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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 (Saner, 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

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

38

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

57

58 The objective of this study is, therefore, to foster technology adoption by obtaining a deeper  
59 understanding of risks in HT-ATES and establishing a risk assessment framework for risk  
60 management and mitigation for future projects. To meet these objectives, risks of HT-ATES

61 are identified based on a review of the past and current HT-ATES activities. The identified  
62 risks are qualitatively analyzed by means of an online survey among experts in geothermal  
63 energy. This generic analysis is complemented by a project-specific risk analysis of a HT-  
64 ATES project in the city of Hamburg to analyze the impact of local and site-specific risks.  
65 The outcome of this study will not only serve as a first basis for a project-specific, holistic  
66 risk mitigation strategy, but also create an awareness for the importance of risk management  
67 in HT-ATES.

## 68 **2. Methods**

### 69 *2.1. High-Temperature Aquifer Thermal Energy Storage*

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

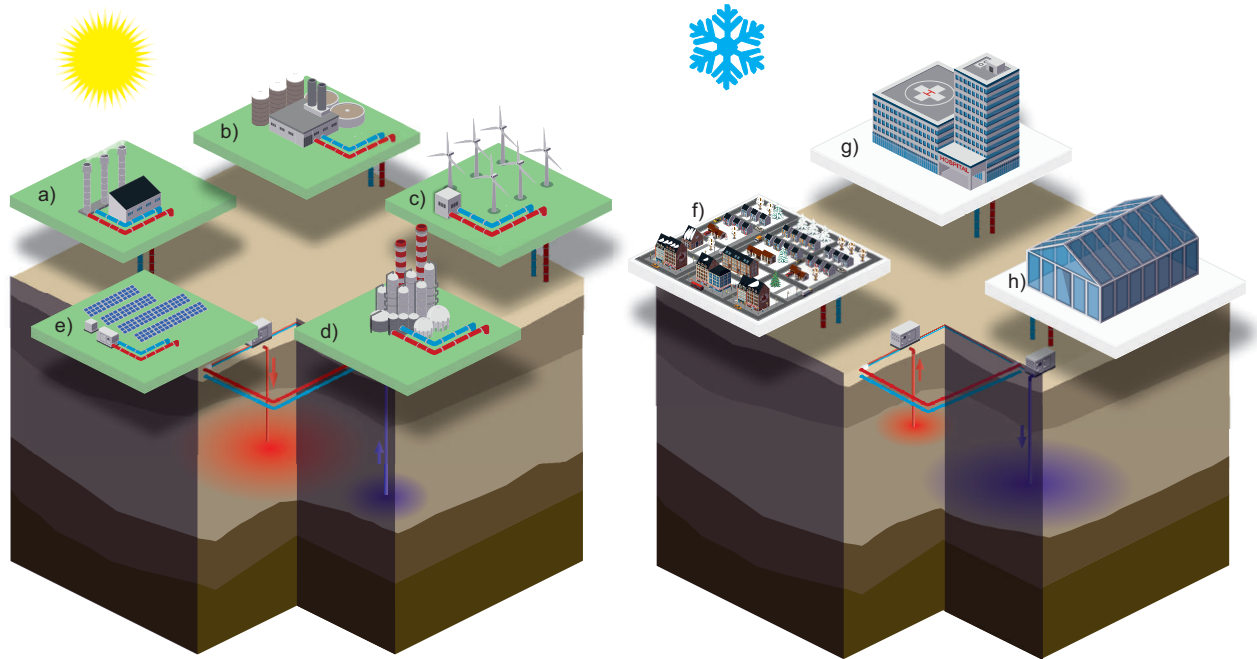


Figure 1: Basic principle of HT-ATES. In summer, the aquifer is charged with surplus heat from (non-)renewable energy sources such as geothermal (a), biomass (b), power-to-heat (c), industrial heat waste (d) or solar (e). The stored heat is recovered in winter to supply district heating (DH) systems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

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

91

92 Since this study is focusing on HT-ATES, we consider only ATES with a storage temperature  
 93 above a certain temperature threshold. However, different threshold values between LT- and  
 94 HT-ATES are defined in the literature. Drijver (2011), Drijver et al. (2012) and Kallesøe  
 95 & Vangkilde-Pedersen (2019) distinguish between LT (< 30 °C), mid-temperature (MT) (30-  
 96 60 °C) and HT- (> 60 °C) ATES. In contrast, other authors define HT-ATES with a storage  
 97 temperature above 50 °C (Bakema et al., 1995; Jenne, 1990; Sanner et al., 2003; Zeghici  
 98 et al., 2014; Andersson & Sellberg, 1992). This discrepancy can be explained as follows:  
 99 from a legal point of view, the temperature levels are stipulated by the maximum allowed  
 100 injection ( $T_{Max}$ ) temperature, which is defined by national or regional legal guidelines. For  
 101 most European countries,  $T_{Max}$  varies between 18 and 25 °C (Hähnlein et al., 2010, 2013).  
 102 Additionally, higher storage temperatures do not only trigger geochemical reactions and affect  
 103 groundwater characteristics (density, viscosity), but also highly affect the choice of materials

104 or components. For instance, water treatment to prevent scaling, clogging or corrosion is  
105 usually not required at temperatures below 50 °C (Kallesøe & Vangkilde-Pedersen, 2019).  
106 Additionally, higher storage temperatures trigger geochemical reactions and also affect the  
107 physical groundwater characteristics by increasing density and decreasing viscosity. The  
108 difference of density and viscosity between the injected warm and the ambient cold water  
109 causes buoyancy flow and therefore mixing of the different water temperatures reducing the  
110 recovery factor (Buscheck et al., 1983; Drijver et al., 2012). According to Doughty et al.  
111 (1982), buoyancy flow is fostered by temperatures above 60 °C. However, below 60 °C and  
112 temperature changes below 10 K, these effects are typically negligible (Hecht-Méndez et al.,  
113 2010). Finally, the threshold can also be established considering the requirements of the  
114 demand. However, the required temperature of the heating system strongly depends on the  
115 DH grid, the energy standards of buildings as well as the requirement of the heat pump. In  
116 this study, the definition established in Annex 12 of the Energy Conservation through Energy  
117 Storage (ECES) of the IEA is followed, where the minimum storage loading temperature is  
118 set to 50 °C.

## 119 *2.2. Definition of risk management*

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



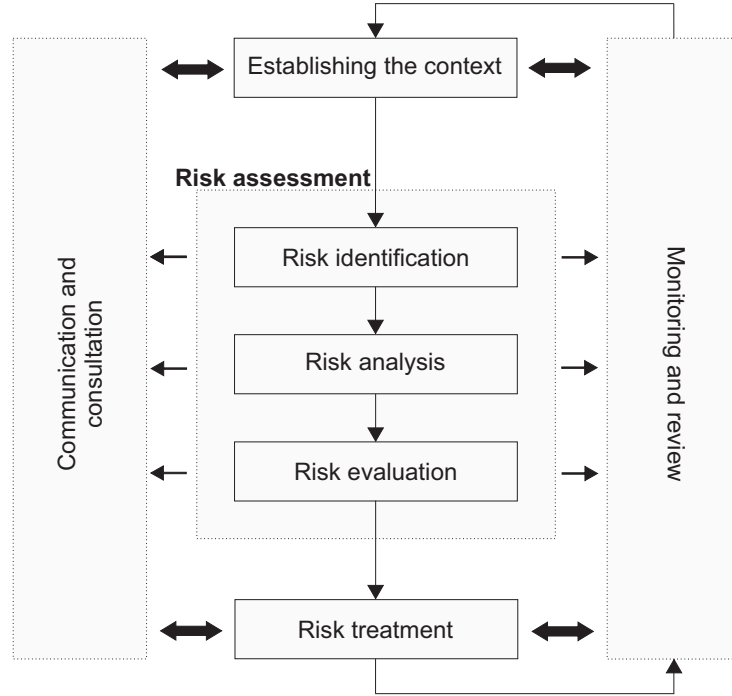


Figure 2: ISO standard risk management process (modified after ISO 31000 (2012)).

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

### 145 2.3. Workflow

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

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

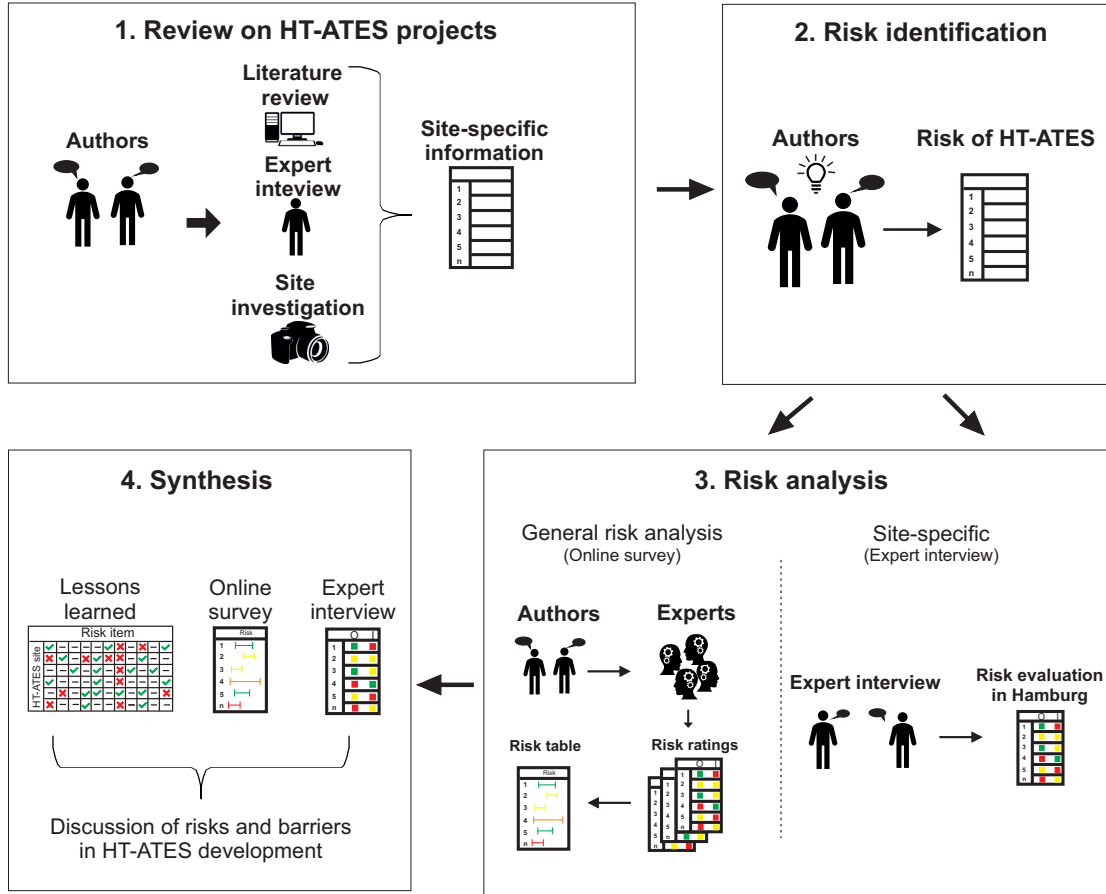


Figure 3: Workflow of the present study.

- 149
- **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);
- 150
- 151
- 152
- 153
- **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;
- 154
- 155
- 156
- 157
- 158
- 159

- **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).

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

189 boundary conditions on risks in HT-ATES.

### 190 3. HT-ATES activities

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

199

#### 200 TestUM (test-site Wittstock) (DE)

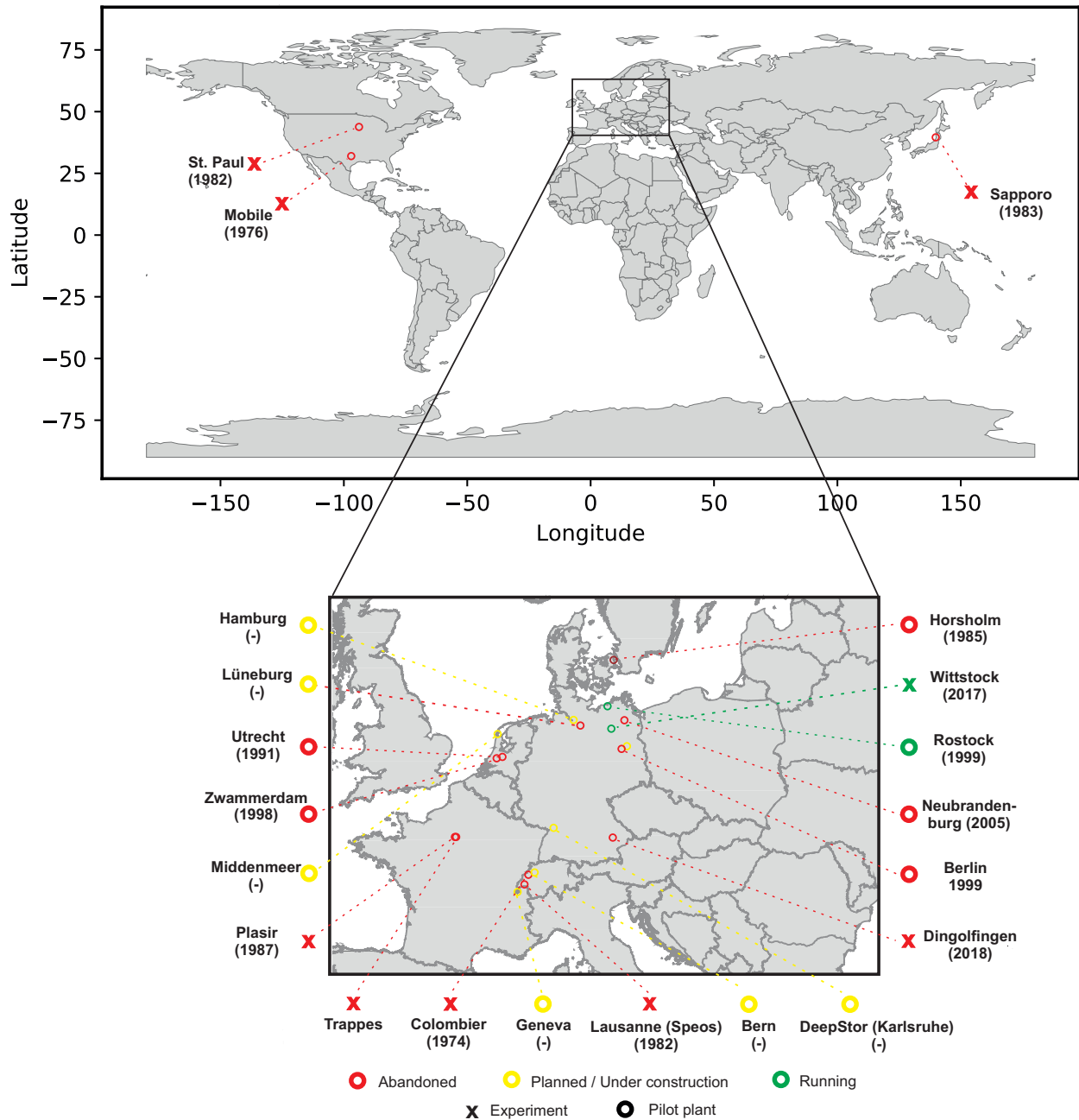


Figure 4: Spatial distribution of abandoned, planned and running HT-ATES projects worldwide.

201 In the project TestUM-Aquifer, a test site is established to investigate multi-phase and heat  
 202 transport processes in shallow aquifers. The aim is to develop methods to detect, predict  
 203 and control geophysical, hydrogeochemical, microbial and hydraulic interactions and effects  
 204 caused by the storage of heat in groundwater. The project strives to support the thermal  
 205 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)

206 guidelines for groundwater protection.

207

## 208 **Beyond Batteries Lab (US)**

209 Two collaborative projects led by the Idaho National Laboratory (INL) received funding by  
 210 the Department of Energy (DOE) to develop concepts to moderate electrical grid’s peaks and  
 211 valleys by storing thermal energy in aquifers. The two projects are part of the Grid Modern-  
 212 ization Initiative (GMI) of the DOE, which explores approaches to utilize geothermal energy  
 213 in order to improve grid reliability, resilience and security. One project strives to develop  
 214 models to store surplus heat (steam) of thermoelectric power plants in the subsurface (INL,  
 215 2018). A second project investigates the storage of concentrated solar heat in the subsurface.  
 216 The recovered HT solar heat could then be used to enhance the load-following characteristics  
 217 of a geothermal power plant. Both projects address not only technical feasibility of subsur-  
 218 face heat storage, but also the power plant designs as well as the economic efficiency.

219

## 220 **Lüneburg (DE)**

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

234

## 235 **Hamburg (DE)**

236 In 2013, the citizens of Hamburg decided in a referendum to re-communalize the energy  
237 supply of the city. The re-acquisition of the DH network from the energy company „Vat-  
238 tenfall Wärme GmbH“ was completed in 2019 (BUE, 2019). At the same time, the city  
239 of Hamburg decided to replace two coal-fired plants (67% of supplied heat) until 2030 by  
240 less  $CO_2$ -intensive heat sources such as industrial waste heat, power-to-heat or wastewater-  
241 heat-recovery. To increase the flexibility of the new heating system, it is also planned to  
242 integrate both short- and long-term heat storages. HT-ATES is considered as key technol-  
243 ogy and different storage concepts, heat sources and storage horizons are currently under  
244 investigation. Potential target formations are the „Upper Braunkohlesande“ (UBKS) at a  
245 depth of 200-300 m and a 1000 m deep Sandstone formation (Radmann, 2019). Due to its  
246 high salt content, the UBKS is not utilizable for drinking water supply and is separated by  
247 a confining layer from the upper groundwater body. In 2017, a test well was drilled on the  
248 Elbe island Dradenau to perform a storage test cycle. With a recovery rate of around 90%,

249 technical feasibility of heat storage in the UBKS was successfully demonstrated (Radmann,  
250 2019). Different storage locations and an efficient integration into the heating network are  
251 currently under investigation (Rabenstein, 2018). A second storage formation (sandstone) is  
252 considered in a depth of around 1000 m (Beckereit, 2019). Again, different heat sources and  
253 sinks as well as storage locations are currently under evaluation. In this context, the project  
254 *IW*<sup>3</sup> received funding from the program „living lab“ of the Federal Ministry of Economic  
255 Affairs and Energy (BMWI). The project builds up on the pre-investigations of the company  
256 „GTW Geothermie Wilhelmsburg GmbH“, which strives to realize a deep geothermal system  
257 in a depth of 3000-4000 m. *IW*<sup>3</sup> aims at establishing a decentralized, fossil-free heat supply  
258 for the district Wilhelmsburg. In this concept, a HT-ATES is planned to enhance the effi-  
259 ciency of different heat sources such as geothermal energy or industrial waste heat (BMWI,  
260 2019).

261

### 262 **DeepStor (Karlsruhe) (DE)**

263 The new KIT project DeepStor strives to store excess heat of a planned geothermal power  
264 plant at temperatures of about 110 °C. With temperatures up to 170 °C in a depth of 3 km,  
265 the largest known thermal anomaly in Germany is located at the KIT Campus North (Kohl,  
266 2020). By utilizing the existing campus infrastructure (heating network), the KIT Campus  
267 North offers promising preconditions for the extraction, seasonal storage and distribution  
268 of geothermal energy (Kohl et al., 2019). The extracted heat from deep geothermal energy  
269 is considered to supply the base load and the excess heat for seasonal storage. The high  
270 temperature storage is planned in a storage depth of around 1 km (tertiary basin) in earlier  
271 oil reservoirs.

272

### 273 **HeatStore**

274 HeatStore is one of nine projects under the GEOTHERMICA - ERA NET Cofund aiming  
275 to facilitate the integration of underground thermal energy storage (UTES) in the heating  
276 and cooling sector. Different types of UTES are investigated and tested at six demonstration  
277 sites in several European countries. Among these pilot projects, three HT-ATES test sites are  
278 planned in Middenmeer (NL), Geneva (CH) and Bern (CH) (Kallesøe & Vangkilde-Pedersen,



279 2019; Koornneef et al., 2020). The aim and characteristics of each HT-ATES site is described  
280 below:

281

### 282 *Middenmeer (NL)*

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

289

### 290 *Geneva (CH)*

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

306

### 307 *Bern (CH)*

308 The „Forsthaus Heat Storage“ project is planned by Geo-Energie Suisse AG (GES) on behalf

309 of the local utility company Energie Wasser Bern (ewb). It is supported by the Swiss Federal  
310 Office of Energy and is part of the Swiss contribution to the European GEOTHERMICA  
311 project. The project site is located in the northern part of the city of Bern (Switzerland) next  
312 to ewb's power production site „Energiezentrale Forsthaus“. The purpose of this project is  
313 to store waste heat from power production (7-10 MWth) with a storage temperature of up to  
314 120°C. The project design anticipates a main well at the center of the system and peripheral  
315 auxiliary wells. The main well is used to inject and produce the energy in the form of hot  
316 water. The auxiliary wells are used to regulate the flow at the boundary, maintain the desired  
317 aquifer reservoir pressure and connect to the surface system.

## 318 4. Risk assessment

### 319 4.1. Risk identification

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

### 333 4.2. Risk analysis

#### 334 4.2.1. Generic risk analysis (online survey)

335 50% of 78 invited experts participated in the online survey, of which 45% were from industry,  
336 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)).

| Category                  | Cause of risk                       |  | Effect on       |                |      |             |
|---------------------------|-------------------------------------|--|-----------------|----------------|------|-------------|
|                           | Sub-category                        | Risk item                                      | Stage*<br>P-C-O | CAPEX/<br>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                         | ●●○             | ●              | ●    | ●           |
|                           |                                     | Improper drilling                              | ●●○             | ●              | ●    | ●           |
|                           | Construction (technical)            | Poor building integration                      | ○●●             | ●              | ●    | ○           |
|                           |                                     | Insufficient components                        | ○●●             | ●              | ●    | ○           |
|                           |                                     | Barring (existing) infrastructure              | ●●○             | ●              | ●    | ○           |
|                           | Construction (geological)           | Ground(water) pollution                        | ●●●             | ○              | ○    | ●           |
|                           |                                     | Induced seismicity                             | ○●○             | ●              | ●    | ○           |
|                           |                                     | Subsidences & swellable formations (HVAC / DH) | ○○●             | ●              | ●    | ○           |
|                           | Operation (technical)               | Well integrity                                 | ●●○             | ●              | ●    | ○           |
|                           |                                     | Loss of heat source                            | ●●○             | ●              | ●    | ○           |
|                           |                                     | Groundwater pollution                          | ○○●             | ○              | ○    | ●           |
|                           | Geochemical and geological risks    | Heat losses                                    | ○●●             | ●              | ○    | ○           |
|                           |                                     | Clogging & scaling                             | ○●●             | ●              | ○    | ○           |
|                           |                                     | Corrosion (wells, pipes, EHX)                  | ○●●             | ●              | ○    | ○           |
|                           |                                     | (Changing) quality of formation water          | ●●○             | ●              | ●    | ○           |
| Induced seismicity (M <3) |                                     | ●●○  | ●               | ●              | ○    |             |
| Induced seismicity (M >3) |                                     | ●●○  | ●               | ●              | ○    |             |
| Organizational            | Subsidences & swellable formations  | ●●○  | ●               | ●              | ○    |             |
|                           | Time management                     | ●○●  | ●               | ○              | ○    |             |
| Political                 | Cooperation of all involved parties | ●○●  | ●               | ●              | ○    |             |
|                           | Varying subsidy programs            | ●○●  | ●               | ○              | ○    |             |
|                           | Taxation regime                     | ●○●  | ●               | ○              | ○    |             |
| Legal                     | Decision-making structure           | ●○●  | ●               | ●              | ○    |             |
|                           | Changing legal framework            | ●●●  | ●               | ●              | ●    |             |
|                           | Complex/uncertain permit procedure  | ●●○  | ●               | ●              | ○    |             |
| Social                    | Safety/monitoring requirements      | ●●○  | ●               | ●              | ○    |             |
|                           | Public perception                   | ●●●  | ●               | ●              | ○    |             |
|                           | Grid connection                     | ●○○  | ●               | ●              | ○    |             |

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

337 originate from: Germany (23), Netherlands (8), Denmark (2), Sweden (2), United States (2),  
338 Norway (1) and Iceland (1). The outcome of the survey, grouped by the severity, occurrence  
339 probability and the uncertainty is illustrated in Fig. 7 in the Appendix. The severity and  
340 occurrence probability together determine the risk level. The respondents judgment are pro-  
341 vided in Fig. 5, in which the uncertainty is expressed by colors from green to red. The median  
342 of all risk items ranges between 5 („Induced seismicity“) and 15.5 („Complex / uncertain  
343 permit procedure“). Thus, all risk items can be classified as low or medium risks. Apart  
344 from the risk items „Exploration risk“ and „Clogging & scaling“, technical risks are expected  
345 to be less critical than political, social, legal and organizational risks. This is remarkable  
346 as past studies in the field of HT-ATES mainly concentrated on technical risks with a spe-  
347 cial focus on heat transfer processes and optimization of storage efficiency (Wesselink et al.,  
348 2018; Fleuchaus et al., 2018). However, this ongoing research seems to be bearing fruit as  
349 the risk of „Heat losses“ received a comparable low risk rating and is estimated to be well  
350 predictable in the planning phase. Low risk values were also given to „Interest rate“ (6),  
351 „Material / Labor costs“ (6), „Changes in quality of formation water“ (6) and „Induced seis-  
352 micity“ (5). In contrast, the experts see the risks of a „Complex legal procedure“ (15.5) and  
353 „Public perception“ (15) as most critical. Considering the standard deviations, experts were  
354 unanimous for the risk items „Loss of heat source“, „Heat losses“ and „Induced seismicity“.  
355 Low agreements were observed for the risks „Insurances“, „Exploration risk“ and „Public  
356 perception“. Different opinions could be explained by different background expertise, but  
357 also by the fact that the risk level of certain risk items is more influenced by local boundary  
358 conditions and therefore, difficult to estimate in general. The latter is addressed by a com-  
359plementary risk analysis for the city of Hamburg in the following section, where the outcome  
360 of the online survey is opposed to the estimated risks for three planned HT-ATES projects.  
361 Finally, in Section 4.3, the expert opinions are evaluated considering problems encountered  
362 at and lessons learned from already realized HT-ATES sites.

#### 363 *4.2.2. Site-specific risk analysis*

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

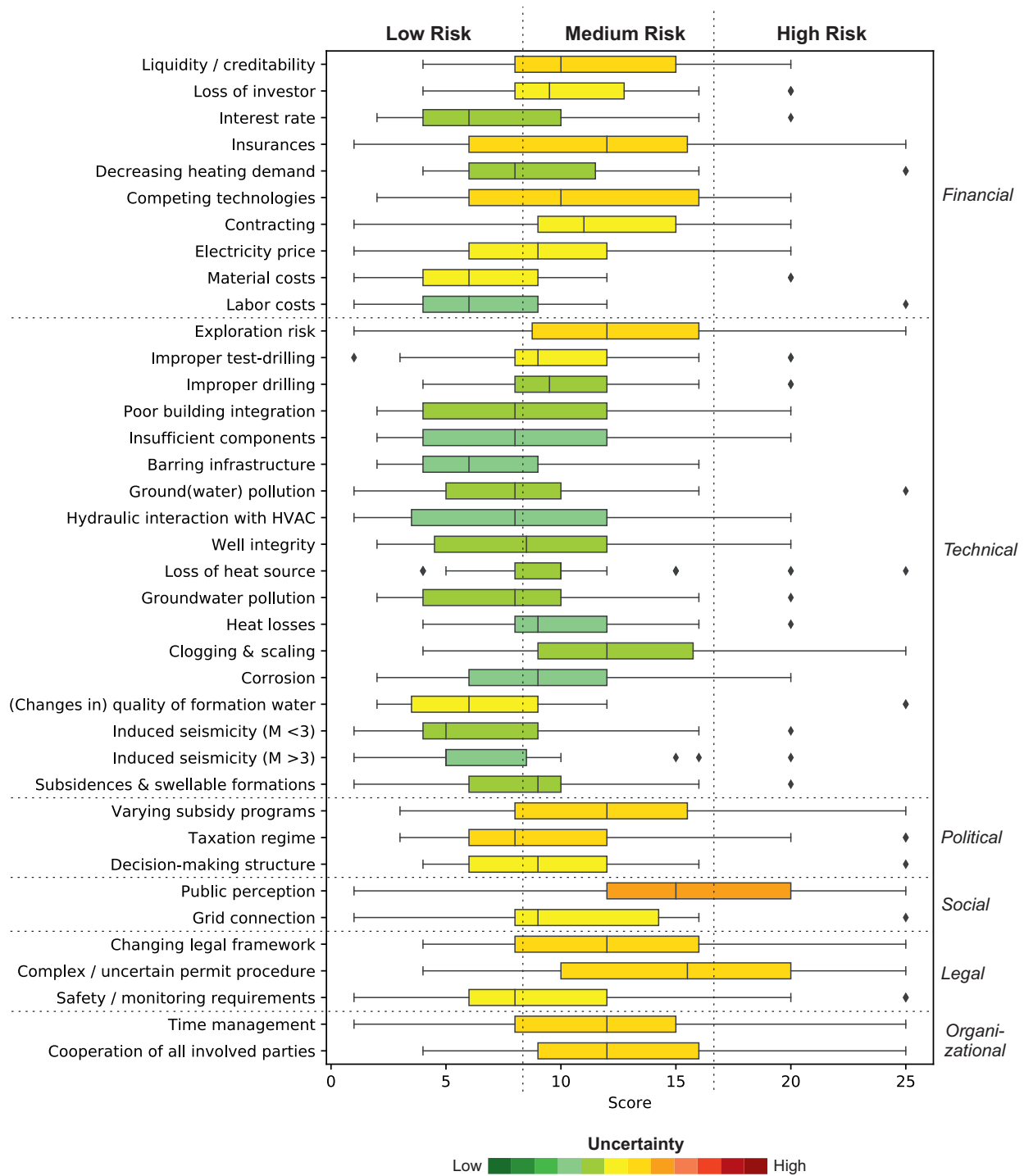


Figure 5: Expert risk ratings calculated by the product of the occurrence probability and severity. The uncertainty is illustrated by colors from green to red.

366 Kai-Justin Radmann (Radmann, 2019). A distinction is made between the risk estimation  
 367 for a shallow (200-300 m) and a deep (1000 m) target formation (Section 3). Considering

368 different technical and legal boundary conditions, causal relationships between expert dis-  
369 agreements in the previous section and differing risk estimations for the Hamburg projects  
370 are analyzed. The site-specific risk ratings are illustrated in Table 4.

371

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

399 The site-specific analysis for Hamburg indicates that some risks highly depend on the local  
400 boundary conditions and are challenging to estimate in general. In Hamburg, this is partic-  
401 ularly the case for the legal and exploration risks, which explains the strong disagreements  
402 among the experts in the previous section. While the site specific risk analysis mainly reflects  
403 the outcome of the online survey, this is not the case for the risk of „Competing technolo-  
404 gies“ and „Public perception“. Due to insufficient charging and discharging temperatures of  
405 the shallow HT-ATES and a high inflexibility, there is a high risk of it being replaced by  
406 a different technology. In addition, the risk of „Public perception“ is expected as low for  
407 the Hamburg projects, even though it received the second highest risk rating by the experts.  
408 This can be explained by a strong support by the population, which decided in a referendum  
409 to replace the existing coal-fired heating supply by less  $CO_2$  intensive technologies (Section  
410 3).

#### 411 *4.3. Evaluation of risk analysis*

412 The following section links the outcome of Section 4.2.1 (online survey) and Section 4.2.2  
413 (expert interviews) with the lessons learned from the past. It is evaluated, if the outcome of  
414 the online survey and the expected risks for HT-ATES projects in Hamburg coincide with  
415 the problems encountered at past HT-ATES sites, which are illustrated in Table 4. Please  
416 consider that some of the identified risks were not particularly relevant for early (experimen-  
417 tal) sites, which were not implemented in a real-case scenario. Hence, HT-ATES projects  
418 in the 1970 and 1980s were mainly facing technical problems, mostly related to carbonate  
419 clogging, corrosion or particle clogging (Table 4). However, new water treatment methods  
420 were developed and new storage concepts designed. At the beginning of the 1990s, HT-ATES  
421 achieved a new stage in the commercialization process as two HT-ATES sites were running for  
422 several years in the Netherlands. Building on the research efforts from the 1970s and 1980s,  
423 less geochemical problems were encountered. Even though considerable experience could be  
424 gained through deep geothermal applications in the past, further research to prevent or re-  
425 duce the appearance of corrosion is crucial and is currently performed in various laboratory  
426 (Huttenloch et al., 2019) and in situ studies (Mundhenk et al., 2013) , respectively. Even  
427 though significant well-clogging was still observed at Utrecht University, most critical was a

428 low recovery of the stored waste heat from a co-generation plant. The major cause for the  
429 low recovery efficiency was not the malfunctioning of the system, but a mismatch with the  
430 heating needs of the connected buildings. Technical problems due to a failure of the pressure  
431 valve and poor knowledge of the system finally lead to a permanent shut down of the system  
432 (Sanner, 2000). In Zwammerdam, no significant geochemical problems were found and the  
433 energy storage worked as expected beforehand (Drijver, 2011). However, the return temper-  
434 ature of the DH grid was higher than expected, causing only a little unloading of the store  
435 (Sanner, 2000). Finally, the HT-ATES was closed down due to financial reasons: the energy  
436 savings by the ATES could not compensate for the extra costs for electricity production by  
437 the CHP. Thus, the electricity production of the unit was decreased, leading to too little heat  
438 excesses to make the HT-ATES economically feasible (IF Technology, 2011). Hence, by ap-  
439 plying HT-ATES in real heating environments with the beginning of the 1990s, relevant risks  
440 were shifting from mainly subsurface related issues towards risks also concerning the heat  
441 source and sink („Decreasing heating demand“, „Competing technologies“, „Poor building  
442 integration“, „Loss of heat source“ or „Hydraulic interaction“).

443

444 This could be also observed for the most recent HT-ATES sites located in the German cities  
445 Berlin, Rostock and Neubrandenburg (Fig. 4). In Berlin, heating and cooling for the Parlia-  
446 ment buildings is supplied by LT- and HT-ATES systems. The thermal energy for heating  
447 and cooling is stored in two separated aquifers at a depth of 60 m (cooling) and 320 m (heat-  
448 ing). Detailed information was published by Kabus & Seibt (2000), Kabus et al. (2005) and  
449 Sanner et al. (2005). While the shallow storage is still in operation, the HT-ATES was shut  
450 down in the beginning of 2018 (Metz, 2018). During more than 15 years of operation, there  
451 was a leakage in the horizontal piping and groundwater pumps had to be replaced every five  
452 years (Metz, 2018). However, none of these problems critically impaired the operation and  
453 a high storage efficiency was technically possible. Nevertheless, high recovery values were  
454 only sparsely reached in practice as the HT-ATES was oversized due to an overestimated  
455 heating demand by imprecise building simulations (Kabus, 2019). Additionally, the amount  
456 of surplus heat during summertime was strongly fluctuating, as most of the CHP heat was  
457 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).

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

\* - = No information, o = Not relevant, ● = Not encountered (low), ● = encountered (medium), ● = Crucial (high)

458 largely underestimated cooling demands of the connected buildings. As a consequence, the  
459 storage was mostly fed with low temperature heat from absorption chillers, thus not reaching  
460 design temperatures (Metz, 2018). Similar to the experiences made in Utrecht, this varying  
461 demand-supply mismatch lead to an inefficient operation and the final shut-down. Neverthe-  
462 less, it is planned to put the HT-ATES back in operation to supply a planned adjacent new  
463 building (Kabus, 2019). In the city of Neubrandenburg, an abandoned geothermal system  
464 was reactivated to store surplus heat of a Combined Cycle Gas Turbine (CCGT) in a depth of  
465 1200 m. The recovered heat was used to supply a small DH network, which was initially fed  
466 by the abandoned geothermal system (Kabus et al., 2006). The HT storage was in operation  
467 for more than ten years. Technical problems were mainly observed at the cold well, where  
468 injection temperatures of 30 °C favored the growth of sulfate reducing bacteria. Geochemi-  
469 cal reactions were monitored, analyzed and published in several studies (Kabus et al., 2009;  
470 Lerm et al., 2013; Würdemann et al., 2014, 2016). Even though corroded well pumps had to  
471 be replaced periodically (Fig 6), this did not significantly affect the operation of the ATES  
472 (Beuster, 2019). Again, the efficiency of the storage was less a matter of subsurface suitabil-  
473 ity, however more a matter of the charging-discharging behavior as function of fluctuating  
474 heating and cooling demands (Beuster, 2019). The system was shut down in the beginning of  
475 2019 after the public utility of Neubrandenburg decided for a change in strategy by switch-  
476 ing from long-term to short-term thermal energy storage. During summertime, excess heat  
477 of the CCGT will be stored from Monday till Friday in an artificial storage tank (Beuster,  
478 2019). The steal tank is 36 m high and has a storage volume of 22.000 m<sup>3</sup> (Fig. 6). The  
479 stored heat is used for hot water supply of the city of Neubrandenburg during the weekend  
480 in the summertime. Thus, no residual heat is available for the HT-ATES. Nevertheless, it is  
481 planned to (re)use the existing wells for a (direct) geothermal system (Beuster, 2019).

482

483 The only currently running HT-ATES system is located in Rostock. With a charging tem-  
484 perature of 50 °C, this system is at the lower temperature threshold between HT- and LT-  
485 ATES and should be considered as hybrid system. A special permit was issued owing to  
486 the demonstration character and the high salt concentrations in the aquifer. Due to the low  
487 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.

488 a building-complex and is fed with solar heat from the roof (Schmidt & Müller-Steinhagen,  
489 2004). Thus, the risk of a changing heating demand and the loss of heat source can be  
490 considered as insignificant. In addition, with a storage depth of around 20 m, exploration  
491 risk and drilling costs were very low. Similar experiences were made in the Netherlands,  
492 where several ATES systems are in operation with a storage temperature between 40 and  
493 45 °C (Drijver et al., 2019). At the ecological research institute NIOO in Wageningen, 40 °C  
494 (solar) is stored in a depth of 295 m. While cooling is provided from a second, more shallower  
495 aquifer, no heat pump is required for heating. Considering the heat pump-free and low-risk

496 operation, there is a huge potential for systems with a storage temperature of 40 to 60 °C to  
497 supply the new/refurbished building stock without significant alterations to the electricity  
498 grid. With a maximum allowed injection temperature of 20-25 °C in shallow aquifers (< 400  
499 m), this kind of system, however, would not receive a permit in most European countries  
500 (Hähnlein et al., 2010, 2013). Considering that urban aquifers are already highly influenced  
501 by anthropogenic activities (Bayer et al., 2019), this legislation practice should be critically  
502 reflected and adjusted, where appropriate. Laboratory investigations indicate a mobilization  
503 of several trace elements and heavy metals (particularly arsenic), but also a return to initial  
504 hydrochemical conditions after completion of ATES operation (Lüders et al., 2019; Bonte  
505 et al., 2013). Further in-situ experiments, as currently performed in the TestUM project  
506 (Section 3), and investigations on the impact on the microbiology are crucial. Building on  
507 profound scientific findings, knowledge-based, site-specific maximum injection temperatures  
508 should be established as function of the existing water quality and local (hydro)geological  
509 boundary conditions.

510

511 Considering the lessons learned from abandoned HT-ATES sites in the Netherlands and  
512 Germany, the risks „Decreasing heating demand“, „Loss of heat source“ and „Competing  
513 technologies“ were underestimated by the planners and experts in Section 4.2.1. This em-  
514 phasizes the requirement for a reorientation of the scientific focus towards studies not only  
515 focusing on subsurface design, but also on the optimal interactions between heat source, sink  
516 and storage. Being designed to operate up to 30 years (Wesselink et al., 2018), HT-ATES  
517 are less flexible than competing technologies and highly sensitive to changes in the thermal  
518 energy demand (heat sink) and supply (heat source). At the same time, building planners  
519 often fail to predict the heating demand even in the short-term. In the long-term, chang-  
520 ing boundary conditions such as refurbishment strategies or increasing ambient temperature  
521 make it challenging to match demand and supply over the entire lifespan. Finally, there is  
522 also a mismatch between Table 4 and the survey results with respect to legal risks. This,  
523 however, can be explained as special permits were issued to early pilot projects. Neither the  
524 HT-ATES in Berlin, nor the HT-ATES in Rostock would obtain a license under the current  
525 legislation policy. All HT-ATES projects, and particularly those affecting aquifers suitable

526 for drinking water supply, are facing an unknown and uncertain permit procedure, which re-  
527 flects the expert opinions. In order to allow a future-proof commercialization, easier, quicker  
528 and less challenging permit procedures have to be developed in Europe and worldwide.

## 529 **5. Conclusion**

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

- 536 • This study revealed that risk assessment in geothermal energy should not only include  
537 technical and financial but also social, political and legal risks. As many risks are  
538 influenced by local boundary conditions (Section 4.2.2 and 4.3), the development of  
539 project-specific risk management strategies is highly recommended. Building on this  
540 first qualitative approach, future studies should strive to establish quantitative risk  
541 assessment in HT-ATES projects. Even though risk assessment is often applied for  
542 geothermal projects, very little is known about the advantages of different methods.  
543 Hence, different quantitative methods such as Monte Carlo (MC) or Bayesian Statistics  
544 should be compared and evaluated for real-case scenarios.
- 545 • The case studies and survey carried out in this research revealed that the most impor-  
546 tant technical risks are related to scaling and clogging of the wells and the projected  
547 energy supply and demand. Even though further efforts are required to prevent scaling  
548 and clogging particularly in high carbonated aquifers, early technical problems were  
549 controlled at recent HT-ATES sites. However, most HT-ATES systems had to be shut  
550 down due to an overestimated heating demand or the loss of the heat source (Utrecht,  
551 Zwammerdam, Neubrandenburg, Berlin). To foster profitable and sustainable opera-  
552 tion of HT-ATES, future research should therefore not only focus on subsurface design,  
553 but also on the development of holistic energy concepts. This should also include the

554 identification of potential heat sources and sinks as well as the consideration of long-  
555 term political, technical and legislative changes during an ATES lifetime of at least 30  
556 years.

- 557 • Uncertainty about risks can be reduced by sharing data and experience. Despite the  
558 successful realization of HT-ATES system across Europe, no information is available  
559 on the economic performance. While Schüppler et al. (2019) and Ghaebi et al. (2017)  
560 performed a theoretical financial analysis for LT-ATES systems, future demonstration  
561 projects should strive to provide more insights into both capital (CAPEX) and oper-  
562 ational (OPEX) costs of HT-ATES. A comprehensive database of economic statistics  
563 is crucial as both, CAPEX and OPEX highly depend on multiple factors such as the  
564 required drilling depth, the storage and recovery temperature or the heat source. A  
565 holistic monitoring covering all energy flows, energy costs and maintenance is indispens-  
566 able to convince future investors to bet on HT-ATES. In addition to Wesselink et al.  
567 (2018), further efforts should be made to perform site- and market-specific analyses to  
568 evaluate economic feasibility of HT-ATES considering not only different supply alter-  
569 natives but also different heat sources and sinks. Both, feasibility as well as real-case  
570 analyses should cover not only costs but also  $CO_2$  emissions.

- 571 • Experiences from Rostock and the Netherlands indicate that storage temperatures of  
572 40 to 60 °C in shallow urban aquifers bear a high potential for the supply of heating  
573 systems in well insulated buildings. The ATES proved not only to be technically robust  
574 but also facilitates establishment of an autarkic energy system. At the same time, the  
575 systems can be coupled with renewable heat sources and do not necessarily require the  
576 support of heat pumps. This technical potential however, is strongly limited by the  
577 current legislation. Hence, in order to establish a science based legal procedure, the  
578 impact of HT-ATES on groundwater quality has to be further investigated. In addition  
579 to the TestUM project (Section 3), research should not only focus on the geochemistry  
580 but also changes in groundwater ecology. Considering the fact that urban aquifers are  
581 already highly influenced by urban activities (Bayer et al., 2019; Tissen et al., 2019;  
582 Menberg et al., 2013), the distinction between natural (unaffected) and thermal or

583 chemical contaminated aquifers are essential for a sustainable solution.

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

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## 855 **Appendix**

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

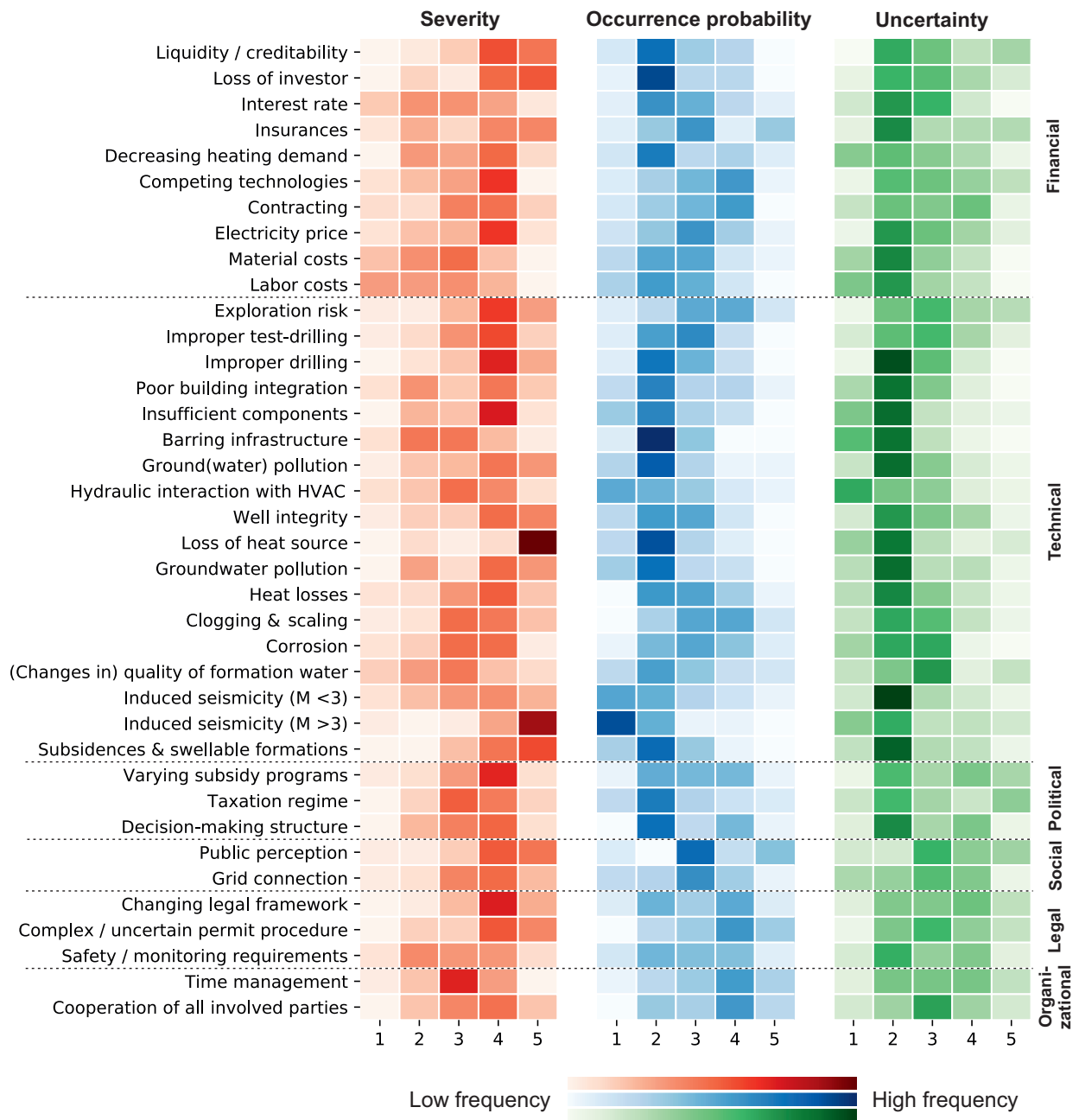


Figure 7: Relative frequencies of the risk item ratings grouped by the severity, occurrence probability and uncertainty.