Large-scale storage capacities as the backbone of a renewable energy system

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ABSTRACT

Thermal energy storage is one of the key challenges of the energy transition, since a large portion of the final energy consumption is used for heating purposes and industrial processes and heat is subject to large seasonal fluctuations in supply and demand. To overcome this seasonal mismatch, geothermal storage offers a large, mostly unexploited potential with capacities that are unequalled by other technologies. The technology of high-temperature thermal storage in aquifers has a crucial role to play, since it could serve the need for large storage capacities. We highlight two aquifer types to which we attach a high importance as future technology.

1. INTRODUCTION

To be able to reach climate neutrality by 2050, it is imperative for Europe and the world to increase and accelerate their current efforts. In light of current political events and the accelerating climate change, the reliance of Europe on fossil fuels needs to decline as fast as possible. An often overlooked but nevertheless major consumer of energy is heating, which represents up to about 50% of final energy consumption, and a bulk of this is produced from hydrocarbon fuels. According to 2020 figures from Eurostat, approximately 75% of heating and cooling is still generated from fossil fuels while only 23% is generated from renewable energy (Eurostat 2020). To follow the EU climate objectives, the heating sector will have to transition away from fossil fuels toward sustainable heat sources like geothermal, solar and waste heat, with thermal energy storage to balance heat supply and demand.

2. THE ESSENTIAL ROLE OF LARGE-SCALE THERMAL STORAGE

2.1 Seasonal storage with ATES

Geothermal (as well as waste heat or biomass) has the capacity to serve as baseload source for energy in many countries. In contrast, solar as a major renewable energy source is marked by a seasonal swing in production which is anticyclic to the heat demand. As a result of this, fossil fuel-based sources are required to provide the seasonal swing in heat demand, consequently limiting the potential of geothermal and solar sources for heating and leading to unnecessary high CO2 emissions. Large-scale seasonal heat storage, especially with high temperature, can solve this key problem and therefore forms an essential role in the future heating sector. It enables the harvesting of renewable heat in mismatching periods with demand and therefore increases the yearly heat production from sustainable sources and reduces the use of fossil fuels and thus, CO2 emissions while providing flexibility and reliability to end-users (EC 2020). Of special importance in this regard are Aquifer Thermal Energy Storages (ATES), as they provide a scale advantage. Heat can be stored in large quantities in the huge subsurface domain, which functions as an already existing storage medium. These systems are typically designed for low storage temperatures and shallow depths for local usage purposes. However, industrial processes and many district heating networks require heat at temperatures exceeding the temperature levels utilized by conventional ATES-systems.

The technology of High-Temperature ATES (HT-ATES) is considered a promising technology in this regard and conceived to cover a higher temperature range (25-100°C). The use of aquifers for thermal energy storage in ATES systems exploits the heat capacity of water and rock in a natural aquifer. In the EU, open aquifer storage in HT-ATES systems is expected to be particularly suited for application in permeable to highly permeable sedimentary basin reservoirs.

2.2 Demand for research and development

Despite the great advantages offered by HT-ATES, this technology has not been widely implemented yet. The underlying reasons for this fact are manifold, including technical, and non-technical challenges. Only a small number of HT-ATES pilot projects have been realized worldwide, most of which were conceived as pure field study from the beginning, never entered the operational phase or had to cease operation after a few years. Reasons for termination were of a technical nature, or problems regarding system integration arised (Sanner 1999). Currently, only a few systems up to 60°C are in operation, such as the HT-ATES system for the German Reichstag in Berlin (Kabus and Seibt 2000) storing water of 60°C at a depth of 300 m. A renewed interest due to the above-mentioned energy and climate policy framework conditions helped to give HT-ATES technology development a new boost. Related technological challenges were identified and began to be solved in GEOTHERMICA projects, especially within the HEATSTORE project (2018-2021). Industrial companies have also invested in HT-ATES technology development.

Even though methods and strategies to minimize environmental impact and to optimize efficiency and energy system integration have been developed, there are still major problems to enable a widespread uptake of HT-ATES in Europe (Fleuchaus et al. 2020). In particular, significant investment risks for the project developer related to inherent subsurface uncertainty, subsurface suitability of a specific location, technical and economic issues as well as regulatory frameworks are hampering the development significantly (Sanner 1999). It is now the task of research to identify processes and environmental risks and develop corresponding strategies for risk mitigation. This also lays the basis for the social acceptability of this new technology. Technical enhancements must also be developed by research and development efforts with the aim of a higher cost efficiency. Then, these technologies could also get independent of government funding, a precondition for large-scale implementation. HT-ATES is considered particularly crucial for urban areas with existing or future large district heating or small-scale heat distribution systems. Considering the complexity and the importance of SSH (Social sciences and humanities) related issues, an integrated system perspective encompassing technical, economic, legal and organizational aspects is crucial. Against this background, the establishment of HT-ATES demonstration plants becomes a critical prerequisite for economic viability and reliability. Demonstration also plays an important role for fostering societal acceptance and triggering further industrial and political action.

3 RISKS, CHANCES, AND CURRENT DEVELOPMENTS

Currently, there are many efforts underway to advance the cause of large scale thermal storage, to build required demonstrators, address the associated risks and accelerate the uptake of HT-ATES in Europe. We consider two subsurface domains particularly important as they offer the highest storage potentials in Europe: shallow aquifer and water-bearing areas of formerly exploited deep oil reservoirs.

3.1 HT-ATES in depleted deep oil reservoirs

The close link between hydrocarbon and geothermal reservoirs has been known for years: Both petroleum reservoirs and positive geothermal anomalies often occur in geologic trap structures (e.g., Moscariello 2019). Geothermal hotspots have often been found in exploratory oil wells (e.g., Dobson 2016), and vice versa, hydrocarbon resources were “accidently” discovered by geothermal exploration (e.g., Böcker 2015). Consequently, geothermal methods have also been used to locate positive anomalies in petroleum exploration (Meyer and McGee 1985). But it is only in the last few years that the geothermal exploitation of hydrocarbon reservoirs has been brought into the focus of science and industry with the concept of co-production or geothermal usage of abandoned wells (Duggal et al. 2022). And only recently the idea of using the well explored hydrocarbon reservoirs for seasonal heat storage has emerged. As these reservoirs are well characterized by their depth, geometry and reservoir properties and have a proven record of production, they have the potential to offer a tremendous amount of seasonal temperature storage all around the world.

On continental Europe, more than 1’000 hydrocarbon fields have been exploited and far over 20’000 wells have been drilled. This implies that the use of even a small fraction for HT-ATES could result in a huge capacity for heat storage. Careful predictions of a pan-European realisation in 100+ oil fields, results in a 1’000+ GWh storage capacity provided. Using exploited or depleted hydrocarbon reservoir as a basis, figure 1 shows a possible are distribution of HT-ATES in Europe. Even considering only the Rhine Graben with its strong industry sector and large population and geoscientifically intensively investigated continental rift system (Böcker et al. 2017), the potential for HT-ATES is remarkable.

Figure 1: Distribution of existing oil/gas wells in Central and Western Europe as potential for HT-ATES (adapted from Pawlewicz 1997)

The suitability of potential geothermal storage formations is primarily defined by hydraulic properties. Adequate porosity and permeability values are a prerequisite for seasonal production and injection cycles. By the hydrocarbon production itself the reservoir has shown a certain permeability allowing flow rates sufficient for oil production. Furthermore, porosity and permeability data to assess storage potentials are typically available from hydrocarbon drillings. Based on such data of oil fields in the Upper Rhine Valley, Stricker et al. (2020) showed with generic THM modeling, that 90% of abandoned wells could provide sufficient reservoir conditions for economic storage usage deploying specific reservoir utilization strategies. It shall be noted that this study did not consider geochemical processes which will, however, play an important role in reservoir behavior and storage efficiency. Geochemical risk assessment for operation scenarios and respective management strategies are considered one of the key factors to a successful HT-ATES application.

As mentioned above, hydrocarbon reservoirs are often associated with positive temperature anomalies. Produced fluids typically have temperatures of approximately 65 °C - 150°C (Liu et al. 2018). In the Upper Rhine Graben as a major area of oil production in Central Europe, geothermal anomalies manifest with temperatures up to 140°C in 2 km depth (Baillieux et al. 2013). These elevated underground temperatures offer a storage efficiency advantage. Stricker et al. (2020) identify a recovery efficiency for HT-ATES systems in depleted oil reservoirs increasing over the years and reaching values of up to >80%.

In contrast to geothermal reservoirs for energy production, the typical geometry of hydrocarbon containing formations are relatively thin layers of limited thickness. E.g., in the Upper Rine Valley, typical formation thicknesses are between <10 m to locally >40 m (Stricker et al. 2020). This geometry poses an opportunity but also a challenge. The reservoir is clearly delimited, but the small contact area of a typical vertical well in these thin layers has to be compensated for by adapted drilling technologies already applied by the oil industry (see below).

The seismic risk and the concerns of the public about induced seismicity are hampering geothermal project development (Meller et al. 2017). Creating framework conditions for a low seismic risk is therefore essential for the success of geothermal projects, especially in densely populated areas such as the Upper Rhine Valley. In this regard, the history of oil production and the many years of experience are very valuable. From a geological point of view, the frequent occurrence of clay-rich layers above hydrocarbon formations can be expected to have a mitigating effect on induced (micro)seismic events. Furthermore, HT-ATES systems do not require high flow rates; scenarios with optimized operation parameters with moderate to low flow rates and reduced pressure application can be expected to further reduce the seismic risk. Based on the findings of Stricker et al. (2020), generic TH modeling of a hypothetical HT-ATES system with a reservoir thickness of 20 m in a depth of 1200 m has been performed to evaluate temporal and spatial changes of pressure and temperature for cyclic injection and production. The three left figures of Figure 2 show the development of the pressure field for an injection flow rate of 2 Ls^{-1} and a reservoir permeability of 6.6x10-14 m². Pressure changes do not exceed 1.5 MPa and no further changes in the pressure field occur after several cycles (e.g., after 9.5 years). The spatial perturbation of the temperature field is limited to the immediate area around the two wells. As the injection temperature at the hot well (140 °C) exceeds the ambient temperature of the reservoir (70 °C), diffusive heat losses lead to a continuous warming around the hot well (three right figures of Figure 2). The area of the temperature perturbation around the hot well increases over time to ca. 60 m after ten years. Additionally, a residual temperature decrease of ca. 20 K can be observed around the cold well due to the reinjection temperature of 50 °C. These different patterns for the perturbation of the pressure and temperature field also have an impact on expected mechanical perturbations within the reservoir and therewith on seismicity. Expected mechanical perturbations are limited to a very constrained area around the hot well. The impact on movements on the surface, however, is expected to be fully controlled by poroelasticity and to be negligible for such low flow rates and a doublet system as used in the generic modeling of this study (e.g., Birdsell and Saar 2020).

Many well characterized hydrocarbon fields in Europe are close to abandonment or end of lifetime. Reusing these reservoirs would not only offer the opportunity to exploit the large amount of data collected by the oil and gas industry, but also the unique opportunity to transfer well proven technology from the oil and gas industry towards renewable energy in the form of geothermal. Specialized exploration, drilling and logging technologies that are state of the art in the petroleum industry are often not yet utilized in geothermal. Foremost to mention here is horizontal drilling with a geosteering system, as many hydrocarbon reservoirs are of narrow thickness. This narrowness often results in a reduced hydraulic connection between reservoir and conventional vertical wells that might not be sufficient to support high flow rates at low pumping power. Horizontal wells can be utilized to increase the surface area between well and aquifer and therefore increase connectivity. First feasibility studies have shown that productivity of horizontal wells is significant higher compared to vertical wells, while at the same time injection pressure could be decreased by 30% (Stricker et al. 2020).

An added benefit that can be assumed of geothermal projects in areas with previous or ongoing oil extraction is a potentially increased technology acceptance of the local citizens. Decades of oil production without perceptible seismic events, personal experiences in this industry, and the proposition to transfer these areas into a sustainable and CO_2 neutral future show increased citizen appeal in a first case study in the Upper Rhine Graben within the GECKO project (www.gecko-geothermie.de). As every infrastructure project needs public approval, especially in critical areas like the energy transition and the use of geothermal, this aspect cannot be undervalued.

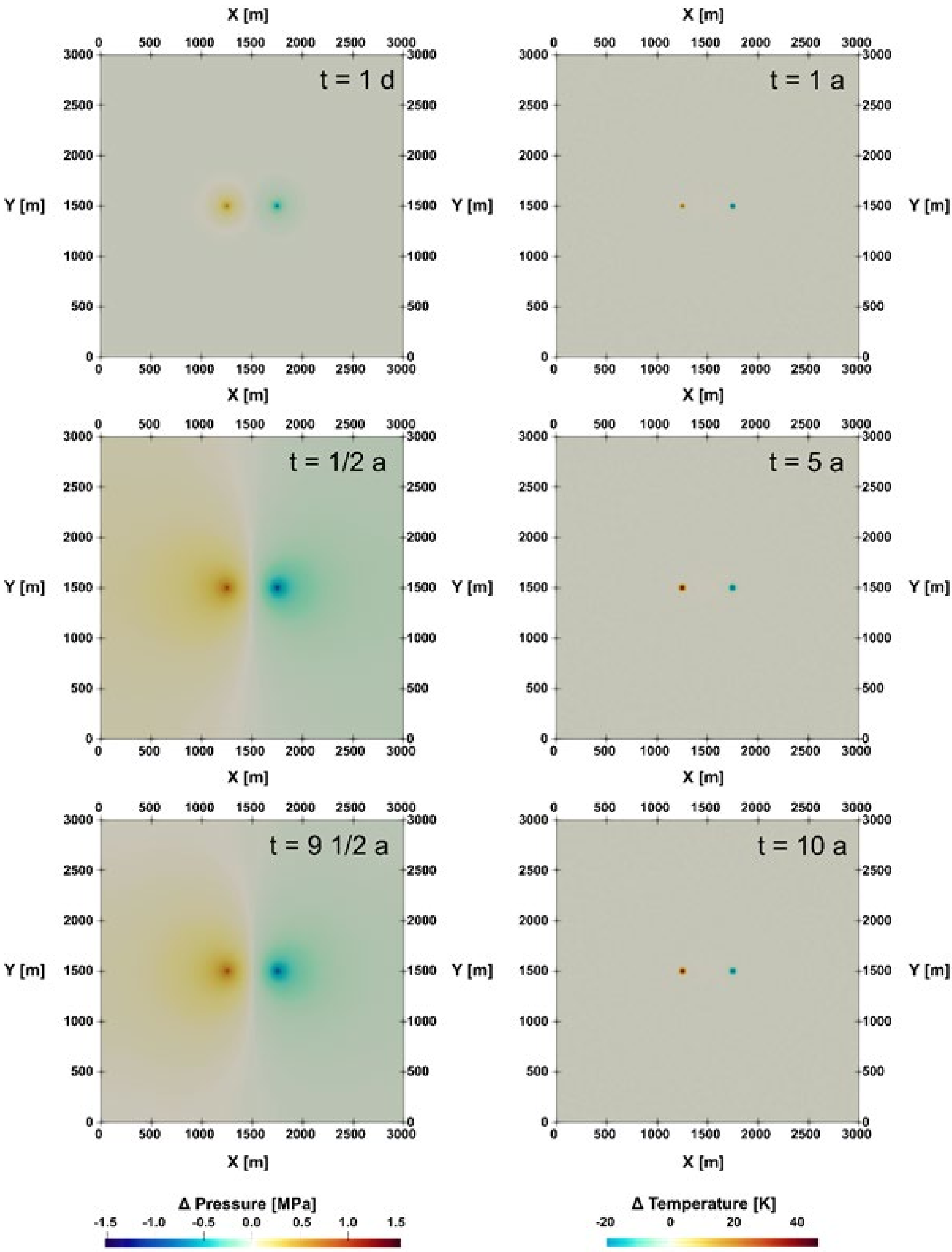

Figure 2: Pressure and temperature perturbations of generic modeling of a cyclic HT-ATES system. The three left figures show the changes of the reservoir pressure after one day (top), one injection period of half a year (middle), and after the tenth injection period (9.5 years, bottom). The three right figures show the changes of the reservoir temperature after one (top), five (middle), and ten (bottom) injection/production cycles.

A pilot project that aims to showcase the feasibility of exploiting former oil reservoirs for HT-ATES is located in the region of Karlsruhe, Germany. The research infrastructure DeepStor at the campus of the Karlsruhe Institute of Technology (KIT) is currently being implemented and is already becoming a regional HT-ATES flagship. Detailed planning and application processes are running, and the first well will be drilled in 2023. The Karlsruhe Institute of Technology (KIT) cooperates here with EnBW, one of the major German utility companies, and other companies to foster technology innovation and transfer. DeepStor will utilize water-bearing rims of exploited oil reservoirs in the Tertiary sedimentary cover of the European Cenzoic Rift System. When fully completed, an annual storage capacity of 5 GWh is planned with an option on future upscaling (Schill et al. 2022).

3.2 HT-ATES in shallow aquifers

An excellent alternative to the re-use of depleted deep oil reservoirs, is high temperature storage in more shallow and highly permeable aquifers. Dinkelman and Van Bergen (2022) proposed favourable aquifer HT-ATES characteristics:

- Aquifers should be sufficiently deep (i.e., >50m), to avoid near surface temperature effects having a negative environmental impact
- They should be sufficiently shallow (i.e., <500m) to avoid high well construction costs.
- Are marked by sufficiently high permeability to accommodate high flow rates at low pumping pressures
- Have sufficient thickness to allow for long term thermal efficiency of ca 75%
- Are marked by saline conditions to avoid interference (buoyancy driven flow) with drinking water resources
- Should be marked by low values of natural groundwater flow (<25 m/y) to ensure lateral containment of the heat storage.

Figure 3 shows the potential map of resulting favourable conditions for HT-ATES in the Netherlands. Similarly, in other EU countries there exists extensive HT-ATES potential in sedimentary aquifers as demonstrated in the HT-UTES screening performed in HEATSTORE[1] (Kallesøe et al. 2019).

Within the GEOTHERMICA HEATSTORE project, the first large scale HT-ATES pilot in a suitable aquifer at ca 350 m depth has been realized in Middenmeer, the Netherlands (Dinkelman et al. 2022; Oerlemans et al. 2022). This pilot provided excellent flow measurements and temperature monitoring data that are evaluated and used for the calibration of subsurface models by the latter authors, including improved predictions of thermal processes for future storage cycles, and their impact on system efficiency are based on the calibrated model, and scope for (generic) improvement for engineering and operation of HT-ATES systems.

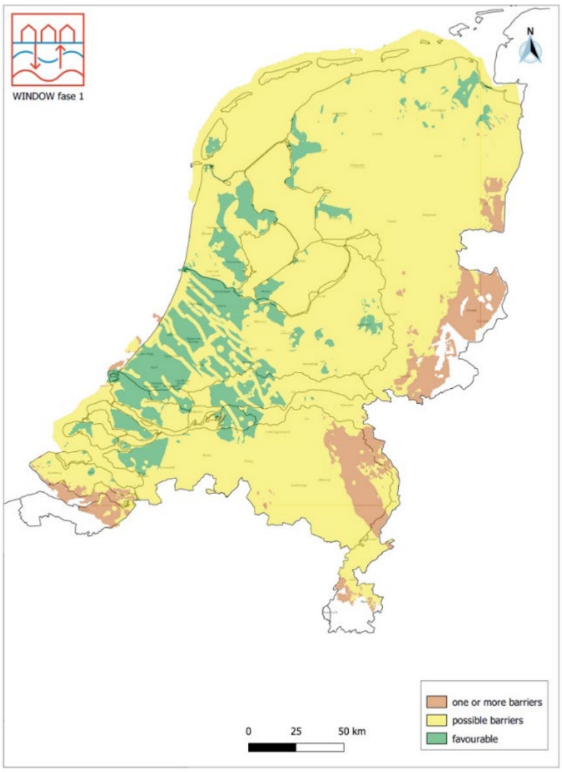

Figure 3: Potential map for HT-ATES in the Dutch subsurface. Note that HT-ATES cannot be applied in the water bodies and waterways (source Dinkelman and Van Bergen 2022).

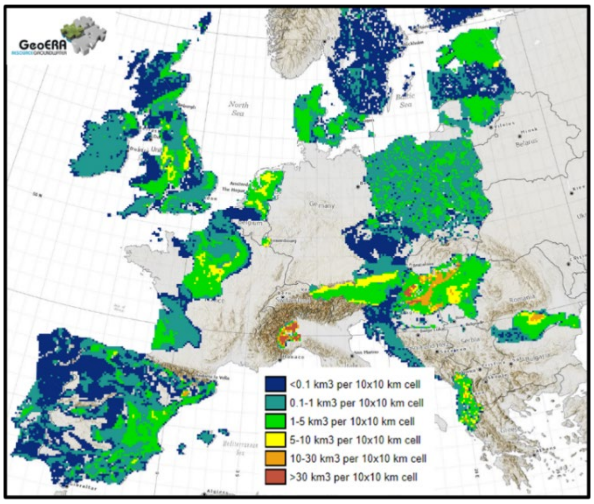

Figure 4: Groundwater storage volume indicative for HT-ATES potential in the EU (please note that only limited number of EU member states have shared relevant data in this database). Taken from the GEOERA RESOURCE project[2]

[1] https://www heatstore.eu/,

[2] *https://geoera.eu/projects/resource9/*

4. DISCUSSION AND OUTLOOK

Currently more than 2'500 lower temperature ATES systems with more than 2.5 TWh annual capacity for heating and cooling are currently being operated across Europe. But to satisfy the heat demand for district heating and industrial processes by renewables, the thermal storage needs to increase in scale and temperature. HT-ATES systems are uniquely suited to solve this challenge and address the seasonal mismatch in supply and demand created by renewable sources. They are a key element of a sustainable, secure, and competitive thermal energy system for the future. In 2020, more than 350 geothermal district heating systems were in operation across Europe. More than 200 further geothermal district heating projects are currently under development and could be assisted by HT-ATES. The implementation of large-scale heat storage for higher temperatures is not only of pivotal energy strategic importance but would also improve the commercial prospects of heat storage by exploiting surplus energy from various processes, which is often available at these temperatures. This concept offers an enormous potential for efficient usage strategies. A higher storage temperature increases the economic viability of underground storage, which would be highly advantageous for the sustainable heat supply of larger communities with district heating networks.

The two subsurface domains highlighted above each offer unique advantages. Formerly exploited deep oil reservoirs are abundant, well suited for HT-ATES regarding basic reservoir characteristics, are well characterized and have a known production behavior. Local production experience could be an advantage in terms of acceptance. The required spatial extension of the storage reservoirs in abandoned hydrocarbon reservoirs is limited as well as the extension of perturbations; environmental impacts and seismic risks are limited. A technology transfer from oil to geothermal industries could help overcome the specific challenges in the field of drilling and logging. The usage of former hydrocarbon reservoirs for seasonal heat storage offers a sustainable after-use to accomplish the switch from a fossil based to a renewable energy system. Additionally, HT-ATES in shallow aquifers provides significant storage potential in the EU (Figure 4, Kallosøe et al. 2019). The feasibility needs to be proven through dedicated mapping of relatively deep groundwater layers and often requires a test drilling to analyze the performance and feasibility of a HT-ATES installation (Dinkelman and Van Bergen 2022).

Both subsurface domains considered for HT-ATES in the paper correspond to sedimentary basin structures which are often marked by excellent data coverage due to past hydrocarbon exploration which makes these areas prospective for the development of geothermal resources (Van Wees et al. 2017). The overlap of HT-ATES and geothermal resource potential allows perspectives to significantly enhance the business case and seasonal swing characteristics of geothermal direct heat resources through nearby seasonal storage, capable of balancing the mismatch in heat demand and geothermal energy supply as exemplary demonstrated in the Middenmeer HT-ATES pilot (Oerlemans et al. 2022). Demonstrators such as Middenmeer and DeepStor could also help to build trust in the society towards this new and urgently needed technology. Demand, development potential and controllable risks open up a substantial market potential.

REFERENCES

Baillieux, P.; Schill, E., Edel, J. and Mauri, G.: Localization of temperature anomalies in the Upper Rhine Graben: Insights from geophysics and neotectonic activity. *International Geology Review*, 55, (2013) 1-19, 10.1080/00206814.2013.794914.

Birdsell, D.T. and Saar, M.O.: Modeling Ground Surface Deformation at the Swiss HEATSTORE Underground Thermal Energy Storage Sites, *Proceedings World Geothermal Congress*, Reykjavik, Iceland (2020).

Böcker, J. Petroleum System and Thermal History of the Upper Rhine Graben: Implications from Organic Geochemical Analyses, Oil-Source Rock Correlations and Numerical Modelling. Ph.D Thesis, RWTH Aachen, Aachen, Germany, (2015).

Böcker, J., Littke, R. and Forster, A. An overview on source rocks and the petroleum system of the central Upper Rhine Graben. *Int. J. Earth Sci*.,106, (2017), 707–742, doi:10.1007/s00531-016-1330-3

Dinkelman, D., Carpentier, S., Koenen, M., Oerlemans, P., Godschalk, B., Peters, E. Bos, W., Vrijlandt, M. and Van Wees, J.D.: High temperature aquifer thermal energy storage performance in Middenmeer, the Netherlands: thermal monitoring and model calibration. *Proceedings of the European Geothermal Congress 2022*, Berlin, Germany, (2022), this issue.

Dinkelman, D. and Van Bergen, F.: Evaluation of the country-wide potential for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Netherlands. *Proceedings of the European Geothermal Congress 2022*, Berlin, Germany, (2022), this issue.

Dobson, P. F.: A review of exploration methods for discovering hidden geothermal systems. *GRC Transactions*, 40, (2016), 695-706.

Duggal, R., Duggal, R., Rayudu, R., Hinkley, J., Burnell, J., Wieland, C. and Keim, M.: A comprehensive review of energy extraction from low-temperature geothermal resources in hydrocarbon fields, *Renewable and Sustainable Energy Reviews*, 154, (2022), 111865.

Eurostat 2020 https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en

EC 2020: Study on energy storage – Contribution to the security of the electricity supply in Europe - Final Report March 2020.

Fleuchaus P, Schüppler, S., Bloemendal, M., Guglielmetti, L., Opel, O. and Blum, P., Risk analysis of High-Temperature Aquifer Thermal Energy Storage (HT-ATES), *Renewable and Sustainable Energy Reviews*, 133, (2020), 110153, doi.org/10.1016/j.rser.2020.110153.

Kabus, F. and Seibt, P.: Aquifer Thermal Energy Storage for the Berlin Reichstag Building—New Seat of the German Parliament. Proceedings World Geothermal Congress, S. 3611–3615. *International Geothermal Association (IGA)*, Kyushu-Tohoku, Japan, (2000).

Kallesøe, A.J. et al.: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. GEOTHERMICA – ERA NET Cofund Geothermal. HEATSTORE deliverable D1.1, (2019), 208.

Meller, C., Schill, E., Bremer, J., Kolditz, O., Bleicher, A., Benighaus, C., et al.: Acceptability of geothermal installations: a geoethical concept for GeoLaB. *Geothermics,* 73, (2018), 133–145. DOI: 10.1016/j.geothermics.2017.07.008.

Meyer, H. J. and McGee, H. W.: Oil and gas fields accompanied by geothermal anomalies in Rocky Mountain region. *AAPG bulletin*, 69(6), (1985), 933-945.

Moscariello, A. Exploring for geo-energy resources in the Geneva Basin (Western Switzerland): Opportunities and challenges. *Swiss Bull. Angew. Geol*. 24, (2019), 105–124.

Oerlemans, P., Drijver, B., Godschalk, B., Koornneef J., Dinkelman, D., Koenen, M. and Bos, W., 2022. First field results on the technical risks and effectiveness of mitigation measures for the full-scale HT-ATES demonstration project in Middenmeer. *Proceedings of the European Geothermal Congress 2022*, Berlin, Germany, (2022), this issue.

Pawlewicz, J. et al..: Open File Report 97-470I, U.S. Department of the Interior U.S. Geological Survey; Map Showing Geology, Oil and Gas Fields, and Geologic Provinces of Europe including Turkey, (1997).

Sanner, B.: High Temperature Underground Thermal Energy Storage State-of-the-art and Prospects *Giessener Geologishe Schriften*, 67, 158 p, Lenz-Verlag, (1999)

Schill, E., Bauer, F., Bremer, J., Grimmer, J.C., Steiner, U. and Kohl, T.: High-temperature underground storage in the deep underground – the DeepStor infrastructure project. *Proceedings of the European Geothermal Congress 2022*, Berlin, Germany, (2022), this issue.

Stricker, K., Grimmer, J.C., Egert, R., Bremer, J., Gholami Korzani, M., Schill, E. and Kohl, T.: The Potential of Depleted Oil Reservoirs for High-Temperature Storage Systems, *Energies*, 13, (2020), 6510.

Van Wees, J.D., Veldkamp, H., Pluymaekers, J., Gessel, S. and Bonte, D.: Unlocking Geothermal Energy in Mature oil and gas basins: The Netherlands success story. In R. Bertani (Ed.), Geothermal Energy, *ICL press*, (2017).