be identified and organized according to a Risk Breakdown Structure (RBS). Based on the risk identification, risk analysis strives to develop an understanding of the risk and serves a basis for the risk evaluation. Risk is analyzed by determining effects and their occurrence probability and other attributes of the risk (ISO 31000, 2012). However, the extent and level of detail of the analysis is dependent on the scope as well as on the amount of available information, data and resources (ISO 31000, 2012). Risk analysis can be qualitative or quantitative. Qualitative analyses are descriptive and based on expertise or assumptions of

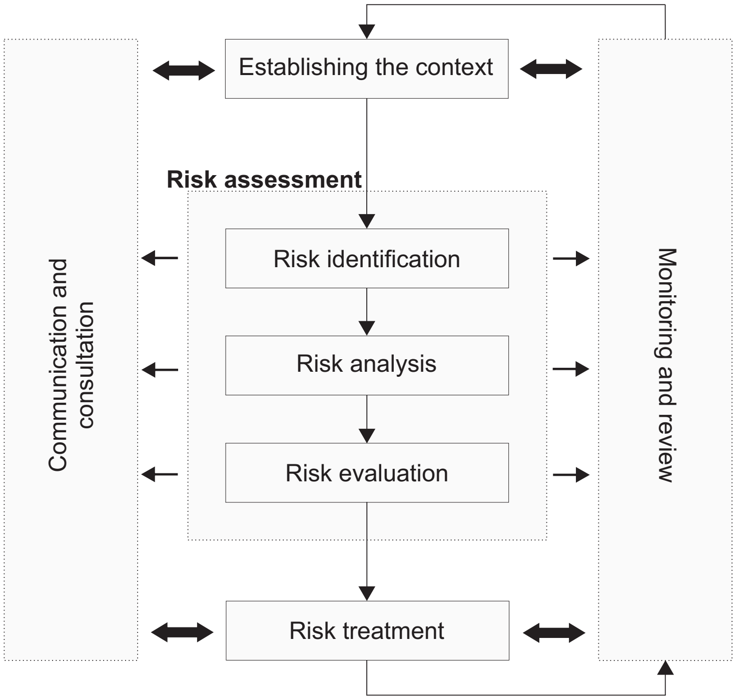

Figure 2: ISO standard risk management process (modified after ISO 31000 (2012)).

single risk issues. In contrast, quantitative methods are based on numerical data and present a global picture of the risk exposure for the project. In practice, detailed, quantitative risk analyses are often limited to those risks that are expected to have a high input on the project success. Multiple kinds of qualitative and quantitative methods were developed over time. The suitability of a method is always depending on the kind and extent of the available data as well as the scope of the risk analysis. A comprehensive overview over all method and their characteristics is given in Alireza et al. (2014) and ISO 31000 (2012) on risk management. According to ISO 31000 (2012), risk evaluation compares the level of risks resulting from the risk analysis. Risk evaluation facilitates the following risk treatment process by an evaluation, categorization and prioritization of all analyzed risks. Based on this comparison, the requirement for treatment can be considered.

2.3. Workflow

The workflow of this study is illustrated in Fig. 3 and is subdivided into four steps:

- **Step 1. Review:** Brief description of technological development reviewing past, present and future research and commercial projects;

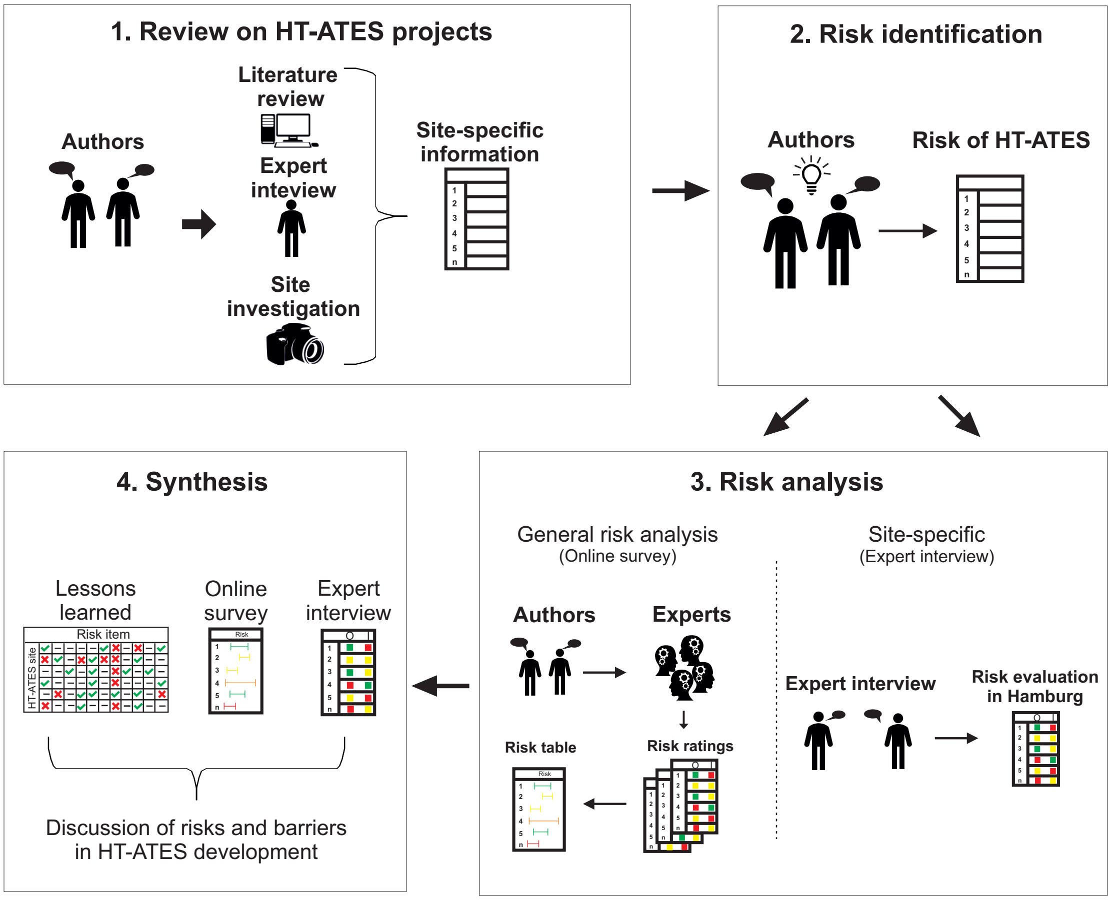

Figure 3: Workflow of the present study.

- **Step 2. Risk identification:** Following from and elaborating on the identified developments in step 1, risks are identified which are categorized in a Risk Breakdown Structure (RBS). The identified causes of risks are classified based on the kind of effect (Ioannou et al., 2017) and the stage of occurrence (planning, construction, operation);

- **Step 3. Risk analysis:** The identified risks are analyzed in an online survey among experts from the field of ATES and geothermal energy. Each risk item is evaluated based on its severity, occurrence probability and uncertainty (Section 2.4). This general approach is complemented by a site-specific risk analysis for two HT-ATES projects in the city of Hamburg. Based on an expert interview, the results of the online survey are evaluated. It is discussed, which risk items are highly influenced by local boundary conditions and have to be site-specifically addressed in future risk analyses;

- **Step 4. Synthesis:** Based on the lessons learned from the past, it is assessed whether the developed framework will be able to identify and mitigate the problems which were encountered at past HT-ATES systems. The lessons learned are opposed to both the general and site-specific risk analysis and barriers for technology development are discussed.

The general approach of the risk analysis (Step 3) is described in more detail in the following section.

2.4. Risk analysis

The reliability of a risk analysis is depending on data availability and the experience of the risk assessor. However, most risk analysis approaches are characterized by several shortcomings when applied to the context of multi-disciplinary, complex, and relatively unknown situations (Markmann et al., 2013). HT-ATES is a complex technology, in which only little experiences were gained in the past. At the same time, risks are highly project specific and quantitative approaches are not applicable. Thus, potential risks of HT-ATES are qualitatively analyzed in this study. In order to cover the manifold, multidisciplinary experiences gained at numerous ATES or geothermal projects in the past, the qualitative risk analysis is conducted by an online survey among experts. All invited experts are asked to rate the occurrence probability (O_P), severity (S_V) and uncertainty (U_C) of all identified sources of risk following a five point Likert scale (Table 1) (Yu et al., 2008; Alireza et al., 2014). The occurrence probability (O_P) is the likelihood of an event to occur, whereas the severity defines the extent of the damage to the institution, its people, and its objectives resulting from a risk event. The uncertainty (U_C) is a measure for the predictability of the occurrence probability and the severity of a risk event. While each expert obtained his/her experiences with HT-ATES or geothermal projects in his/her country, the results are expected to reflect the multi-perspective views within the community on risks in HT-ATES. Hence, all identified risks are also site-specifically analyzed for a shallow (350 m) and a deep (1000 m) HT-ATES project in the city of Hamburg. Considering the different character of both projects, it is evaluated whether different risk ratings for both projects reflect a high disagreement for the same risk in the online survey. This site-specific analysis allows conclusions on the influence of local

Table 1: Five point Likert scale for the evaluation of the occurrence probability (O_P), severity (S_V) and uncertainty (U_C) (Yu et al., 2008; Alireza et al., 2014).

	Occurrence probability (O_P)	**Severity (S_V)**	**Uncertainty (U_C)**
1	**Very low frequency:** It may occur only in very exceptional circumstances.	**Insignificant:** No impact on system operation or revenue.	**Very low uncertainty:** The risk is well predictable.
2	**Low frequency:** It is unlikely to occur in most circumstances.	**Minor:** Little disruption or low increase in costs.	**Low uncertainty:** Low uncertainty by a careful pre-investigation.
3	**Moderate Frequency:** It may occur sometimes.	**Moderate:** Moderate impact, some manageable disruptions or increasing in costs.	**Moderate uncertainty:** Moderate uncertainty despite a careful pre-investigation.
4	**High Frequency:** It may occur in most circumstances.	**Major:** High impact, system significantly compromised.	**High uncertainty:** Risk occurrence and severity is hard to predict.
5	**Very High Frequency:** It is almost certain and expected to occur in most circumstances.	**Severe:** Major impact, complete failure of system.	**Very high uncertainty:** The occurrence probability and severity is very hard to predict.

boundary conditions on risks in HT-ATES.

3. HT-ATES activities

There is a 50-year history of R&D activities in HT-ATES. A detailed description on early activities was summarized in Fleuchaus et al. (2018). Fig. 4 illustrates past, current and future projects. Technical and geological details are complemented in Table 2. Currently, there is only one HT-ATES (Rostock) in operation worldwide. Any other HT-ATES plant had to be abandoned due to different reasons. More information on the operational experiences, reasons for abandonment and lessons learned can be found in Chapter 4.3. The following section focuses on the ongoing HT-ATES activities and provides information on each project site.

TestUM (test-site Wittstock) (DE)

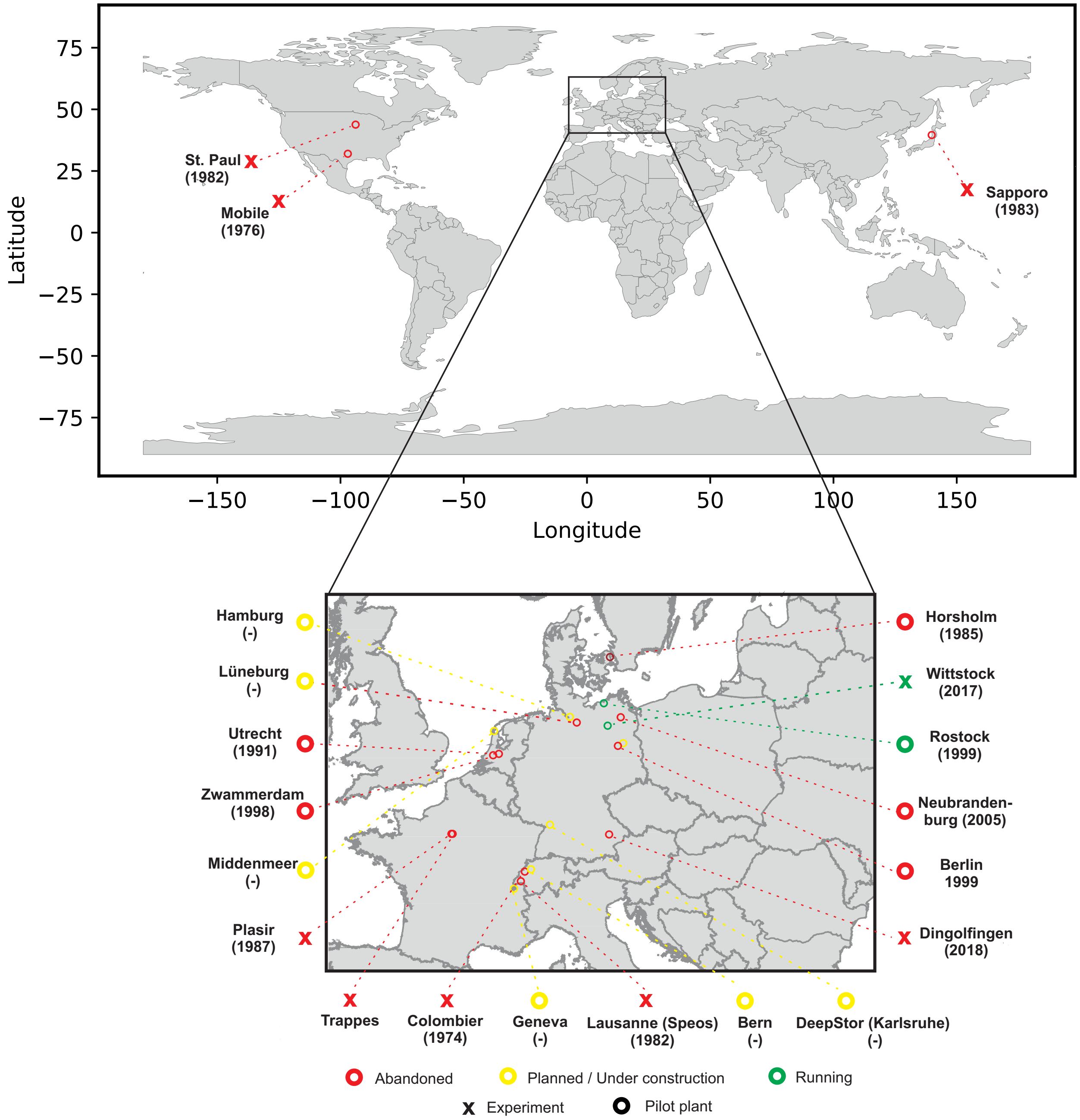

Figure 4: Spatial distribution of abandoned, planned and running HT-ATES projects worldwide.

In the project TestUM-Aquifer, a test site is established to investigate multi-phase and heat transport processes in shallow aquifers. The aim is to develop methods to detect, predict and control geophysical, hydrogeochemical, microbial and hydraulic interactions and effects caused by the storage of heat in groundwater. The project strives to support the thermal energy storage in an urban environment by facilitating the establishment of scientific based

Table 2: Technical and geological characterization of past, present and future HT-ATES projects.

#	Location	**Year**	**Scope**	Heat source	Injection Temp. [°C]	Storage depth [m]	Geology
1	Colombier, CH	1974	E	-	70	Shallow	Sand and gravel
2	Mobile, US	1976	E	Industrial	55	39-61	Sand and clay
3	ST. Paul, US	1982	E	Industrial	117	182-244	Sandstone
4	Lausanne, CH	1982	E	Industrial	40-80	7-24	Silt and sand
5	Sapporo, JP	1883	E	Solar	40-60	95	Sand and clay
6	Hørsholm, DK	1885	A*	Industrial	100	10-25	Sand
7	Plaisir, FR	1987	A*	Industrial	180	500	Sand and clay
8	Utrecht, NL	1991	A*	Cogeneration	90	192-290	Sand
9	Zwammerdam, NL	1998	A*	Cogeneration	90	135-150	Sand
10	Berlin, DE	1999	A*	Cogeneration	70	320	Sandstone
11	Rostock, DE	1999	A*	Solar	50	13-27	Sand and gravel
12	Neubrandenburg, DE	2005	A*	Cogeneration	80	1250	Sandstone
13	Dingolfingen, DE	2016	E	Cogeneration	120	500-700	Molasse
14	Wittstock (test-site), DE	2016	E	Artificial	-	Shallow	Sediments
15	Lüneburg, DE	-	A	Cogeneration	90	450	Sand
17	Hamburg, DE	-	A	Industrial	90	300	Sand
18	Middenmeer, NL	-	A	Geothermal	90	300-400	-
19	Geneva, CH	-	A	Industrial	90	500-1000	Limestone
20	Bern, CH	-	A	Power plant	120	500	Molasse
21	DeepStor, DE	-	A	Geothermal	110	1000	Tertiary

[*] E = Experimental, A= Applied, A*= Applied (realized)

guidelines for groundwater protection.

Beyond Batteries Lab (US)

Two collaborative projects led by the Idaho National Laboratory (INL) received funding by the Department of Energy (DOE) to develop concepts to moderate electrical grid's peaks and valleys by storing thermal energy in aquifers. The two projects are part of the Grid Modernization Initiative (GMI) of the DOE, which explores approaches to utilize geothermal energy in order to improve grid reliability, resilience and security. One project strives to develop models to store surplus heat (steam) of thermoelectric power plants in the subsurface (INL, 2018). A second project investigates the storage of concentrated solar heat in the subsurface. The recovered HT solar heat could then be used to enhance the load-following characteristics of a geothermal power plant. Both projects address not only technical feasibility of subsurface heat storage, but also the power plant designs as well as the economic efficiency.

Lüneburg (DE)

The Bockelsberg District in Lüneburg is supplied with heat from bio-methane-fired CHP-units. The planned HT-ATES storage is used to minimize heat from natural-gas fired peak-load vessels to achieve about 95% CHP heat. The heating systems of the University Campus as part of the Bockelsberg district and the heat supply of the new central building are designed to make use of low energy heat, thus annual heat recovery factors of >75% are achieved, although, only a potential of 3-3.5 GWh/a of a theoretical potential of the aquifer storage of >10 GWh/a is used. The ATES is part of a climate neutrality concept of the Leuphana University (Opel et al., 2017). Despite intensive research and pre-investigations emphasizing the technical and economical feasibility of the planned system, the support for actual implementation is currently low due to unclear risk perception by decision makers involved and several local political and economic circumstances. However, the ATES is still regarded as a promising option for future development of the bio-methane-CHP based energy system in the city of Lüneburg.

Hamburg (DE)

In 2013, the citizens of Hamburg decided in a referendum to re-communalize the energy supply of the city. The re-acquisition of the DH network from the energy company „Vattenfall Wärme GmbH“ was completed in 2019 (BUE, 2019). At the same time, the city of Hamburg decided to replace two coal-fired plants (67% of supplied heat) until 2030 by less CO_2-intensive heat sources such as industrial waste heat, power-to-heat or wastewater-heat-recovery. To increase the flexibility of the new heating system, it is also planned to integrate both short- and long-term heat storages. HT-ATES is considered as key technology and different storage concepts, heat sources and storage horizons are currently under investigation. Potential target formations are the „Upper Braunkohlesande“ (UBKS) at a depth of 200-300 m and a 1000 m deep Sandstone formation (Radmann, 2019). Due to its high salt content, the UBKS is not utilizable for drinking water supply and is separated by a confining layer from the upper groundwater body. In 2017, a test well was drilled on the Elbe island Dradenau to perform a storage test cycle. With a recovery rate of around 90%, technical feasibility of heat storage in the UBKS was successfully demonstrated (Radmann, 2019). Different storage locations and an efficient integration into the heating network are currently under investigation (Rabenstein, 2018). A second storage formation (sandstone) is considered in a depth of around 1000 m (Beckereit, 2019). Again, different heat sources and sinks as well as storage locations are currently under evaluation. In this context, the project IW^3 received funding from the program „living lab“ of the Federal Ministry of Economic Affairs and Energy (BMWI). The project builds up on the pre-investigations of the company „GTW Geothermie Wilhelmsburg GmbH“, which strives to realize a deep geothermal system in a depth of 3000-4000 m. IW^3 aims at establishing a decentralized, fossil-free heat supply for the district Wilhelmsburg. In this concept, a HT-ATES is planned to enhance the efficiency of different heat sources such as geothermal energy or industrial waste heat (BMWI, 2019).

DeepStor (Karlsruhe) (DE)

The new KIT project DeepStor strives to store excess heat of a planned geothermal power plant at temperatures of about 110 °C. With temperatures up to 170 °C in a depth of 3 km, the largest known thermal anomaly in Germany is located at the KIT Campus North (Kohl, 2020). By utilizing the existing campus infrastructure (heating network), the KIT Campus North offers promising preconditions for the extraction, seasonal storage and distribution of geothermal energy (Kohl et al., 2019). The extracted heat from deep geothermal energy is considered to supply the base load and the excess heat for seasonal storage. The high temperature storage is planned in a storage depth of around 1 km (tertiary basin) in earlier oil reservoirs.

HeatStore

HeatStore is one of nine projects under the GEOTHERMICA - ERA NET Cofund aiming to facilitate the integration of underground thermal energy storage (UTES) in the heating and cooling sector. Different types of UTES are investigated and tested at six demonstration sites in several European countries. Among these pilot projects, three HT-ATES test sites are planned in Middenmeer (NL), Geneva (CH) and Bern (CH) (Kallesøe & Vangkilde-Pedersen, 2019; Koornneef et al., 2020). The aim and characteristics of each HT-ATES site is described below:

Middenmeer (NL)

In the Dutch town Middenmeer, six geothermal wells with a depth of 2000 m each are used for geothermal heat supply for greenhouses. In order to increase the heating capacity, surplus heat of the geothermal system is supposed to be stored in a depth of 300-400 m with a storage temperature of 90°C (HeatStore, 2019). R&D activity is focusing on gaining in-depth knowledge on CO_2 water treatment, optimized material selection and potential benefits of an insulation of the ATES wells (Kallesøe & Vangkilde-Pedersen, 2019).

Geneva (CH)

The Geneva HT-ATES site is linked to the „Geothermie 2020“ strategy of the Canton of Geneva and aims at assessing the feasibility of seasonal storage of 35 GWh/a surplus heat from the Cheneviers waste incinerator (Collignon et al., 2020; Quiquerez, 2017). Several target aquifers exist at different depths and are currently being explored and characterized by two exploration wells (GEo-01 and GEo-02) in the Lower Cretaceous and the Upper Jurassic (Malm) carbonate units. As the target aquifers are characterized by an unknown geology, current activity is focusing on the identification of the optimal and reliable storage formation. These challenges are tackled by establishing a workflow that includes a flexible reservoir modeling approach combining static reservoir models, thermo-hydraulic (TH), thermo-hydraulic-chemical (THC) and thermo-hydraulic-mechanical (THM) models (Guglielmetti et al., 2020). In the framework of the HeatStore project funded by the EU GEOTHERMICA funding program, the outcomes of such approach will be combined to energy systems scenarios. These scenarios will be transposed to detailed risk assessment and business models in order to assess the technical, environmental and financial feasibility and support local authorities for improvement of the legal framework.

Bern (CH)

The „Forsthaus Heat Storage“ project is planned by Geo-Energie Suisse AG (GES) on behalf of the local utility company Energie Wasser Bern (ewb). It is supported by the Swiss Federal Office of Energy and is part of the Swiss contribution to the European GEOTHERMICA project. The project site is located in the northern part of the city of Bern (Switzerland) next to ewb's power production site „Energiezentrale Forsthaus“. The purpose of this project is to store waste heat from power production (7-10 MWth) with a storage temperature of up to 120°C. The project design anticipates a main well at the center of the system and peripheral auxiliary wells. The main well is used to inject and produce the energy in the form of hot water. The auxiliary wells are used to regulate the flow at the boundary, maintain the desired aquifer reservoir pressure and connect to the surface system.

4. Risk assessment

4.1. Risk identification

Renewable energy projects are considered as successful as they meet time, budget and performance goals. However, the success of the project might be jeopardized by different sources of risk. Table 3 shows the outcome of the risk identification process described in Section 2. While all identified risks can negatively affect the merit of the project, some might also cause a time delay or harm the environment. In addition, some risks have to be considered throughout the entire project, others just during the phase of planning, construction or operation. In order to facilitate the risk analysis by the online survey, some minor sources of risks were aggregated into more general risks. The risk item „well integrity“, for instance, could be further subdivided into „material degradation“, „collapse/buckling of casing“ or „breakdown“. Additionally, it is important to consider that there is mutual interaction between individual risk items. The risk of „public perception“ could be, for instance, highly influenced by the occurrence of the risk induced „seismicity“. Table 3 serves as the basis for the risk analysis in Section 4.2.

4.2. Risk analysis

4.2.1. Generic risk analysis (online survey)

50% of 78 invited experts participated in the online survey, of which 45% were from industry, 37% were from science and 18% came from authorities or energy agencies. The respondents

Table 3: Identified risks of HT-ATES categorized based on the source of risk with information on the time of occurrence as well as the type of consequence (classification based on Ioannou et al. (2017)).

Cause of risk				Effect on		
Category	**Sub-category**	**Risk item**	**Stage* P-C-O**	**CAPEX/ OPEX**	**Time**	**Environment**
Financial	**Financing**	Liquidity / creditability	●●○	●	◑	○
		Loss of investor	●●○	●	●	○
		Interest rate	●●○	●	●	○
		Insurances	●●●	●	●	○
	Market	Decreasing heating demand	○○●	●	○	○
		Competing technologies	◑○●	●	○	○
		Contracting	●◑●	●	◑	○
	Costs	Electricity price	○○●	●	○	○
		Material costs	●●○	●	◑	○
		Labor costs	○◑●	●	◑	◑
Technical	**Site-investigation**	Exploration risk	●●○	●	●	◑
		Improper test-drilling	●●○	●	●	●
	Construction (technical)	Improper drilling	●●○	●	●	●
		Poor building integration	◑●●	●	●	◑
		Insufficient components	◑●●	●	●	◑
		Barring (existing) infrastructure	●●○	●	●	◑
		Ground(water) pollution	●●●	◑	◑	●
	Construction (geological)	Induced seismicity	◑●◑	●	●	◑
		Subsidences & swellable formations	◑●◑	●	●	◑
	Operation (technical)	(HVAC / DH)	○○●	●	●	◑
		Well integrity	●●◑	●	●	○
		Loss of heat source	●●◑	●	●	○
		Groundwater pollution	○○●	◑	○	●
		Heat losses	○◑●	●	○	○
	Geochemical and geological risks	Clogging & scaling	○◑●	●	◑	◑
		Corrosion (wells, pipes, EHX)	○◑●	●	◑	◑
		(Changing) quality of formation water	●●◑	●	●	○
		Induced seismicity (M <3)	●●◑	●	●	○
		Induced seismicity (M >3)	●●◑	●	●	○
		Subsidences & swellable formations	●●◑	●	●	○
Organizational		Time management	●◑●	●	◑	○
		Cooperation of all involved parties	●◑◑	●	●	○
Political		Varying subsidy programs	●◑●	●	◑	○
		Taxation regime	●◑●	●	○	○
		Decision-making structure	●◑◑	●	●	○
Legal		Changing legal framework	●●●	●	●	●
		Complex/uncertain permit procedure	●●◑	●	●	○
		Safety/monitoring requirements	●●◑	●	●	○
Social		Public perception	●●●	●	●	○
		Grid connection	●○○	●	●	○

* P = Planning, C= Construction, O= Operation, ● = Applies, ◑ = Partly applies, ○ = Not applies

originate from: Germany (23), Netherlands (8), Denmark (2), Sweden (2), United States (2), Norway (1) and Iceland (1). The outcome of the survey, grouped by the severity, occurrence probability and the uncertainty is illustrated in Fig. 7 in the Appendix. The severity and occurrence probability together determine the risk level. The respondents judgment are provided in Fig. 5, in which the uncertainty is expressed by colors from green to red. The median of all risk items ranges between 5 („Induced seismicity“) and 15.5 („Complex / uncertain permit procedure“). Thus, all risk items can be classified as low or medium risks. Apart from the risk items „Exploration risk“ and „Clogging & scaling“, technical risks are expected to be less critical than political, social, legal and organizational risks. This is remarkable as past studies in the field of HT-ATES mainly concentrated on technical risks with a special focus on heat transfer processes and optimization of storage efficiency (Wesselink et al., 2018; Fleuchaus et al., 2018). However, this ongoing research seems to be bearing fruit as the risk of „Heat losses“ received a comparable low risk rating and is estimated to be well predictable in the planning phase. Low risk values were also given to „Interest rate“ (6), „Material / Labor costs“ (6), „Changes in quality of formation water“ (6) and „Induced seismicity“ (5). In contrast, the experts see the risks of a „Complex legal procedure“ (15.5) and „Public perception“ (15) as most critical. Considering the standard deviations, experts were unanimous for the risk items „Loss of heat source“, „Heat losses“ and „Induced seismicity“. Low agreements were observed for the risks „Insurances“, „Exploration risk“ and „Public perception“. Different opinions could be explained by different background expertise, but also by the fact that the risk level of certain risk items is more influenced by local boundary conditions and therefore, difficult to estimate in general. The latter is addressed by a complementary risk analysis for the city of Hamburg in the following section, where the outcome of the online survey is opposed to the estimated risks for three planned HT-ATES projects. Finally, in Section 4.3, the expert opinions are evaluated considering problems encountered at and lessons learned from already realized HT-ATES sites.

4.2.2. Site-specific risk analysis

The site-specific risk analysis for the HT-ATES projects in Hamburg is following a low-medium-high risk scale and is based on an expert interview with the project coordinator

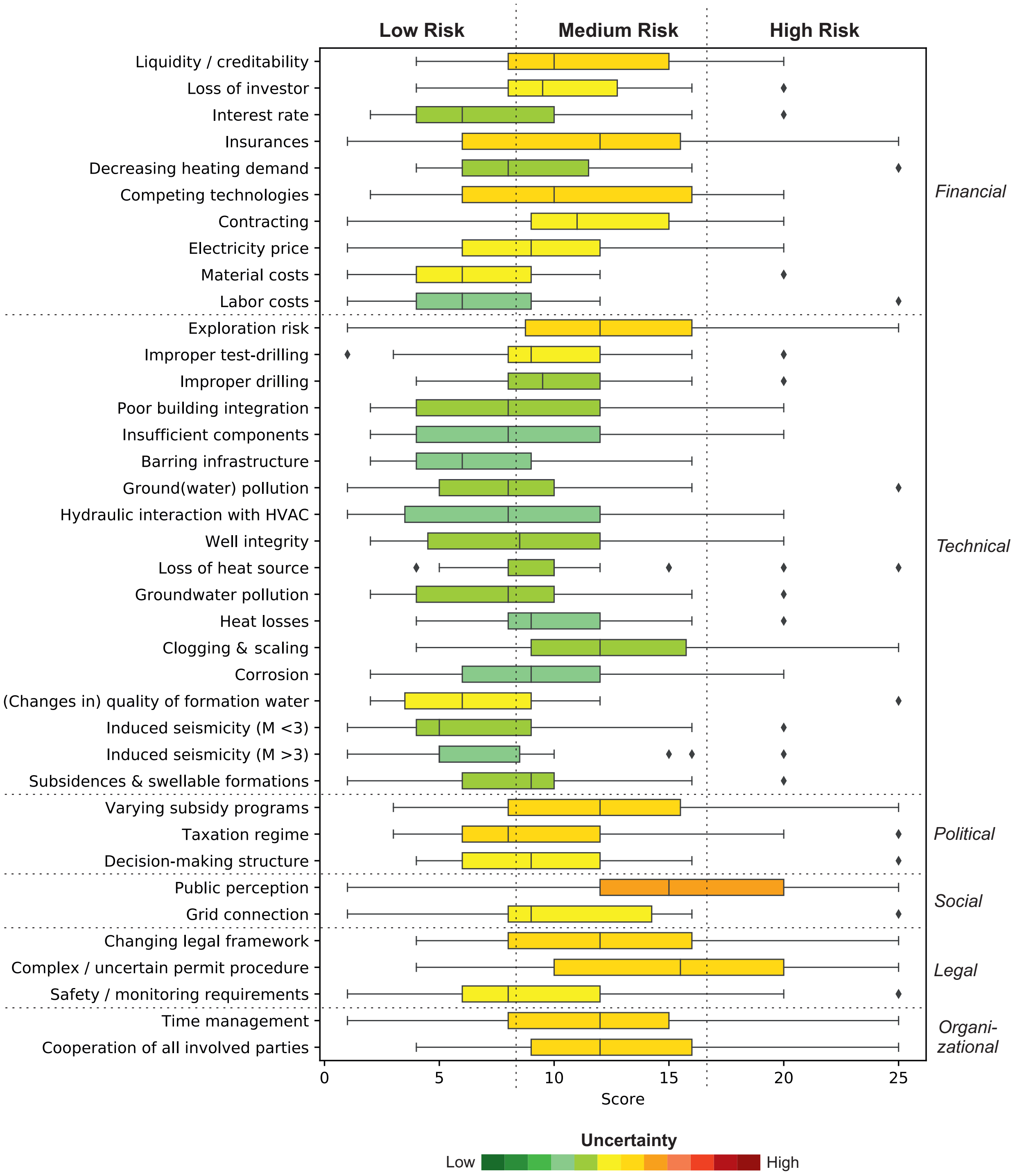

Figure 5: Expert risk ratings calculated by the product of the occurrence probability and severity. The uncertainty is illustrated by colors from green to red.

Kai-Justin Radmann (Radmann, 2019). A distinction is made between the risk estimation for a shallow (200-300 m) and a deep (1000 m) target formation (Section 3). Considering different technical and legal boundary conditions, causal relationships between expert disagreements in the previous section and differing risk estimations for the Hamburg projects are analyzed. The site-specific risk ratings are illustrated in Table 4.

As described in Section 3, an injection-recovery-test was completed and technical feasibility of heat storage was successfully demonstrated in the the shallow sandstone formation called UBKS. No technical problems were encountered and more than 90% of the injected heat was recovered. Hence, most technical risks such as „Exploration risk“ or „Heat losses“ can be expected as low. Nevertheless, suitable water-treatment measures will be important to prevent scaling and clogging considering the high storage temperatures and complex chemistry of the salty aquifer. According to Radmann (2019), the most crucial risks for the shallow HT-ATES are, however, of financial and legal nature. Financial issues are mainly attributed to the temperature level (inlet and outlet) of the DH grid. Extra costs are expected to match the recovery temperatures of the ATES (~70 °C) with the inlet temperature of the DH (~90 °C). In addition, it is important to lower the injection temperature of the cold well to allow a high storage capacity and to prevent thermal interferences. Pre-investigations indicate that a cascade of four heat pumps would be required to reach injection temperatures below 40 °C. This results in higher capital costs and increases the risk of increasing electricity and maintenance costs. From a legal point of view, high risks are associated with the plan of the city of Hamburg to reserve the salty aquifers of the UBKS as a backup reservoir for drinking water supply. Complex permit requirements both for installation and monitoring are therefore, rather likely. In contrast, the second target formation is characterized by a higher storage temperature (90 °C) and a deeper storage depth (~1000 m). Similar to the more shallow HT-ATES concepts, the risks of „Competing technologies“, „Clogging & Scaling“ and a complex „Decision-making structure“ are expected as high. Since less experiences were gained with the target sandstone formation, the exploration risk is also expected to be high, particularly when considering a lack of insurance for HT-ATES in Germany. In contrast to the shallower projects, legislative risks are low. This is also the case for the electricity costs, as the abstraction and injection temperature meet the temperature level of the DH network.

The site-specific analysis for Hamburg indicates that some risks highly depend on the local boundary conditions and are challenging to estimate in general. In Hamburg, this is particularly the case for the legal and exploration risks, which explains the strong disagreements among the experts in the previous section. While the site specific risk analysis mainly reflects the outcome of the online survey, this is not the case for the risk of „Competing technologies“ and „Public perception“. Due to insufficient charging and discharging temperatures of the shallow HT-ATES and a high inflexibility, there is a high risk of it being replaced by a different technology. In addition, the risk of „Public perception“ is expected as low for the Hamburg projects, even though it received the second highest risk rating by the experts. This can be explained by a strong support by the population, which decided in a referendum to replace the existing coal-fired heating supply by less CO_2 intensive technologies (Section 3).

4.3. Evaluation of risk analysis

The following section links the outcome of Section 4.2.1 (online survey) and Section 4.2.2 (expert interviews) with the lessons learned from the past. It is evaluated, if the outcome of the online survey and the expected risks for HT-ATES projects in Hamburg coincide with the problems encountered at past HT-ATES sites, which are illustrated in Table 4. Please consider that some of the identified risks were not particularly relevant for early (experimental) sites, which were not implemented in a real-case scenario. Hence, HT-ATES projects in the 1970 and 1980s were mainly facing technical problems, mostly related to carbonate clogging, corrosion or particle clogging (Table 4). However, new water treatment methods were developed and new storage concepts designed. At the beginning of the 1990s, HT-ATES achieved a new stage in the commercialization process as two HT-ATES sites were running for several years in the Netherlands. Building on the research efforts from the 1970s and 1980s, less geochemical problems were encountered. Even though considerable experience could be gained through deep geothermal applications in the past, further research to prevent or reduce the appearance of corrosion is crucial and is currently performed in various laboratory (Huttenloch et al., 2019) and in situ studies (Mundhenk et al., 2013) , respectively. Even though significant well-clogging was still observed at Utrecht University, most critical was a low recovery of the stored waste heat from a co-generation plant. The major cause for the low recovery efficiency was not the malfunctioning of the system, but a mismatch with the heating needs of the connected buildings. Technical problems due to a failure of the pressure valve and poor knowledge of the system finally lead to a permanent shut down of the system (Sanner, 2000). In Zwammerdam, no significant geochemical problems were found and the energy storage worked as expected beforehand (Drijver, 2011). However, the return temperature of the DH grid was higher than expected, causing only a little unloading of the store (Sanner, 2000). Finally, the HT-ATES was closed down due to financial reasons: the energy savings by the ATES could not compensate for the extra costs for electricity production by the CHP. Thus, the electricity production of the unit was decreased, leading to too little heat excesses to make the HT-ATES economically feasible (IF Technology, 2011). Hence, by applying HT-ATES in real heating environments with the beginning of the 1990s, relevant risks were shifting from mainly subsurface related issues towards risks also concerning the heat source and sink („Decreasing heating demand“, „Competing technologies“, „Poor building integration“, „Loss of heat source“ or „Hydraulic interaction“).

This could be also observed for the most recent HT-ATES sites located in the German cities Berlin, Rostock and Neubrandenburg (Fig. 4). In Berlin, heating and cooling for the Parliament buildings is supplied by LT- and HT-ATES systems. The thermal energy for heating and cooling is stored in two separated aquifers at a depth of 60 m (cooling) and 320 m (heating). Detailed information was published by Kabus & Seibt (2000), Kabus et al. (2005) and Sanner et al. (2005). While the shallow storage is still in operation, the HT-ATES was shut down in the beginning of 2018 (Metz, 2018). During more than 15 years of operation, there was a leakage in the horizontal piping and groundwater pumps had to be replaced every five years (Metz, 2018). However, none of these problems critically impaired the operation and a high storage efficiency was technically possible. Nevertheless, high recovery values were only sparsely reached in practice as the HT-ATES was oversized due to an overestimated heating demand by imprecise building simulations (Kabus, 2019). Additionally, the amount of surplus heat during summertime was strongly fluctuating, as most of the CHP heat was used for absorption cooling during summer. Even new CHP-units did not compensate for the

Table 4: Problems encountered at past and present HT-ATES sites (left) and expected risks for the HT-ATES projects in Hamburg analyzed by Radmann (2019).

	Experiences from abandoned and running projects											**Expected risk**	
Source of risk	Colombier	Mobile	St. Paul	Lausanne	Hørsholm	Plaisir	Utrecht	Zwammerdam	Berlin	Rostock	Neubrandenburg	Hamburg - shallow	Hamburg - deep
Liquidity / creditability	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Loss of investor	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Interest rate	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Insurances	○	○	○	○	○	○	-	-	○	○	○	🟡	🔴
Decreasing heating demand	○	○	○	○	○	○	🔴	-	🔴	🟢	🟢	🟢	🟢
Competing technologies	○	○	○	○	○	○	🔴	🔴	🟡	🟢	🔴	🔴	🔴
Contracting	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Electricity price	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🔴	🟢
Material costs	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟡	🟡
Labor costs	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Exploration risk	🟡	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🔴
Improper test-drilling	○	○	○	○	○	○	○	○	🟢	🟢	○	🟢	🔴
Improper drilling	○	🔴	🟢	○	○	○	🟢	🟢	🟢	🟢	○	🟢	🟢
Poor building integration	○	○	○	○	○	○	🟡	-	🟡	🟢	○	🟢	🟢
Insufficient components	○	○	○	○	🔴	○	🟡	🟢	🟢	🟢	🟡	🟢	🟡
Barring infrastructure	○	○	○	○	○	○	○	○	🟡	🟢	🟢	🟡	🟡
Hydraulic interaction	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢
Well integrity	-	-	-	-	-	-	🔴	🟢	🟢	🟢	🟡	🟢	🟢
Loss of heat source	○	○	○	○	🟢	○	🔴	🔴	🔴	🟢	🔴	🟡	🟢
Groundwater pollution	-	-	-	-	-	-	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Heat losses	🔴	🔴	🟢	🟡	🟡	-	🟡	🟡	🟢	🟢	🟢	🟢	🟢
Clogging & scaling	-	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟡	🔴	🔴
Corrosion	-	-	🟡	🔴	🔴	-	🟢	🟡	🟡	🟢	🟡	🟢	🟡
(Changing) quality of form. water	-	-	-	🟡	-	🔴	-	-	🟢	🟢	🟡	🟡	🟢
Induced seismicity	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Induced seismicity (M >3)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Subsidences & swellable formations	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Varying subsidy programs	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢
Taxation regime	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢
Decision-making structure	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🔴	🔴
Public perception	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Grid connection	○	○	○	○	○	○	🟢	🟢	○	○	🟢	🟢	🟢
Changing legal framework	○	○	○	○	○	○	-	-	🟢	🟢	🟡	🟢	🟢
Complex permit procedure	○	○	🟡	-	-	-	-	🟡	🟢	🟢	🟢	🔴	🟢
Safety/monitoring requirements	-	-	🟡	-	-	-	-	🟡	🟢	🟢	🟡	🔴	🟢
Time management	-	○	○	○	○	○	-	-	🟢	🟢	🟢	🟢	🟢
Cooperation of all involved parties	○	○	○	○	○	○	-	-	🟢	🟢	🟢	🟡	🟡

[*] - = No information, ○ = Not relevant, 🟢 = Not encountered (low), 🟡 encountered (medium), 🔴 = Crucial (high)

largely underestimated cooling demands of the connected buildings. As a consequence, the storage was mostly fed with low temperature heat from absorption chillers, thus not reaching design temperatures (Metz, 2018). Similar to the experiences made in Utrecht, this varying demand-supply mismatch lead to an inefficient operation and the final shut-down. Nevertheless, it is planned to put the HT-ATES back in operation to supply a planned adjacent new building (Kabus, 2019). In the city of Neubrandenburg, an abandoned geothermal system was reactivated to store surplus heat of a Combined Cycle Gas Turbine (CCGT) in a depth of 1200 m. The recovered heat was used to supply a small DH network, which was initially fed by the abandoned geothermal system (Kabus et al., 2006). The HT storage was in operation for more than ten years. Technical problems were mainly observed at the cold well, where injection temperatures of 30 °C favored the growth of sulfate reducing bacteria. Geochemical reactions were monitored, analyzed and published in several studies (Kabus et al., 2009; Lerm et al., 2013; Würdemann et al., 2014, 2016). Even though corroded well pumps had to be replaced periodically (Fig 6), this did not significantly affect the operation of the ATES (Beuster, 2019). Again, the efficiency of the storage was less a matter of subsurface suitability, however more a matter of the charging-discharging behavior as function of fluctuating heating and cooling demands (Beuster, 2019). The system was shut down in the beginning of 2019 after the public utility of Neubrandenburg decided for a change in strategy by switching from long-term to short-term thermal energy storage. During summertime, excess heat of the CCGT will be stored from Monday till Friday in an artificial storage tank (Beuster, 2019). The steal tank is 36 m high and has a storage volume of 22.000 m^3 (Fig. 6). The stored heat is used for hot water supply of the city of Neubrandenburg during the weekend in the summertime. Thus, no residual heat is available for the HT-ATES. Nevertheless, it is planned to (re)use the existing wells for a (direct) geothermal system (Beuster, 2019).

The only currently running HT-ATES system is located in Rostock. With a charging temperature of 50 °C, this system is at the lower temperature threshold between HT- and LT-ATES and should be considered as hybrid system. A special permit was issued owing to the demonstration character and the high salt concentrations in the aquifer. Due to the low injection temperature, no technical problems were encountered. The ATES system supplies

Figure 6: Left: Corroded well pump of the cold well of the HT-ATES in Neubrandenburg. Right: Artificial storage tank to balance short-term supply-demand mismatch.

a building-complex and is fed with solar heat from the roof (Schmidt & Müller-Steinhagen, 2004). Thus, the risk of a changing heating demand and the loss of heat source can be considered as insignificant. In addition, with a storage depth of around 20 m, exploration risk and drilling costs were very low. Similar experiences were made in the Netherlands, where several ATES systems are in operation with a storage temperature between 40 and 45 °C (Drijver et al., 2019). At the ecological research institute NIOO in Wageningen, 40 °C (solar) is stored in a depth of 295 m. While cooling is provided from a second, more shallower aquifer, no heat pump is required for heating. Considering the heat pump-free and low-risk operation, there is a huge potential for systems with a storage temperature of 40 to 60 °C to supply the new/refurbished building stock without significant alterations to the electricity grid. With a maximum allowed injection temperature of 20-25 °C in shallow aquifers (< 400 m), this kind of system, however, would not receive a permit in most European countries (Hähnlein et al., 2010, 2013). Considering that urban aquifers are already highly influenced by anthropogenic activities (Bayer et al., 2019), this legislation practice should be critically reflected and adjusted, where appropriate. Laboratory investigations indicate a mobilization of several trace elements and heavy metals (particularly arsenic), but also a return to initial hydrochemical conditions after completion of ATES operation (Lüders et al., 2019; Bonte et al., 2013). Further in-situ experiments, as currently performed in the TestUM project (Section 3), and investigations on the impact on the microbiology are crucial. Building on profound scientific findings, knowledge-based, site-specific maximum injection temperatures should be established as function of the existing water quality and local (hydro)geological boundary conditions.

Considering the lessons learned from abandoned HT-ATES sites in the Netherlands and Germany, the risks „Decreasing heating demand“, „Loss of heat source“ and „Competing technologies“ were underestimated by the planners and experts in Section 4.2.1. This emphasizes the requirement for a reorientation of the scientific focus towards studies not only focusing on subsurface design, but also on the optimal interactions between heat source, sink and storage. Being designed to operate up to 30 years (Wesselink et al., 2018), HT-ATES are less flexible than competing technologies and highly sensitive to changes in the thermal energy demand (heat sink) and supply (heat source). At the same time, building planners often fail to predict the heating demand even in the short-term. In the long-term, changing boundary conditions such as refurbishment strategies or increasing ambient temperature make it challenging to match demand and supply over the entire lifespan. Finally, there is also a mismatch between Table 4 and the survey results with respect to legal risks. This, however, can be explained as special permits were issued to early pilot projects. Neither the HT-ATES in Berlin, nor the HT-ATES in Rostock would obtain a license under the current legislation policy. All HT-ATES projects, and particularly those affecting aquifers suitable for drinking water supply, are facing an unknown and uncertain permit procedure, which reflects the expert opinions. In order to allow a future-proof commercialization, easier, quicker and less challenging permit procedures have to be developed in Europe and worldwide.

5. Conclusion

Due to a constant technology development, the storage of heat in aquifers has gained some levels in technology readiness level (6-9). Successful demonstration plants and promising projects in the planning phase, particularly in European countries, are nourishing justified hopes for a breakthrough of the technology. The following key conclusions from this study help to realize more robust HT-ATES projects in practice. This study also revealed some recommendations to be considered in future R&D activities.

- This study revealed that risk assessment in geothermal energy should not only include technical and financial but also social, political and legal risks. As many risks are influenced by local boundary conditions (Section 4.2.2 and 4.3), the development of project-specific risk management strategies is highly recommended. Building on this first qualitative approach, future studies should strive to establish quantitative risk assessment in HT-ATES projects. Even though risk assessment is often applied for geothermal projects, very little is known about the advantages of different methods. Hence, different quantitative methods such as Monte Carlo (MC) or Bayesian Statistics should be compared and evaluated for real-case scenarios.

- The case studies and survey carried out in this research revealed that the most important technical risks are related to scaling and clogging of the wells and the projected energy supply and demand. Even though further efforts are required to prevent scaling and clogging particularly in high carbonated aquifers, early technical problems were controlled at recent HT-ATES sites. However, most HT-ATES systems had to be shut down due to an overestimated heating demand or the loss of the heat source (Utrecht, Zwammerdam, Neubrandenburg, Berlin). To foster profitable and sustainable operation of HT-ATES, future research should therefore not only focus on subsurface design, but also on the development of holistic energy concepts. This should also include the identification of potential heat sources and sinks as well as the consideration of long-term political, technical and legislative changes during an ATES lifetime of at least 30 years.

- Uncertainty about risks can be reduced by sharing data and experience. Despite the successful realization of HT-ATES system across Europe, no information is available on the economic performance. While Schüppler et al. (2019) and Ghaebi et al. (2017) performed a theoretical financial analysis for LT-ATES systems, future demonstration projects should strive to provide more insights into both capital (CAPEX) and operational (OPEX) costs of HT-ATES. A comprehensive database of economic statistics is crucial as both, CAPEX and OPEX highly depend on multiple factors such as the required drilling depth, the storage and recovery temperature or the heat source. A holistic monitoring covering all energy flows, energy costs and maintenance is indispensable to convince future investors to bet on HT-ATES. In addition to Wesselink et al. (2018), further efforts should be made to perform site- and market-specific analyses to evaluate economic feasibility of HT-ATES considering not only different supply alternatives but also different heat sources and sinks. Both, feasibility as well as real-case analyses should cover not only costs but also CO_2 emissions.

- Experiences from Rostock and the Netherlands indicate that storage temperatures of 40 to 60 °C in shallow urban aquifers bear a high potential for the supply of heating systems in well insulated buildings. The ATES proved not only to be technically robust but also facilitates establishment of an autarkic energy system. At the same time, the systems can be coupled with renewable heat sources and do not necessarily require the support of heat pumps. This technical potential however, is strongly limited by the current legislation. Hence, in order to establish a science based legal procedure, the impact of HT-ATES on groundwater quality has to be further investigated. In addition to the TestUM project (Section 3), research should not only focus on the geochemistry but also changes in groundwater ecology. Considering the fact that urban aquifers are already highly influenced by urban activities (Bayer et al., 2019; Tissen et al., 2019; Menberg et al., 2013), the distinction between natural (unaffected) and thermal or chemical contaminated aquifers are essential for a sustainable solution.

Different geothermal application types were being developed over time, ranging from closed to open loop, from direct to storage and from LT to HT systems. While all forms are characterized by shortcomings, none is able to cover the entire heating and cooling demand worldwide. HT-ATES is capable of increasing the flexibility of most renewable technologies and therefore, able to foster the integration of geothermal energy into the energy market. Further R&D activities are required to guarantee successful demonstration plants in the next decade to enhance trust in the technology and risk management must play an integral role.

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Appendix

Fig 7 illustrates the outcome of the survey, grouped by the severity, occurrence probability and the uncertainty. In general the respondents associate low risks also with low uncertainties, indicating that the respondents implicitly seem take uncertainty into account on their judgment on probability. The severity of most risk items was rated by most experts as „Moderate“ (3) or „Major“ (4). The technical risks „Loss of heat source“, „Induced seismicity (>3)“ and „Subsidences and swellable formations“ were rated as „Severe“ (5). In contrast, the occurrence probability was estimated to be „Very low“ (1) to „Moderate“ (3) for most risk items. This is particularly the case for technical risks, as social, political, legal and organizational issues are estimated to occur more often. A similar pattern can be observed for the uncertainty.

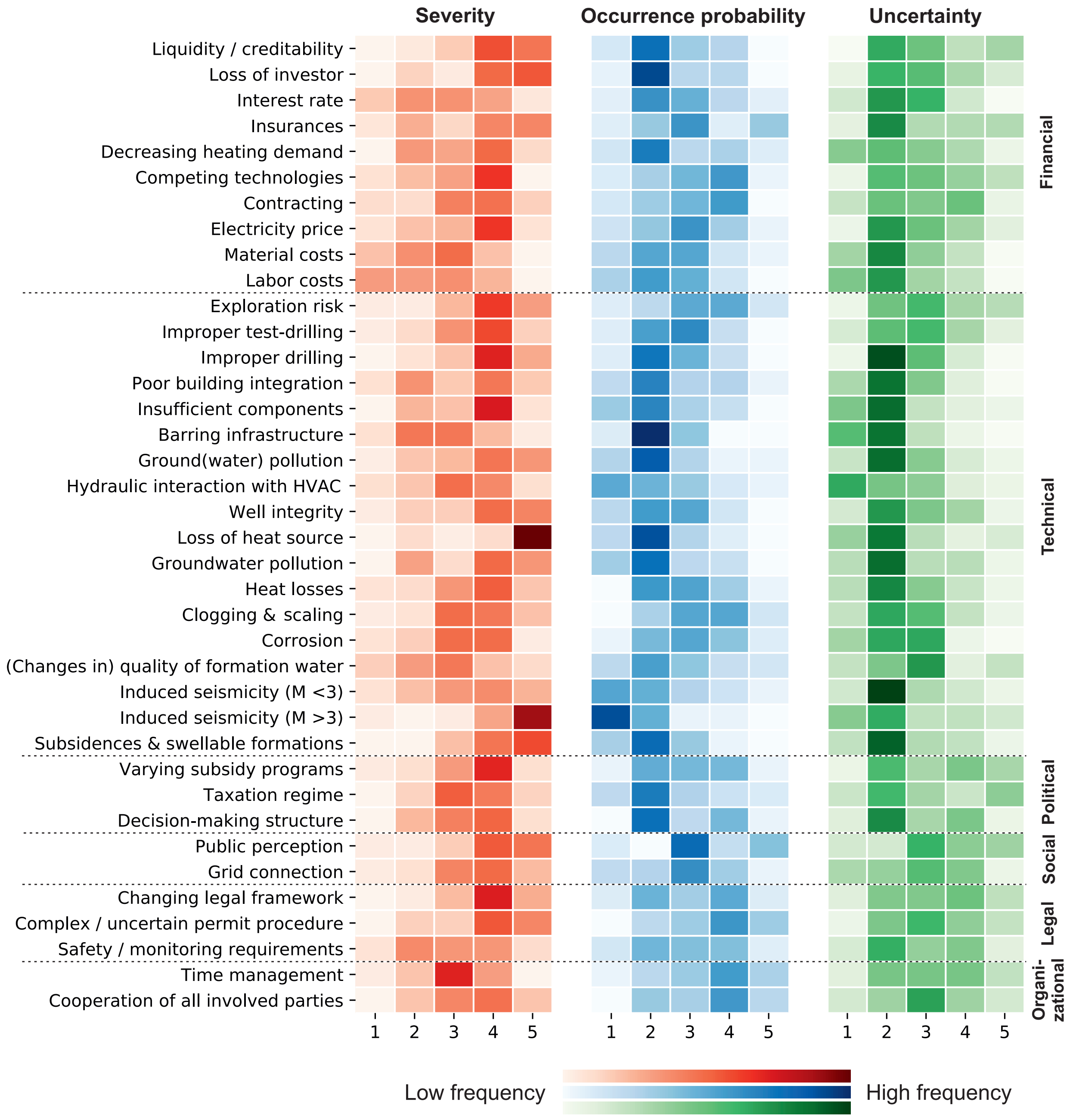

Figure 7: Relative frequencies of the risk item ratings grouped by the severity, occurrence probability and uncertainty.