Global application, performance and risk analysis of Aquifer Thermal Energy Storage (ATES)

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Abstract

Renewable heat sources are intermittent in nature, which is why they are characterized by an abundant but limited instantaneous availability. Peak time shaving and shifting by thermal energy storage are thus considered as a key to the transition of the heating and cooling sector from fossil-based to zero-carbon. To balance the temporal variations in the availability and demand, Aquifer Thermal Energy Storage (ATES) is characterized by high storage capacities and low storage costs and is, therefore, drawing growing attention. However, only very little is known about global application and distribution of ATES. Consequently, barriers and driving forces for a global technology adoption are still not comprehensively understood.

In order to provide a clear picture of ATES technology, the first study reviews the historical development and current application status worldwide. Based on a holistic literature review, different concepts and designs developed over time are summarized and discussed. With a 50-year history of research and development (R&D), there are currently more than 2,800 ATES systems in operation worldwide. 99% are low temperature systems (LT-ATES) with storage temperatures of <25 °C. Most of these systems (85%) are located in the Netherlands, and a further 10% are found in Sweden, Denmark, and Belgium. The great discrepancy in global ATES development is attributed to several market barriers that impede market penetration. Such barriers are mainly of socio-economic and legislative nature.

With respect to the identified market barriers, study 2 aims at facilitating global technology adoption by evaluating the technical performance of LT-ATES in the Netherlands. Based on the monitoring data of 73 Dutch LT-ATES systems, operational characteristics are identified and the optimization potential is discussed. With abstraction temperatures of 10 °C in summer and 15 °C in winter, the temperature difference (ΔT) between abstraction and injection is by 3-4 K lower compared to the optimal design value. This can be mainly explained by insufficient charging of the ATES by the heating and cooling system. In addition, the monitored ATES store only 50% of the capacities originally licensed by the authorities. To allow LT-ATES to be sustainably applied on a global scale, the interaction between subsurface and building has to be optimized by a holistic design and monitoring of the entire energy system.

In contrast to LT-ATES, the storage of temperatures higher than 40-50 °C (HT) faces multidisciplinary risks. However, no attempt was made to identify and assess all potential risks of geothermal and in particular HT-ATES projects. Hence, in the third study, risks of HT-ATES projects are identified based on the experiences made in the past and analyzed by experts from the field of geothermal energy. An online survey among 38 international experts revealed that technical risks are expected to be less critical than, in particular, 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. Critical issues were, however, primarily attributed to a loss of the heat source and fluctuating or decreasing heating demands. When considering a lifetime of more than 30 years, it is crucial to develop holistic energy concepts that account for changing boundary conditions both for heat sources and heat sinks. A project-specific risk management is, therefore, indispensable and should be addressed in future HT-ATES projects.

Within the scope of this thesis, a clear picture of ATES technology was developed, showing that ATES technology has a high potential to tackle significant energy markets. Further research is, however, required to facilitate market penetration of both the LT- and HT-ATES technology. For LT-ATES, future studies should strive to optimize operational efficiency by (1) enhancing the subsurface-building interaction and by (2) facilitating urban underground planning by creating synergies between common subsurface users, particularly in areas with high population densities. For HT-ATES, more research is required to increase operational robustness. Research should, therefore, not only focus on subsurface design, but also on the development of holistic energy concepts. This should also include the identification of potential heat sources and sinks and should, in addition, consider of long-term political, technical and legislative changes during an expected ATES lifetime of 30 years.

Kurzfassung

Aufgrund des jahreszeitlichen Versatzes zwischen Wärmeangebot und -nachfrage herrscht im Bereich der gemäßigten Klimazone weniger ein Energie- als ein Speicherproblem. Die saisonale Speicherung von Wärme und Kälte in Grundwasserkörpern, auch genannt Aquiferspeicherung (ATES), zeichnet sich im Vergleich zu anderen Speichertechnologien durch geringe Speicherkosten und hohe Speicherkapazitäten aus. Deshalb ist die Technologie in den vergangenen Jahren verstärkt in den Fokus gerückt. Allerdings gibt es nur sehr wenige Informationen über die weltweite Verbreitung sowie die Art der Nutzung von ATES. Folglich ist der Einfluss unterschiedlicher Marktbarrieren auf eine weltweite Kommerzialisierung der Technologie noch weitgehend unbekannt.

Ziel der ersten Studie ist es deshalb, einen Überblick über die historische Entwicklung sowie die weltweite ATES Nutzung zu geben. Auf Grundlage einer umfassenden Literaturrecherche werden unterschiedliche Konzepte und Nutzungsformen zusammengefasst und diskutiert. Mit einer 50-jährigen Entwicklungsgeschichte befinden sich derzeit weltweit mehr als 2.800 ATES Systeme im Einsatz. Über 99% aller ATES sind Niedrigtemperaturspeicher (LT-ATES) mit einer Speichertemperatur von < 25°C. 85% aller Aquiferspeicher befinden sich in den Niederlanden, weitere 10% in Schweden, Belgien und Dänemark. Diese Unterschiede in der globalen Aquiferspeicherentwicklung lassen sich weniger durch Untergrund-spezifische Faktoren, als vielmehr durch sozioökonomische und legislative Marktbarrieren erklären.

In Studie 2 wird basierend auf den Monitoringdaten von 73 niederländischen Anlagen die technischen Leistungsdaten und energetische Effizienz von LT-ATES untersucht sowie Optimierungsmöglichkeiten diskutiert. Mit einer durchschnittlichen Entnahmetemperatur von 10 °C im Sommer und rund 15 °C im Winter ist die Differenz zwischen Entnahme- und Einspeisetemperatur (ΔT) mit 3-4 K deutlich geringer als ursprünglich geplant. Dies ist weniger auf Speicherverluste im Untergrund, als auf eine ineffiziente Beladung des Speichers durch die gebäudeseitige Heizungs- und Klimatisierungsanlage zurückzuführen. Zudem wird im Durschnitt nur 50% des Untergrundes genutzt, der jeweils von der Genehmigungsbehörde für die geothermische Nutzung freigegeben wurde. Eine exakte Analyse des erwarteten Energieverbrauchs sowie ein effizientes Zusammenspiel zwischen ATES und Gebäude sind deshalb entscheidend um eine nachhaltige Nutzung von LT-ATES weltweit zu gewährleisten.

Im Gegensatz zu LT-ATES birgt die Speicherung von Temperaturen über 40-50 °C (HT-ATES) deutliche höhere Risiken. In Studie 3 werden deshalb potentielle Risken von HT-ATES Projekten basierend auf den Erfahrungen vergangener Projekte identifiziert und von Geothermieexperten analysiert. Eine online Umfrage unter 38 internationalen Experten hat gezeigt, das technische Risiken weniger kritisch eingeschätzt werden als insbesondere rechtliche, soziale oder organisatorische Risiken. Dies bestätigen die Erfahrungen aus vergangenen HT-ATES Projekten, wo hohe Wiedergewinnungsraten erzielt, und die technische Machbarkeit erfolgreich demonstriert werden konnte. Schwerwiegende Probleme waren dagegen häufig auf schwankende oder sinkende Energiebedarfe oder einen Verlust der Wärmequelle zurückzuführen. Bei einer zu erwarteten Laufzeit von über 30 Jahren, ist es deshalb entscheidend, ganzheitliche Energiekonzepte zu entwickeln, die sowohl sich verändernde Randbedingungen im Bereich der Wärmequelle, als auch Wärmesenke berücksichtigen. Ein projekt-spezifisches Risikomanagement ist deshalb essenziell und sollte auch in der Forschung stärker Berücksichtigung finden.

Im Rahmen dieser Arbeit konnte gezeigt werden, dass die Aquiferspeicherung ein hohes Potenzial hat, bedeutende Energiemärkte zu erschließen. Sowohl im Bereich LT-ATES als auch HT-ATES bedarf es allerdings weitere Forschung, um eine flächendeckende Kommerzialisierung voranzutreiben: Im Niedrigtemperaturbereich sollten zukünftige Studien darauf abzielen, die Betriebseffizienz weiter zu optimieren. Dies betrifft (1) die Interaktion zwischen Untergrund und Gebäude sowie (2) ein urbanes Untergrundmanagement, wo durch die Schaffung von Synergien benachbarter Untergrundnutzer der verfügbare Raum noch nachhaltiger genutzt werden soll. Für HT-ATES sind weitere Forschungsarbeiten erforderlich um die betriebliche Stabilität zu erhöhen. Die Forschung sollte sich daher nicht nur auf die Gestaltung des Untergrundes konzentrieren, sondern auch auf die Entwicklung von ganzheitlichen Energiekonzepten. Dies sollte auch die Identifizierung potentieller Wärmequellen und -senken sowie die Berücksichtigung langfristiger politischer, technischer und gesetzlicher Änderungen während einer ATES-Lebensdauer von 30 Jahren umfassen.

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Chapter 1

1 Introduction

1.1 General motivation

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC), human induced warming reached between 0.8 and 1.2 °C above pre-industrial levels in 2017. Impacts on natural and human systems from global warming are already apparent and ambitious mitigation actions are indispensable to limit global warming to 1.5 °C [1]. Reductions in net CO_2 emissions can be achieved through different portfolios of mitigation measures. The replacement of fossil-based technologies by renewable energy sources is imperative to reach the ambitious goals. The share of renewable energies in meeting global energy consumption is expected to increase by one-fifth to reach 12.4% in 2023 [2]. Even though more than half of the final energy consumption is attributed to the thermal energy sector, the share of renewables is stagnating at around 10% [2]. From 2013 to 2017, the growth rate of renewables in the power sector was five times higher compared to the thermal sector. This is not only attributed to an increasing global heating and cooling energy demand, but also to the fact that political decisions are primarily directed at the power sector [2].

According to Stryi-Hipp [3], the political focus on the power sector can be explained historically: while governments of industrial countries always had to secure power supply by the installation and control of the power infrastructure, thermal energy for cooking, space heating or industrial processes has traditionally produced individually. Society is, therefore, facing a paradigm shift in the design of future sustainable energy strategies. From an energetic point of view, the main bottleneck of a widespread use of renewable heating and cooling (RHC) technologies is, however, more attributed to seasonal temperature variations, as demand for heating or cooling does not coincide with RHC supply in most developed economies [4]. This is made evident by the excess heat emissions of Europe's industry and electricity production which (theoretically) covers the heating demand of all European buildings [5]. Seasonal thermal energy storage (TES) is, therefore, essential to cut peak time supply by transforming transient available energy into long-term accessible energy. According to Arce et al. [6], TES is capable of decreasing the EU energy consumption by 7.8%.

Different types of TES solutions were developed over time, which can be subdivided based on their storage material into sensitive, thermochemical and latent techniques. However, as chemical and latent TES are not competitive yet [7], sensible storage solutions are mostly applied [8, 9]. Sensible TES can be further subdivided into Underground Thermal Energy Storage (UTES) and closed artificial storage tanks. The latter are independent of (hydro) geological conditions [9] and thus the preferred choice for high temperature storage (>70 °C) of renewable and non-renewable heat sources. Closed artificial storage tanks are, however, highly space intensive. The storage volume of 245 Olympic swimming pools would, for instance, be required to store the thermal energy supplied by the world largest ATES system at Technical University of Eindhoven (TU/e). A widespread heating supply by artificial storage tanks is, therefore, highly limited by a lack of space in areas where thermal energy demand is highest. By contrast, heat and cold storage in groundwater also referred to as Aquifer Thermal Energy Storage (ATES) offers a high storage capacity and is not limited by a lack of surface space. Contrary to artificial storage tanks, ATES technology is highly dependent on the existence of suitable aquifers. However, as the development of most industrial nations was favoured by the access to drinking water and a moderate climate, the potential for global ATES application can be considered to be high. Schaetzle and Brett [10], for instance, estimated that aquifers suitable for ATES are located below the surface of around 60% of the US land area. In addition, Bloemendal et al. [11] analyzed that around 65% of the world population lives in an area with a medium or high suitability for ATES.

1.2 Basic principle

A detailed literature overview on ATES application is given in Chapter 2. In its basic form, an ATES system consists of two groundwater wells (called a doublet) and operates in a seasonal mode. With research and development (R&D) activities of more than 50 years, different concept designs are applied in practice, which can be distinguished based on different characteristics such as the well design or the storage depth. Most significant, however, is the classification of ATES into low temperature (LT) and high temperature (HT) systems. LT-ATES is characterized by a maximum injection temperature of 25 °C and is typically used for heating and cooling. The basic operational principle is illustrated in Fig. 1.1. In summer, cold groundwater stored in winter is extracted from the cold well to cool the building. In

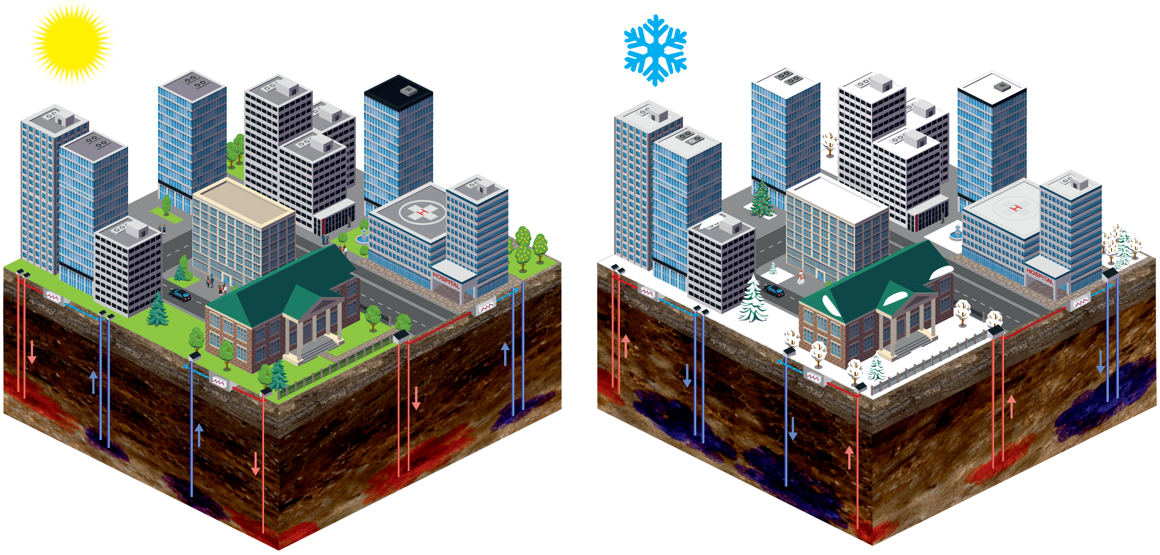

Figure 1.1: Basic principle of LT-ATES. The left hand site illustrates winter operation, the right hand site shows summer operation.

most cases, the temperature level is sufficient for direct cooling without the application of a heat pump. However, heat pumps can also be utilized for active cooling. The waste heat of the cooling process is re-injected into the warm well and stored in the aquifer for winter heating. The pump direction is reversed with the beginning of the heating season, and the stored heat is extracted for heating purpose. The recovery temperature, which ranges between 15 and 20 °C, has to be increased by heat pumps to meet the required temperature level of the heating system. LT-ATES systems are considered in most cases for buildings or industrial applications with a high, balanced heating and cooling demand. External heat or cold sources, such as free cooler or solar panels are considered in case of an unbalanced heating and cooling demand or supply. LT-ATES is only applicable for buildings for the new/refurbished building stock.

By contrast, HT-ATES systems are defined by storage temperatures above 40-50 °C [12–14]. As the maximum injection temperature is limited to 15-25 °C in most countries [15–17], HT-ATES systems are usually characterized by a greater storage depth compared to LT-ATES systems. While LT-ATES systems store the excess heat and cold of the heating and cooling process, heat sources and sinks of HT-ATES are independent from each other. Potential heat sources can be renewable energies (solar, geothermal, biomass, power to heat) or waste heat from industrial applications (Fig. 1.2). With recovery temperatures of up to 100 °C, HT-ATES systems are also suitable for feeding high temperature heating systems.

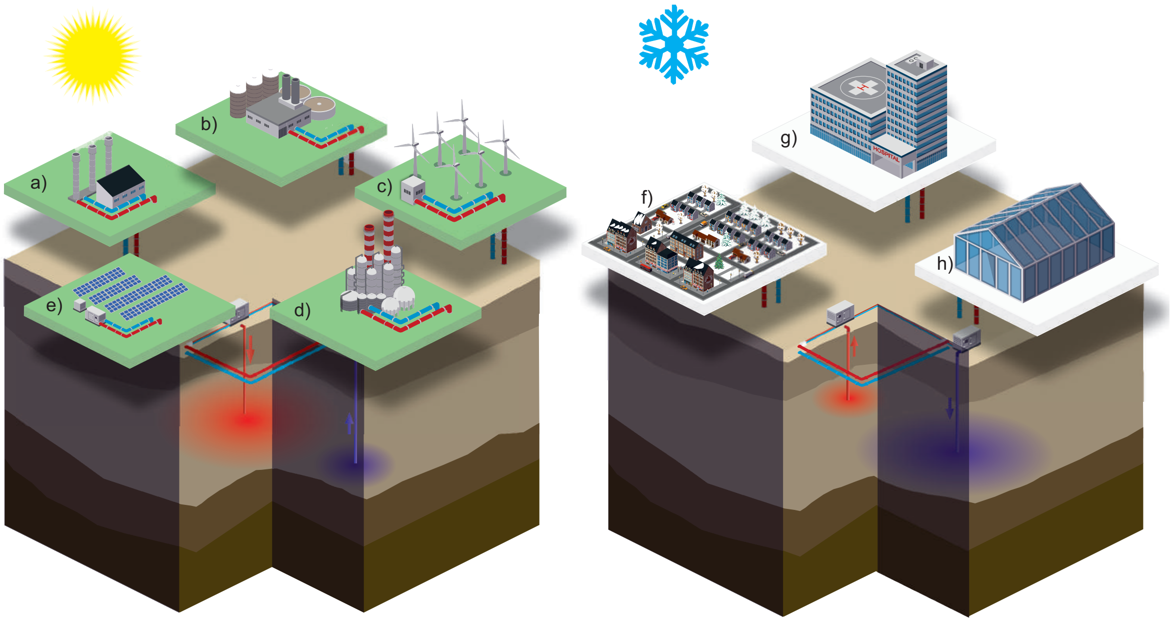

Figure 1.2: Basic principle of HT-ATES. In summer, the aquifer is charged with surplus heat from (non-) renewable energy sources, such as geothermal (a), biomass (b), power-to-heat (c), industrial waste heat (d) or solar thermal energy (e). The stored heat is recovered in winter to supply district heating (DH) systems (f), large building complexes (g) or industrial applications such as greenhouses (h).

1.3 Objectives

Even though there is a history of R&D of more than 50 years [18, 19], ATES can still be considered to be a fairly unknown technology. At the same time, only limited information is available on the number of ATES systems in operation worldwide and how ATES is applied in practice (Chapter 2). Sound statistics on the current application status are, however, important to compare the market penetration in different countries, in order to identify and analyze various boundary conditions that influence the development of the underlying technology. In addition, lessons learned from the past and present ATES projects are crucial for the technical optimization processes in order to overcome relevant market barriers. The objective of this thesis is, to contribute to a better understanding of ATES technology by reviewing the past, analyzing the present and identifying risks and barriers for future application.

- A first goal is, therefore, to provide a comprehensive overview over the past and present ATES application worldwide to get a clear idea of different concepts and designs developed over time. It is aimed to compile statistics on the global numbers of ATES and to identify socio-economic barriers for market penetration.

- Only little knowledge is available on the operational characteristics of LT-ATES. In order to fill this knowledge gap, a further goal is to provide a deep understanding of the Dutch operation principle for countries where the technology is still not applied.
- The last part of this work focuses on HT-ATES, which has hardly been applied to the present day. In order to promote technology development, this study will identify and analyze risks of HT-ATES.

1.4 Structure of the thesis

The presented cumulative thesis consists of three individual studies enclosed in Chapters 2 - 4. The synthesis in Chapter 5 establishes a connection between the results and findings of the presented studies. All studies were submitted to peer-reviewed (ISI-listed) journals, whereas two of them have already been published and one is currently under review.

Chapter 2 contains the first study *"Worldwide application of Aquifer Thermal Energy Storage - A review"*, which was published in *Renewable and Sustainable Energy Reviews* and analyzes the global status of ATES, reviewing historical ATES development and current operational statistics. Based on a comprehensive literature review, different concept designs are summarized, and country statistics compiled. Considering the spatial distribution of ATES systems worldwide, market barriers for technology adoption are identified and discussed.

Chapter 3 presents the second study entitled *"Performance Analysis of Aquifer Thermal Energy Storage (ATES)"*, published in *Renewable Energy*. Based on the results of Chapter 2, this study provides insights into the operating principle of LT-ATES in the Netherlands. To this end, monitoring data of 73 Dutch LT-ATES systems from 2016 to 2018 are analyzed. The monitoring data comprise the volume of pumped groundwater, the abstracted thermal energy and the injection and abstraction temperature for heating and cooling. Based on a holistic data analysis, ATES performance and optimization strategies are discussed to improve the sustainable use of the available subsurface space, considering the current licensing practice in the Netherlands.

Chapter 4 contains the third study *"Risk analysis of High Temperature Aquifer Thermal Energy Storage (HT-ATES)"*. It is currently under review at *Renewable and Sustainable Energy Reviews*. In a first step, risks of HT-ATES are identified, building on the lessons learned from abandoned and running sites. All identified risks are analyzed based on an online survey among experts from the field of ATES and geothermal energy. Each risk item is rated by the severity, occurrence probability and uncertainty. The online survey is complemented by expert interviews evaluating the risks of planned HT-ATES projects in the city of Hamburg. Considering the results of the risk analysis, risk mitigation strategies are discussed to enhance the reliability of HT-ATES systems.

Finally, Chapter 5 evaluates the findings of the three studies and highlights the important aspects to understand the successful operation of ATES worldwide. Pending research questions and proposals based on this thesis are compiled.

Chapter 2

Worldwide application of Aquifer Thermal Energy Storage - a review

Reproduced from: Fleuchaus P, Godschalk B, Stober I, Blum P (2018) Worldwide application of Aquifer Thermal Energy Storage - A review. RSER, 94:861-876, doi:10.1016/j.rser.2018.06.057

Abstract

To meet the global climate change mitigation targets, more attention has to be paid to the decarbonization of the heating and cooling sector. Aquifer Thermal Energy Storage (ATES) is considered to bridge the gap between periods of highest energy demand and highest energy supply. The objective of this study, therefore, is to review the global application status of ATES underpinned by operational statistics from existing projects. ATES is particularly suited to provide heating and cooling for large-scale applications such as public and commercial buildings, district heating, or industrial purposes. Compared to conventional technologies, ATES systems achieve energy savings between 40% and 70% and CO_2 savings of up to several thousand tons per year. Capital costs decline with increasing installed capacity, averaging 0.2 million € for small systems and two million € for large applications. The typical payback time is 2-10 years. Worldwide, there are currently more than 2,800 ATES systems in operation, abstracting more than 2.5 TWh of heating and cooling per year. 99% are low temperature systems (LT-ATES) with storage temperatures of < 25 °C. 85% of all systems are located in the Netherlands, and a further 10% are found in Sweden, Denmark and Belgium. However, there is an increasing interest in ATES technology in several countries such as Great Britain, Germany, Japan, Turkey and China. The great discrepancy in global ATES development is attributed to several market barriers that impede market penetration. Such barriers are of socio-economic and legislative nature.

2.1 Introduction

The global community has to face a paradigm shift towards a sustainable energy supply to keep the increase in the global average temperature to within 2 °C above pre-industrial levels. While the share of renewables in the power generation sector increases continuously, less attention is paid to the decarbonization of the heating and cooling sector. In 2015, heating and cooling accounted for half of the total world final energy consumption, with three-quarters produced from fossil fuels. The share of modern renewable technologies is currently estimated at only 8% [20]. At the same time, global energy consumption for heating and cooling is expected to further increase with rising prosperity, population growth and climate change. According to IPCC (Intergovernmental Panel on Climate Change), power consumption for air conditioning alone is expected to rise 33-fold by 2100 [21]. To achieve the climate change mitigation targets, increasing attention has to be paid to the decarbonization of the thermal energy sector. The key challenge of increasing the share of renewables in the heating and cooling sector is attributed to the seasonal offset between thermal energy demand and supply. To tackle this seasonal mismatch, the idea of Thermal Energy Storage (TES) has attracted increasing attention [22]. The selection of an appropriate storage method depends on several factors such as storage capacity, storage duration and supply and demand temperature [23, 24]. Underground Thermal Energy Storage (UTES) is a sensible TES method, characterized by high storage efficiencies [25, 26] and high storage capacities and is, therefore, the preferred choice for long-term TES. The most popular sensible seasonal UTES techniques are illustrated in Fig. 2.1. UTES can be further subdivided into open-loop or closed-loop systems. In open-loop systems, also referred to as Aquifer Thermal Energy Storage (ATES), sensible heat and cold is temporarily stored in the subsurface through injection and withdrawal of groundwater [27–29]. Closed-loop systems are more or less independent of the permeability of the subsurface and are called Borehole Thermal Energy Storage (BTES). In Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES) and Cavern Thermal Energy Storage (CTES), heat and cold is stored in thermally stratified storage tanks, dug pits filled with gravel and water, or naturally occurring cavities, respectively. Table 2.1 compares these UTES techniques regarding technical and subsurface-related aspects. Among different seasonal UTES concepts, ATES is characterized by the highest storage capacities and is, therefore, most suitable for large-scale applications [30]. However, ATES application requires the presence of an aquifer and suitable hydrogeological

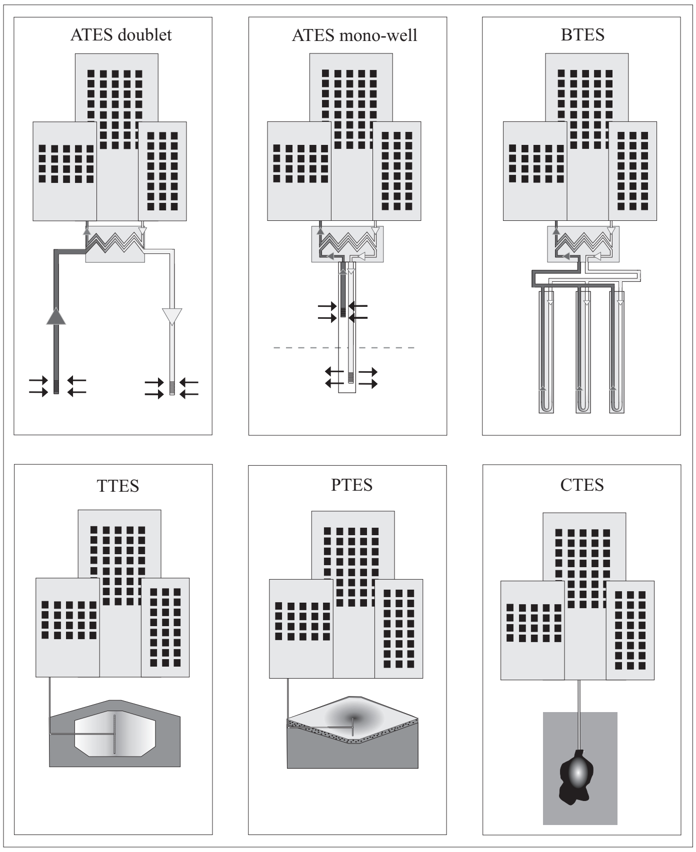

Figure 2.1: Seasonal sensible UTES techniques. BTES, Borehole thermal energy storage; TTES, Tank thermal energy storage; PTES, Pit thermal energy storage; CTES, Cavern thermal energy storage.

Table 2.1: Comparison of seasonal Underground thermal energy storage (UTES) concepts (+++ high; ++ moderate; + low).

	PTES / TTES	**ATES**	**BTES**
Storage medium	Water; water/gravel	Groundwater/sediments	Groundwater/sediments
Subsurface requirements	+	+++	++
Required pre-investigation	+	+++	++
Maximum storage capacity [kwh/m^3]	+++	++	+
Storage volumes	+	+++	++
Space requirement	+++	+	+
Investment costs	+++	+	++
Maintenance	+	+++	+
Environmental interaction	+	+++	++

conditions such as a low groundwater flow, high permeabilities and geochemical conditions that prevent clogging and corrosion of wells. Compared to standard open-loop geothermal systems, ATES systems require a more complex pre-investigation and are typically more sensitive to groundwater flow and aquifer heterogeneities. The seasonal storage of heat and cold, however, enables a more efficient operation.

The objective of this work is to review the historical development and the current global application status of ATES. Based on the reviewed literature, system designs, trends and ideas developed over time are summarized with special attention on operational parameters of successfully implemented ATES systems. Since the literature lacks statistics on the number of implemented ATES systems, the review of previous work is complemented by an analysis of the current ATES application status. Based on these country-by-country statistics, market barriers for entering a commercialization level are finally identified and discussed in order to stimulate future ATES research and projects.

2.2 Historical and technical development of ATES worldwide

2.2.1 A retrospective: from idea to market penetration

The idea of storing heat and cold in aquifers can be traced back to the mid-1960s [18, 19, 31–36]. To reduce subsidence as a consequence of long-term groundwater over-pumping, artificial recharge (AR) was successfully proposed in Shanghai in the early 1960s [37]. Soon, investigations indicated that the injected surface water preserved its temperature over several months. Subsequently, Shanghai's textile industry became aware of the great potential of AR for industrial cooling, and several factories started to actively store winter cold for summer cooling [36, 38–40]. Given the high demand for industrial cooling, the number of ATES applications increased gradually in the following years. Fig. 2.2 illustrates early ATES applications for industrial cooling in Shanghai. By 1984, more than 400 wells were used for both injection and extraction, storing a total of 1100 TJ of cooling energy in Shanghai annually [35]. Utilization of ATES peaked in the early 1980s, with more than 20 cities promoting ATES in China [32, 33]. However, these projects were not sustainable. Clogging of wells or heat exchangers due to hydrochemical properties of the aquifer fluid and inappropriate well configuration forced many ATES systems to stop operating [41]. With the beginning of the

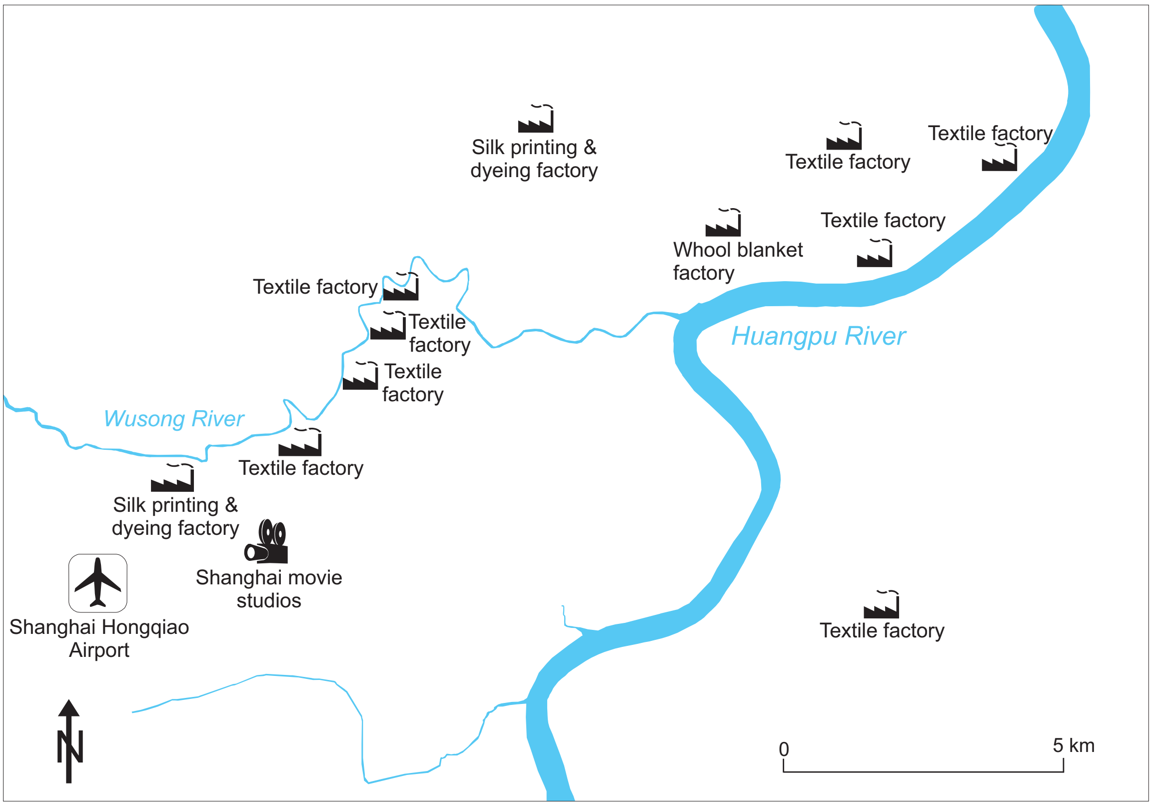

Figure 2.2: Early ATES sites in Shanghai used for industrial cooling (modified based on [18]).

oil crisis in the mid-1970s, the research into and development of energy storage were intensified, and the idea of storing thermal energy in aquifers started in North America and Europe [14, 42]. Fig. 2.3 visualizes ATES development over time, highlighting important research projects as well as experimental and commercial ATES milestones. Pioneering work was done by Kazmann [43], Rabbimov et al. [44], Meyer and Todd [45] and Sauty et al. [46, 47], who carried out early theoretical and also field studies. Based on this theoretical framework, several field experiments were designed and conducted (Table 2.2). The first ATES experiment was performed by the University of Neuchâtel (Switzerland) in 1974 [34, 48, 49], followed by a three-stage experimental project at Auburn University (US) in 1976 [50–54]. Further countries such as France, Japan, Germany, or Canada started participating in ATES research with their own experimental field sites. While Shanghai's industry applied ATES predominantly for industrial cooling, early research in ATES also focused on the storage of higher temperatures (> 40 °C).

As practical experience with the storage of high temperatures was rare, many early ATES sites faced considerable difficulties. The most frequent problems were related to:

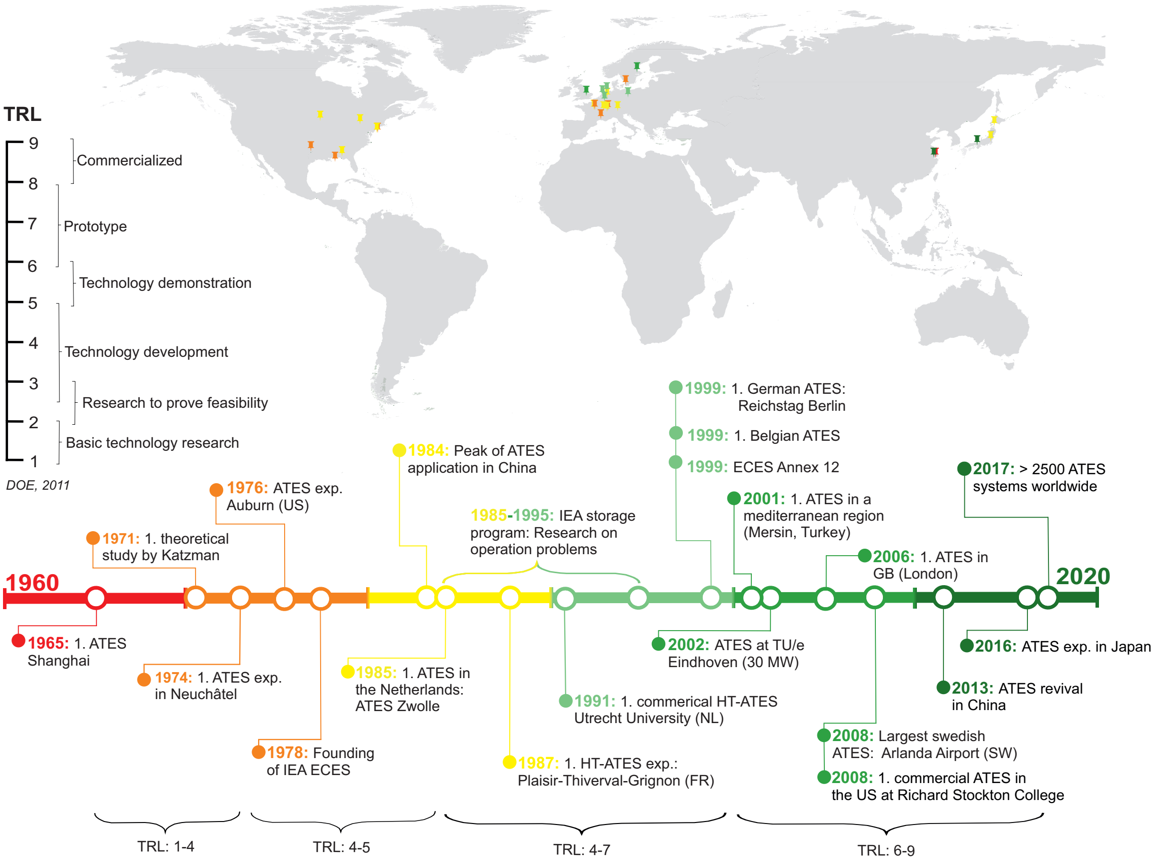

Figure 2.3: Chronology and milestones of global ATES development with the technical readiness level (TRL) according to DOE [55].

- Scaling and clogging of wells and heat exchangers [52, 59, 74, 79, 105, 107–114];
- Corrosion of wells [14, 65, 74, 78, 82, 83, 88, 100, 109, 115];
- Buoyancy flow or thermal breakthrough [14, 50, 59, 60, 116–119];
- Unbalance between stored heat and cold [14, 120];
- Swelling of clay minerals [74, 105, 111].

In 1978, the International Energy Agency (IEA) established the implementing agreement on Energy Conservation through Energy Storage (ECES) [121–124]. The target of ECES was to support research into and development of energy storage systems [125]. Periodic “Stock“ conferences were established to share experiences with TES, starting in Versailles in 1981 [126]. Within this framework, great efforts were made to develop measures to prevent scaling and clogging [50, 74, 83, 103, 106, 114, 127–131], to overcome thermohydraulic-related problems such as thermal breakthrough, buoyancy flow, or unbalance between the stored

Table 2.2: Overview of early ATES test sites.

Country	**Locations**	**Year**	**Temperature**	**TRL** (Acc. to [55])	**References**
USA	Auburn University	1976	HT	2	[38, 52–54, 56–60]
	ST. Paul	1982	HT	3	[58, 61–65]
	Tuscaloosa, Alabama	1982	LT	3	[10, 66–72]
	Stony Brook	1982	LT/HT	3	[73, 74]
	Melville	1985	LT	3	[75, 76]
	Texas A&M University	1978	LT	3	[38]
Switzerland	Colombier	1974	HT	1	[34, 48, 49, 77]
	Lusanne-Dorigny	1982	HT	2	[78]
France	Aulnay-Sous-bois	1983	LT	3	[79]
	Plaisir	1987	HT	3	[80–83]
	Trappes	-	HT	3	[74, 84]
	Bonnaud	1976	LT	3	[46, 47, 77, 84–89]
	Campuget	1977	LT	3	[34, 74, 88, 90]
	Montreuil	-	LT	4	[74]
Canada	Scarborough	1985	HT	6	[91–96]
	Carleton University	1990	LT	7	[95, 97]
Japan	Yamagata Yonezawa	1977	LT	3	[38, 77, 98, 99]
	Hokkaido Sapporo	1982	HT	3	[36, 38, 79]
Sweden	Lomma	1991	LT	6	[14, 100, 101]
Germany	University of Stuttgart	1985	LT/HT	1	[102]
	Krefeld	1974	LT/HT	1	[103, 104]
Netherlands	Groningen	-	-	4	[79]
	Bunnik	1985	LT	6	[83]
	Utrecht	1991	HT	6	[105, 106]
Denmark	Horsholm	1982	HT	5	[74]

* LT > 40 °C; HT < 40 °C

heat and cold [46, 50, 51, 89, 119, 132–150] and also to evaluate potential impacts of ATES on the environment [103, 115, 151–155]. The research showed that most problems can be avoided by careful pre-investigation and an appropriate operational design [74]. Nevertheless, since fewer problems were encountered in the years that followed, the interest moved from high temperature (HT) ATES (> 40 °C) to low temperature (LT) ATES (< 40 °C) in the following years [156, 157]. After engineering feasibility had been demonstrated in various projects, LT-ATES was successfully established in the energy markets of the Netherlands and Sweden [14, 101, 158]. While early research mainly concentrated on solving technical, geochemical and engineering problems, the scientific focus in the year that followed shifted towards an optimization of ATES performance. Table 2.3 presents an overview of various studies, analyzing the impact of hydrogeological and thermodynamic parameters on the storage efficiency. This ongoing research and optimization process is reflected in an increasing ATES attractiveness. Market incentive programs [72, 101] and the open-mindedness of the (Dutch) authorities to support ATES [101, 158] led to a growing number of projects, particu-

Table 2.3: Analytical and numerical studies analyzing storage efficiency and heat transfer processes of ATES (adapted from [159]). (+ considered; - not considered).

Ref.	**LT**	**HT**	**Ground-water flow**	**Buoyancy flow**	**Dis-persion**	**Thermal inter-ference**	**Aquifer hetero-geneity**	**Building integration**
[140, 160–163]	+	-	+	-	+	-	-	-
[50, 133, 136, 164–168]	-	+	-	+	-	-	-	-
[161, 169–171]	+	-	-	-	+	-	+	-
[27, 172–175]	+	-	-	-	-	+	+	-
[132, 149]	+	+	+	+	-	-	-	-
[176–178]	+	-	-	+	+	-	+	-
[179–186]	+	-	-	-	-	+	-	-
[187, 188]	+	-	+	-	-	+	-	-
[189]	-	+	-	-	+	-	-	-
[190]	-	+	-	+	+	+	-	-
[191]	+	+	+	-	-	-	-	+
[192]	+	-	-	-	-	-	-	+
[193]	-	+	-	-	-	-	-	+
[159, 194, 195]	+	-	-	-	-	-	-	+
[196–204]	-	+	-	-	-	-	-	-
[89, 205]	-	+	+	-	+	-	-	-

larly in the Netherlands. This growth, however, is attributed to LT-ATES systems only. After early test sites and pilot projects faced significant problems [206], investors and planners lost confidence in HT-ATES systems [207]. To our knowledge, there are only five HT-ATES in operation worldwide, which means that 99% of all systems are represented by LT- ATES systems.

2.2.2 Technical development and application statistics

Each ATES project has to meet site-specific requirements, which are of geological, climatic, regulatory or building-specific nature. Consequently, a wide range of operational and technical specifications have been developed in the last decades. Such developments were summarized and discussed by several authors: in the early 1980s, Schaetzle et al. [208] first published a pioneering in-depth summary of ATES designs and applications with focus on technical and economic aspects. When ATES was successfully penetrating the energy market in Sweden and the Netherlands, Andersson [209] and Bakema et al. [12] reported on their experiences with ATES, concentrating more on application statistics and economic and environmental benefits. Furthermore, Lee [28, 210], Nordell et al. [157] and Snijders and Drijver [211] presented a holistic description of operational principles, field investigations, aquifer characteristics, wellfield designs and maintenance. Based on this previous work, the following sections summarize the technical developments of ATES, underpinned by practical examples. The key requirement for ATES is the availability of an aquifer. The vast majority of ATES systems use unconsolidated aquifers as storage media. Deeper systems typically utilize sandstone or highly fractured rock [212]. The suitability of the subsurface depends on several hydrogeological characteristics such as aquifer thickness, hydraulic conductivity, or groundwater flow velocity. More detailed information on geological and hydrogeological requirements were described e.g, by Schaetzle et al. [208], Snijders and Drijver [211], Lee [181], or Sanner and Knoblich [213]. Fig. 2.4 characterizes ATES system designs in terms of operational, underground-related and technical aspects. The literature distinguishes between mono-directional and bi-directional systems [173, 210]. This differentiation, however, is quite misleading, since mono-directional systems simply use the prevailing groundwater temperature by continuously pumping and reinjecting groundwater in one direction, like in geothermal doublets. Hence, only bi-directional systems can be referred to as ATES, as groundwater flow can be reversed to actively store cold and/or heat, respectively [29]. There are two different well designs (Fig. 2.1): multi-well systems use one or more well doublets to store thermal energy horizontally. In mono-well systems, heat and cold are separated vertically [214–216]. Mono-well systems show lower capital costs, since only one borehole has to be drilled. Thus, mono-well systems are mainly considered for HT-ATES systems with high drilling depths, or small-scale systems with low injection and production rates. The disadvantage of mono-well systems is the high susceptibility to thermal interference, hence thick aquifers are required. Depending on regional climatic conditions and specific building requirements, ATES is applied to direct cooling, direct or indirect heating and hybrid systems [28, 42, 209]. Indirect systems are required if the outlet temperature of the ATES does not meet the inlet temperature demand of the heating system. To charge an ATES with thermal energy, different kinds of heat and cold sources are considered, such as waste heat from cogeneration, renewable energies or dry cooler (Fig. 2.4). However, the standard case is to re-use the seasonal heat and cold of the building. To illustrate the wide range of specifications, Table 2.4 summarizes the technical and economic parameters of 25 worldwide ATES systems. The capacity of an ATES system ranges between 0.1 and 0.3 MW for small-scale and between five and 30 MW for large-scale systems. While the well number and the pumping rate are approximately proportional to the heating and cooling capacity, several projects indicate a decline in specific capital costs (€/kW) with increasing system size. This is because larger systems can be designed more efficiently than smaller ones [42,

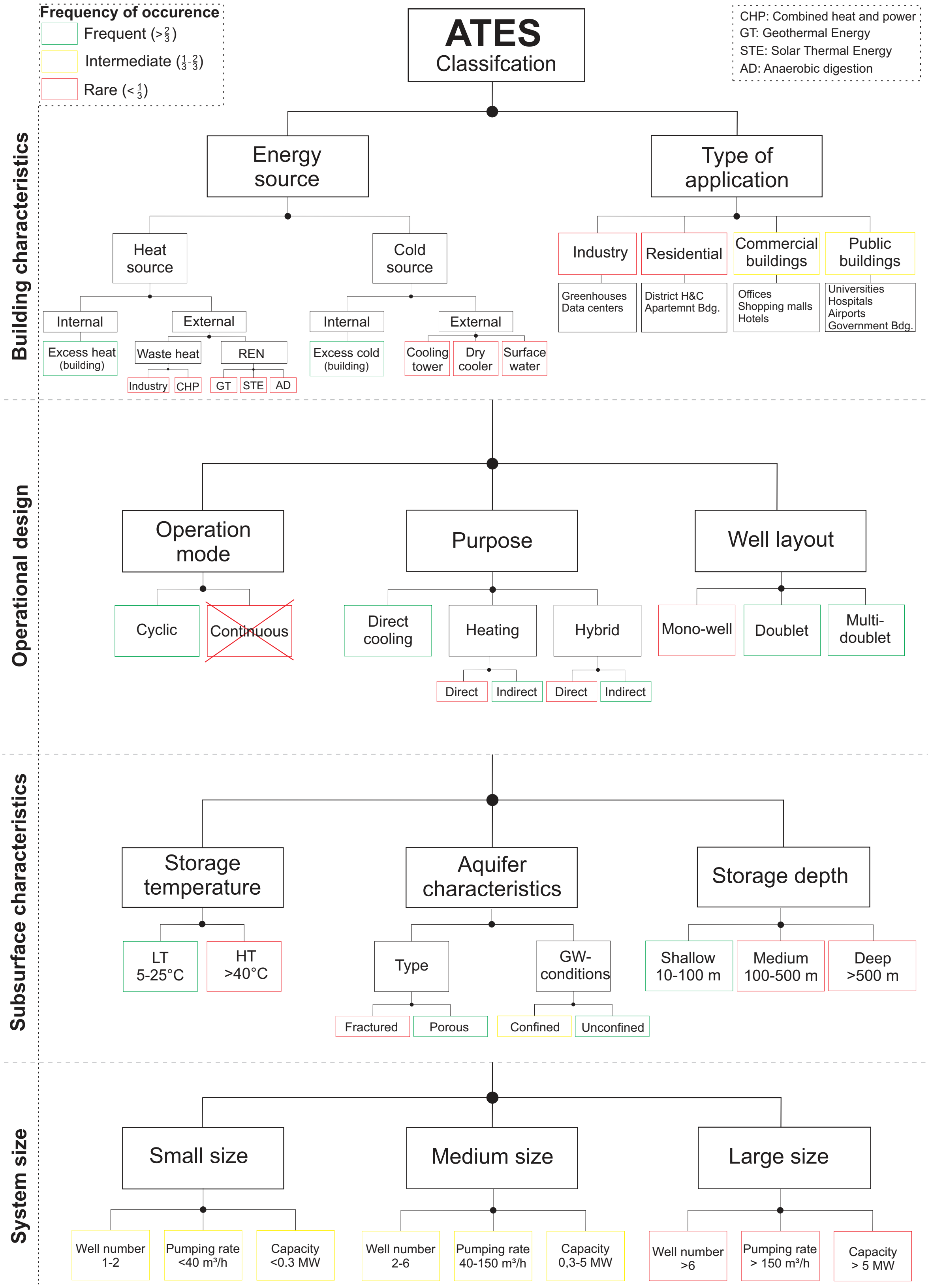

Figure 2.4: ATES characterization in terms of building characteristics, operational design, subsurface characteristics and system size.

Table 2.4: Summary of technical, energetic and financial parameters of worldwide ATES systems.

City (Country)	**Purpose**	**Facility**	**Year**	**Well depth [m]**	**Well number**	**Max. flow rate** $[m^3/h]$	**Capacity [MW]**	**Capital costs [€]**	**Payback time [years]**	CO_2 **savings [t/a]**	**Ref.**
Amersfoort (NL)	H+C	IKEA Store	-	-	2	200	1.4	-	-	-	[217]
Utrecht* (NL)	HT	University	1991	260	2	100	2.6	1.1	5	750	[124, 218]
Amersfoort (NL)	H+C	Office building	1996	240	2	-	2	1.0	6.5	-	[219]
Oslo (NW)	H+C	Airport	1998	45	18	200	7	2.65	2	-	[220–222]
Zwammerdam* (NL)	HT	Hospital	1998	150	2	20	0.6	1.3	-	-	[218]
Berlin (DE)	H+C	Reichstag	1999	60 / 300	12	100/300	-	-	-	-	[223, 224]
Rostock (DE)	H	District heating	1999	20	2	15	-	1.02	-	-	[225, 226]
Amsterdam (NL)	H+C	District heating	2000	130	4	500	8.3	-	6	-	[227]
Brasschaat (BE)	H+C	Hospital	2000	65	2	100	1.2	0.7	8.4	427	[228–230]
Malmö (SW)	H+C	Expo building	2001	75	10	120	1.3	0.35	1.5	-	[231, 232]
Mersin (TR)	C	Supermarket	2001	100	2	-	-	-	-	-	[233]
Agassiz (CA)	H+C	Research Center	2002	60	5	40	0.563	0.22	6	-	[169]
Eindhoven (NL)	H+C	University	2002	28-80	36	3000	20	14.7	6-10	13,300	[156, 234–236]
Malle ETAP (BE)	C	Office building	2003	67	2	90	0.6	0.34	7-15	23	[229]
Neubrandenburg (DE)	H	District heating	2005	1200	2	100	3.3	-	-	-	[237, 238]
New Jersey (US)	C	University	2008	60	6	272	2	2.6	12	-	[122, 236, 239]
Arlanda (SW)	H+C	Airport	2009	20	11	720	10	5.0	5	7700	[240, 241]
Copenhagen (DK)	H+C	Hotel	2009	-	2	-	2.4	-	6-7	366	[242]
Malmö (SW)	H+C	IKEA Store	2009	90	11	180	1.3	-	4.5	-	[243]
Copenhagen (DK)	H+C	Office building	2010	100	10	250	2.8	-	4	644	[244]
Greenwich (UK)	H+C	Museums quarter	2011	60	2	45	0.33	-	-	-	[245, 246]
Shinshu (JP)	H+C	University	2011	50	5	-	-	-	-	-	[247, 248]
London (UK)	H+C	Apartments	2013	70	8	400	2.9	-	-	-	[249]
Amsterdam (NL)	H+C	District heating	2015	-	7	1100	20	25.0	-	2900	[250]
Copenhagen (DK)	H+C	Airport	2015	110	10	-	5	8.0	8	1000	[251, 252]

* No longer in operation.

209, 235]. Direct cooling systems achieve storage efficiencies of up to 90%, indirect systems reach 40-85% [26, 174, 184, 194, 199, 212]. Typical payback times compared to conventional systems range from two to ten years [75, 101, 209, 230, 253–257]. ATES for cooling show lower payback times, since the stored cold can be used directly without a heat pump [14, 235]. The lifetime of an ATES system is estimated at 25 years by Hartog et al. [258] and at 30-50 years by Bloemendal et al. [216]. The investigation of 74 ATES systems in the Netherlands has revealed an average CO_2 saving of 0.46 kg per m^3 of pumped groundwater [259, 260]. This corresponds to an estimated annual reduction in CO_2 emissions of 150 t/a for a small-scale system and of up to 1500 t/a for a large-scale system. By comparison, the average CO_2 savings for a ground-source heat pump (GSHP) unit ranges between 1.8 and 4.0 t/a, depending on the replaced heating system and used electricity mix [261]. The largest ATES worldwide at the campus of the University of Technology in Eindhoven (NL) saves more than 13,000 t of CO_2 per year [236]. This is equivalent to the average annual CO_2 footprint of 800 American or 1300 German citizens. In the Netherlands, about 70% of all ATES systems supply energy for public and commercial buildings (e.g. offices, shopping malls, hospitals, hotels). The remaining 30% are installed in industrial or residential buildings [157, 262]. Similar proportions are reported from Sweden [255] and Denmark [263]. Recently, ATES has been increasingly considered to reduce the high energy costs of greenhouses and data centers [162, 207, 263–267].

2.3 Worldwide ATES spatial distribution

The establishment of renewables in the energy market is often impeded by several market barriers (Section 2.4). Even though the economic and technical viabilities have been successfully demonstrated, only a small proportion of the potential of ATES technology has been tapped yet. Statistics on the global application of ATES are indispensable for identifying such country-specific market barriers. Despite this great significance, the literature lacks such statistics. So far, only Lee [28] discussed the status of ATES in all relevant countries. However, the figures compiled are neither up-to-date nor complete. Beyond that, several authors summarized their experiences with ATES in several country updates [13, 33, 42, 95, 156, 222, 226, 253, 268–277]. These country updates are analyzed to provide a global overview of ATES applications. In cases where data from the literature were not sufficient, further inquiries for additional information were sent to ATES experts. The latter was done for ATES systems in China, Denmark, Sweden, Turkey and the US. To our knowledge, more than 2,800 ATES projects have been successfully implemented worldwide. The total amount of heat and cold produced by all ATES systems is estimated at more than 2.5 TWh per year, which equals the average thermal energy consumption of 150,000 households in Central Europe. However, this success story is contributed by only a few countries: around 85% of all systems are installed in the Netherlands (2,500); a further 10% are found in Sweden (220), Belgium (30) and Denmark (55). Fig. 2.5 illustrates the global application statistics and global spatial distribution of ATES. The comparison of Figs. 2.3 and 2.5 indicates that

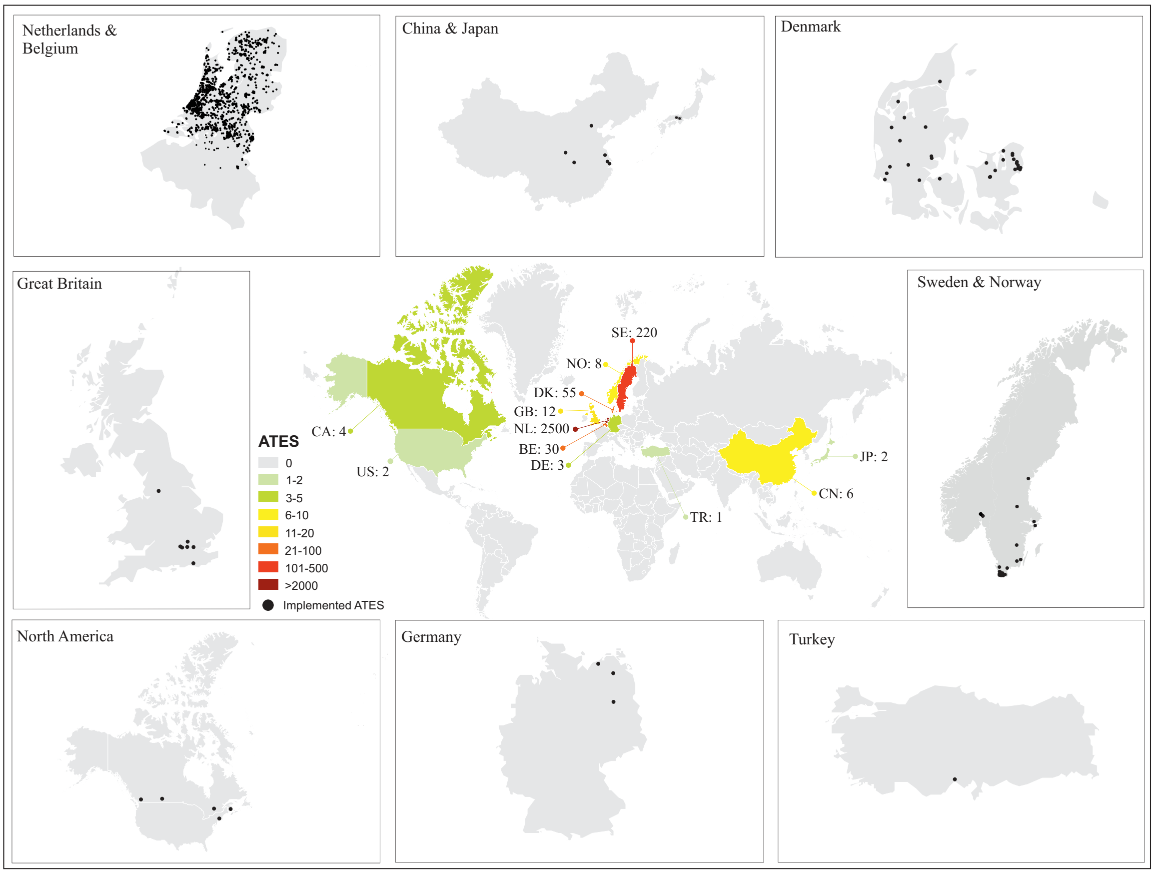

Figure 2.5: Global spatial distribution of ATES.

countries that were active in research in the 1970s and 1980s have now lost their interest in ATES. This is especially the case for Switzerland (0), France (0), the US (2) and Canada (4). Regardless of the great discrepancy in ATES application worldwide, the number of ATES systems is expected to increase further. Significant growth rates are reported from the Netherlands, Sweden, Denmark and Belgium [268, 278]. Furthermore, progressively more countries show an interest in ATES technology. After the first ATES system was realized in Great Britain in 2006 [279], almost a dozen projects were implemented in the course of the last decade. As many large UK cities have subsurface conditions suitable for ATES, further projects are expected [280]. In Germany, ATES was considered first in the early 1980s as a consequence of the oil crisis and in order to provide an alternative to expensive cooling methods for nuclear power plants [104]. Currently, there are, however, only four operating ATES systems for heating and/or cooling purposes. Consolidated findings were gained from these projects [192, 200, 201, 223, 224, 226, 237, 238, 281–290]. In Germany, there has been an increasing interest in storage technologies again recently. Hence, four ATES projects are in the planning or construction phases:

- An ATES for the new campus building of the Leuphana University in Lüneburg [290–292];
- The collaborative project called "GeoSpeicher.bw" aims for the implementation of three ATES systems in the federal state of Baden-Württemberg;
- The BMW Group, supported by TU Munich, designs a HT-ATES for storing temperatures of up to 130 °C with an injection rate of 280 m^3/h in a Jurassic limestone aquifer at a depth of about 500 m [293, 294];
- The city of Hamburg strives to store waste heat from an incineration and a sewage plant with the long-term aim to supply heating for 8,000 households. Feasibility of the project was successfully demonstrated by a pilot ATES with one well doublet. The pilot plant is expected to be up-scaled in the near future.

In China, ATES is experiencing the beginning of a revival. After early projects had to be shut down due to technical problems, six ATES systems have been successfully implemented since 2013. ATES provides heat and cold for a poultry farm, for two public buildings and three greenhouses [41]. In Japan, two demonstration plants were successfully realized, and further projects are expected [295]. Although there are currently no further plans for ATES in Turkey [296], an ATES for the cooling of a supermarket and several feasibility studies have proven the economic and technical feasibility of ATES in Mediterranean regions [233, 265, 297, 298]. A team of experts from universities, authorities, and the industry is trying to evaluate potential barriers to the penetration of the Turkish energy market [296].

2.4 Market barriers

The country-by-country statistics presented in the previous section raise the question for the reasons for the great discrepancies in ATES development worldwide. In the most industrial countries, expect for in Sweden or the Netherlands, ATES has not been in the focus yet. This reveals a trend that does not reflect the high suitability for ATES [11] and is opposite to the great demand for sustainable heating and cooling in these countries. Thus, the development of ATES application is not only influenced by subsurface and climate conditions, but also by several market barriers, which are of socio-economic, regulatory, technical and political natures (Sections 2.4.1 - 2.4.3) [299]. However, the kind of market barrier influencing technology development is subject to a dynamic process. Hence, the country-specific market development has to be considered when identifying potential market barriers on a global level. Van Mourik [158] first analyzed market barriers for ATES development. He concentrated on cooling systems in the Netherlands. Within the framework of the project “e-use“, Bloemendal et al. [300] conducted a questionnaire in order to assess market barriers for ATES in the Netherlands, Belgium, Germany, Italy and Spain. More generally, Dincer and Rosen [30] analyzed hurdles to be overcome for TES systems, and Monti et al. [301] studied obstacles to geothermal projects. Based on these previous works, Fig. 2.6 illustrates market barriers for ATES commercialization as a function of the market development level. The following section analyzes potential barriers (1) from the perspective of an emerging market phase, (2) from the perspective of a growth phase and (3) from the perspective of a maturity phase.

2.4.1 Market barriers in the emerging market phase

More than 2,800 ATES systems have been successfully implemented worldwide. According to Andersson and Sellberg [14], there are no unsolved technical problems if the storage temperature is restricted to less than 40 °C. Although feasibility was demonstrated and benefits are significant, ATES, in most countries, has not yet penetrated the energy market. Thus, until entering the stage of commercialization, the dominating hurdle is less a matter of technical feasibility than a lack of awareness of the technology [96, 300]. However, this is not the case for HT-ATES, where serious technical problems, such as scaling or corrosion of wells, have to be solved first. In most countries, politicians, stakeholders and HVAC (heating, ventilation and air conditioning) installers often do not consider ATES and, therefore, this technology

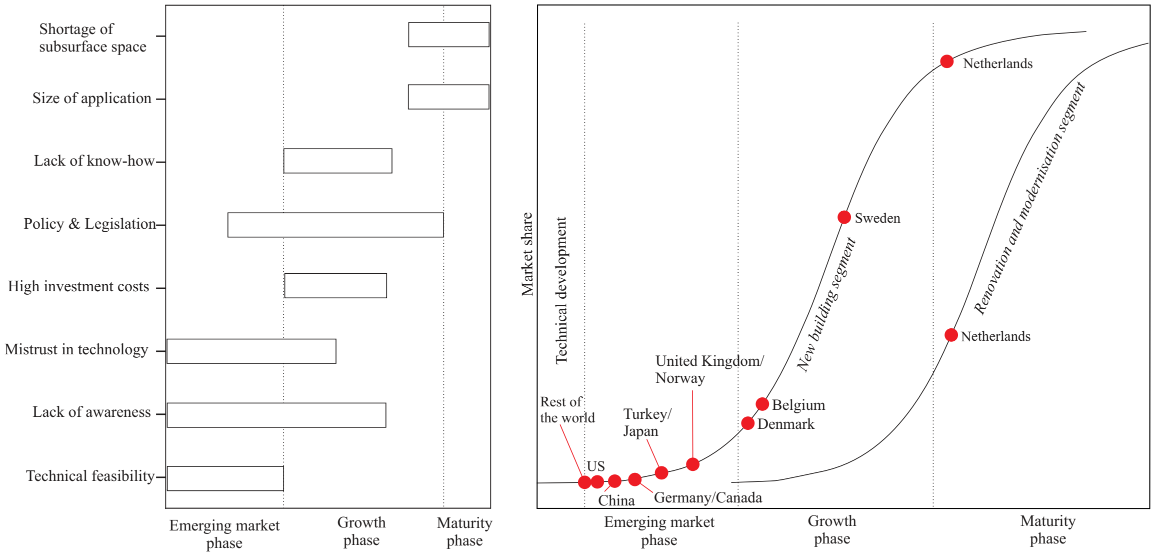

Figure 2.6: Left: market barriers limiting ATES development as a function of the market development level. Please note that suitable subsurface and climatic conditions are assumed. Right: market development of ATES in all relevant countries considering new building and renovation segments.

is not part of the new energy design. The most promising way to promote a new technology in the population is the successful realization of demonstration projects [151, 302]. Such projects not only draw public attention but also prove technical and often economic feasibility. The term “demonstration project“, however, implies that it is not sufficient to just take care of the technical installations. It is also essential to propagate the environmental and economic benefits of the technology. The Reichstag building in Berlin with over three million visitors per year serves as a good example: an ATES has been providing heating and cooling for more than 15 years. Even though the energy system of the Reichstag has been the first of its kind in Germany, there is no information panel providing background data about the technology. Probably only a small proportion of the visitors and members of parliament (MP) realizes, how the German parliament is actually heated and cooled. As awareness of the technology increases, any renewable initially is facing prejudices and mistrust [303]. Hence, it is of utmost importance that the success of the first projects installed in a country is guaranteed. However, this means that contractors have to invest in the project to guarantee its success and clients have to accept difficulties in the start-up phase [304]. Another great hurdle for early ATES projects is the high initial investment compared to conventional systems. High capital costs, especially for the drillings, make ATES appear unattractive at first glance. While financial evaluations are rare in the field of ATES research, decision-makers are often not aware of the typical low payback times of such systems [305]. Another issue is the question of who is taking the exploration and investment risks. Test drillings are often indispensable in order to explore the essential subsurface suitability for ATES (i.e., technical feasibility). However, there is no guarantee for the success of a test drilling, which means some uncertainty and poses a specific risk to the client.

2.4.2 Market barriers in the growth phase

Entering the commercialization stage, the type of potential barrier shifts from socio-economic to more regulatory issues. Since experiences gained with ATES are rare in most countries, numerous legal questions have to be addressed, discussed and finalized in regulations or even laws [306]. This applies especially to the permitted injection temperature, the minimum distance to other geothermal applications, the maximum drilling depth and the distance to contaminated sites. Environmental risks of shallow geothermal energy can be subdivided into hydrogeological, thermal, chemical and microbiological impacts [307]. Potential impacts of ATES on groundwater quality were investigated by several field monitoring campaigns [258]. For temperature levels of below 30 °C, groundwater quality is predominantly affected by mixing of stratified groundwater and less by temperature effects [258]. However, according to Bonte [307], an early identification of interferences and synergies between different subsurface activities can avoid negative interference of ATES with other subsurface functions. At present, there are significant differences in the legal framework both at international [15, 16, 308] and even national levels [15, 308]. Experience gained in the Netherlands have illustrated that courage of the authorities to create a proper legislative framework is indispensable for enabling technology growth in a country [274]. Authorities have to strike the right balance between the protection of groundwater and an acceptable limitation of a promising technology. In Sweden, for instance, the permit procedure averages 12 months [270]. After introduction of a new legislative framework in the Netherlands in 2014, the permit procedure was shortened from 12 to two months for normal,- low-risk projects. Only in the case of high-risk projects (complex hydrogeological settings), it may take up to six months. Hence, top priority should be placed on a standardized, transparent and coherent legal framework. To support authorities in establishing appropriate, scientific-based guidelines, negative effects of ATES on groundwater quality or neighboring underground users have to be assessed. In recent years, much research was undertaken to identify negative effects on groundwater quality [307–316], changes in groundwater chemistry [258, 317–329] and potential impacts on microbiology [321, 330–334]. In order to facilitate a scientific-based permit procedure, the knowledge gained has to be bundled and expressed in the form of specific guidelines for authorities, planners and industry. First steps in this direction were recently made in the Netherlands with the collaborative research program “Meer met Bodemenergie“ (“more with subsurface energy“). Within this framework, all relevant actors were involved in determining the long-term influence of geothermal energy on the subsurface. The main recommendations to the authorities were to limit the maximum injection temperature to 25 °C and to intensify underground management [300]. In this context, there has been also a growing interest in the combination of enhanced groundwater remediation and ATES [319, 335–346]. Another obstacle in the early commercialization phase is the lack of knowledge among national and local consultancies. This was observed with pilot projects in the Netherlands at the end of the 1980s [158]. Large consultancies often do not want to harm their reputation by an unknown new technology and small consultancies often do not have the capabilities to manage large and new projects [158]. As rich experiences have been gained with ATES in several countries, initiation of a cross-national knowledge transfer is important to guarantee the success of early projects [158, 304].

2.4.3 Market barriers in the maturity phase

With a successful establishment in the energy market and a steadily increasing number of implemented systems, a scarcity of subsurface space can also be a limiting factor. In many Dutch cities, the increasing demand for ATES exceeds subsurface space. Permits for new shallow geothermal energy systems are currently given on a “first-come-first-pump“ basis [216]. Hence, there is an increasing demand for a cross-sectoral subsurface management [27, 300, 308, 347–351]. Growing concerns about this issue are, however, not only limited to the Netherlands. In Germany, 12% of the underground excludes the use of geothermal technologies [300]. This area does not include potential horizons for Carbon Capture and Storage (CCS) technology, nuclear waste repositories and over 15,000 contaminated sites. Additionally, in Germany, there are already more than 350,000 GSHP systems in operation [352]. These figures illustrate that underground space is already highly limited even without ATES activity. To be able to facilitate a sustainable permit procedure, other countries could and should learn from the lessons learned in the Netherlands and apply an underground management system from the early beginning. Early ATES pilot projects usually focus on new buildings, where the energy system can be adjusted to ATES-specific requirements. Nevertheless, there is also a great demand for a sustainable heating and cooling for the old building stock. In the very early days of ATES application in the Netherlands, nearly 90% of ATES projects had to be cancelled due to an insufficient building integration [159]. The main problem of integrating ATES in an old building is to replace the existing HVAC installations, which would drastically exceed the budget of an ATES project. In residential areas, ATES often has to compete with oil or gas boilers. As the old system has been proving its functionality for decades, it is difficult to convince homeowners of investing in a new heating and cooling system. Another hurdle is the size of residential buildings: due to the smaller system capacity, financial savings are significantly lower compared to those through ATES for large buildings. To enhance the ability of ATES to compete with other storage techniques in the residential sector, it will be crucial to match the high energy supply of ATES to the low energy demand of the small building stock. The combination of district heating or cooling with ATES, however, is a promising solution [193, 270, 353] but requires a regional or urban energy management.

2.5 Conclusion

With more than 2,800 systems in operation worldwide, ATES technology has proven its ability to efficiently tackle the seasonal mismatch between periods of highest energy supply and highest energy demand. Nevertheless, this success story is almost entirely limited to a few north-western European countries. Despite the high potential in most developed economies, ATES still has difficulties in capturing significant positions in relevant energy markets. To benefit from the growing interest in TES technologies, political and institutional actors are obliged to create a suitable framework for ATES development, which includes an appropriate legislative basis and well-placed financial subsidies. Based on the reviewed literature, the following research gaps have to be carefully addressed by future research and public activities:

Economic evaluation

The literature is comprehensively reviewed in this work, but profound economic considerations are quite rare in the field of ATES. Even though several authors have summarized payback times and capital costs from several projects, only Ghaebi et al. [354] have carried out a comprehensive economic analysis. This is remarkable, as many authors have identified the lack of awareness of financial benefits as a key barrier to market penetration. Future studies should, therefore, collect and analyze financial parameters of existing projects in order to evaluate the economic competitiveness of ATES compared to both conventional energy systems and other TES solutions. The identification of parameters, which affect the economic performance of an ATES, would not only be a first step towards a financial optimization of ATES plants, but also a tremendous support for stakeholders and decision makers to estimate capital costs and financial payback times.

Further research into HT-ATES

The total amount of solar radiation reaching the roof of a typical building is more than its annual heating demand. The storage of solar thermal energy (STE) is becoming increasingly important [199]. Different storage solutions are considered for STE storage in practice [355, 356]. ATES has attracted very little attention in this field, as storage temperatures of STE can be up to 95 °C [357]. In order to build up confidence in HT-ATES, more attention has to be paid to crucial hydrogeochemical-related problems such as corrosion or scaling of wells and heat exchangers. The vast majority of modeling studies focuses on heat transfer processes in the subsurface. However, experiences from existing projects identified the connection of subsurface and energy system to be the main bottleneck. The dynamic change in heating and cooling demand of a building is often neglected, which is reflected by a mismatch between simulation results and reality [358]. Additionally, HVAC designs are often based upon conservative assumptions, resulting in oversized ATES systems. The development of smart energy concepts and design models would, therefore, support optimizing the dimensioning of ATES systems.

Potential studies

Several authors have analyzed the potential of ATES on a local [359], regional [360–362], or global scale [11, 363, 364]. However, these studies only allow a first estimation of ATES potential, since important factors were not considered. Even though Bloemendal et al. [11] indicated that ATES suitability is high in almost all developed economies, there is an urgent need for quantification of the ATES potential [365]. As potential maps serve as a useful tool to stimulate the decision-making process of new energy concepts, future investigations should also take local characteristics into account. This especially relates to geographical, regulatory, hydrogeological and climatic factors.

- Geological & hydrogeological parameters (potential storage horizons, groundwater flow, aquifer thickness, groundwater temperature, fluid chemistry, oxygen concentration);
- Geographical parameters (thermal energy sources, thermal energy demand, existing infrastructure, potential conflicts with other subsurface users);
- Regulatory parameters (groundwater protection areas, maximum drilling depth, maximum distance to geothermal systems);
- Climatic parameters (temperature, solar radiation, heating and cooling degree days).

Almost 3,000 ATES systems are in operation worldwide demonstrating the large potential of ATES to significantly reduce GHG emissions of the thermal energy sector. Several market barriers still impede ATES market entrance in most economies. Nevertheless, decarbonization of the heating and cooling sector is indispensable to achieve COP21 targets. Thus, further research and development (R&D) activities are required to promote ATES development beyond north-western Europe.

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Chapter 3

Performance analysis of Aquifer Thermal Energy Storage (ATES)

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Abstract

The objective of the current study is to assess the technical performance of Aquifer Thermal Energy Storage (ATES) based on the monitoring data from 73 Dutch ATES systems. With a total abstraction of 30.4 GWh heat and 31.8 GWh cold per year, the average annual amount of supplied thermal energy was measured as 932.8 MWh. The data analysis revealed only small thermal imbalances and small temperature losses during the storage period. The abstraction temperatures are around 10 and 15 °C during summer and winter, respectively. However, the temperature difference between the abstraction and injection wells is 3 to 4 K smaller compared to the optimal design value. This indicates insufficient interaction between the energy system and the subsurface by an inadequate charging of the aquifer. In addition, the amount of stored and abstracted thermal energy is approximately 50% lower than the capacities licensed by the authorities. This results in an unsustainable utilization of the subsurface. Even though ATES technology proved its enormous potential to significantly reduce CO_2 emissions, the operation still can be optimized. This applies in particular to an adequate planning and maintenance of the building energy system and a more efficient use of the available subsurface space.

3.1 Introduction

As most industrial nations are located in the moderate climate zone with winter and summer, the decarbonization of the thermal energy sector is less a matter of energy scarcity and more an issue of seasonal storage. Water, and in particular groundwater is considered to be a promising storage medium due to its high heat capacity and low thermal conductivity. Due to its widespread availability, the seasonal storage of heat and cold in shallow groundwater (< 400 m), also referred to as low temperature Aquifer Thermal Energy Storage (LT-ATES), is gaining increasing popularity [222, 253, 268, 366]. However, with more than 2,800 systems in operation worldwide, to date ATES are most widely used in the Netherlands [366]. In contrast, countries such as Germany or France mainly use groundwater for heating and cooling by groundwater heat pump (GWHP) systems. While there is growing attention for LT-ATES in many countries [367, 368], there is also a great interest in the lessons learned from the Netherlands. Thus, a performance analysis of running systems is not only important to optimize ATES application in the Netherlands, but also to facilitate global development of ATES technology.

The performance of an ATES can be evaluated based on various performance criteria such as recovery rate, sustainability and economic efficiency. Each of these criteria are influenced by certain boundary conditions such as subsurface, building or design related parameters. A comprehensive literature review on LT-ATES revealed that 55 (28%) of 199 publications analyzed the performance based on certain boundary conditions. Fig. 3.1 illustrates the frequency of the analyzed performance criteria as a function of each boundary condition. So far, the studies mainly focused on the influence of geological and design related parameters on the recovery rate (storage efficiency) and abstraction temperature. In contrast, building related aspects such as optimal integration of the ATES into the heating and cooling system were only rarely addressed. Additionally, most of the reviewed performance evaluations are only based on theoretical assumptions. Studies analyzing real monitoring data are however, only sparsely found.

On behalf of the Dutch Ministry of Economic Affairs, IF Technology analyzed the monitoring data of 125 Dutch LT-ATES systems. The results were published in a Dutch report by Willemsen [383]. The monitoring data comprise of the measured temperatures as well as the volume of pumped groundwater. The monitoring data revealed small thermal imbalances

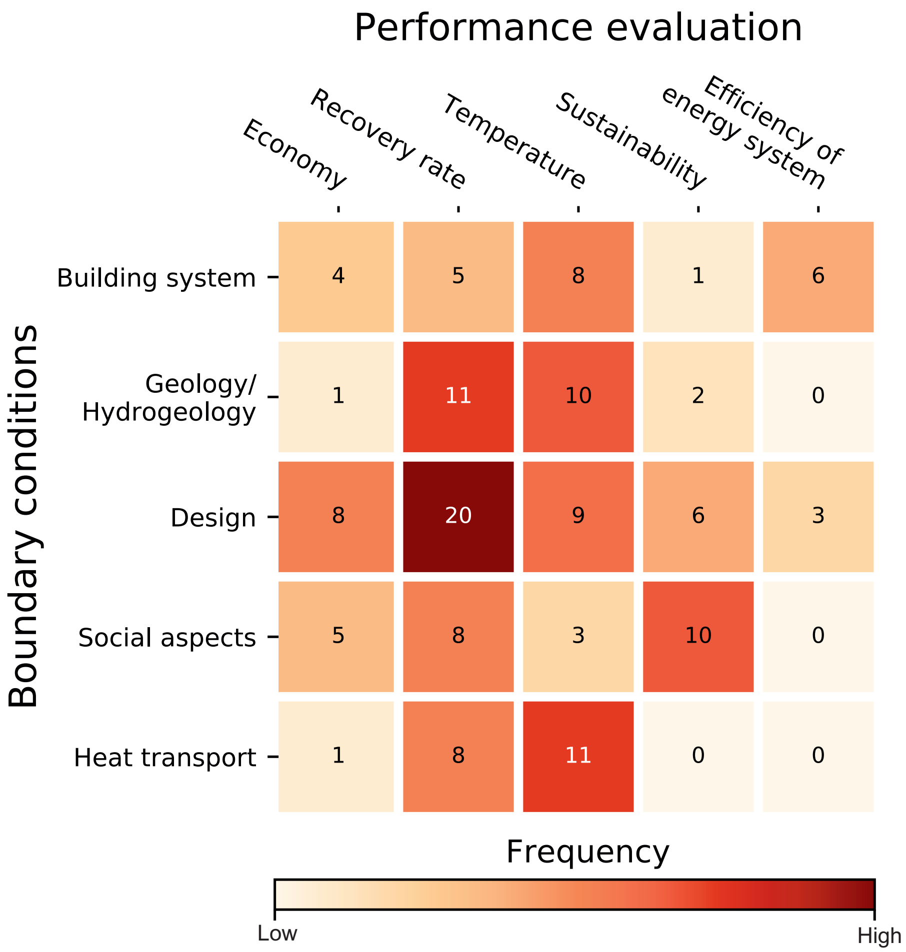

Figure 3.1: Frequency of research activity addressing the performance of LT-ATES as a function of various boundary conditions. Considered studies: Bakema et al. [12], Sommer [27], Morofsky [35], Xiao-Bo and Jie [39], Midkiff et al. [69, 70], Xue et al. [144], Bozkaya et al. [159], Yapparova et al. [164], Bridger and Allen [169], Bridger and Allen [170], Visser et al. [171], Sommer et al. [172], Ganguly et al. [176], Bourbiaux [177], Bakr et al. [179], Ganguly et al. [180], Lee [181], Gao et al. [182], Sommer et al. [184], Kim et al. [187], Lee [188], Ghaebi et al. [191], Kranz and Frick [192], Drenkelfort et al. [195], Li et al. [196], Kranz and Bartels [201], AlZahrani and Dincer [204], Lee [210], Bloemendal et al. [216], Birhanu et al. [220], Vanhoudt et al. [230], Behi et al. [234], Koenders and Zwart [259], Anibas et al. [278], Jaxa-Rozen et al. [299], Bloemendal and Hartog [348], Bloemendal et al. [350, 351], Ghaebi et al. [354], Abuasbeh and Acuña [369], Bloemendal and Hartog [370], Bloemendal and Olsthoorn [371], Bozkaya and Zeiler [372], Bozkaya et al. [373], Hendriks and Velvis [374], Hermans et al. [375], Jaxa-Rozen et al. [376], Jiuchen et al. [377], Lesparre et al. [378], Rostampour et al. [379, 380], Schepper et al. [381], Schüppler et al. [382], and Willemsen [383].

between 15 and 25% as well as ΔT values of below 5 K. However, neither conclusions on the performance nor possible optimization strategies were discussed. Sommer et al. [172] analyzed the monitoring data of the ATES at Utrecht University from 2005 to 2012. The heat transport was monitored by distributed temperature sensing (DTS) with six fiber optic cables and showed that there is no thermal interference between warm and cold well but preferential flow due to aquifer heterogeneity. Abuasbeh and Acuña [369] conducted a monitoring campaign for an ATES system supplying heat and cold for two office buildings located in Solna, Sweden. Preliminary results of the first year of monitoring revealed low storage efficiencies of 33% explained by thermal losses due to groundwater flow and a strong thermal imbalance. Hendriks and Velvis [374] compared the operational performance of ATES and Borehole Thermal Energy Storage (BTES) systems in the Netherlands. They concluded that although the monitoring results showed high economic and financial savings, the total efficiency of the energy system depends not only on the performance of the ATES but also on the required building supply and return temperatures. They recommended to not only focus on functional performance and permit compliance but also on energetic performance. Additionally, Kranz and Frick [192], who analyzed the performance of the cold storage of the German Parliament Building in Berlin, identified the regeneration temperature of the ATES and the temperature level of the cooling network as key parameters. Hoes et al. [229] evaluated the techno-economic performance of three Belgian ATES systems and showed an average energy savings of at least 60%. They recommended to keep the ATES installation as simple as possible but to have them in an optimal shape. Vanhoudt et al. [230] conducted an economic analysis of the operating ATES system of the Klina hospital in Brasschaat, Belgium, based on operating data. The ATES system showed a good performance reaching a simple payback time of about eight years.

While Willemsen [383] only focused on subsurface aspects, the literature lacks on information on the performance of LT-ATES based on long-term monitoring data. These data are not only crucial to specify the input parameter for theoretical simulations, but also to provide valuable information for system optimization in the Netherlands and countries, where ATES is not yet frequently used. The objective of this study is therefore to analyze the monitoring data of 73 Dutch LT-ATES systems measured in a period from 2016 to 2018. Based on a holistic data analysis, valuable conclusions are drawn both on the performance of the ATES and also on the quality of the building-subsurface interaction. Optimization strategies are discussed to further enhance the technical performance of ATES and also to improve the sustainable use of the available subsurface space, considering the current licensing practice in the Netherlands.

3.2 Material and methods

3.2.1 Recovery ratio and storage temperatures

The term “cold energy“ does not exist from a thermodynamic point of view. However, in order to enhance the comprehensibility, the term “cold “ is used throughout this thesis to express the amount of stored or abstracted thermal energy used for cooling. The recovery efficiency (η_E) of an ATES system is a measure for the thermal losses during the storage period and is influenced by hydrogeological, design-specific and anthropogenic factors. Based on Sommer et al. [174], η_E can be calculated with Eq. 1,

$$\eta_E\left(t_0 \to t\right) = \frac{\int_{t_0}^{t} Q_{Abs}\left(T_{Abs} - T_{Amb}\right) dt}{\int_{t_0}^{t} Q_{Inj}\left(T_{Inj} - T_{Amb}\right) dt} \tag{3.1}$$

with T_{Amb} the ambient groundwater temperature and Q the injected or abstracted groundwater volume during time step t. In contrast, the recovery ratio (η_R) provides information on the amount of injected thermal energy, recovered after the storage period and is calculated by the difference between abstraction and injection temperature, measured before and after the heat exchanger [370].

$$\eta_R\left(t_0 \to t\right) = \frac{E_{Abs}}{E_{Inj}} = \frac{\int_{t_0}^{t} \Delta T_{Abs}\, Q_{Abs}\, dt}{\int_{t_0}^{t} \Delta T_{Inj}\, Q_{Inj}\, dt} \tag{3.2}$$

The natural groundwater temperature in the Netherlands can be estimated to be around 10 and 12 °C [384]. However, the natural groundwater temperature can be influenced by anthropogenic activity especially in urban environments. Several studies reported of elevated groundwater temperatures of more than 5 K in cities due to the subsurface urban heat island effect (SUHI) [385]. Assuming a natural groundwater temperature of around 11 °C, the calculation of η_E can lead to misleading efficiency values. Since the dataset lacks information on site specific ambient groundwater temperatures, the performance is only evaluated based on η_R in this study.

In addition, the thermal imbalance of an ATES is defined by the amount of injected heat and cold and should be in balance over a heating and cooling season [386]. The thermal imbalance is determined in this study following Eq. 3 [172].

$$Imbalance = \frac{E_{Inj}(cold) - E_{Inj}(warm)}{E_{Inj}(cold) + E_{Inj}(warm)} \tag{3.3}$$

The performance of an ATES system can also be analyzed based on the recovery temperatures. The measured temperatures are not only a criterion to evaluate the performance of the subsurface part, but also for the technical interaction between building and ATES. The injection and abstraction temperatures, measured before and after passing the heat exchanger, can be analyzed based on three ΔT values, depending on the time and location of the measurement. The calculation of each ΔT is illustrated in Fig. 3.2. Given the pumping rate Q,

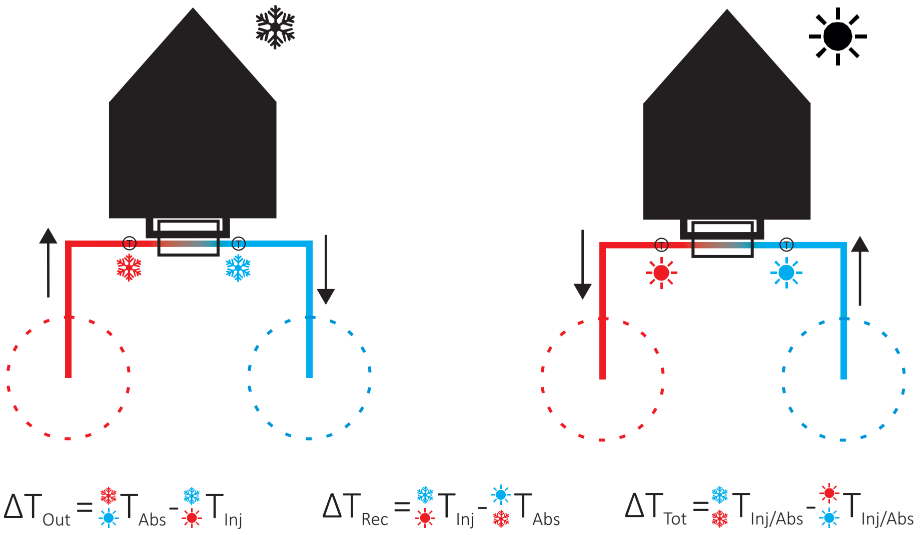

Figure 3.2: Depending on the season (winter or summer) and location (abstraction or injection well), the measured temperature differences ΔT of an ATES system can be subdivided into three different values: the difference between abstraction and injection temperature ΔT_{Out}, the temperature loss during storage period ΔT_{Rec}, and the difference between warm and cold well ΔT_{Tot}. The time and location of measurement for each type of ΔT is marked by the winter and summer symbol.

ΔT_{Out} is a measure of the transferred energy from the subsurface to the building given by

$$\Delta T_{Out} = T_{Abs} - T_{Inj} \tag{3.4}$$

ΔT_{Out} should be as large as possible to allow proper charging temperatures and a high energy transfer from the subsurface system to the building. ΔT_{Rec} is a measure of the temperature change during the storage period, which is attributed to an imbalanced charging and discharging behavior and also to temperature losses to the surroundings. ΔT_{Rec} is calculated by the temperature difference between the stored and recovered groundwater, expressed by

$$\Delta T_{Rec} = T_{Inj}(storage) - T_{Abs}(recovery) \tag{3.5}$$

ΔT_{Rec} should be as small as possible to guarantee appropriate temperature levels. ΔT_{Tot} is the difference between ΔT_{Out} and ΔT_{Rec} and is often referred to as the temperature difference between warm and cold wells in the literature.

$$\Delta T_{Tot} = T_{Abs/Inj} - T_{Abs/Inj} \tag{3.6}$$

To optimize ATES efficiency, ΔT_{Tot} should be as high as possible to enable an optimal energy transfer from the subsurface to the building and also to avoid thermal losses to the surroundings.

3.2.2 Data

Monitoring data

The Dutch General Administrative Order on Ground Energy obliges the owner of an ATES to monitor the operational parameter and report them annually to the local authorities. The authorities control if the monitored data are within the authorized limits. The present data comprise of the monitoring data of 73 Dutch LT-ATES systems from 2016 to 2018 covering the following parameters:

- Volume of pumped groundwater [m^3];
- Abstracted thermal energy for heating and cooling [MWh];
- Abstraction temperature heating and cooling [°C];
- Injection temperature heating and cooling [°C];
- Minimum and maximum injection temperature for heating and cooling [°C].

In this study, the monitoring data were gathered by an energy management software (EMS) called Lift. The latter is a web-based EMS developed in particular for shallow geothermal systems [374]. The injection and abstraction temperatures are measured on both sides of the heat exchanger and averaged to monthly values. According to Sommer [27], heat losses between the wells and the heat exchanger are negligible. The monitoring data are compared in this study with design and license values, which are required by the authorities in the permit procedure. The licensing values comprise of the minimum and maximum allowed injection temperatures as well as the amount of abstracted groundwater. The design values comprise the injection and abstraction temperatures as well as the abstracted and injected thermal energies. In contrast to the licensed values, the design values serve more as orientation for the authorities and do not necessarily have to be met.

Location and climatic conditions

Fig. 3.3 illustrates the location, the capacity and the type of building of the analyzed ATES systems. The capacity ranges between less than 0.5 GWh for small and more than 1.5 GWh

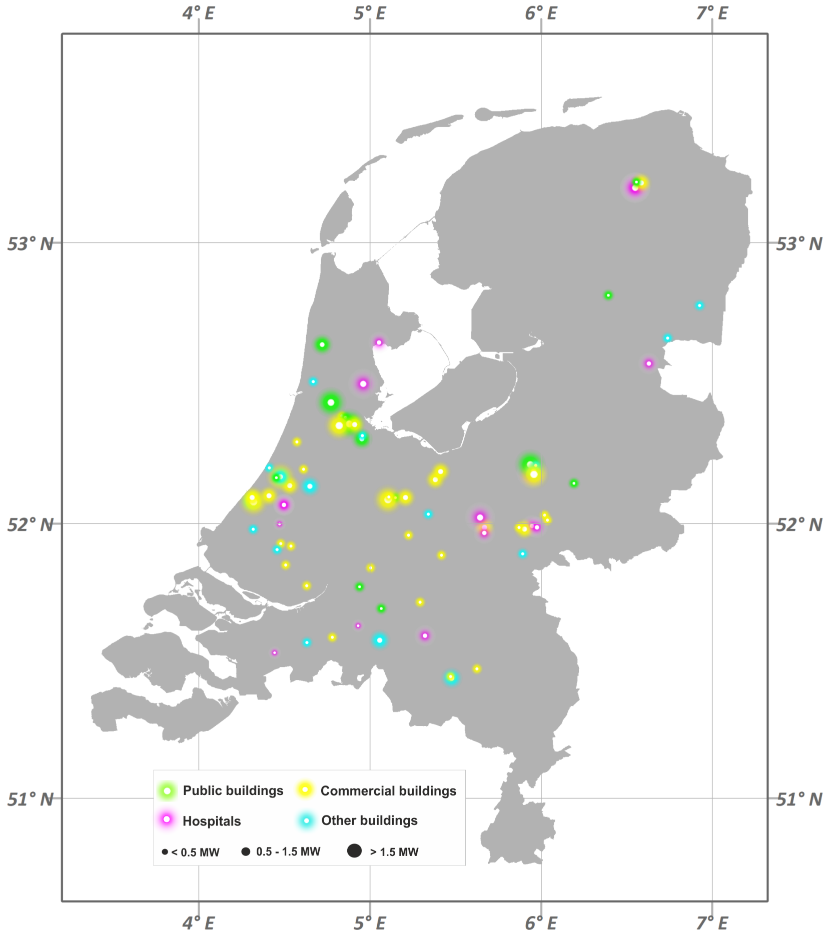

Figure 3.3: Location, heating and cooling capacity as well as type of building of the analyzed ATES systems.

for large systems. 42% of the analyzed systems are commercial buildings such as offices or hotels. Public buildings such as schools, museums and governmental buildings as well as hospitals make up 21% and 20%, respectively. The remaining 16% are multi-functional or residential buildings. The heating and cooling demand of a building is highly affected by the number of heating and cooling degree days (HDD and CDD). Hence, it is important to consider the climate boundary conditions of the monitoring period. Fig. 3.4 shows the average monthly temperature of the Central Netherlands and the temperature anomaly compared to the mean temperatures from 1985 to 2015. The years of 2016, 2017, and 2018 are within the warmest years ever measured. The summer of 2016 and in particular the second half of 2018 were characterized by high average and also peak temperatures. The winter of 2016/2017 was slightly colder, the end of winter 2017/2018 significantly colder compared to the average temperatures.

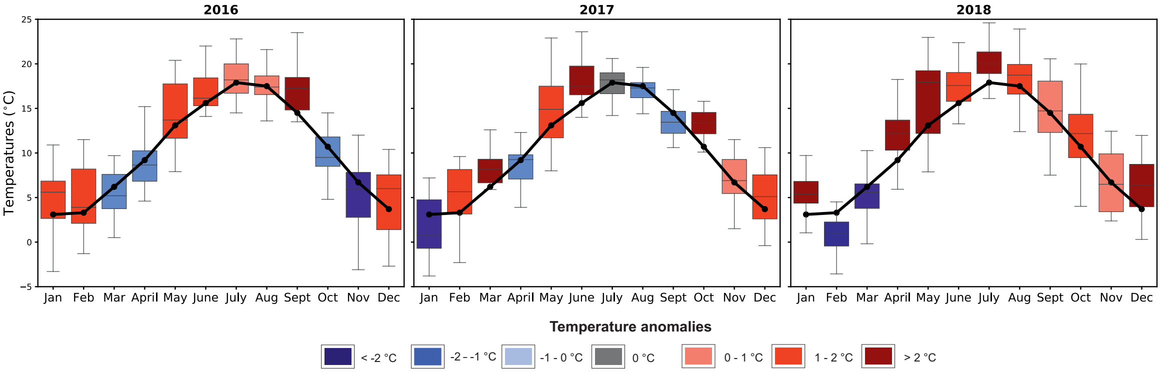

Figure 3.4: The solid line of the boxes illustrate the mean temperatures of the years 2016, 2017, and 2018. The black line shows the average monthly temperature values from 1980 to 2018. The colors of the boxes represent the monthly temperature anomalies compared to the historic temperature values (Data: Koninklijk Nederlands Meteorologisch Instituut).

3.3 Data analysis

3.3.1 Pumped energy

In Fig. 3.5 each dot illustrates the amount of abstracted thermal energy of each ATES system per month from 2016 to 2018. The solid line shows the average abstracted energy for heating (red) and cooling (blue) of all systems. With a total amount of abstracted heat and cold of 30.4 GWh and 31.8 GWh per year, the average pumped energy per system for heating and cooling was measured as 455.8 MWh (± 484.9) and 477.0 MWh (± 575.4), respectively.

The high standard deviation (±) indicates a large range in terms of the system size of the analyzed ATES. With about 2,500 ATES systems in operation, the abstracted thermal energy can therefore be estimated to more than two TWh in the Netherlands per year. However, ATES contributes only to two % of the thermal energy demand (127 TWh) of the built environment in the Netherlands [387]. In comparison, 20% of the buildings in Sweden were heated by geothermal heat pumps in 2015 [388]. With an average annual volume of 153,000 (± 146) m^3 of pumped groundwater, the total volume of all ATES systems in the Netherlands can be estimated to 384 million m^3 per year. Bonte et al. [308] estimated the amount of pumped groundwater to be 350 million m^3 per year based on licensing data. In comparison, the amount of abstracted groundwater for drinking water supply in 2016 was estimated to be 692 million m^3 [389]. The industry and the agriculture is attributed to about 9 and 15%, respectively [390]. Therefore, about 27% of the abstracted groundwater is used for ATES application in the Netherlands. While the groundwater extraction in the Netherlands steadily decreases [389], the share of ATES is expected to further increase. However, it is important to note that the same volume of abstracted groundwater is injected back into the aquifer by the ATES system after passing the heat exchanger.

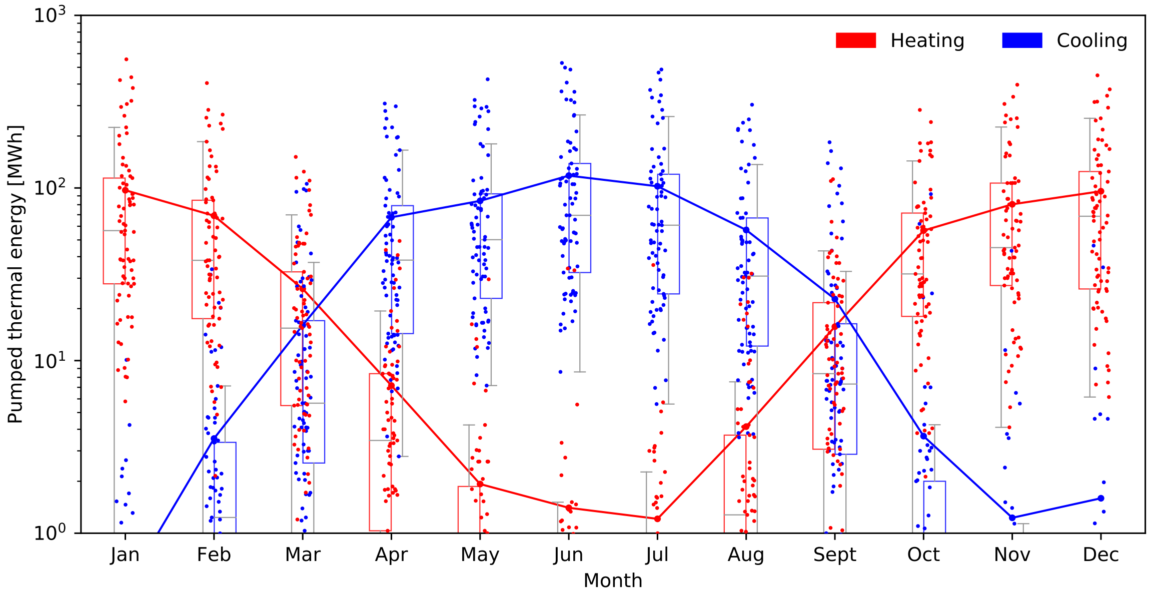

Figure 3.5: Average pumped thermal energy per month of 73 studied Dutch ATES systems. The average pumped energy for cooling and heating is indicated by the solid line.

3.3.2 Thermal imbalance

The Dutch General Administrative Order on Ground Energy requires a balanced amount of injected heat and cold into the subsurface [322, 386]. These regularities were established in order to minimize a thermal contamination of the subsurface [27, 316] and also to guarantee an optimal technical performance [373, 391, 392]. Since climatic fluctuations highly influence the heating and cooling demand of a building, a thermal balanced system is not required for each year. However, each province of the Netherlands has its own specifications. While Friesland, for instance, allows a deviation of 25% in a period of five years, the Province of Flevoland requires that the thermal balance has to be met at least every second year [393]. Fig. 3.6 shows the annual amount of injected heat and cold for each system. Red colors indicate a high heat injection resulting from a high cooling demand. The thermal imbalance was calculated based on Eq. 3. The closer a scatter is to +/- one the higher the thermal imbalance. In the period from 2016 to 2018, the amount of injected thermal energy of the 73 ATES in total was almost in balance (imbalance of -2.3%). This shows that the net groundwater temperature in the Netherlands is minimally affected by ATES activity. The slightly higher amount of injected heat can be explained by the hot summer in 2018 (Fig. 3.4), with extremely high cooling loads. Even though a balanced energy ratio is required, the

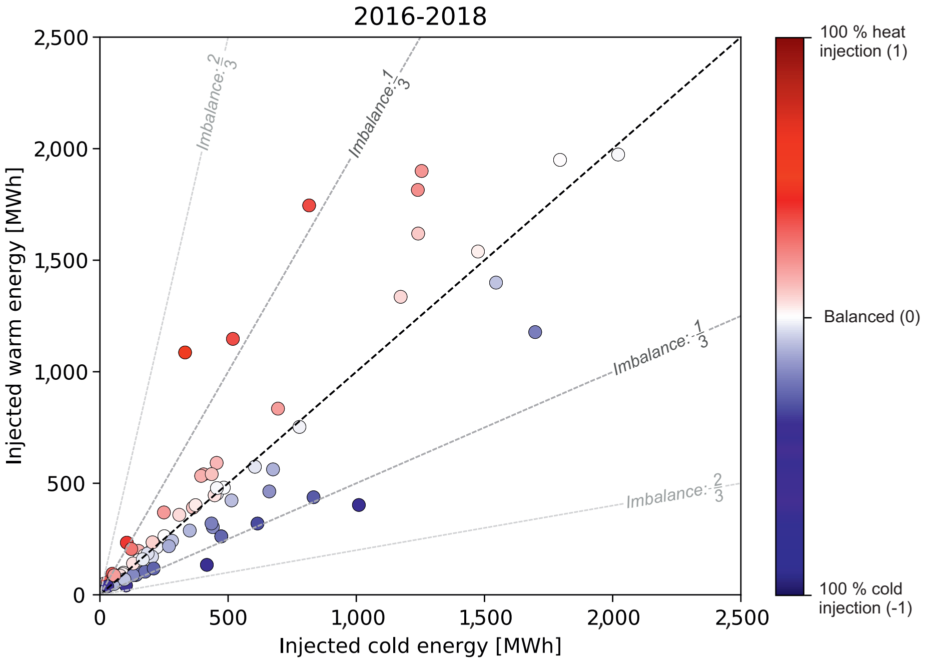

Figure 3.6: Each scatter represents the injected thermal energy per ATES system in the period from 2016 to 2018. Blue colors indicate a higher cold injection (heating dominated systems), red colors a higher heat injection (cooling dominated system).

monitoring data indicate that most systems show a slight thermal imbalance. This was also shown by Willemsen [383], who calculated an average thermal imbalance of 22%. Smaller thermal imbalances can be explained by changing heating and cooling demand patterns due to climatic fluctuations and are unavoidable. However, strong thermal imbalances result in most cases from an insufficient monitoring and energy management. In a well designed and managed heating and cooling system, the EMS is able to automatically detect unbalanced injection patterns and counterbalance this mismatch by the activation of external heat or cold sources. Heat pumps, cooling towers, solar panels, free coolers, air handling units or air ventilation are considered to balance heating or cooling dominated systems [372].

3.3.3 Injection and abstraction temperatures

Fig. 3.7 shows the injection and abstraction temperature for heating (top) and cooling (bottom) season. The temperature was measured before and after the heat exchanger once per hour. It is important to note that the hourly measured data were averaged to monthly values. Hence, peak abstraction and injection temperatures are not illustrated in Fig. 3.7. The average abstraction temperature decreases from 15 to 14 °C during winter and increases from 9.5 to 10.5 °C during summer. Compared to the natural groundwater temperature in the Netherlands, which typically range between 10 and 12 °C [384], the storage effect results in 2 to 3 K warmer (winter) or colder (summer) production temperature. However, for about 15% of the analyzed systems, the abstraction temperatures are close to the natural groundwater temperature showing that these ATES systems operate more like standard GWHP systems using natural groundwater temperature instead of actively storing energy. However, it is important to note that some of the monitored injection and abstraction temperatures are likely influenced by anthropogenic activity especially in urban environments (Section 3.1). The monitoring of ATES should therefore also include the measurement of temperature profiles of the ambient groundwater temperature. Even though hourly peak-time values can go up to 20 K, the average ΔT_{Out} for heating and cooling was measured as 5.2 (± 1.8) and 5.4 (± 1.8) K, respectively. In comparison, Willemsen [383] reported of lower ΔT values of 4.6 K (heating) and 4.0 K (cooling), although it is not clearly defined whether he is referring to ΔT_{Out} or ΔT_{Tot} values. Additionally, several studies reported of higher (heating) or lower (cooling) abstraction temperatures in theoretical simulations [163, 191, 195]. However, these temperature levels are only rarely observed. In practice, the average temperature differences

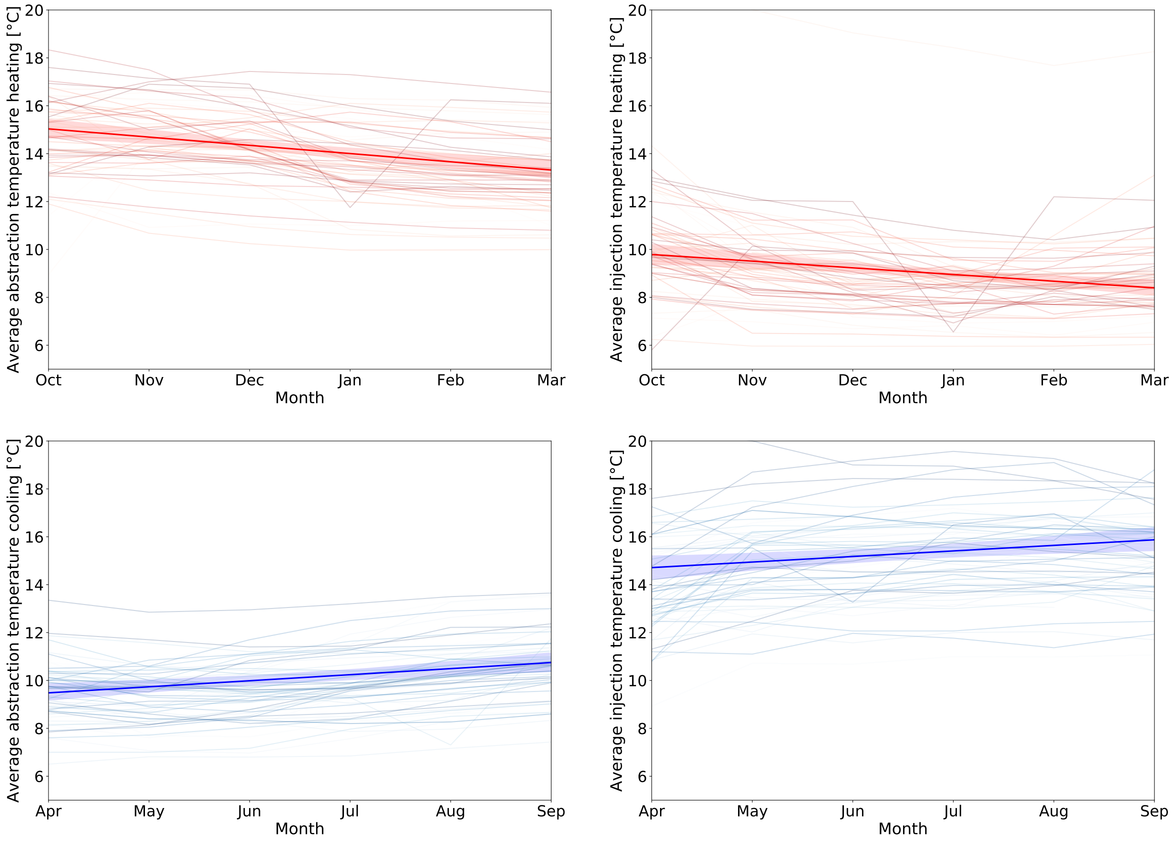

Figure 3.7: Average monthly abstraction (left) and injection (right) temperatures for heating (red) and cooling season (blue). The bold line represents the average temperature of all analyzed systems.

measured before and after the heat exchanger are on average 3 K less than initially designed. Considering the fact that early ATES systems in the Netherlands only achieved a ΔT_{Out} between 1 and 2 K, there is a continuous improvement of operational efficiencies. Nevertheless, authorities still argue to further optimize injection and abstraction temperatures. Since lower ΔT_{Out} are compensated by higher pumping rates, an optimization here would not only result in a reduced electricity demand for pumping, but also in lower specific storage volumes (kWh/m^3) and hence, a more sustainable utilization of the subsurface.

3.3.4 Effect of thermal imbalance on ΔT

As described in Section 3.2.1, the performance of an ATES system can be analyzed based on the recovery ratio (η_R), which is a measurement of the amount of injected heat or cold recovered during the storage period. Fig. 3.8 shows the relation between η_R, ΔT_{Rec} and ΔT_{Out}. ΔT_{Rec} defines the temperature drop during the storage period and slightly increases about 1 K with increasing η_R. This can be explained as groundwater of the thermal unaffected zone

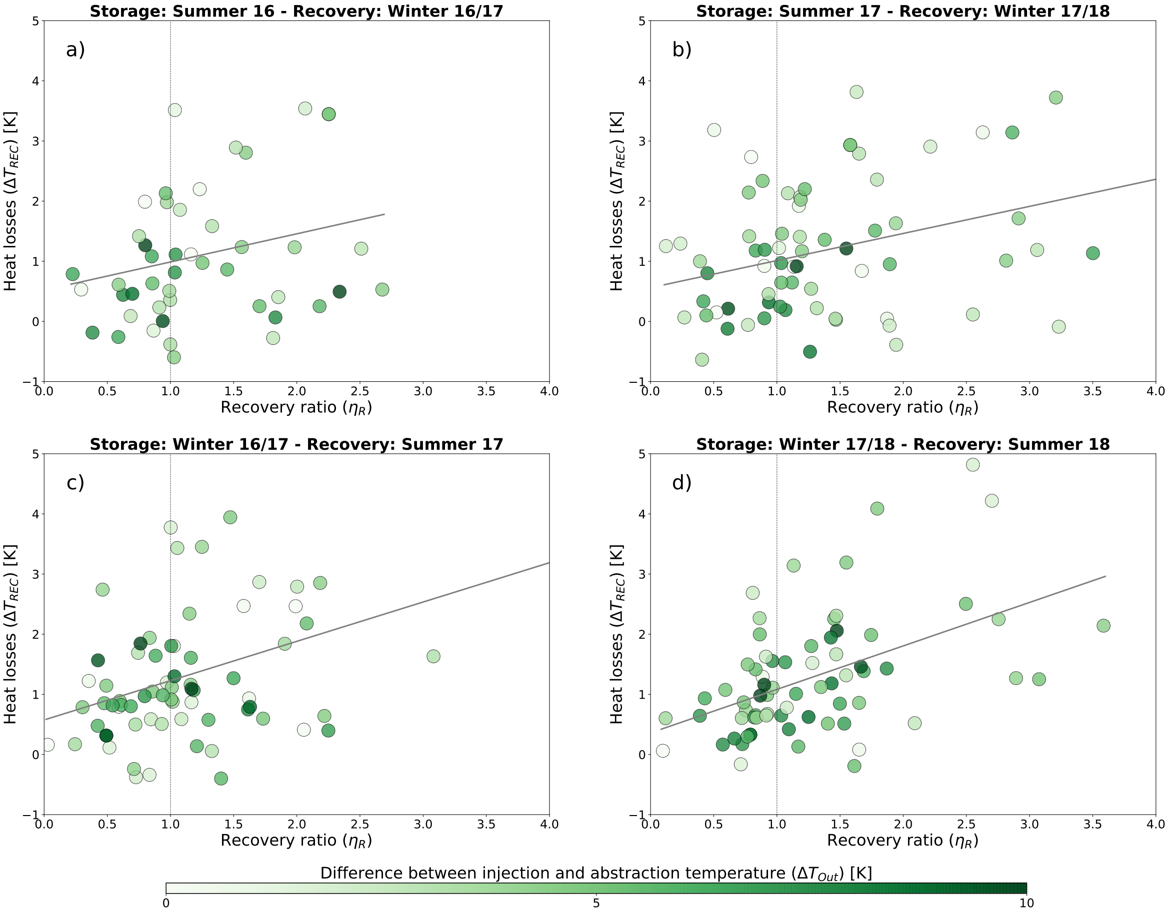

Figure 3.8: Relationship between the ratio of stored and abstracted thermal energy (η_R) and the measured temperature losses during the storage periods (ΔT_{Rec}) for four different storage-recovery cycles (a-d). The difference between injection and abstraction temperature (ΔT_{Out}) is expressed by the color range.

(natural groundwater temperature) is pumped at the end of the storage period in case of high η_R values. However, low R^2 values of around 0.1 indicate that ΔT_{Rec} is not only affected by η_R but also by low storage efficiencies (η_E) attributed to convection, conduction or thermal interference. The storage efficiency was not assessed in this study due to missing monitoring data on the ambient groundwater temperature (Section 3.1). The average ΔT_{Rec} of all analyzed system was measured as 1.3 K (± 1.2). Apart from several outliers, there is only a small range in the measured temperature losses. This can be explained by constant subsurface conditions in the Netherlands with a low groundwater flow and high permeability. At the same time, Fig. 3.8 shows no correlation between η_R and ΔT_{Out}. ΔT_{Out} gives information on the efficiency of which the aquifer is charged with the heating and cooling system. Even though there are some ATES achieving ΔT_{Out} of more than 8 K, the average value for heating and cooling is approximately 5 K (Section 3.3.3). Thus, in order to optimize ATES efficiency in the Netherlands, it is not only important to enhance subsurface storage efficiency, but to ensure a smooth integration of the ATES into the energy system.

3.3.5 Comparison of licensed (design) and measured parameters

The Dutch legal regulations require a licensing procedure, where the dimensions of the planned ATES have to be defined based on specific design values. These indications are crucial to guarantee that neither the subsurface nor other subsurface users are negatively affected. The owner of the license is responsible to meet the requirements of the permit. Fig. 3.9 compares the design and licensed values with the monitoring data analyzed in this study. Even though most system are within the issued permits, there is a strong deviation from the permitted values. Considering the abstracted thermal energy, the analyzed systems achieve on average only half of the licensed capacities. Fig. 3.9 indicates that large systems are more inclined to meet the licensed values than smaller systems, which is especially the case for the abstracted thermal energy (left graph) and the ΔT_{Out} values (right graph). Considering climatic fluctuations, changes in demand patterns or structural extensions, the exact required thermal energy can be only estimated using sophisticated building energy models. This, however, is only hardly observed in practice. While the lower ΔT_{Out} values are mainly a matter of technical issues and defined by the building system, the discrepancies between measured and permitted groundwater and energy volume are therefore more a matter of safeguarding against demand fluctuations [376]. The result is an insufficient exploitation of the subsurface, particularly in urban areas. To guarantee a sustainable utilization of the subsurface, both owners and authorities should strive to minimize unused subsurface space. In some Dutch provinces, the authorities began to negotiate with permit holders to reduce the licensed capacity in case it is not fully used.

3.4 Optimization strategies

3.4.1 Optimization of operational performance

The key challenge for the planning, installation, and operation of LT-ATES is to ensure both a cost-effective and sustainable exploitation of the subsurface [358]. The Seasonal Performance Factor (SPF) of a shallow geothermal system is influenced by several factors, summarized, categorized, and illustrated in Fig 3.10. As discussed in Section 1 (Fig. 3.1), research

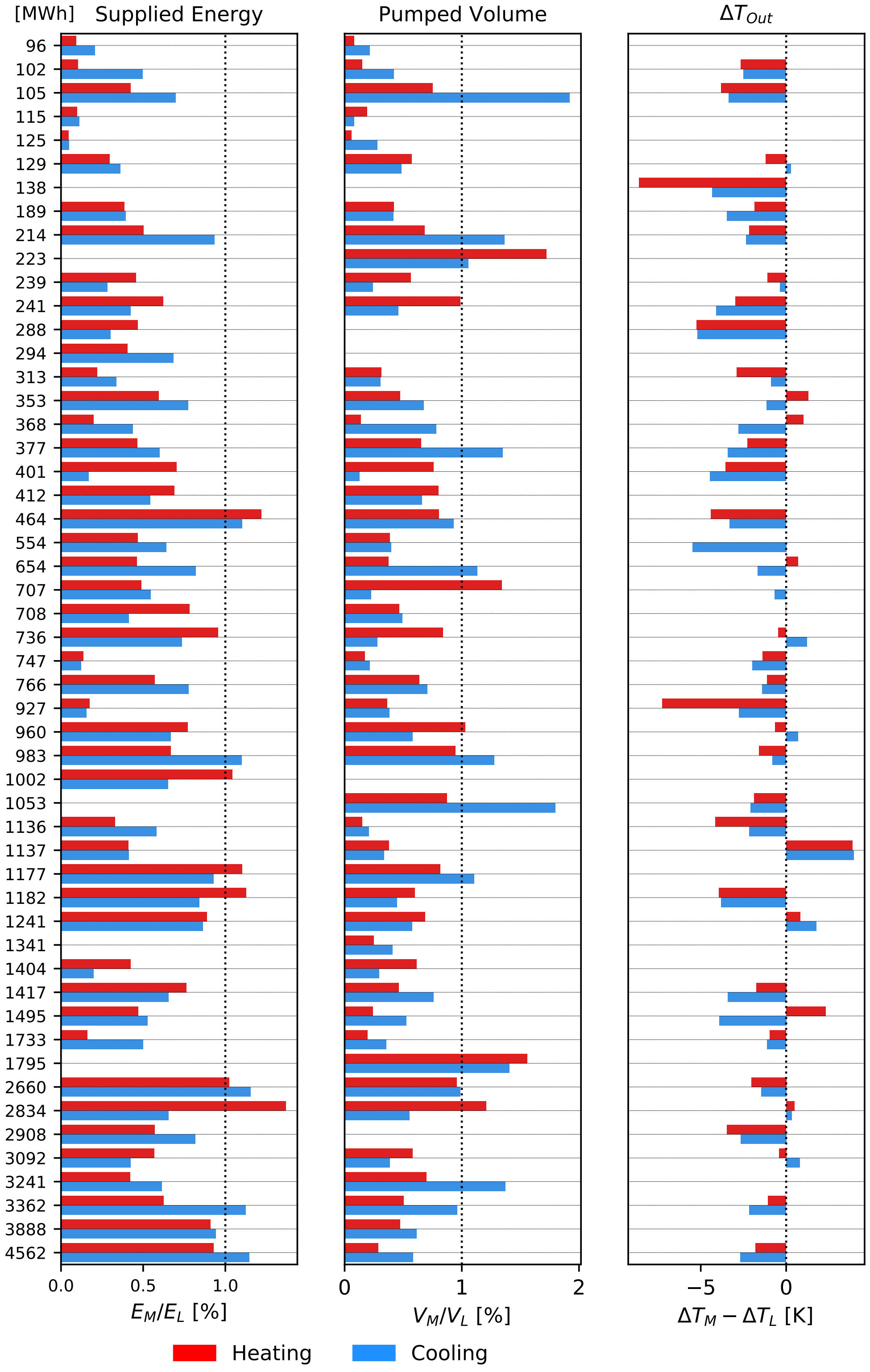

Figure 3.9: Comparison of licensed (L) and monitored (M) values for supplied energy (E), pumped groundwater volume (V), and the difference between abstraction and injection temperature (ΔT_{Out}). The dotted vertical line represents the value, where the monitored ATES meets the licensed capacity or temperature. The ATES are sorted ascending by the system capacity.

in the field of LT-ATES mainly focused on the storage efficiency of the ATES, influenced by (hydro)geological, technical or social boundary conditions. However, the monitoring data revealed a good storage performance indicated by low temperature losses in the storage period (ΔT_{Rec}). Even though strongly imbalanced systems should be impeded, the temperature losses are on average below 1.5 K. At the same time, low ΔT_{Out} values indicate an insufficient charging of the aquifer by the heating and cooling system. Many ATES systems only reach ΔT_{Out} values below 4 K, resulting in inadequate abstraction temperatures close to the natural groundwater temperature. On the other hand, ΔT_{Out} values higher than 8 K demonstrate that an efficient interaction between ATES and building (Fig. 3.10) is technically feasible. Even though a proper building integration seems to have the highest impact on the entire system performance [192, 200, 201, 394], this issue is only rarely addressed in the literature (Fig. 3.1). According to van Wijck [394], 70% of all Dutch buildings supplied with heat and cold by ATES run inefficiently. Fig. 3.9 indicates an increase of ΔT_{Out} with increasing system size. For large buildings, it is common to invest in an energy management taking care of a comprehensive monitoring and maintenance. Owners of small buildings, however, often do not invest in optimization strategies and only take care of a smooth operation. In order to guarantee a sustainable and economic operation of ATES technology, both scientific-based planning as well as a continuous monitoring of the operational performance is crucial. In the planning phase, the ATES system has to be designed based on the building requirements

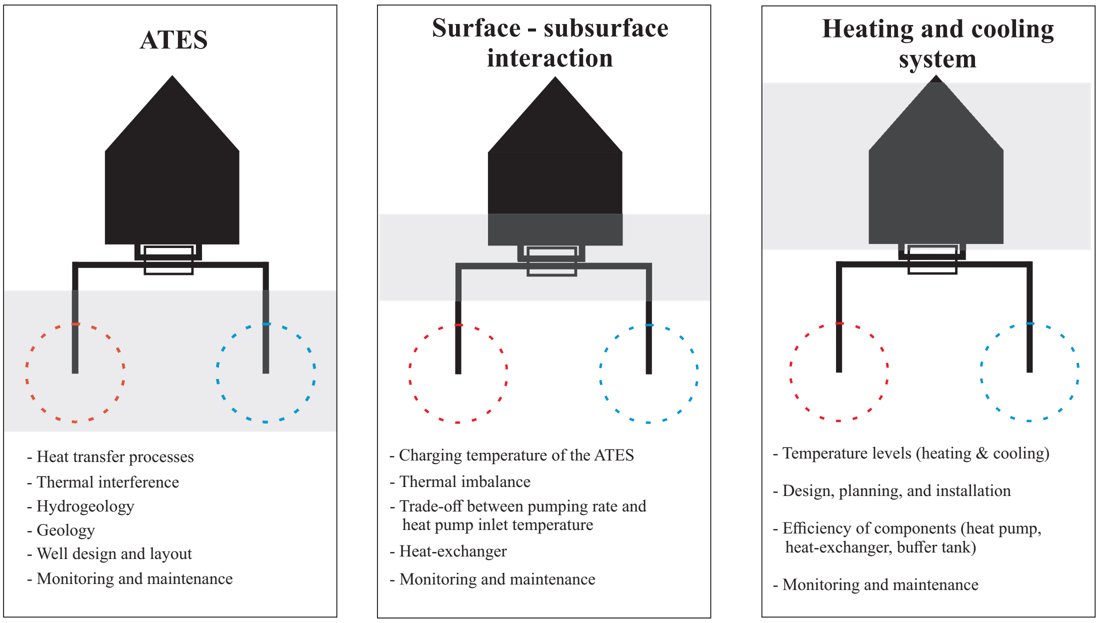

Figure 3.10: Components influencing the SPF of the overall heating and cooling system.

focusing on the base load supply. However, since sophisticated building energy models such as EnergyPlus, Modelica or TRNSYS are applied only sparsely in practice, the heating and cooling loads are often overestimated to safeguard against demand fluctuations. This results in higher investment costs for the energy system and over-claimed subsurface space in urban areas (Section 3.4.2).

The analysis of the monitoring data in the present study revealed low ΔT_{Out} values, insufficient injection temperatures, and thermal imbalanced systems. This indicates an inefficient integration of the ATES into the HVAC system [192]. To optimize this integration, the design and dimensioning particularly of large buildings, should be based on thermal simulations coupled with building energy models. However, research activity in ATES mainly focused on the optimization of the storage efficiency (Section 3.1). According to Bozkaya et al. [159], only a few studies [191, 192, 195] simulated LT-ATES performance in combination with building loads. Co-simulation approaches, however, are indispensable to harmonize the interaction between ATES and HVAC system by responding to social, technical, climatic, and subsurface conditions. A first step into this direction was done by Bozkaya et al. [373], who coupled TRNSYS with Comsol considering varying building loads. This study clearly demonstrated the benefit of a co-simulation approach by quantifying the impact of an imbalanced thermal injection on the system performance. In addition, to guarantee high energy savings, the performance of the entire energy system should be monitored in the beginning at least twice a year and then annually. The maintenance should not only focus on the groundwater wells but also on the replacement of outdated components of the heating and cooling system. The entire system should be adjusted to changing requirements, demand patterns or infrastructure.

3.4.2 Optimization strategies for common subsurface use

Thinking in terms of a holistic optimization strategy, it is not only important to enhance the techno-economic performance of each individual ATES system, but also to optimize the available subsurface space [216, 351, 376]. Considering the fact that the volume of pumped groundwater is indirectly proportional to ΔT_{Out}, an optimization does not only reduce pumping costs, but also significantly reduces the thermal footprint. Moreover, according to Section 3.3.5, the amount of stored thermal energy is only less than half the amount, which was initially designed. The result is an insufficient exploitation of the subsurface, especially in urban areas [350]. Although, a certain buffer is reasonable to cover building demand fluctuations, these over-estimations have to be reduced. It is also crucial to avoid strong thermal interference between allocated ATES systems. However, Rostampour et al. [380] demonstrated in a case study for the city of Utrecht that a dynamic management of thermal interactions can significantly increase the efficiency of ATES application on an urban scale. Compared to the common practice, a smart information exchange between ATES systems in combination with a denser layout policy for ATES wells resulted in 21% total GHG savings. In order to allow a denser utilization of ATES in urban environments, they recommend to revise spatial planning policies of the subsurface, which is hardly considered worldwide. In addition, for certain building types such as data centers or greenhouses, a balanced energy ratio is not feasible. A smart alternative to external energy sources such as free coolers is to create synergies between allocated subsurface users. This, for example, is currently happening at the Science Park of Amsterdam, where a heating dominated building structure is supplied by an ATES. This imbalance is used to counter a cooling dominated load profile of an adjacent data center and vice versa. This is one of the most efficient ATES system in the Netherlands [394] and demonstrates the great demand for a comprehensive and sustainable subsurface management.

The first step in this direction was achieved by the project “Development of master plans for geothermal energy“ [349]. Options, strategies, and barriers were analyzed to develop a holistic energy concept on urban scale. A promising idea is to establish subsurface zones of only heating or cooling in order to tackle problems addressed in this study such as thermal imbalance or over-sizing. Positive thermal interference between allocated ATES systems could even enhance operational efficiency by reducing the negative effect of groundwater flow. This, however, requires to collect and process data on existing and potentially affected subsurface users. While good progress is made in the Netherlands [215, 307, 349], other countries such as Germany still lack a comprehensive data acquisition and processing strategy. Monitoring data of existing and design values of planned geothermal systems have to be integrated into analytical or ideally numerical groundwater models on the city scale [395, 396]. As most cities lack such models, it is a matter of policy, who is in charge of investing the required man-power and financial means [385]. This issue has to be solved locally or nationally.

3.5 Conclusion

The monitoring data of 73 Dutch ATES provided significant insights into the operational performance of LT-ATES in the Netherlands. Low ΔT_{Out} values as well as strong discrepancies between the design/licensed and the monitored values indicated that the operation of ATES systems still can be optimized. Both HVAC planners and authorities should therefore carefully consider and optimize the interaction between building and subsurface (Section 3.4.1) as well as a more efficient and sustainable use of the available subsurface space (Section 3.4.2). While this study only focused on the injected and abstracted thermal energy, groundwater volume and temperature, future studies should strive to extend the proposed monitoring analysis by considering the following recommendations:

- Extension of the dataset by a longer monitoring period of at least five years and a higher number of monitored systems;
- Including the ambient groundwater temperature at each ATES site in order to estimate the storage efficiency and to estimate the influence of different subsurface users on ATES activity;
- Spatial analysis evaluating the impact of geological, hydrogeological, technical and geographical factors on the operational performance;
- Linking the subsurface and HVAC monitoring in order to quantify the impact of the ATES efficiency on the SPF of the heating and cooling system.

Some of the monitored ATES systems in this study showed abstraction temperatures close to the natural groundwater temperature (Section 3.3.3). From an energetic point of view, these ATES are operating similarly to standard GWHP systems. However, in the case of a well performing heating and cooling system, ATES technology bares several advantages compared to the direct use of groundwater. This is in particular the case for the summer season, where constant lower abstraction temperatures can significantly increase the efficiency of the cooling system [373]. While about 90% of all LT-ATES systems are operated in the Netherlands, the share of LT-ATES on the global number of open shallow geothermal systems is still fairly low [211]. Thus, in order to promote ATES technology worldwide, it is crucial to analyze also the economic and technical advantage of LT-ATES compared to GWHP systems. In this context, it would also be interesting to address the influence of subsurface urban heat islands (SUHI) on the techno-economic performance of both ATES and GWHP systems, which could be demonstrated by Rivera et al. [397] for vertical ground source heat pump (GSHP) systems. According to Bayer et al. [385], the potential of SUHI was only analyzed in terms of determining the potential of covering the heating and cooling demand on an urban scale. However, it would also be important to address the impact of SUHI on the energetic performance of individual ATES or GWHP systems.

Acknowledgments

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Chapter 4

Risk assessment 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), offers 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 of enhancing 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 crucial 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.

4.1 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% [2]. Considering that around 50% of the global energy consumption is attributed to the thermal energy sector [20], 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 [8]. However, artificial storage tanks are highly space-intensive and hence, hardly suitable to store significant amounts of energy in an urban environment. By 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 [366]. 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 [36]. 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 [366]. 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 [2, 20]. Consequently, HT-ATES is moving back into the scientific focus and several projects were recently initiated, particularly in Central Europe (Section 1).

In order to establish HT-ATES as a key technology in the energy transition, future demonstration plants should strive to proof technical reliability to build up trust among investors, politicians and the population. However, compared to other renewable technologies, the storage of heat in the subsurface is associated with multidisciplinary and complex risks. Thus, a comprehensive risk management should be an integral part of any project to develop site-specific risk mitigation strategies. Despite its importance, risk management in HT-ATES has not been addressed by past research activities, yet. Risk related research was focusing on direct geothermal utilization, addressing only specific risks such as induced seismicity [398–401], exploration risks [402, 403] or well integrity [404–406]. This was also stated by Lohne et al. [407], who reviewed 54 studies in the course of the project "EU Horizon 2020 GeoWell". They concluded that most studies focus on geological and financial risks, whereas environmental, social or legal risks as well as risk-management strategies are hardly ever considered. Even though risk assessment is often applied in practice [408], current literature still lacks research focusing on holistic risk assessment approaches. So far, no attempt was made to identify and assess all potential risks of geothermal and in particular HT-ATES projects.

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

4.2 Methods

4.2.1 High Temperature Aquifer Thermal Energy Storage

The basic principle of ATES was described by numerous studies [29, 208, 384] and is illustrated in Fig, 4.1. ATES systems consist of at least one groundwater well-doublet. In summer, groundwater is abstracted from the "cold" well, charged with surplus heat from renewable or non-renewable sources and injected into the “warm“ well. The pump direction is reversed in winter to recover the injected heat from the warm well. Over time, various concepts and designs have developed. These concepts are differentiated based on several characteristics, such as the storage depth, the storage temperature, the system design (mono- or multi-well) or the energy source and consumer [366]. Since this study is focusing on HT-ATES, we consider only ATES with a storage temperature above a certain temperature threshold. However, different threshold values between LT and HT ATES are defined in the literature. Drijver [338], Drijver et al. [207] and Kallesøe and Vangkilde-Pedersen [409] distinguish between LT (< 30 °C), mid-temperature (MT) (30-60 °C) and HT (> 60 °C) ATES. In contrast, other authors define HT-ATES with a storage temperature above 50 °C [12–14, 83, 193]. This discrepancy can be explained as follows: from a legal point of view, the temperature levels are stipulated by the maximum allowed injection (T_{Max}) temperature, which is defined by national or regional legal guidelines. For most European countries, T_{Max} varies between 18 and 25 °C [15, 16]. Additionally, higher storage temperatures do not only trigger geochemical reactions and affect groundwater characteristics (density, viscosity), but also highly affect the choice of materials or components. For instance, water treatment to prevent scaling, clogging or corrosion is usually not required at temperatures below 50 °C

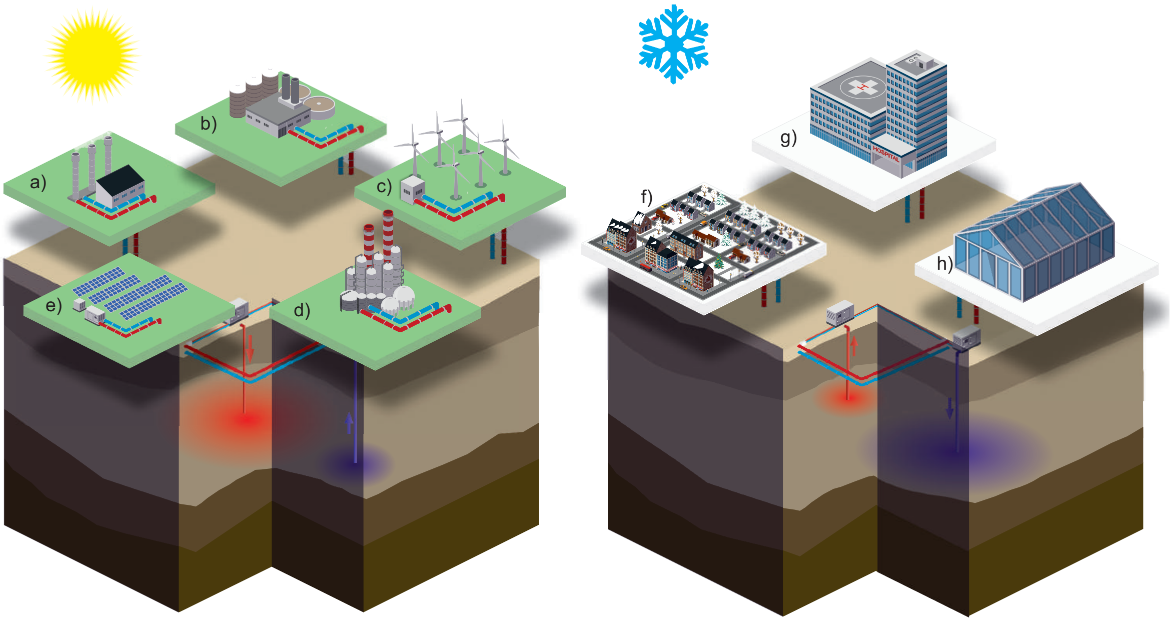

Figure 4.1: Basic principle of HT-ATES. In summer, the aquifer is charged with surplus heat from (non-) renewable energy sources such as geothermal (a), biomass (b), power-to-heat (c), industrial heat waste (d) or solar (e). The stored heat is recovered in winter to feed district heating (DH) systems (f), large building complexes (g) or industrial applications such as greenhouses (h).

[409]. The same threshold applies to the changes in density, triggering buoyancy flow at >50 °C. Finally, the threshold can also be established considering the requirements of the demand. However, the required temperature of the heating system strongly depends on the DH grid, the energy standards of buildings as well as the requirement of the heat pump. In this study, the definition established in Annex 12 of the Energy Conservation through Energy Storage (ECES) of the IEA is followed, where the minimum storage loading temperature is set to 50 °C.

4.2.2 Definition of risk management

Risk is defined by ISO-31000-2018 as an effect of uncertainty on objectives and is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence [410]. The central pillar of the risk management process is the risk assessment comprising of risk identification, analysis and evaluation (Fig. 4.2). Risk identification includes finding, recognizing and describing potential risks ensuring that all risks and lessons learned from past projects are considered in the risk management process [411]. All sources of risk associated with the project objectives should be identified and organized according to a Risk Breakdown Structure (RBS). Based on the risk identification, risk analysis strives to develop an understanding of the risk and serves a basis for the risk evaluation.

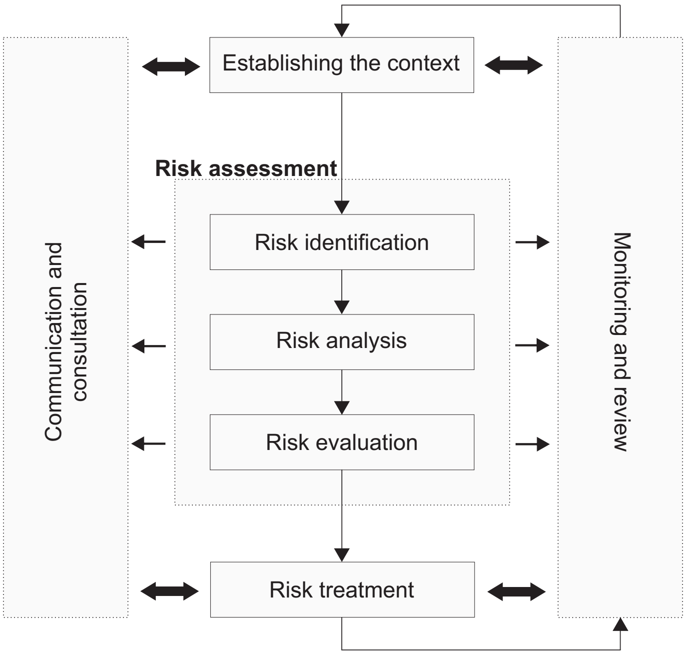

Figure 4.2: ISO standard risk management process (modified after [410]).

Risk is analyzed by determining effects and their occurrence probability and other attributes of the risk [410]. However, the extent and level of detail of the analysis is dependent on the scope as well as on the amount of available information, data and resources [410]. Risk analysis can be qualitative or quantitative. Qualitative analyses are descriptive and based on expertise or assumptions of single risk issues. In contrast, quantitative methods are based on numerical data and present a global picture of the risk exposure for the project. In practice, detailed, quantitative risk analyses are often limited to those risks that are expected to have a high input on the project success. According to ISO 31000 [410], risk evaluation compares the level of risks resulting from the risk analysis. Risk evaluation facilitates the following risk treatment process by an evaluation, categorization and prioritization of all analyzed risks. Based on this comparison, the requirement for treatment can be considered.

4.2.3 Workflow

The workflow of this study is illustrated in Fig. 4.3 and is subdivided into four steps:

- **Step 1. Review:** Brief description of technological development reviewing past, present and future research and commercial projects;
- **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 [412] 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 4.2.4). 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

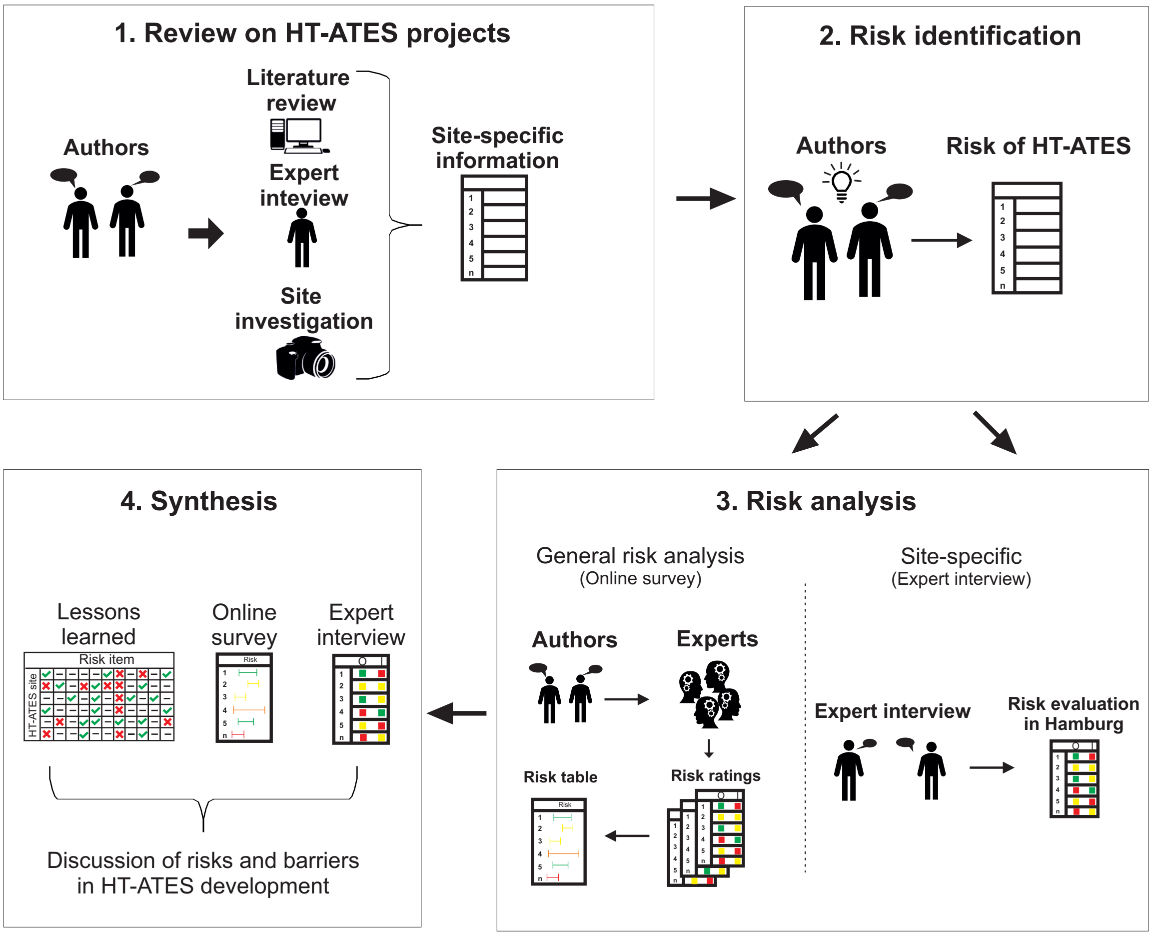

Figure 4.3: Workflow of the present study.

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.

4.2.4 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 [413]. 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 4.5) [414, 415].

Table 4.5: Five point Likert scale for the evaluation of the occurrence probability (O_P), severity (S_V) and uncertainty (U_C) [414, 415].

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

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 (1,000 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 boundary conditions on risks in HT-ATES.

4.3 HT-ATES activities

There is a 50-year history of R&D activities in HT-ATES. A detailed description on early activities was summarized in Fleuchaus et al. [366]. Fig. 4.4 illustrates past, current and future projects. Technical and geological details are complemented in Table 4.6. Currently, there is only one HT-ATES (Rostock) in operation worldwide. Any other HT-ATES plant had to be abandoned due to different reasons. More information on the operational experiences, reasons for abandonment and lessons learned can be found in Chapter 4.4.3. The following section focuses on the ongoing HT-ATES activities and provides information on each project site.

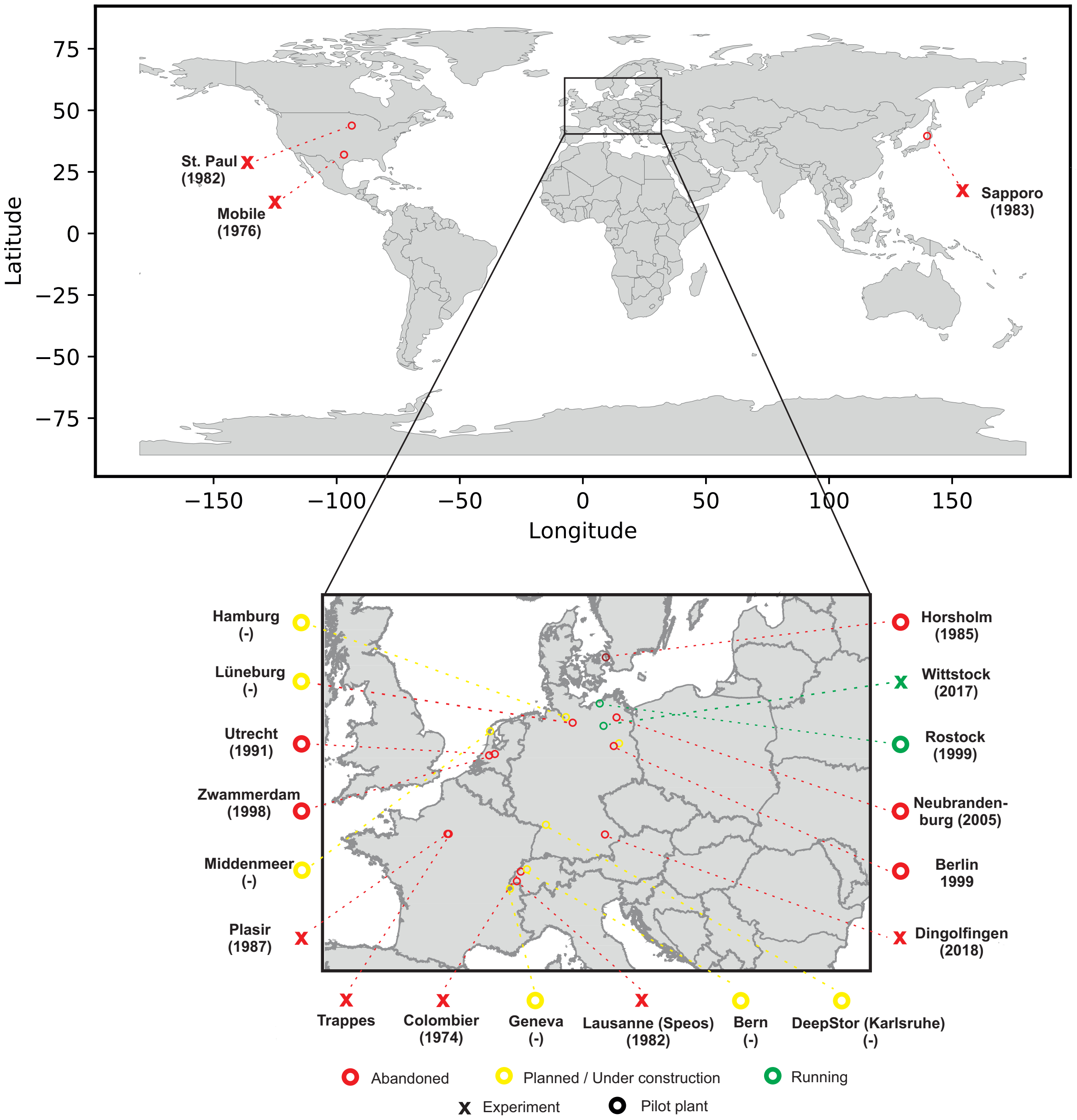

Figure 4.4: Spatial distribution of abandoned, planned and running HT-ATES projects worldwide.

Table 4.6: 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	1,250	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	500-1,000	Limestone
20	Bern, CH	-	A	Power plant	120	500	Molasse
21	DeepStor, DE	-	A	Geothermal	110	1,000	Tertiary

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

TestUM (test-site Wittstock) (DE)

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 guidelines for groundwater protection.

Beyond Batteries Lab (US)

Two collaborative projects led by the Idaho National Laboratory (INL) received funding by the Department of Energy (DOE) to develop concepts to moderate electrical grid's peaks and valleys by storing thermal energy in aquifers. The two projects are part of the Grid Modernization Initiative (GMI) of the DOE, which explores approaches to utilize geothermal energy in order to improve grid reliability, resilience and security. One project strives to develop models to store surplus heat (steam) of thermoelectric power plants in the subsurface [416]. A second project investigates the storage of concentrated solar heat in the subsurface. The recovered HT solar heat could then be used to enhance the load-following characteristics of a geothermal power plant. Both projects address not only technical feasibility of subsurface heat storage, but also the power plant designs as well as the economic efficiency.

Lüneburg (DE)

The Bockelsberg District in Lüneburg is supplied with heat from bio-methane-fired CHP-units. The planned HT-ATES storage is used to minimize heat from natural-gas fired peak-load vessels to achieve about 95% CHP heat. The heating systems of the University Campus as part of the Bockelsberg district and the heat supply of the new central building are designed to make use of low energy heat, thus annual heat recovery factors of >75% are achieved, although, only a potential of 3-3.5 GWh/a of a theoretical potential of the aquifer storage of >10 GWh/a is used. The ATES is part of a climate neutrality concept of the Leuphana University [292]. Despite intensive research and pre-investigations emphasizing the technical and economical feasibility of the planned system, the support for actual implementation is currently low due to unclear risk perception by decision makers involved and several local political and economic circumstances. However, the ATES is still regarded as a promising option for future development of the bio-methane-CHP based energy system in the city of Lüneburg.

Hamburg (DE)

In 2013, the citizens of Hamburg decided in a referendum to re-communalize the energy supply of the city. The re-acquisition of the DH network from the energy company "Vattenfall Wärme GmbH" was completed in 2019 [417]. At the same time, the city of Hamburg decided to replace two coal-fired plants (67% of supplied heat) until 2030 by less CO_2-intensive heat sources such as industrial waste heat, power-to-heat or wastewater-heat-recovery. To increase the flexibility of the new heating system, it is also planned to integrate both short- and long-term heat storages. HT-ATES is considered as key technology and different storage concepts, heat sources and storage horizons are currently under investigation. Potential target formations are the “Upper Braunkohlesande“ (UBKS) at a depth of 200-300 m and a 1,000 m deep Sandstone formation [418]. Due to its high salt content, the UBKS is not utilizable for drinking water supply and is separated by a confining layer from the upper groundwater body. In 2017, a test well was drilled on the Elbe island Dradenau to perform a storage test cycle. With a recovery rate of around 90%, technical feasibility of heat storage in the UBKS was successfully demonstrated [418]. Different storage locations and an efficient integration into the heating network are currently under investigation [419]. A second storage formation (sandstone) is considered in a depth of around 1,000 m [420]. Again, different heat sources and sinks as well as storage locations are currently under evaluation. In this context, the project IW^3 received funding from the program “living lab“ of the Federal Ministry of Economic Affairs and Energy (BMWI). The project builds up on the pre-investigations of the company “GTW Geothermie Wilhelmsburg GmbH“, which strives to realize a deep geothermal system in a depth of 3,000-4,000 m. IW^3 aims at establishing a decentralized, fossil-free heat supply for the district Wilhelmsburg. In this concept, a HT-ATES is planned to enhance the efficiency of different heat sources such as geothermal energy or industrial waste heat [421].

DeepStor (Karlsruhe) (DE)

The new KIT project DeepStor strives to store excess heat of a planned geothermal power plant at temperatures of about 110 °C. With temperatures up to 170 °C in a depth of 3 km, the largest known thermal anomaly in Germany is located at the KIT Campus North Kohl [422]. By utilizing the existing campus infrastructure (heating network), the KIT Campus North offers promising preconditions for the extraction, seasonal storage and distribution of geothermal energy Kohl et al. [423]. The extracted heat from deep geothermal energy is considered to supply the base load and the excess heat for seasonal storage. The high temperature storage is planned in a storage depth of around 1 km (tertiary basin) in earlier oil reservoirs.

HeatStore

HeatStore is one of nine projects under the GEOTHERMICA - ERA NET Cofund aiming to facilitate the integration of underground thermal energy storage (UTES) in the heating and cooling sector. Different types of UTES are investigated and tested at six demonstration sites in several European countries. Among these pilot projects, three HT-ATES test sites are planned in Middenmeer (NL), Geneva (CH) and Bern (CH) [409, 424]. The aim and characteristics of each HT-ATES site is described below:

Middenmeer (NL)

In the Dutch town Middenmeer, six geothermal wells with a depth of 2,000 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 [425]. 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 [409].

Geneva (CH)

The Geneva HT-ATES site is linked to the “Geothermie 2020“ strategy of the Canton of Geneva and aims at assessing the feasibility of seasonal storage of 35 GWh/a surplus heat from the Cheneviers waste incinerator [426, 427]. Several target aquifers exist at different depths and are currently being explored and characterized by two exploration wells (GEo-01 and GEo-02) in the Lower Cretaceous and the Upper Jurassic (Malm) carbonate units. As the target aquifers are characterized by an unknown geology, current activity is focusing on the identification of the optimal and reliable storage formation. These challenges are tackled by establishing a workflow that includes a flexible reservoir modeling approach combining static reservoir models, thermo-hydraulic (TH), thermo-hydraulic-chemical (THC) and thermo-hydraulic-mechanical (THM) models [428]. In the framework of the HeatStore project funded by the EU GEOTHERMICA funding program, the outcomes of such approach will be combined to energy systems scenarios. These scenarios will be transposed to detailed risk assessment and business models in order to assess the technical, environmental and financial feasibility and support local authorities for improvement of the legal framework.

Bern (CH)

The “Forsthaus Heat Storage“ project is planned by Geo-Energie Suisse AG (GES) on behalf of the local utility company Energie Wasser Bern (ewb). It is supported by the Swiss Federal

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

4.4 Risk assessment

4.4.1 Risk identification

Renewable energy projects are considered as successful as they meet time, budget and performance goals. However, the success of the project might be jeopardized by different sources of risk. Table 4.7 shows the outcome of the risk identification process described in Section 4.2.3. While all identified risks can negatively affect the merit of the project, some might also cause a time delay or harm the environment. In addition, some risks have to be considered throughout the entire project, others just during the phase of planning, construction or operation. In order to facilitate the risk analysis by the online survey, some minor sources of risks were aggregated into more general risks. The risk item "well integrity", for instance, could be further subdivided into "material degradation", "collapse/buckling of casing" or "breakdown". Additionally, it is important to consider that there is mutual interaction between individual risk items. The risk of "public perception" could be, for instance, highly influenced by the occurrence of the risk induced "seismicity". Table 4.7 serves as the basis for the risk analysis in Section 4.4.2.

4.4.2 Risk analysis

Generic risk analysis (online survey)

50% of 78 invited experts participated in the online survey, of which 45% were from industry, 37% were from science and 18% came from authorities or energy agencies. The respondents originate from: Germany (23), Netherlands (8), Denmark (2), Sweden (2), United

Table 4.7: 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. [412]).

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

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

States (2), Norway (1) and Iceland (1). The outcome of the survey, grouped by the severity, occurrence probability and the uncertainty is illustrated in Fig. 4.7 in the Appendix. The severity and occurrence probability together determine the risk level. The respondents judgment are provided in Fig. 4.5, in which the uncertainty is expressed by colors from green to red. The median of all risk items ranges between 5 ("Induced seismicity") and 15.5 ("Com-

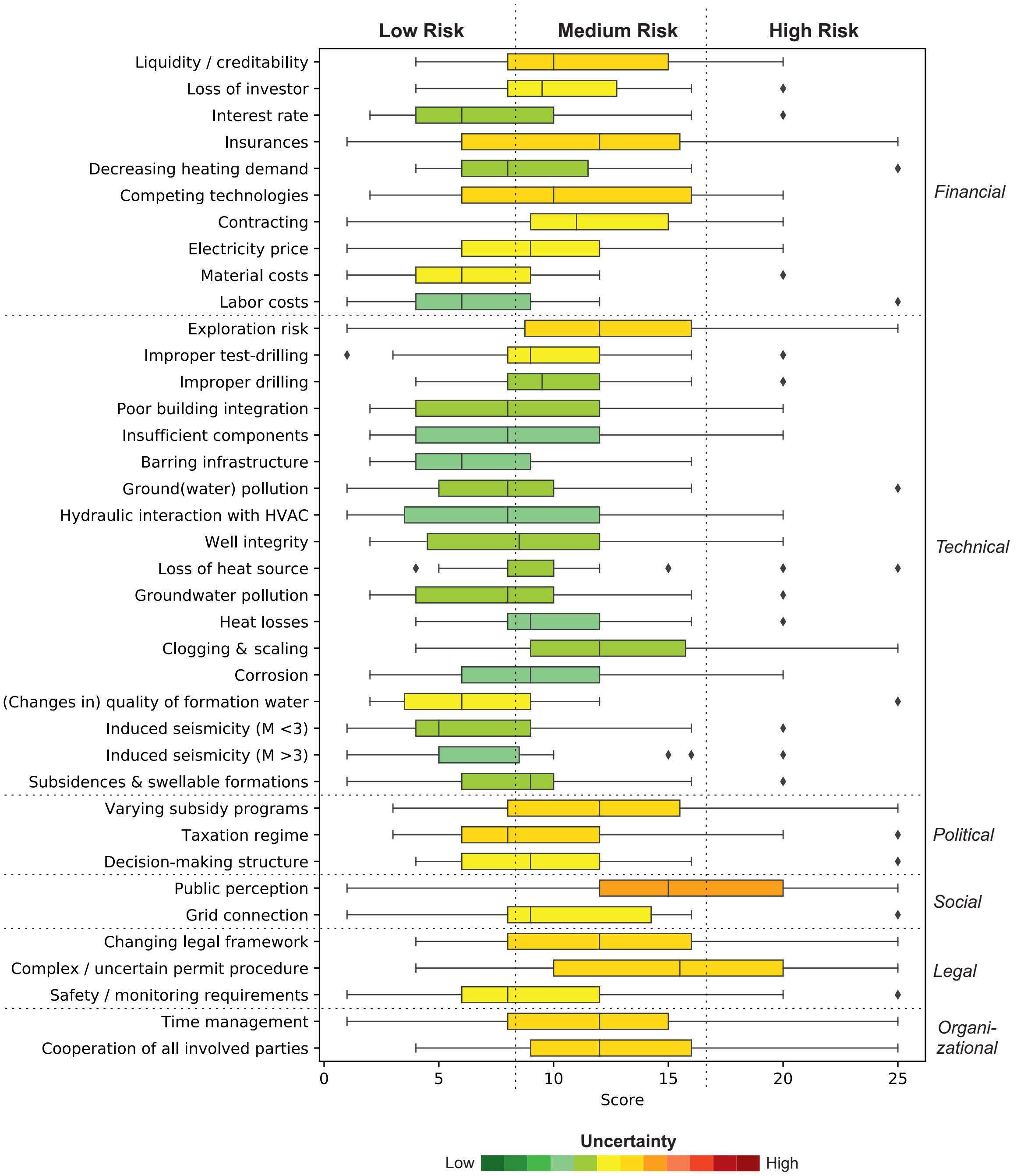

Figure 4.5: Expert risk ratings calculated by the product of the occurrence probability and severity. The uncertainty is illustrated by colors from green to red.

plex/uncertain permit procedure“). Thus, all risk items can be classified as low or medium risks. Apart from the risk items “Exploration risk“ and “Clogging & scaling“, technical risks are expected to be less critical than political, social, legal and organizational risks. This is remarkable as past studies in the field of HT-ATES mainly concentrated on technical risks with a special focus on heat transfer processes and optimization of storage efficiency [359, 366]. However, this ongoing research seems to be bearing fruit as the risk of “Heat losses“ received a comparable low risk rating and is estimated to be well predictable in the planning phase. Low risk values were also given to “Interest rate“ (6), “Material/Labor costs“ (6), “Changes in quality of formation water“ (6) and “Induced seismicity“ (5). In contrast, the experts see the risks of a “Complex legal procedure“ (15.5) and “Public perception“ (15) as most critical. Considering the standard deviations, experts were unanimous for the risk items “Loss of heat source“, “Heat losses“ and “Induced seismicity“. Low agreements were observed for the risks “Insurances“, “Exploration risk“ and “Public perception“. Different opinions could be explained by different background expertise, but also by the fact that the risk level of certain risk items is more influenced by local boundary conditions and therefore, difficult to estimate in general. The latter is addressed by a complementary risk analysis for the city of Hamburg in the following section, where the outcome of the online survey is opposed to the estimated risks for three planned HT-ATES projects. Finally, in Section 4.4.3, the expert opinions are evaluated considering problems encountered at and lessons learned from already realized HT-ATES sites.

Site-specific risk analysis

The site-specific risk analysis for the HT-ATES projects in Hamburg is following a low-medium-high risk scale and is based on an expert interview with the project coordinator Kai-Justin Radmann [418]. A distinction is made between the risk estimation for a shallow (200-300 m) and a deep (1,000 m) target formation (Section 4.3). 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 4.8.

As described in Section 4.3, an injection-recovery-test was completed and technical feasibility of heat storage was successfully demonstrated in the the shallow sandstone formation called UBKS. No technical problems were encountered and more than 90% of the injected heat was recovered. Hence, most technical risks such as “Exploration risk“ or “Heat losses“ can be expected as low. Nevertheless, suitable water-treatment measures will be important to prevent scaling and clogging considering the high storage temperatures and complex chemistry of the salty aquifer. According to Radmann and Hansen [418], the most crucial risks for the shallow HT-ATES are, however, of financial and legal nature. Financial issues are mainly attributed to the temperature level (inlet and outlet) of the DH grid. Extra costs are expected to match the recovery temperatures of the ATES (∼70 °C) with the inlet temperature of the DH (∼90 °C). In addition, it is important to lower the injection temperature of the cold well to allow a high storage capacity and to prevent thermal interferences. Pre-investigations indicate that a cascade of four heat pumps would be required to reach injection temperatures below 40 °C. This results in higher capital costs and increases the risk of increasing electricity and maintenance costs. From a legal point of view, high risks are associated with the plan of the city of Hamburg to reserve the salty aquifers of the UBKS as a backup reservoir for drinking water supply. Complex permit requirements both for installation and monitoring are therefore, rather likely. In contrast, the second target formation is characterized by a higher storage temperature (90 °C) and a deeper storage depth (∼1,000 m). Similar to the more shallow HT-ATES concepts, the risks of “Competing technologies“, “Clogging & Scaling“ and a complex “Decision-making structure“ are expected as high. Since less experiences were gained with the target sandstone formation, the exploration risk is also expected to be high, particularly when considering a lack of insurance for HT-ATES in Germany. In contrast to the shallower projects, legislative risks are low. This is also the case for the electricity costs, as the abstraction and injection temperature meet the temperature level of the DH network.

The site-specific analysis for Hamburg indicates that some risks highly depend on the local boundary conditions and are challenging to estimate in general. In Hamburg, this is particularly the case for the legal and exploration risks, which explains the strong disagreements among the experts in the previous section. While the site specific risk analysis mainly reflects the outcome of the online survey, this is not the case for the risk of “Competing technologies“ and “Public perception“. Due to insufficient charging and discharging temperatures of the shallow HT-ATES and a high inflexibility, there is a high risk of it being replaced by a different technology. In addition, the risk of “Public perception“ is expected as low for the Hamburg projects, even though it received the second highest risk rating by the experts. This can be explained by a strong support by the population, which decided in a referendum to replace the existing coal-fired heating supply by less CO_2 intensive technologies (Section 4.3).

4.4.3 Evaluation of risk analysis

The following section links the outcome of Section 4.4.2 (online survey) and Section 4.4.2 (expert interviews) with the lessons learned from the past. It is evaluated, if the outcome of the online survey and the expected risks for HT-ATES projects in Hamburg coincide with the problems encountered at past HT-ATES sites, which are illustrated in Table 4.8. Please consider that some of the identified risks were not particularly relevant for early (experimental) sites, which were not implemented in a real-case scenario. Hence, HT-ATES projects in the 1970 and 1980s were mainly facing technical problems, mostly related to carbonate clogging, corrosion or particle clogging (Table 4.8). However, new water treatment methods were developed and new storage concepts designed. At the beginning of the 1990s, HT-ATES achieved a new stage in the commercialization process as two HT-ATES sites were running for several years in the Netherlands. Building on the research efforts from the 1970s and 1980s, less geochemical problems were encountered. Even though significant well-clogging was still observed at Utrecht University, most critical was a low recovery of the stored waste heat from a co-generation plant. The major cause for the low recovery efficiency was not the malfunctioning of the system, but a mismatch with the heating needs of the connected buildings. Technical problems due to a failure of the pressure valve and poor knowledge of the system finally lead to a permanent shut down of the system [218]. In Zwammerdam, no significant geochemical problems were found and the energy storage worked as expected beforehand [338]. However, the return temperature of the DH grid was higher than expected, causing only a little unloading of the store [218]. Finally, the HT-ATES was closed down due to financial reasons: the energy savings by the ATES could not compensate for the extra costs for electricity production by the CHP. Thus, the electricity production of the unit was decreased, leading to too little heat excesses to make the HT-ATES economically feasible [429]. Hence, by applying HT-ATES in real heating environments with the beginning of the 1990s, relevant risks were shifting from mainly subsurface related issues towards risks also concerning the heat source and sink (“Decreasing heating demand“, “Competing technologies“, “Poor building integration“, “Loss of heat source“ or “Hydraulic interaction“).

This could be also observed for the most recent HT-ATES sites located in the German cities Berlin, Rostock and Neubrandenburg (Fig. 4.4). In Berlin, heating and cooling for the Parliament buildings is supplied by LT- and HT-ATES systems. The thermal energy for heating and cooling is stored in two separated aquifers at a depth of 60 m (cooling) and 320 m (heating). Detailed information was published by Kabus and Seibt [283], Kabus et al. [281] and Sanner et al. [223]. While the shallow storage is still in operation, the HT-ATES was shut down in the beginning of 2018 [430]. During more than 15 years of operation, there was a leakage in the horizontal piping and groundwater pumps had to be replaced every five years [430]. However, none of these problems critically impaired the operation and a high storage efficiency was technically possible. Nevertheless, high recovery values were only sparsely reached in practice as the HT-ATES was oversized due to an overestimated heating demand by imprecise building simulations [431]. Additionally, the amount of surplus heat during summertime was strongly fluctuating, as most of the CHP heat was used for absorption cooling during summer. Even new CHP-units did not compensate for the largely underestimated cooling demands of the connected buildings. As a consequence, the storage was mostly fed with low temperature heat from absorption chillers, thus not reaching design temperatures [430]. Similar to the experiences made in Utrecht, this varying demand-supply mismatch lead to an inefficient operation and the final shut-down. Nevertheless, it is planned to put the HT-ATES back in operation to supply a planned adjacent new building [431]. In the city of Neubrandenburg, an abandoned geothermal system was reactivated to store surplus heat of a Combined Cycle Gas Turbine (CCGT) in a depth of 1200 m. The recovered heat was used to supply a small DH network, which was initially fed by the abandoned geothermal system [237]. The HT storage was in operation for more than ten years. Technical problems were mainly observed at the cold well, where injection temperatures of 30 °C favored the growth of sulfate reducing bacteria. Geochemical reactions were monitored, analyzed and published in several studies [284, 328, 432, 433]. Even though corroded well pumps had to be replaced periodically (Fig 4.6), this did not significantly affect the operation of the ATES [434]. Again, the efficiency of the storage was less a matter of subsurface suitability, however more a matter of the charging-discharging behavior as function of a fluctuating heating and cooling demands [434]. The system was shut down in the beginning of 2019 after the public utility of Neubrandenburg decided for a change in strategy by switching from long-term to short-term thermal energy storage. During summertime, excess heat of the CCGT will be

Table 4.8: Problems encountered at past and present HT-ATES sites (left) and expected risks for the HT-ATES projects in Hamburg analyzed by Radmann and Hansen [418].

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

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

stored from Monday till Friday in an artificial storage tank [434]. The steal tank is 36 m high and has a storage volume of 22,000 m^3 (Fig. 4.6). The stored heat is used for hot water supply of the city of Neubrandenburg during the weekend in the summertime. Thus, no residual heat is available for the HT-ATES. Nevertheless, it is planned to (re)use the existing wells for a (direct) geothermal system [434].

Figure 4.6: 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.

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 a building-complex and is fed with solar heat from the roof [225]. Thus, the risk of a changing heating demand and the loss of heat source can be considered as insignificant. In addition, with a storage depth of around 20 m, exploration risk and drilling costs were very low. Similar experiences were made in the Netherlands, where several ATES systems are in operation with a storage temperature between 40 and 45 °C [435]. At the ecological research institute NIOO in Wageningen, 40 °C (solar) is stored in a depth of 295 m. While cooling is provided from a second, more shallower aquifer, no heat pump is required for heating. Considering the heat pump-free and low-risk operation, there is a huge potential for systems with a storage temperature of 40 to 60 °C to supply the new/refurbished building stock without significant alterations to the electricity grid. With a maximum allowed injection temperature of 20-25 °C in shallow aquifers ($<$ 400 m), this kind of system, however, would not receive a permit in most European countries [15, 16]. Considering that urban aquifers are already highly influenced by anthropogenic activities [385], this legislation practice should be critically reflected and adjusted, where appropriate. Laboratory investigations indicate a mobilization of several trace elements and heavy metals (particularly arsenic), but also a return to initial hydrochemical conditions after completion of ATES operation [315, 436]. Further in-situ experiments, as currently performed in the TestUM project (Section 4.3), and investigations on the impact on the microbiology are crucial. Building on profound scientific findings, knowledge-based, site-specific maximum injection temperatures should be established as function of the existing water quality and local (hydro)geological boundary conditions.

Considering the lessons learned from abandoned HT-ATES sites in the Netherlands and Germany, the risks “Decreasing heating demand“, “Loss of heat source“ and “Competing technologies“ were underestimated by the planners and experts in Section 4.4.2. This emphasizes the requirement for a reorientation of the scientific focus towards studies not only focusing on subsurface design, but also on the optimal interactions between heat source, sink and storage. Being designed to operate up to 30 years [359], HT-ATES are less flexible than competing technologies and highly sensitive to changes in the thermal energy demand (heat sink) and supply (heat source). At the same time, building planners often fail to predict the heating demand, even in the short-term. In the long-term, changing boundary conditions such as refurbishment strategies or increasing ambient temperature make it challenging to match demand and supply over the entire lifespan. Finally, there is also a mismatch between Table 4.8 and the survey results with respect to legal risks. This, however, can be explained as special permits were issued to early pilot projects. Neither the HT-ATES in Berlin, nor the HT-ATES in Rostock would obtain a license under the current legislation policy. All HT-ATES projects, and particularly those affecting aquifers suitable for drinking water supply, are facing an unknown and uncertain permit procedure, which reflects the expert opinions. In order to allow a future-proof commercialization, easier, quicker and less challenging permit procedures have to be developed in Europe and worldwide.

4.5 Conclusion

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

- This study revealed that risk assessment in geothermal energy should not only include technical and financial but also social, political and legal risks. As many risks are influenced by local boundary conditions (Section 4.4.2 and 4.4.3), the development of project-specific risk management strategies is highly recommended. Building on this first qualitative approach, future studies should strive to establish quantitative risk assessment in HT-ATES projects. Even though risk assessment is often applied to geothermal projects, very little is known about the advantages of different methods. Hence, different quantitative methods such as Monte Carlo (MC) or Bayesian Statistics should be compared and evaluated for real-case scenarios.

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

- Uncertainty about risks can be reduced by sharing data and experience. Despite the successful realization of HT-ATES system across Europe, no information is available on the economic performance. While Schüppler et al. [382] and Ghaebi et al. [354] performed a theoretical financial analysis for LT-ATES systems, future demonstration projects should strive to provide more insights into both capital (CAPEX) and operational (OPEX) costs of HT-ATES. A holistic monitoring covering all energy flows, energy costs and maintenance is indispensable to convince future investors to bet on HT-ATES. In addition to Wesselink et al. [359], further efforts should be made to perform site- and market-specific analyses to evaluate economic feasibility of HT-ATES considering not only different supply alternatives but also different heat sources and sinks. Both, feasibility as well as real-case analyses should cover not only costs but also CO_2 emissions.
- Experiences from Rostock and the Netherlands indicate that storage temperatures of 40 to 60 °C in shallow urban aquifers bear a high potential for the supply of heating systems in well insulated buildings. The ATES proved not only to be technically robust but also facilitates establishment of an autarkic energy system. At the same time, the systems can be coupled with renewable heat sources and do not necessarily require the support of heat pumps. This technical potential however, is strongly limited by the current legislation. Hence, in order to establish a science based legal procedure, the impact of HT-ATES on groundwater quality has to be further investigated. In addition to the TestUM project (Section 4.3), research should not only focus on the geochemistry but also changes in groundwater ecology. Considering the fact that urban aquifers are already highly influenced by urban activities [385, 437, 438], the distinction between natural (unaffected) and thermal or chemical contaminated aquifers are essential for a sustainable solution.

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

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Appendix

Fig 4.7 illustrates the outcome of the survey, grouped by the severity, occurrence probability and the uncertainty. In general the respondents associate low risks also with low uncertainties, indicating that the respondents implicitly seem take uncertainty into account on their judgment on probability. The severity of most risk items was rated by most experts as “Moderate“ (3) or “Major“ (4). The technical risks “Loss of heat source“, “Induced seismicity (>3)“ and “Subsidences and swellable formations“ were rated as “Severe“ (5). In contrast,

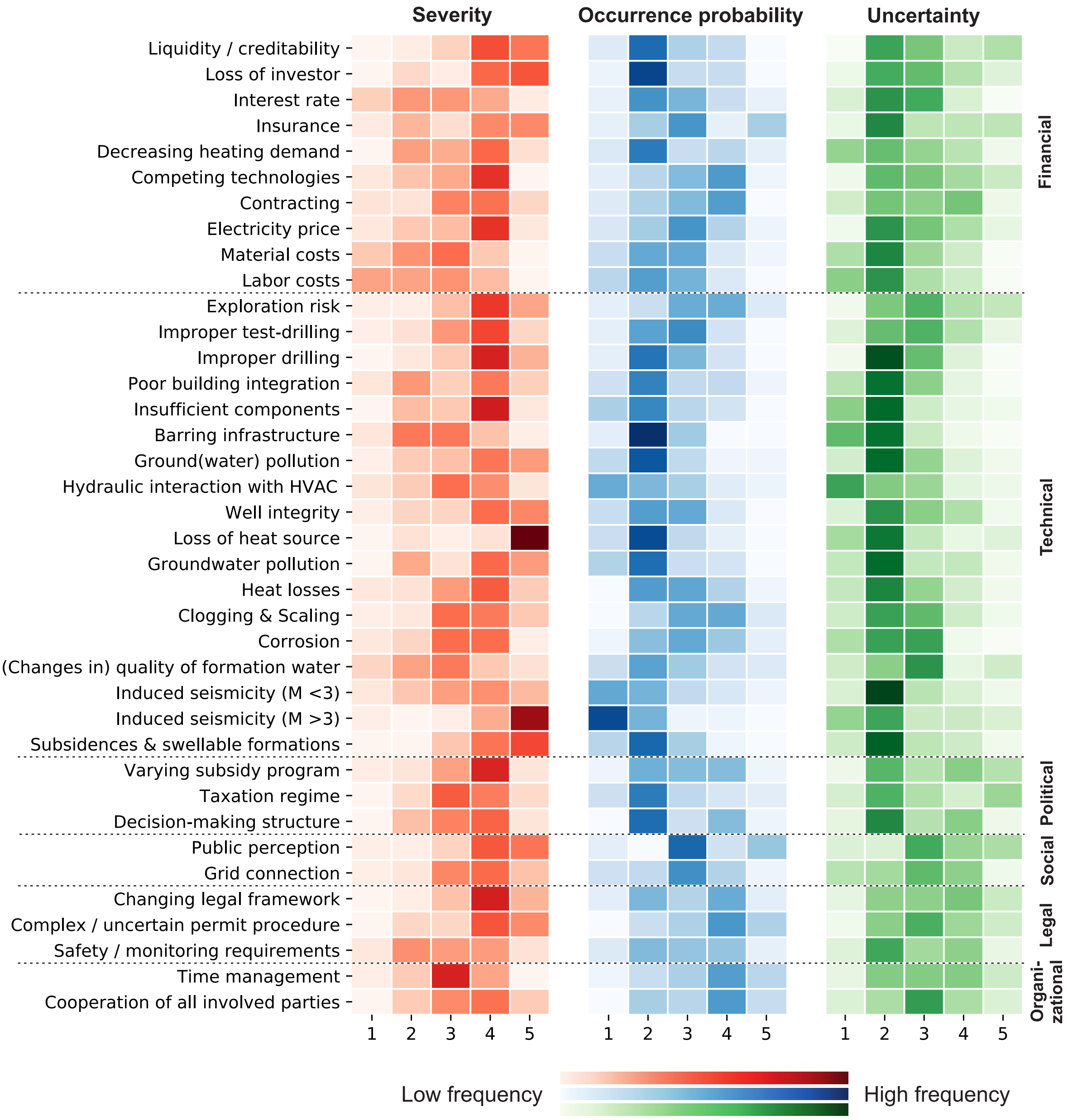

Figure 4.7: Relative frequencies of the risk item ratings grouped by the severity, occurrence probability and uncertainty.

the occurrence probability was estimated to be “Very low“ (1) to “Moderate“ (3) for most risk items. This is particularly the case for technical risks, as social, political, legal and organizational issues are estimated to occur more often. A similar pattern can be observed for the uncertainty.

Chapter 5

Synthesis

5.1 Conclusion

Due to a constant further development of concepts and designs, a wide spectrum of geothermal application types is available today, ranging from high to low temperature, from open- to closed-loop or from storage to non-storage solutions. In order to tap the full potential of geothermal heating and cooling, it is crucial to adapt the choice of the geothermal concept to the local boundary conditions, considering the strengths and weaknesses of each technology. Therefore, profound knowledge is mandatory for all application types. With ATES, it is possible to combine different geothermal applications, and integrate other renewable and non-renewable heat and cold sources. This allows it to take urban energy concepts to the next level. Nevertheless, ATES has been widely neglected by energy planners worldwide. This is due to the fact that both, LT- and HT-ATES development is impaired by certain market barriers, which are mainly attributed to a lack of knowledge concerning the technical and financial performance, potential risks and an unfamiliarity with the technology in general. This knowledge gap is addressed by this thesis. As a conclusion of Chapter 2-4, the following remarks address the market potential of ATES, considering competing technologies.

Fig. 5.1 illustrates the advantages and disadvantages of shallow geothermal application types. It is well known that open-loop systems (LT-ATES and GWHP systems) operate more efficiently than closed loop (BTES and BHE) systems due to a higher heat extraction rate. However, LT-ATES and GWHP systems strongly depend on subsurface conditions, such as the existence of productive aquifers. Additionally, closed loop systems have a higher operational robustness. Consequently, closed loop systems are often the preferred choice, even tough subsurface conditions allow ATES or GWHP utilization. The result is an inefficient exploitation of the geothermal potential [439]. The difference between LT-ATES and GWHP systems, by contrast, has not yet been addressed. While ATES technology is hardly known worldwide, all open loop systems are called ATES in the Netherlands (Herman Velvis). Technically, both concepts can be clearly defined depending on whether or not the pump direction is seasonally shifted. Considering the monitoring data from the Netherlands (Section 2.5), a distinction can also be made from an energetic point of view: the average abstraction temperature of LT-ATES is by around three °C higher (winter) or lower (summer), considering the natural groundwater temperature. Even though the increased temperature level during wintertime increases the COP of the heat pump, the resulting energy savings can be considered to be low. More significant, however, is a lower abstraction temperature in summer owing to the active storage of winter cold. The air-conditioning system of particularly old buildings requires inlet temperatures of between six and nine °C. By harnessing the stored

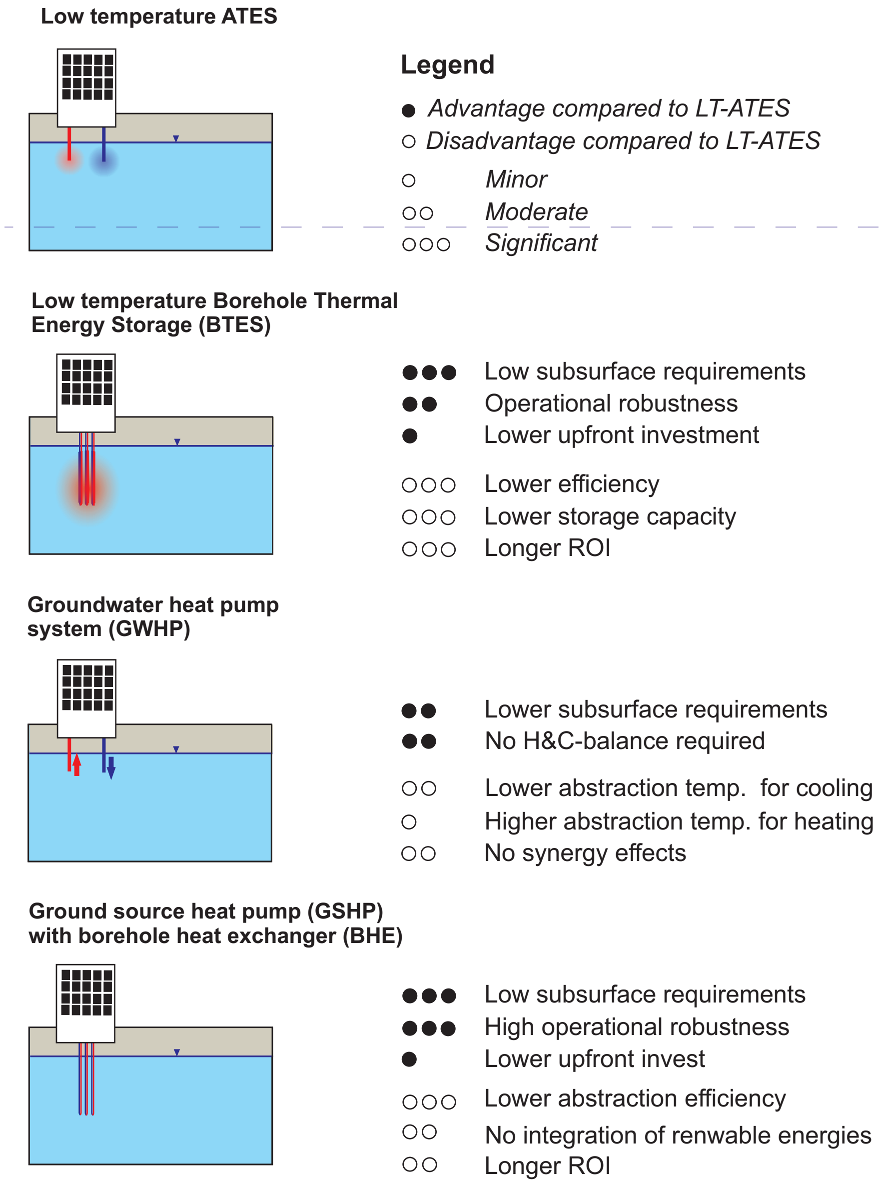

Figure 5.1: Advantages and disadvantages of LT-ATES compared to shallow geothermal application types (modified based on Bayer et al. [385]).

winter cold, electricity-intensive heat pumps can be replaced by free-cooling in summer. Global warming, increasing percentages of glazing and growing demands for comfort cooling will open a huge market for groundwater cooling. Considering increasing groundwater temperatures particularly below city centers [437, 438, 440, 441], the seasonal storage of thermal energy for summer cooling will gain importance over the next decades. From an environmental point of view, LT-ATES also contributes to a more sustainable utilization of the geothermal potential particularly in urban environments. Higher Δ T values between injection and abstraction allow lower pumping rates and hence reduce the thermally affected zone of each system. Finally, LT-ATES also reduces the thermal impact on the subsurface by the active storage of winter cold. To conclude, LT-ATES can significantly contribute to the decarbonization of the heating and cooling sector, but has to be operated in the appropriate environment. Considering the outcome of Chapter 2.5, it is crucial to focus future R&D activities not only on subsurface issues, but also to facilitate an optimal building integration of ATES systems. It is widely observed in practice that poorly designed HVAC systems make a profound subsurface design insignificant. While it is expected that around 70% of Dutch LT-ATES systems are characterized by an insufficient building integration [394], this problem is not only limited to LT-ATES and the Netherlands, but to any shallow geothermal application worldwide.

With storage temperatures of up to 120 °C and deeper storage horizons, HT-ATES projects are more challenging and therefore not only influenced by socio-economic market barriers, but also multiple risks. Chapter 3.5 revealed that the most important technical risks of HT-ATES are related to scaling and clogging of the wells and the projected energy supply and demand. Thus, HT-ATES requires not only comprehensive planning and design, but also intensive monitoring and maintenance. In comparison, HT-BTES, and in particular artificial storage tanks, do not (or less so) depend on certain subsurface conditions and are characterized by a high operational robustness (Fig. 5.2). For stakeholders, planners and investors, for whom energy safety is an important factor, this is a decisive decision criterion.

This could be recently seen in Neubrandenburg, where a seasonal HT-ATES was replaced by a short-term artificial storage tank (Section 4.4.3). In addition, artificial storage tanks are very flexible and can be easily integrated into complex, multiple-technology heating concepts (Section 2.2). HT-ATES is nevertheless facing a huge market potential due to its high storage capacity, while storage tanks and BTES are not sufficient to store large amounts of surplus heat seasonally. The advantages of deep geothermal systems are potentially higher

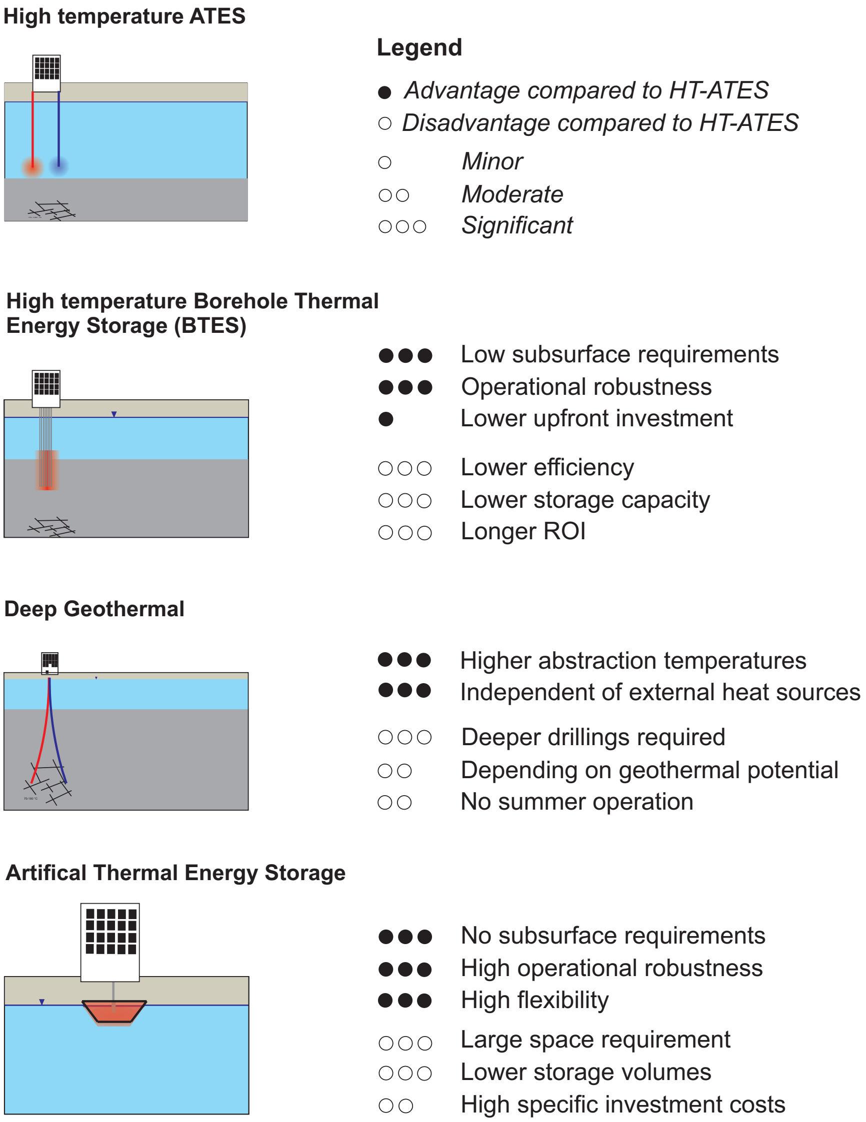

Figure 5.2: Advantages and disadvantages of HT-ATES compared to high temperature heating technologies (modified based on Bayer et al. [385]).

abstraction temperatures and a constant and permanent available heat source. Direct geothermal utilization is, however, only applicable in areas with a high geothermal potential and requires deeper drillings than HT-ATES systems. In areas with a lower geothermal potential, the storage of heat at more shallow depth can significantly decrease exploration risks and drilling costs. To conclude, HT-ATES has significant advantages compared to all competitive technologies summarized in Fig. 5.2 and is facing a huge market potential worldwide. As the technological feasibility has already been successfully demonstrated at several demonstration plants, it is now crucial to build up trust among investors and stakeholders. Further efforts are, therefore, required to increase operational robustness, particularly considering geochemical issues. The widespread application of deep geothermal systems for heating purposes has already been successfully demonstrated, for instance in the city of Munich. The experiences show that multiple risks can be mitigated by a sound energy concept. For HT-ATES, long-term energy concepts have to consider not only the future development of the thermal energy demand, but also a constantly available heat source. This has been a main issue with recent projects and has to be overcome in the future.

5.2 Perspective

Considering the findings of Chapter 2-4, further research efforts are required to establish a basis for a global application of ATES. Different needs for research were identified and are described in the following section, which are categorized by research topics addressing the efficiency of LT-ATES, the potential of ATES as well as legal- and risk-related aspects:

Efficiency of LT-ATES

- **Optimization of building integration:** Chapter 3 indicates a significant potential to increase operational efficiency of LT-ATES by optimizing the integration into the HVAC system. Similar experiences are also reported from the LT-ATES systems at the “Bonner Bogen“ in West Germany [442], the ATES at the Parliament Building in Berlin [200, 431] or GSHP installations in Great Britain [443]. Based on the monitoring data of six German GSHP systems, Bockelmann and Fisch [444] showed that even with detailed, careful planning, malfunctions often occur during operation. While reliability of supply is the essential premise of all energy planners, additional investments in monitoring equipment, data analysis or employees to control operational performance are often not made. This is also the case at the Campus North of the Karlsruhe Institute of Technology (KIT), where about 15 GWh of cooling is supplied by decentralized compression chillers. No information is, however, available on the installed cooling capacity, power consumption by the chillers or the cooling demand of the buildings. This results in an inefficient and cost intensive cooling system and impedes the replacement by renewable technologies [445]. Particularly for large buildings, the following aspects in planning and operating LT-ATES systems are highly recommended:

  - precise analysis of heating and cooling demand based on building simulations;
  - careful and detailed design of the HVAC and ATES system;
  - keep the systems as simple as possible;
  - comprehensive monitoring of all building energy flows and electricity demands;
  - comprehensive underground management (injection/abstraction temperature, groundwater chemistry, pumped volume);
  - development of building-specific control strategies;
  - calculation of SPF factor;
  - training of energy planners in the operation of ATES.

- **Urban energy concepts:** 2,800 ATES systems supply currently only 2% of the Dutch thermal energy demand of the built environment (Section 3.3). Considering not only geothermal but all kinds of existing underground infrastructure such as sewer systems, subways or basements, there is, however, already a lack of subsurface space in areas with high population densities. To allow significant growth rates of LT-ATES worldwide, urban energy concepts are indispensable to guarantee a sustainable utilization of the available resource. One way is to optimize the injection temperatures or to prevent over-claimed subsurface space by precise building simulations (Chapter 2.5). In addition, the establishment of an underground management is highly recommended to tackle efficiency losses by both thermal interference and a high groundwater flow, and to create synergies between allocated heat (cold) sources and sinks. However, an effective underground management requires an extensive data base of existing geothermal and non-geothermal subsurface users, which has to be integrated into a groundwater model. The latter has to be continuously updated. It is, however, a matter of policy, who is in charge of investing the required man-power and financial means [385].

Potential of ATES

- **Subsurface potential:** The ATES potential can be analyzed on an urban, regional or national or global scale, considering hydro(geological), geographical, regulatory and climatic conditions. So far, the ATES potential has only been globally assessed, whereas important factors have not been considered. Potential maps are, however, not only useful to estimate whether or not ATES technology is feasible, but also to convince stakeholders of investing in the technology by further pre-investigations. In addition to hydrogeological and climatic factors, future studies should also strive to include geographical and regulatory aspects.

- **Economic and environmental potential:** A review of 50 years of ATES research provides only little information on financial or environmental benefits. Facts and figures such as payback times or storage costs (€/kWh) are the most important criteria for stakeholders whether or not to invest in ATES technology. For LT-ATES, previous studies by Schüppler et al. [382], Ghaebi et al. [354] and Vanhoudt et al. [230] revealed low payback times compared to fossil-based technologies. While LT-ATES has to compete with other renewable technologies on the future energy market, comparisons to technologies such as absorption chillers, biomass heating or air-source heat pumps would be crucial. Considering HT-ATES, no information on economic or environmental savings has been published. In addition, future studies should not only cover payback times, but also the entire life cycle costs (LCC) and environmental impact (LCA).

- **Heat and cold sources and sinks:** There is only a market for ATES in areas with a heating and/or cooling demand. In addition, the ATES potential can significantly increase by an access to freely available thermal energy sources. Despite their importance, both factors were not considered by past studies analyzing the ATES potential. This is due to the fact that both thermal energy demand and supply are extremely difficult to quantify and accurate data only barely exist [445]. The application of such data, however, goes beyond the planning of ATES systems and is extremely relevant for many issues addressing the decarbonization of the thermal energy sector. This is, for instance, the case for the planning of new district heating and cooling grids or refurbishment strategies. The development and application of new methods for a widespread quantification of the thermal energy demand is highly recommended by utilizing remote sensing techniques and building simulation models. While cooling demand has not been analyzed on an urban scale, a first idea would be the development of an image recognition algorithm, which localizes the demand for cooling based on compression chillers detected from satellite images [446].

Risks and Legacy

- **Risk assessment:** Risk assessment is crucial for large energy projects. It is essential for project managers to develop risk mitigation strategies to achieve the project goals, and for potential investors to act more confidently on future business decisions. HT-ATES projects are not only characterized by high upfront investments but also by multiple risks as described in Chapter 3.5. Nevertheless, risk of HT-ATES has not been addressed in research and is hardly applied in practice. Considering the outcome of Chapter 3.5, future studies should strive to develop risk assessment methods that can be applied in practice. Using quantitative approaches such as Monte Carlo simulation or Bayesian Statistics, it is recommended to perform a risk assessment for a case study, such as the planned HT-ATES in the city of Hamburg. All kinds of risks should be considered and not only technical risks as in past geothermal risk analyses. The results should be examined and verified to develop a blueprint for future projects.
- **Legal aspects:** The outcome of the online survey revealed that a complex permit procedure is estimated to be the most crucial risk in HT-ATES. To accelerate and simplify this process, authorities, scientists, energy suppliers, legal experts and drilling companies are encouraged to simplify the permit procedure by defining minimal requirements, while duly accounting for all interests. It is also recommended to reconsider the differentiation between deep and shallow as well as HT and LT systems considering site-specific injection temperatures (Section 2.5). Therefore, more research is required to fully understand the impact of different injection temperatures on geochemistry, however also changes in groundwater ecology.

Extensive subsidy programs and the ever louder calls for sustainable solutions particularly by the young population build up an unprecedented economic environment for the ATES technology. After more than 50 years of R&D, ATES is still facing significant market barriers that impede the global adoption of the technology. Considering the outcome of this thesis, it is crucial to set the focus of R&D not entirely on technical (subsurface related) issues, but also address aspects dealing with economics, public relations, risks or multidisciplinary urban energy concepts.

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Declaration of Authorship

Study 1

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Declaration of authorship: Philipp Blum, Paul Fleuchaus (PF) and Ingrid Stober designed the study. Bas Godschalk provided information on the current application status of ATES in several countries and also provided insights into the characteristics of ATES especially in the Netherlands. PF wrote the manuscript. The final manuscript was reviewed by all authors.

Study 2

Citation: Fleuchaus P, Schüppler S, Godschalk B, Bakema G, Blum P (2020) Performance Analysis of Aquifer Thermal Energy Storage (ATES). Renew Energy, 146:1536-1548, doi:10.1016/j.renene.2019.07.030

Declaration of authorship: Paul Fleuchaus (PF), Philipp Blum and Simon Schüppler designed the study. Bas Godschalk and Guido Bakema provided the monitoring data. PF wrote the manuscript, which was finally reviewed by all authors.

Study 3

Citation: Fleuchaus P, Schüppler S, Bloemendal M, Guglielmetti L, Opel O, Blum P: Risk analysis of High Temperature Aquifer Thermal Energy Storage (HT-ATES). RSER [under review].

Declaration of authorship: Paul Fleuchaus (PF) and Philipp Blum designed the study. All authors participated in the risk identification process. PF and Simon Schüppler designed the online survey. PF wrote the manuscript. The final manuscript was reviewed by all authors.

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[446] Salomon R (2019) Analyse der installierten Kälteleistung am KIT CN mittels Luftbildern. Masterthesis. Karlsruhe: Karlsruhe Institute of Technology.

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EDUCATION AND RESEARCH EXPERIENCE

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Lawrence Berkeley National Laboratory (LBL)
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M.Sc. Angewandte Geowissenschaften *Oct 2014 - Nov 2016*
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MSc-Thesis: G*IS-based statistical landslide susceptibility analysis on a landslide prone area on the Swabian Alb.* (Grade: 1.0)

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Istanbul Technical University (ITÜ), Turkey

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University of Bremen (Grade: 1.8)

Language school April 2011 - Aug 2011
International Language School San Francisco and Vancouver

Military service Sept 2010 - March 2011
Local hospital Marktheidenfeld

Highschool (A-Level) Sept 2001 - June 2010
Balthasar-Neumann-Gymnasium, Marktheidenfeld

TEACHING

Co-supervised M.Sc.-Theses

- Robert Salomon (2019) Analyse der installierten Kälteleistung am KIT CN mittels Luftbildern.
- Antoine Duchesne (2019) Wirtschaftlichkeitsanalyse der Kälteversorgung eines Forschungszentrums.
- Max Kessler (2018) Thermisch-hydraulische Modellierung eines unterirdischen Wärmespeichers im Raum Friedrichshafen.
- Simon Schüppler (2017) Wirtschaftlichkeit von Aquiferwärmespeichern (ATES) gegenüber konventionellen Versorgungsalternativen.

Co-supervised project studies

- Daniel Bolz (2019) 3D-Modell des geologischen Untergrundes am KIT Campus Nord.
- Jose Bastias (2018) Numerical model of ATES system at KIT Campus North.

Co-supervised B.Sc.-Theses

- Larissa Blesch (2018) Erstellung von Grundwassergleichenplänen zur Bestimmung der Grundwasserfließrichtung für einen geplanten Aquiferspeicher am KIT Campus Nord.
- Deborah Dold (2017) Dreidimensionale Untergrundmodellierung mit GeoModeller für den geplanten Aquiferspeicher am Standort Aquadrom in Hockenheim.

Lecture
Lecture on Aquifer Thermal Energy Storage (Thermal use of shallow groundwater, Philipp Blum)

PEER-REVIEWED PUBLICATIONS

Fleuchaus P, Schüppler S, Bloemendal Martin, Guglielmetti L, Opel O, Blum P (2020) Risk analysis of High Temperature Aquifer Thermal Energy Storage (HT-ATES). Submitted to Renewable and Sustainable Energy Reviews.

Fleuchaus P, Blum P, Wilde M, Terhorst B, Butscher C (2020) Retrospective Evaluation of Landslide Susceptibility Maps. Submitted to Bulletin of Engineering Geology and the Environment.

Fleuchaus P, Schüppler S, Bakema G, Godschalk B, Blum P (2020) Performance analysis of Aquifer Thermal Energy Storage (ATES). Renewable Energy, 146, 1536-1548.

Schüppler S, **Fleuchaus P**, and Blum P (2019) Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage (ATES) in Germany. Geothermal Energy 7(1):669 doi: 10.1186/s40517-019-0127-6.

Fleuchaus P, Godschalk B, Stober I, Blum P. (2018) Worldwide application of Aquifer Thermal Energy Storage - A review. Renewable and Sustainable Energy Reviews 94:861-876 doi:10.1016/j.rser.2018.06.05

Fleuchaus P, Blum P (2017) Damage event analysis of vertical ground source heat pump systems in Germany. Geotherm Energy, 5(1):1256.

CONFERENCE PROCEEDINGS

Fleuchaus P, Schüppler S, Godschalk B, Bakema G, Zorn R, Blum P (2020) Techno-economic performance evaluation of Aquifer Thermal Energy Storage. World Geothermal Congress (WGC), Reykjavik, Iceland.

Godschalk B, **Fleuchaus P**, Schüppler S, Velvis H, Blum P (2019) Aquifer Thermal Energy Storage (ATES) systems at universities. European Geothermal Congress (EGC), Den Haag, The Netherlands.

SELECTED TALKS

Fleuchaus P, Schüppler S, Bakema G, Godschalk B, Blum P (2019) Aquifer Thermal Energy Storage (ATES) - global applications and market barriers. American Geophysical Union (AGU), San Francisco, US.

Fleuchaus P, Blum P, Wilde M, Terhorst B, Butscher C (2019) Retrospektive Evaluierung statistischer Gefährdungskarten von Hangrutschungen. Fachsektionstage Geotechnik, Würzburg, Germany.

Fleuchaus P, Godschalk B, Stober I, Blum P (2019) Global application of Aquifer Thermal Energy Storage (ATES). European Geothermal Workshop (EGW), Karlsruhe, Germany. **(Best Poster Award).**

Fleuchaus P, Blum P (2019) Schadensfallanalyse von Erdwärmesonden in Baden-Württemberg und benachbarten Gebieten. Geo-Ressourcen-Herbstkurs 2019: Untiefe Geothermie, Zürich, Switzerland.

Fleuchaus P, Godschalk B, Schüppler S, Velvis H, Blum P (2019) Aquifer Thermal Energy Storage (ATES) systems at universities. European Geothermal Congress (EGC), Den Haag, The Netherlands.

Fleuchaus P (2019) Kongress Energieautonome Komunen (KEK) Freiburg, Germany
(Video: https://vimeo.com/user57892917/download/319817227/88411166ed)

Fleuchaus P, Godschalk B, Stober I, Blum P. (2017) Aquifer Thermal Energy Storage - A review on global application status. European Geosciences Union (EGU), Vienna, Austria.

Fleuchaus P, Godschalk B, Stober I, Blum P. (2017) Worldwide application of Aquifer Thermal Energy Storage - A review. 27. Tagung der Fachsektion Hydrogeologie (FH-DGGV), Bochum, Germany (Poster).

IN THE MEDIA

Deutschlandfunk Nova - Update (30.10.2019) - Alternative Maßnahmen gegen die Hitze - Klimafreundliche Klimaanlagen

Deutschlandfunk - Wissenschaft aktuell (08.10.2018) - Grundwasserspeicher helfen beim Energiesparen

Hessischer Rundfunk - alle Wetter (02.10.2018) - Heizen mit Grundwasserspeicher

WDR 5 - Quarks (15.08.2018) Wärme- und Kältespeicherung im Grundwasser