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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

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 1. Introduction

Most governments have undertaken to reduce greenhouse gas emissions to prevent the worst 2 effects of global warming. While the majority of efforts are focusing on electricity production, 3 the share of renewable energies in the heating and cooling sector is stagnating at around 10%4 (REN21, 2019). In addition, with rising prosperity, human well-being in buildings including 5 thermal and air comfort is gaining significantly more importance (Cuce et al., 2017, 2019). 6 Thus, energy saving technologies are becoming increasingly popular over the last decades 7 (Sher et al., 2019). Considering that around 50% of the global energy consumption is at-8 tributed to the thermal energy sector (REN21, 2016), climate change mitigation strategies 9 must be reconsidered and should also include renewable heating and cooling (RHC) solu-10 tions. The challenge of integrating renewable technologies into the thermal energy sector is 11 that demand for heating or cooling does not coincide with RHC supply in most cases. Un-12 derground thermal energy storage (UTES) is considered as promising technology to bridge 13 this seasonal demand-supply gap (Dincer & Rosen, 2011). However, artificial storage tanks 14 are highly space-intensive and hence, hardly suitable to store significant amounts of energy 15 in an urban environment. In contrast, the storage of temperatures below 25 °C in shal-16 low aquifers (LT-ATES) is characterized by high storage capacities, but not compatible with 17 other renewable technologies (solar, biomass, geothermal) or industrial heat waste (Fleuchaus 18 et al., 2018). Depending on the type of application, solar thermal collectors, for instance, are 19 characterized by a large range of operating temperatures, which particularly exceed 100 °C 20 (Danesharzarian et al., 2018) enabling higher storage temperatures and, therefore, requiring 21 greater storage depths. High-Temperature Aquifer Thermal Energy Storage (HT-ATES) (> 22 50 °C), in contrast, has the potential to cost-efficiently store large energy volumes at high 23 temperatures. 24

25

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

57

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.

68 2. Methods

69 2.1. High-Temperature Aquifer Thermal Energy Storage

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



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

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

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

119 2.2. Definition of risk management

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



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

145 2.3. Workflow

¹⁴⁶ 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.

167 2.4. Risk analysis

The reliability of a risk analysis is depending on data availability and the experience of the risk 168 assessor. However, most risk analysis approaches are characterized by several shortcomings 169 when applied to the context of multi-disciplinary, complex, and relatively unknown situations 170 (Markmann et al., 2013). HT-ATES is a complex technology, in which only little experiences 171 were gained in the past. At the same time, risks are highly project specific and quantitative 172 approaches are not applicable. Thus, potential risks of HT-ATES are qualitatively analyzed in 173 this study. In order to cover the manifold, multidisciplinary experiences gained at numerous 174 ATES or geothermal projects in the past, the qualitative risk analysis is conducted by an 175 online survey among experts. All invited experts are asked to rate the occurrence probability 176 (O_P) , severity (S_V) and uncertainty (U_C) of all identified sources of risk following a five point 177 Likert scale (Table 1) (Yu et al., 2008; Alireza et al., 2014). The occurrence probability 178 (O_P) is the likelihood of an event to occur, whereas the severity defines the extent of the 179 damage to the institution, its people, and its objectives resulting from a risk event. The 180 uncertainty (U_C) is a measure for the predictability of the occurrence probability and the 181 severity of a risk event. While each expert obtained his/her experiences with HT-ATES 182 or geothermal projects in his/her country, the results are expected to reflect the multi-183 perspective views within the community on risks in HT-ATES. Hence, all identified risks are 184 also site-specifically analyzed for a shallow (350 m) and a deep (1000 m) HT-ATES project 185 in the city of Hamburg. Considering the different character of both projects, it is evaluated 186 whether different risk ratings for both projects reflect a high disagreement for the same risk 187 in the online survey. This site-specific analysis allows conclusions on the influence of local 188

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 im- pact, some manageable dis- ruptions or increasing in costs.	Moderateuncertainty:Moderate uncertainty despitea careful pre-investigation.
4	High Frequency: It may occur in most circumstances.	Major: High impact, system significantly compromised.	High uncertainty: Risk oc- currence and severity is hard to predict.
5	Very High Frequency: It is al- most certain and expected to oc- cur in most circumstances.	Severe: Major impact, complete failure of system.	Very high uncertainty:The occurrence probabilityand severity is very hard topredict.

¹⁸⁹ boundary conditions on risks in HT-ATES.

190 3. HT-ATES activities

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

199

²⁰⁰ 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

-#	Transform	V	C	TT	Injection	Storage	Carlana	
#	Location	rear	Scope	Heat source	Temp. $[^{\circ}C]$	depth [m]	Geology	
1	Colombier, CH	1974	Е	-	70	Shallow	Sand and gravel	
2	Mobile, US	1976	Е	Industrial	55	39-61	Sand and clay	
3	ST. Paul, US	1982	Е	Industrial	117	182-244	Sandstone	
4	Lausanne, CH	1982	Е	Industrial	40-80	7-24	Silt and sand	
5	Sapporo, JP	1883	Е	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	Ε	Cogeneration	120	500-700	Molasse	
14	Wittstock (test-site), DE	2016	Ε	Artificial	-	Shallow	Sediments	
15	Lüneburg, DE	-	А	Cogeneration	90	450	Sand	
17	Hamburg, DE	-	А	Industrial	90	300	Sand	
18	Middenmeer, NL	-	А	Geothermal	90	300-400	-	
19	Geneva, CH	-	А	Industrial	90	500-1000	Limestone	
20	Bern, CH	-	А	Power plant	120	500	Molasse	
21	DeepStor, DE	-	А	Geothermal	110	1000	Tertiary	

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

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

²⁰⁶ guidelines for groundwater protection.

207

²⁰⁸ Beyond Batteries Lab (US)

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

219

220 Lüneburg (DE)

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

234

235 Hamburg (DE)

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

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

261

²⁶² DeepStor (Karlsruhe) (DE)

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

272

273 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:

281

282 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).

289

290 Geneva (CH)

The Geneva HT-ATES site is linked to the "Geothermie 2020" strategy of the Canton of 291 Geneva and aims at assessing the feasibility of seasonal storage of 35 GWh/a surplus heat 292 from the Cheneviers waste incinerator (Collignon et al., 2020; Quiquerez, 2017). Several tar-203 get aquifers exist at different depths and are currently being explored and characterized by 294 two exploration wells (GEo-01 and GEo-02) in the Lower Cretaceous and the Upper Jurassic 295 (Malm) carbonate units. As the target aquifers are characterized by an unknown geology, 296 current activity is focusing on the identification of the optimal and reliable storage formation. 297 These challenges are tackled by establishing a workflow that includes a flexible reservoir mod-298 eling approach combining static reservoir models, thermo-hydraulic (TH), thermo-hydraulic-299 chemical (THC) and thermo-hydraulic-mechanical (THM) models (Guglielmetti et al., 2020). 300 In the framework of the HeatStore project funded by the EU GEOTHERMICA funding pro-301 gram, the outcomes of such approach will be combined to energy systems scenarios. These 302 scenarios will be transposed to detailed risk assessment and business models in order to as-303 sess the technical, environmental and financial feasibility and support local authorities for 304 improvement of the legal framework. 305

306

$_{307}$ Bern (CH)

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

318 4. Risk assessment

319 4.1. Risk identification

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

333 4.2. Risk analysis

334 4.2.1. Generic risk analysis (online survey)

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

C		ause of risk		Effect o				
Cate- gory	Sub-category	Risk item	Stage* P-C-O	CAPEX/ OPEX	Time	Environ- ment		
		Liquidity / creditability	••0	•	0	0		
	Financing	Loss of investor	••0	٠	•	0		
		Interest rate	••0	•	•	0		
-		Insurances	•••	•	•	0		
ncia		Decreasing heating demand	000	•	0	0		
ina	Market	Competing technologies		•	0	0		
Ξ.		Contracting	• • •	•	0	0		
		Electricity price	000	•	0	0		
	Costs	Material costs	••0	•	0	0		
		Labor costs	00	•	0	0		
	Site-	Exploration risk	••0	٠	•	0		
	investigation	Improper test-drilling	••0	٠	•	•		
		Improper drilling	••0	•	•	•		
		Poor building integration	0●●	٠	•	0		
	(technical)	Insufficient components	$0 \bullet \mathbf{\bullet}$	•	•	0		
	(Barring (existing) infrastructure	••0	•	•	0		
	Construction (geological)	Ground(water) pollution	•••	0	0	•		
		Induced seismicity	0 • 0	•	•	0		
F		Subsidences & swellable formations	000	•	•	0		
nice		(HVAC / DH)	000	•	•	0		
echi	Omenation	Well integrity	$\bullet \bullet 0$	٠	•	0		
Ĕ	(technical)	Loss of heat source	$\bullet \bullet 0$	٠	•	0		
	()	Groundwater pollution	000	0	0	•		
		Heat losses	000	٠	0	0		
		Clogging & scaling	000	•	0	0		
		Corrosion (wells, pipes, EHX)	000	٠	0	0		
	Geochemical and	(Changing) quality of formation water	$\bullet \bullet 0$	٠	•	0		
	geological risks	Induced seismicity (M <3)	$\bullet \bullet \bullet$	٠	•	0		
		Induced seismicity (M >3)	$\bullet \bullet 0$	٠	•	0		
		Subsidences & swellable formations	$\bullet \bullet 0$	٠	•	0		
~ ·	Cause of risk ate- ory Sub-category Risk item Financing Liquidity / creditabilit Loss of investor Interest rate Insurances Decreasing heating det Decreasing heating det Market Competing technologie Costs Material costs Site- investigation Exploration risk Improper test-drilling Improper drilling Induced seismicity Poor building integrat Induced seismicity Subsidences & swellab (technical) Subsidences & swellab (technical) Subsidences & swellab (technical) Subsidences & swellab (technical) Corrosion (wells, pipes Operation Conging & scaling (technical) Corrosion (wells, pipes Geochemical and geological risks Cooperation of all invo Organizational Time management Cooperation of all invo Varying subsidy progr Induced seismicity (M Subsidences & swellab (HVAC / DH) Induced seismicity (M Subsidences & swellab Corrosion (wells, pipes Cologing & scaling Cooperation of	Time management	• • •	٠	0	0		
Organiz	zational	Cooperation of all involved parties	•••	•	•	0		
		Varying subsidy programs	• • •	Effect on CAPEX/ Time OPEX OPEX O O O O O O O O O O O O O	0			
Politica	վ	Taxation regime	• • •	٠	PEX/ Time Envir ment 0 0	0		
		Decision-making structure	•••	٠	•	0		
		Changing legal framework	•••	٠	•	•		
Legal		Complex/uncertain permit procedure	Stage* CAPEX/ OPEX Immed ment $\bullet \circ \circ$ 0 0 $\circ \circ \circ \circ$ 0					
		Safety/monitoring requirements	••0	٠	•	0		
a • •		Public perception	•••	P-C-O OPEX • • 0 • • • 0	0			
Social		Grid connection	• • •	•	•	0		

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)).

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

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

363 4.2.2. Site-specific risk analysis

The site-specific risk analysis for the HT-ATES projects in Hamburg is following a lowmedium-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.

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

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

411 4.3. Evaluation of risk analysis

The following section links the outcome of Section 4.2.1 (online survey) and Section 4.2.2412 (expert interviews) with the lessons learned from the past. It is evaluated, if the outcome of 413 the online survey and the expected risks for HT-ATES projects in Hamburg coincide with 414 the problems encountered at past HT-ATES sites, which are illustrated in Table 4. Please 415 consider that some of the identified risks were not particularly relevant for early (experimen-416 tal) sites, which were not implemented in a real-case scenario. Hence, HT-ATES projects 417 in the 1970 and 1980s were mainly facing technical problems, mostly related to carbonate 418 clogging, corrosion or particle clogging (Table 4). However, new water treatment methods 419 were developed and new storage concepts designed. At the beginning of the 1990s, HT-ATES 420 achieved a new stage in the commercialization process as two HT-ATES sites were running for 421 several years in the Netherlands. Building on the research efforts from the 1970s and 1980s, 422 less geochemical problems were encountered. Even though considerable experience could be 423 gained through deep geothermal applications in the past, further research to prevent or re-424 duce the appearance of corrosion is crucial and is currently performed in various laboratory 425 (Huttenloch et al., 2019) and in situ studies (Mundhenk et al., 2013), respectively. Even 426 though significant well-clogging was still observed at Utrecht University, most critical was a 427

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

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This could be also observed for the most recent HT-ATES sites located in the German cities 444 Berlin, Rostock and Neubrandenburg (Fig. 4). In Berlin, heating and cooling for the Parlia-445 ment buildings is supplied by LT- and HT-ATES systems. The thermal energy for heating 446 and cooling is stored in two separated aquifers at a depth of 60 m (cooling) and 320 m (heat-447 ing). Detailed information was published by Kabus & Seibt (2000), Kabus et al. (2005) and 448 Sanner et al. (2005). While the shallow storage is still in operation, the HT-ATES was shut 449 down in the beginning of 2018 (Metz, 2018). During more than 15 years of operation, there 450 was a leakage in the horizontal piping and groundwater pumps had to be replaced every five 451 years (Metz, 2018). However, none of these problems critically impaired the operation and 452 a high storage efficiency was technically possible. Nevertheless, high recovery values were 453 only sparsely reached in practice as the HT-ATES was oversized due to an overestimated 454 heating demand by imprecise building simulations (Kabus, 2019). Additionally, the amount 455 of surplus heat during summertime was strongly fluctuating, as most of the CHP heat was 456 used for absorption cooling during summer. Even new CHP-units did not compensate for the 457

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							Expe	Expected				
Source of risk	Colombier	Mobile	St. Paul	Lausanne	Hørsholm	Plaisir	Utrecht	Zwammerdam	Berlin	Rostock	Neubrandenburg	risk Hamburg - shallow	Hamburg - deep
Liquidity / creditability	0	0	0	0	0	0	٠	٠	٠	٠	٠	•	٠
Loss of investor	0	0	0	0	0	0	٠	٠	٠	٠	٠	•	٠
Interest rate	0	0	0	0	0	0	٠	٠	٠	٠	٠	•	٠
Insurances	0	0	0	0	0	0	-	-	0	0	0	•	•
Decreasing heating demand	0	0	0	0	0	0	•	-	•	•	•	•	•
Competing technologies	0	0	0	0	0	0	•	•	•	•	•	•	•
Contracting	0	0	0	0	0	0	•	•	•	•	•	•	•
Electricity price	0	0	0	0	0	0	•	•	•	•	•	•	•
Material costs	0	0	0	0	0	0	•	•	•	•	•	•	•
Labor costs	0	0	0	0	0	0	•	•	•	•	•	•	•
Exploration risk	•	0	0	0	0	0	•	•	•	•	•	•	•
Improper test-drilling	0	0	0	0	0	0	0	0	٠	٠	0	•	•
Improper drilling	0	٠	٠	0	0	0	٠	•	٠	٠	0	•	٠
Poor building integration	0	0	0	0	0	0	•	-	•	•	0	•	•
Insufficient components	0	0	0	0	•	0	•	•	•	•	•	•	•
Barring infrastructure	0	0	0	0	0	0	0	0	•	•	•	•	•
Hydraulic interaction	0	0	0	0	0	0	0	0	•	٠	٠	•	•
Well integrity	-	-	-	-	-	-	•	•	•	٠	•	•	•
Loss of heat source	0	0	0	0	٠	0	•	•	•	٠	•	•	•
Groundwater pollution	-	-	-	-	-	-	•	•	•	٠	٠	•	•
Heat losses	•	•	٠	•	•	-	•	•	•	٠	٠	•	•
Clogging & scaling	-	•	•	•	•	•	•	•	•	٠	•	•	•
Corrosion	-	-	•	•	•	-	•	•	•	٠	•	•	•
(Changing) quality of form. water	-	-	-	•	-	•	-	-	•	٠	•	•	•
Induced seismicity	•	٠	٠	٠	٠	•	•	•	•	٠	٠	•	•
Induced seismicity (M >3)	•	٠	٠	٠	٠	•	•	•	•	٠	٠	•	•
Subsidences & swellable formations	•	٠	٠	•	٠	•	٠	•	٠	٠	•	•	٠
Varying subsidy programs	0	0	0	0	0	0	0	0	٠	٠	•	•	٠
Taxation regime	0	0	0	0	0	0	0	0	٠	٠	٠	•	٠
Decision-making structure	0	0	0	0	0	0	0	0	٠	٠	•	•	•
Public perception	•	٠	٠	٠	٠	•	٠	•	٠	٠	•	•	٠
Grid connection		0			_ 0	0	•	•	_ 0		•	•	•
Changing legal framework	0	0	0	0	0	0	-	-	•	٠	•		٠
Complex permit procedure	0	0	•	-	-	-	-	•	•	٠	٠	•	٠
Safety/monitoring requirements		-	•					•	•	•		•	•
Time management	-	0	0	0	0	0	-	-	•	•	•	•	٠
Cooperation of all involved parties	0	0	0	0	0	0	-	-	٠	٠	٠	•	•

Experiences from abandoned and running projects Euro tod

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

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

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

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

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

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.

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.

• This study revealed that risk assessment in geothermal energy should not only include 536 technical and financial but also social, political and legal risks. As many risks are 537 influenced by local boundary conditions (Section 4.2.2 and 4.3), the development of 538 project-specific risk management strategies is highly recommended. Building on this 539 first qualitative approach, future studies should strive to establish quantitative risk 540 assessment in HT-ATES projects. Even though risk assessment is often applied for 541 geothermal projects, very little is known about the advantages of different methods. 542 Hence, different quantitative methods such as Monte Carlo (MC) or Bayesian Statistics 543 should be compared and evaluated for real-case scenarios. 544

• The case studies and survey carried out in this research revealed that the most impor-545 tant technical risks are related to scaling and clogging of the wells and the projected 546 energy supply and demand. Even though further efforts are required to prevent scaling 547 and clogging particularly in high carbonated aquifers, early technical problems were 548 controlled at recent HT-ATES sites. However, most HT-ATES systems had to be shut 549 down due to an overestimated heating demand or the loss of the heat source (Utrecht, 550 Zwammerdam, Neubrandenburg, Berlin). To foster profitable and sustainable opera-551 tion of HT-ATES, future research should therefore not only focus on subsurface design, 552 but also on the development of holistic energy concepts. This should also include the 553

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

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

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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

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



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