Final report

1. Project details

Project title	EUDP 18 ERA NET Geothermica: HEATSTORE – High Temperature Underground Thermal Energy Storage
File no.	64018-0301
Name of the funding scheme	Energiteknologisk Udviklings- og Demonstrations Program (EUDP)
Project managing company / institution	Geological Survey of Denmark and Greenland (GEUS)
CVR number (central business register)	55145016
Project partners	PlanEnergi
Submission date	15 December 2021

2. Summary

2.1 English summary

The Danish EUDP project HEATSTORE was part of the overall EU Geothermica project HEATSTORE with 23 partners from 9 European countries. The participants in the Danish project were GEUS and PlanEnergi.

The aim of the project has been to explore the potential for Underground Thermal Energy Storage (UTES) in Denmark and pave the way for further implementation of the technology.

The objectives were to:

- Provide knowledge for the exploitation of UTES from existing projects and the demonstration projects in the European project.
- Introduce 3D geological information and perform more detailed geological characterization of the subsurface in selected areas based on specific interests among stakeholders.
- Test new codes and modelling workflows and validate new and existing calculations against monitoring data on selected Danish cases.
- Support the development of UTES in Denmark by stakeholder engagement and knowledge sharing with relevant target groups.

More than 40 existing UTES projects worldwide have been analysed and the leassons learned translated into general specifications and best practice guidelines for ATES, BTES, PTES and MTES. Four existing Danish

systems (1 BTES and 3 PTES) have been used as case studies in HEATSTORE and a validation of previous modelling against monitoring results have been carried out as well as characterization of selected Danish district heating networks with regard to implementation of UTES.

An existing screening of the subsurface potential for UTES in Denmark was updated and the associated web-based screening tool was expanded with the integration of 3D geological data. More detailed geological characterization was carried out in five selected areas covering different geological settings and ensuring relevance for a wide group of stakeholders.

It is expected that the generated knowledge will contribute to the development of new UTES construction projects and increase the utilization of waste heat and renewable energy sources.

2.2 Danish summary

Det Danske EUDP-projekt HEATSTORE har været en del af EU Geothermica projektet HEATSTORE med 23 partnere fra 9 Europæiske lande. Deltagere i det Danske projekt har været GEUS og PlanEnergi.

Projektet har sigtet mod at udforske potentialet for varmelagring i undergrunden (Underground Thermal Energy Storage, UTES) i Denmark og bane vejen for yderligere implementering af teknologien.

Formålet har været at:

- Bidrage med viden fra eksisterende projekter og demo-projekterne i det Europæiske projekt der kan understøtte implementeringen af UTES.
- Introducere 3D geologisk information og foretage en mere detaljeret geologisk karakterisering af undergrunden i udvalgte områder baseret på konkret input fra interessenter.
- Teste nye koder og modellerings-workflows og validere nye og eksisterende beregninger mod moniteringsdata på udvalgte Danske cases.
- Understøtte udviklingen af UTES i Danmark gennem interaktion med interessenter og videndeling med relevante målgrupper.

Mere end 40 eksisterende UTES projekter verden over er blevet analyseret og erfaringerne fra disse har dannet baggrund for generelle specifikationer og best-practice vejledninger for ATES, BTES, PTES og MTES. Fire eksisterende Danske anlæg (1 BTES og 3 PTES) har indgået som cases i HEATSTORE og der er foretaget validering af tidligere modelleringsresultater mod moniteringsdata samt karakterisering af udvalgte Danske fjernvarme anlæg med hensyn til implementering af UTES.

En tidligere screening af potientalet for varmelagring i undergunden i Danmark er blevet opdateret og et tilhørende webtool er blevet udvidet med integration af 3D geologiske data og der er gennemført mere detaljeret geologisk karakterisering i fem udvalgte områder som dækker forskellige typer geologiske forhold og dermed sikrer relevans for et bredt udsnit af interessenter.

Det forventes, at den viden der er genereret i HEATSTORE, vil bidrage til udviklingen af nye UTES anlægsprojekter og øge anvendelsen af overskudsvarme og vedvarende energikilder.

3. Project objectives

The Danish EUDP project HEATSTORE has been part of the overall EU Geothermica project HEATSTORE with 23 partners from the Netherlands, Switzerland, Germany, France, Denmark, Belgium, Spain, Iceland and the Azores and coordinated by TNO in the Netherlands. The participants in the Danish part of the project were GEUS and PlanEnergi, with GEUS coordinating the Danish activities.

The three primary objectives of the project have been to lower the costs, reduce the risks, and optimize the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (UTES) technologies through case studies and implementation and demonstration of novel subsurface heat storage applications, integrated into distinct configurations of heat source networks, combining both heat storage, and heat utilization. The specific research and demonstration objectives of the project were to:

- Characterize the (local) geological, hydrogeological, and hydro-chemical settings necessary to allow UTES technologies to perform under different geological settings, heating demands and heat sources.
- Compose, improve and validate a toolbox that can be used to predict subsurface dynamics, system performance and economically optimise the integration of the geothermal energy storage project within the local heat distribution networks and power infrastructures.
- Design and implement pilot demonstration projects integrating UTES and demand side management in various heat system configurations.
- Monitor the performance of pilot demonstration sites and existing UTES projects focussing on thermal/hydraulic/mechanical/chemical changes in the environment to understand the technical impacts of heat storage. Validate and improve existing process models to enhance prediction of site performance in order to optimize performance and longevity for UTES facilities.
- Determine the current and required stakeholder engagement and regulatory conditions necessary to allow UTES to take place in countries within the HEATSTORE consortium.
- Deliver a fast-track market uptake trajectory for Europe (including: regulations, stakeholder engagement, new business models) promoting development from demonstration phase to commercial deployment within 2 to 5 years on the European market and provide an outlook towards utilization of full potential in 2030 and 2050.

For the Danish part of the project the objectives were to:

- Provide important knowledge necessary for the exploitation of the potential for UTES in Denmark by analysing existing projects and learning from planned demonstration projects in HEATSTORE.
- Perform more detailed characterization and 3D geological modelling of the subsurface conditions in selected areas in Denmark based on a survey of specific interests.
- Test new codes and modelling workflows and validate new and existing calculations against monitoring data on selected Danish cases in order to introduce state-of-the-art methodology.
- Support the development of UTES in Denmark by stakeholder engagement and knowledge sharing with different relevant target groups and levels.

4. Project implementation

In the beginning of the project, the actual start of work was slightly delayed as some national contracts in other countries was delayed. A few deliverables and milestones were consequently also delayed for some time, but were made up later without any problems for the overall timeschedule. Later it turned out that some of the European demonstration projects were delayed for different reasons (technical, administrative, economical and covid-19) with the consequence that no or less monitoring data from the systems have been available for planned validation of the established system integration models in spite of a six month extension of the project. Instead, intended validation methodology for the demonstration sites have been described.

The cooperation in the project has been effective and smooth both among the Danish partners and with the rest of the European consortium. The covid-19 pandemic was an unexpected obstacle for the project work and physical and meetings, but the entire consortium was very efficient in quickly picking up video-conference facilities for both dissemination and cooperation.

The Danish national project has been a screening and case study and activities have taken place according to plans with only minor delays that were later made up and all deliverables finalized by the end of the project. The overall budget was not changed, but minor reallocations between salary and costs were requested and approved during implementation as well as a six month extension of the project was approved.

The risks associated with conducting the Danish project was:

- European partners delaying or failing to contribute to work and deliverables led by the Danish partners – this was mitigated by active follow up in the HEATSTORE Executive Board/Project Management Team and adapting and following an alternative time schedule in case of delays.
- Delays in the planned European demonstration projects – this was mitigated by requesting a six-month extension of the project and adapting alternative plans for system integration model validation.
- Unforeseen changes in key personnel/resource allocation – this was mitigated by a strong and constant focus on the necessary resources and precautions to be able to make these available.

5. Project results

5.1 Overview of project results

The Danish EUDP HEATSTORE project has been an integrated part of the overall EU Geothermica HEATSTORE project and the overview of project results below refers to the entire European project including the demonstration sites and to which the Danish partners GEUS and PlanEnergi has contributed significantly.

WP 1 Specifications and characterization for UTES concepts

General summary

The objective of WP1 was to provide general design considerations and recommendations for different UTES technologies and carry out a screening of the national sub-surface potential for UTES in selected partner countries.

The starting point was a thorough analysis of existing UTES projects and collation of lessons learned leading to a description of general specifications for ATES, BTES, PTES and MTES technologies, respectively.

Finally, the lessons learned from existing UTES projects and the experience gained from the demonstration projects and case studies in HEATSTORE was synthesized into technology dependent best-practice guidelines for developing large scale UTES systems.

The screening of the national potential for UTES has been focusing mainly on the subsurface geological conditions and the results are presented in a dedicated GIS webtool.

Task 1.1 Analysis of existing UTES projects: lessons learned

In Task 1.1 existing and previous UTES projects (ATES, BTES, PTES and MTES) were analysed. The study has been based on both experience from direct participation by HEATSTORE partners and in some cases on literature and other information search. Where possible, details on subsurface conditions, pre-investigations carried out, design, system integration, operation and monitoring information and other relevant framework conditions/prerequisites such as economy and legislation has been collected and the essential lessons learned for each technology has been extracted.

The existing and previous UTES systems and the findings have been described in a written report (D1.1) summarizing the current experience and lessons learned and the results has also been feeding into the demonstration projects in WP4 and the recommendations for replication and upscaling in WP6 together with the work in WP 2, 3 and 5.

In the main report 5 High-Temperature (HT) ATES systems with a maximum storage temperature above 60 degree C and 1 HT-ATES feasibility study are described in more detail and another 4 HT-ATES systems and 2 HT-ATES feasibility studies are part of the overview and background material, while 4 Medium-Temperature (MT) systems with a maximum storage temperature between 30 and 60 degree C and 1 HT-ATES feasibility study has been described in the Appendices as well as 3 of the HT-ATES systems also included in the main report. Out of 9 included HT-ATES systems, 2 is still in operation in Germany and 7 were explorative or demo projects and/or has been closed down for various technical/economic reasons.

For BTES, 8 HT-BTES and 4 MT-BTES systems have been described as well as 5 Low-Temperature (LT) BTES systems for heating and cooling of buildings. For PTES, 5 existing HT-PTES systems and one planned HT-PTES have been described. For MTES a number of Mine-water projects for LT heat extraction heat have been described as well as the plans for the state-of-the-art HEATSTORE MTES demonstration project in Bochum in Germany.

Task 1.2 General specification and design for UTES systems

In Task 1.2, the lessons learned extracted and described in Task 1.1 was translated into general specifications and design for ATES, BTES, PTES and MTES systems. The work resulted in a written report (D1.2) describing physical framework conditions and regulatory and environmental framework conditions for the different technologies as well as description of application and construction and detailed design requirements of the technologies and specifications related to the local geological settings, thermal energy demand and heat sources.

Furthermore, as part of the work in Task 1.2, a generic workflow for fast-track reprocessing of seismic data for better subsurface characterization of shallow aquifers for ATES has been developed in the Netherlands (MS1.3). And in Denmark an initial screening process for identification of the potential for UTES in terms of existing energy systems and favorable geological conditions has been described (MS1.2) based on available existing subsurface data and heating/energy infrastructure data.

Task 1.3 Screening of national potential for UTES

The work carried out in Task 1.3 comprise a screening of the national potential for UTES in the Netherlands, Switzerland, Germany, Denmark and France. Geological, hydrogeological, geochemical, etc. parameters (sedimentary basins, mining basins, host rock formations) have been analysed to identify and characterize locations with more favorable conditions for different types of UTES systems. The work is described in a written report (D1.3).

In the Netherlands, three different types of subsurface potential maps illustrate a high subsurface potential at a regional scale for HT-ATES, especially in the western part of the country, where, conveniently, heat demand likewise is high (metropolitan area, greenhouses, high geothermal potential).

In Switzerland a spatial multi-criteria play-fairway framework was implemented, focussing on the potential of implementation of HT-ATES systems in two main geologic units: the Cenzoic sediments (target of the Bern project) and the fractured Upper Mesozoic carbonates (target of the Geneva project). Subsurface data down to 2000 meters of depth as well as surface constraints have been combined to produce a set of favourability maps representing different potential scenarios.

In Germany focus was directed to the Ruhr-area thanks to its significant amounts of former collieries and the highest population density in Germany. This offers a large potential for including MTES in modern low exergy heat grids.

In France the ATES potential was evaluated according to available public data, by combining subsurface data (e.g. depth of the targeted geological formation, thickness, petrophysical parameters, temperature distribution at different depth, geochemistry of waters), surface data (e.g. location of district heating and cooling networks, land occupation) and energy data (e.g. heat demand, heat demand distribution in time, excess heat sources, excess heat supply in time, geographical distribution). The results show that HT-ATES could be implemented in the Dogger carbonate reservoirs and have the potential to play a key role in increasing the share of waste heat in district heating networks.

In Denmark, an existing initial screening was updated and to improve and ease the UTES screening process further for the Danish stakeholders, an initial first edition web-based screening tool has been expanded with new data and added value in HEATSTORE. Information on aquifers and aquitards from the national Danish groundwater mapping program in terms of the 3D hydrostratigraphical FOHM model provided by Miljøstyrelsen (The Danish Environmental Protection Agency) has been compiled and incorporated in the web tool. The additional data input will strengthen the applicability for the end-users and give a better overview and more detailed information in the process of appointing areas potentially suitable for especially ATES/HT-ATES and BTES, but also for PTES. Furthermore, geological characterization was carried out in five selected areas based on the results of a survey of interest and subsequently dialogue with several interested district heating utilities. An important criterion in this work has been to cover different geological settings in the Danish subsurface and thereby ensure relevance for a wide group of stakeholders.

Task 1.4 Best practice-guideline development for UTES

In Task 1.4, the lessons learned from existing UTES projects and the experience gained from the demonstration projects in WP4 has been synthesized into a set of best-practice guidelines for developing large scale UTES systems (ATES, BTES, PTES, MTES). The guidelines comprise recommendations for pre-investigation and feasibility study, design and construction and operation, monitoring and maintenance.

Six demonstration projects have been established in HEATSTORE covering a wide range of technologies (3 ATES, 1 BTES, 1 MTES and 1 focussing on demand side management), final number of users and amount of heat to be stored.

an overview on the results of the work is given in a written report of the HEATSTORE demonstration projects (D1.4&D4.2&D4.3) as they stand at the very end of the project (October 2021) including a short description of each demo sites. For the eight case studies included in HEATSTORE (4 ATES, 1 BTES and 3 PTES) a short description is also given including challenges and highlights during implementation, lessons learned and recommendations for further test operations. Based on the technical feedback and an analysis of the challenges faced by the demo sites and cases studies, general recommendations for UTES implementation are given and the report is a combined WP1 and WP4 deliverable covering “D1.4 Best practice guidelines for UTES systems”, “D4.2 Summary report of HEATSTORE demonstration projects and case studies – experiences with project implementation” and “D4.3 Demonstrator synthesis & best practice guidelines for replication”.

WP 2 Tools and workflows for modelling the subsurface dynamics

General summary

The main objective of HEATSTORE'S work package 2 (WP2) was to establish modelling workflows and the necessary software tools as an integral part of HT-UTES project development. The objective was approached in three tasks that focused on (T2.1) Modelling toolsets and workflows for optimal and efficient HT-UTES of different types, (T2.2) Integrating advanced academic simulation codes into diverse geothermal project development workflows, and (T2.3) Benchmarking, and improving models of subsurface heat storage dynamics. An added component was to explore how some of the modelling tools could be applied in workflows for other geothermal projects such as high-enthalpy resources on the Azores or assessing conditions of superhot resources in Iceland.

Main outcomes

A strong advantage of HEATSTORE compared to other UTES projects was the diversity of the different case studies that prevented a one-tool-fits-all mentality and allowed broad testing of very different approaches and tools. Given that the different case studies addressed different stages of HT- UTES project development, the modelling activities spanned a wide range from integration of exploration and site characterization results into conceptual/geological model building and reservoir process modelling, through scenario development and modelling for risk assessment, project planning and decision, furthermore modelling for system design and optimization of performance and sustainability to, finally, environmental impact assessment. The example results below shall illustrate how the modelling approaches can be employed to arrive at useful input for project planning and optimization. The full range of results is available as HEATSTORE's deliverable 2.1.

Reliability of modelling approaches

A collaborative benchmarking effort demonstrated that all involved groups were able to accurately model relevant heat and fluid processes, even though workflows and tools varied significantly. An example result is given in Figure 1, which shows good agreement between most groups, only a commercial simulation tool that is not usually employed in HT-UTES modelling showed significant deviation (pink curve). This study showed that the technical maturity of many modern modelling tools al-lows for robust assessment of the subsurface processes acting in HT-UTES, giving credibility to modelling as an efficient and reliable key method in geothermal project development.

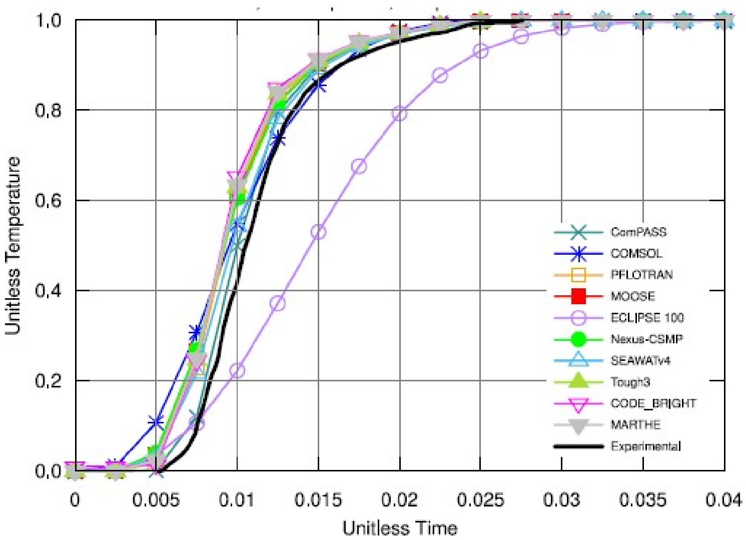


Figure 1. Benchmarking result for advective heat transport in a porous medium.

Prediction and optimization of system operation

A large part of modelling activities related to the prediction of HT-UTES system performance and how it would change for different operational schemes. This allows pre-drilling assessment of the viability of a project. An example of such model is given in Figure 2 that shows how temperature cycles would vary as a function of pumping scheme at the Dutch Agriport A7 HT-ATES demonstration site. Equivalent models were successfully run for other aquifer storage projects (Netherlands, Switzerland), storage in multiple aquifers (Berne, Switzerland), borehole storage (France), mine storage (Germany) and pit storage schemes (Denmark).

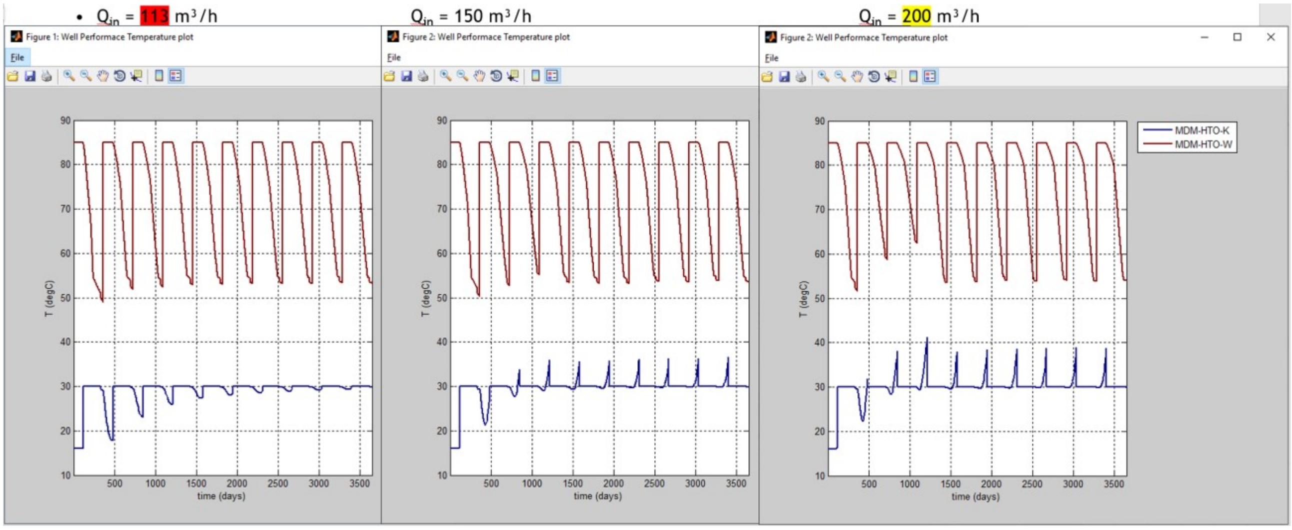


Figure 2. Predicted temperature cycles for different pumping rates for the Dutch Agriport A7 case study.

Further aspects studied addressed, in the pre-operation phase, the possible effect of different geologic parameters on system efficiency (Geneva, Switzerland), the effect of chemical reaction between the operating fluid and the reservoir rocks on scaling and/or corrosion in the system (Agriport A7, Geneva, Berne, Iceland case studies), or the integration into district heating networks (Geneva).

Environmental impact assessment

An activity of high implementation relevance in WP2 was environmental impact assessment via modelling. Many countries have regulations about the maximum extent to which operators are allowed to affect the subsurface temperature, namely in shallow aquifers relevant as drinking water resources.

Shallow HT-ATES may also induce displacement (uplift and subsidence) of the surface in response to injection and withdrawal of water as well as to thermal expansion. Such effects can potentially damage surface infrastructure and impact societal acceptance of HT-ATES operations.

Figure 3 shows examples for these two applications that allow to assess the potential environmental impact already in the planning phase and to test possible mitigation strategies or to optimize operation strategies towards minimizing environmental impact.

Integrating academic modelling tools into diverse geothermal project development workflows for HT-UTES and beyond

A key feature of WP2 was the ambition to demonstrate that advanced academic modelling tools are mature enough to be incorporated into real-world geothermal project development workflows. Several case studies (namely Koppert-Cress, Geneva, and Berne) successfully showed this for application to HT-UTES.

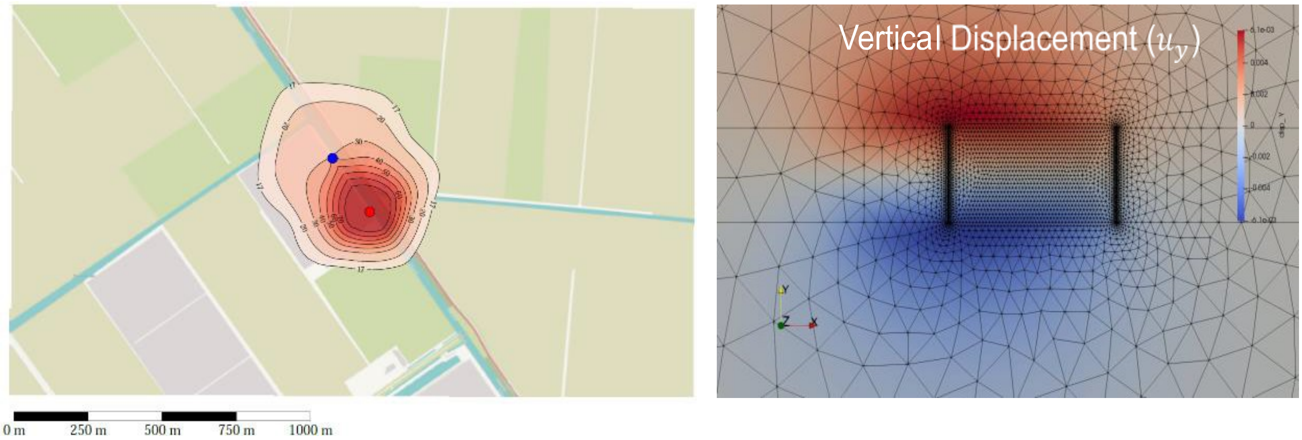


Figure 3. Top: predicted temperature distribution at top of storage aquifer after 30 years of operation at Agriport A7. Bottom: vertical displacement around a storage aquifer at Geneva.

Furthermore, some of the modelling tools employed in HEATSTORE can also be used in assessing high- and superhigh temperature geothermal problems. This was demonstrated for assessing the possible subsurface structure of a volcano-hosted, magma-driven geothermal system on the Azores (Figure 4) and for a pre-drilling assessment of the possible location of superhot geothermal resources in southwestern Iceland.

It is important to note that standard industry tools are unable to model such scenarios. The success of these modelling exercises in HEATSTORE demonstrates how significant value can be added to project development workflows by incorporating advanced academic tools.

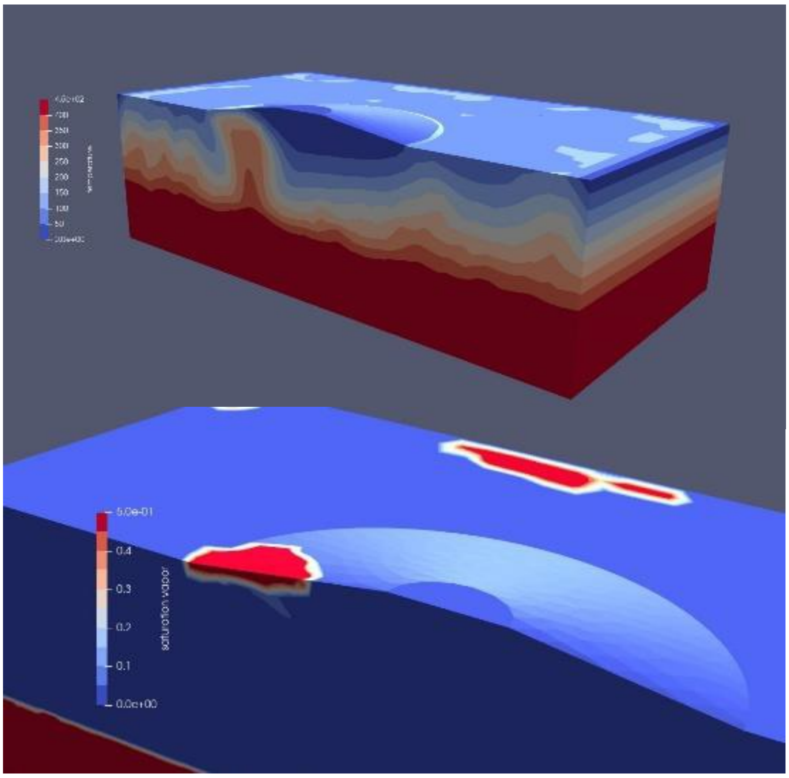


Figure 4. Geothermal system resulting from groundwater flow around a magma body underneath a volcano on the Azores. Top: temperature, bottom: steam saturation.

WP 3 Heating System integration and optimisation of design and operation

General summary

Work package 3 focusses on the integration of UTES in heating systems. The baseline situation for each demonstrator is described in the first task. Next, system simulations were carried out to define optimal design and control strategies. Finally, economical aspects and business cases that support UTES systems in district heating network infrastructure were evaluated.

Task 3.1 Characterization of existing DHC network / situation regarding (flexibility of) demand, supply and grid operation

The thermal characteristics of heat supply and demand at the different HEATSTORE demonstrator sites are summarized. The boundary conditions and thermal characteristics of the heating network (and related infra-structure) are described more in detail, such as heat load profiles, operational temperature regimes and base-line control strategies.

This report also gives an overview on the characteristics of district heating and cooling in Denmark and France based on more general data and or case studies. Here the focus lies more on the different concepts applied in both countries and how they relate to the demonstrators in the HEATSTORE project as well as their repli-cation potential.

Task 3.2 Progressing models and tools for system integration and optimization

The main objective of the work reported in this deliverable is to define and design optimal control strategies for the HEATSTORE demonstrator sites. This deliverable focusses on the system simulations that were carried out in this perspective by each demo partner. Here the term 'system simulations' is interpreted as computer simulations that are carried out on a system level focusing on the thermal aspects which are relevant when implementing UTES technology such as:

- UTES requirements, design and components
- Heat sources (geothermal, solar, waste heat, …)
- Building heating systems
- District heating
- Control systems

The work also builds further on conclusions and lessons learned from HEATSTORE D1.1 about UTES state-of-the-art, example cases and lessons learned. For example; Storage design must take into account the heat consumer specifications and boundary conditions of the heating system where it is connected to (e.g. building heating system) and vice versa. The whole energy chain, from generation to storage and consumer should be optimized. This is where system simulations play an important role. A brief overview of the simulation software and tools used by each partner is presented in Figure .

When looking into the design, integration and operation of UTES in heating systems, many aspects have to be considered. It is key to first understand the associated questions and problems involved before setting up a simulation framework that can be used to provide the necessary answers in order to come to an optimal solution. This is typically linked with the project phase or 'application level' as described in Figure and this can also be concluded from the different focus of each simulation framework discussed in this deliverable.

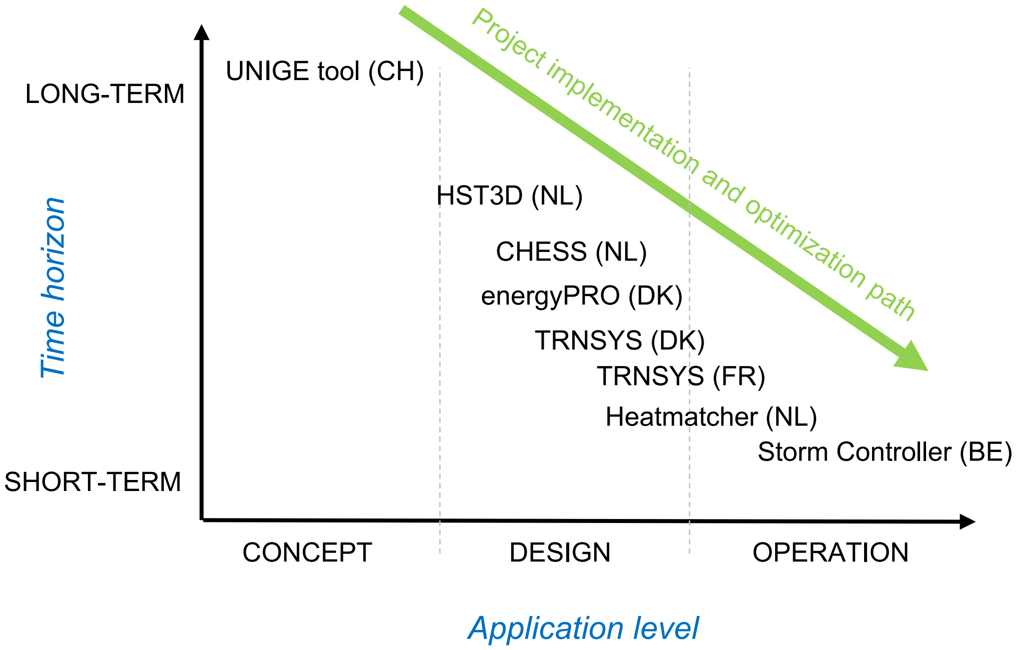


Figure 5. Mapping of the different simulation software and tools according to the time horizon and application level at the demonstration sites.

Performing system simulations requires expertise in different fields which has to be brought together. For instance, geologists can model the subsurface dynamics in great detail while engineers focus more on how the heat can be used. Therefore, system simulations can become very complex and expensive due to the inherent complexity and level of detail of the models used. Simplified models can be used to make system simulations manageable (e.g. TNO used a simplified ATES model in the CHESS simulation environment to speed up the simulation time). Also, when performing system simulations on a higher level, e.g. related to strategical or planning aspects, simplified models can be used to give first insights and to save time.

In addition, each modelling software has its strengths and limitations when considering the whole energy system. It is often necessary to combine different models or software packages in order to construct an all-encompassing system model. This is not always straightforward and sometimes creativity is needed to set up the necessary interactions between different models.

Task 3.3 Design & execution of business case model

The goal of this deliverable is to examine which business model set ups exist to launch increasing levels of thermal energy storage (TES) or DSM in DH grids and to properly understand the benefits of it. In this regard it is important to understand that the benefits of UTES and DSM could be spread out over multiple stakeholders. It is therefore necessary to examine or to take into account the impact of these technologies on other DH stakeholders and on the profitability of the DH network (Figure 6).

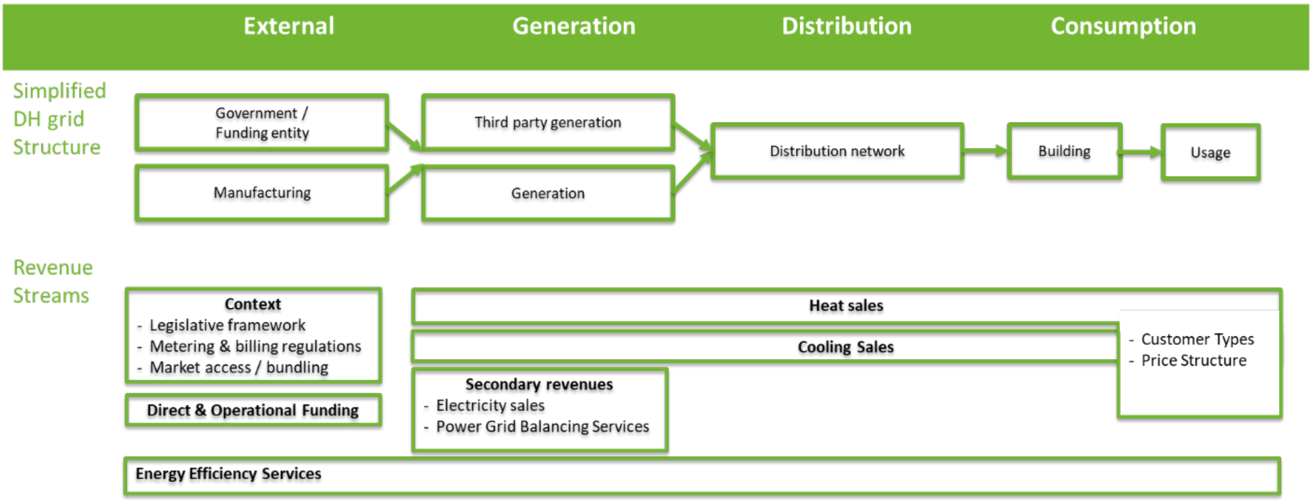


Figure 6. Potential revenue streams in a DHC network (VITO).

District heating grids are increasingly evolving towards a multi-actor system in which multiple (new) actors are involved in different parts of the system (third-party (waste) heat suppliers, storage operators (e.g. HT-UTES), electricity suppliers…), each taking into account the global system situation and possible system interactions. The consequence of this is that an increasing number of actors is affected by changes in the DH grids and/or need to be actively involved to ensure optimal system management. For example, the return temperature of a DH grid is a very determining factor for a DH grid performance. However, the return temperature is highly dependent on the performance of the end-consumers' substations, user installations and behavior. Furthermore, consumers are becoming prosumers as they could potentially deliver residual heat or thermal flexibility to the DH grid by means of thermal energy storage (TES) and DSM. This is demonstrated from a business models perspective for the HEATSTORE demonstration sites and case studies.

Deviations from the original workplan

The goal of the second workshop on system integration (Milestone 3.5) was to evaluate design and operational strategies based on monitoring data from the demonstration sites. Since insufficient data was available as a result of delays in the monitoring campaigns and due to the changes in the French demonstration site, the workshop could not be organized.

WP 4 Demonstrations and case studies: Detailed design and implementation in practice

General summary

The overall objective of WP4 was to develop diverse European demonstration projects, innovative methods and technologies for investigation, design and implementation of heat storage facilities and demand side management in modern district heating networks. The methodology within the demo sites was based on the subsequent replicable development framework:

- Feasibility assessment and technical design
- Construction and proof of concept
- Operation and monitoring phase

A strong emphasis was set on the connection of the WP4 (demo sites) results with the monitoring concepts within WP5, so that the gained storage measurements were utilized for the calibration of the subsurface modelling tools developed in WP2. The outcome in terms of design and operation were synthetized together with the development of best practice guidelines for replication in other European and worldwide locations within WP6.

Due to the complexity and non-standard regulatory framework conditions of the pilot sites, the majority of the demonstration projects faced a delay compared to the original timeline.

Task 4.1 Case study feasibility assessment and technical design for demonstration

During the 1st Annual Meeting of the HEATSTORE consortium, which was held at the TNO offices in Utrecht on 3-4 July 2019, The Netherlands, the current status of the feasibility assessment and design for demonstration projects was presented and discussed by all participating HEATSTORE partners. These findings were summarized in a deliverable (D4.1) with the focus on previous highlights, current status and foreseen challenges of the demo sites and case studies.

In detail all demonstration projects shared their feasibility assessment and their current design status of their project sites and case studies. Important lessons learned from the discussions were the following:

- Thorough understanding of the local geology and hydrogeology is required before making a preliminary design of a storage project, in order to review business opportunities and technical challenges.
- Exploration drilling and testing is strongly advised and should be performed in the projects to gain a better understanding of the local geological and hydrogeological parameters.
- Smart setting of the storage site is highly important from both subsurface and surface points of view. This applies to location specific limitations (buildings, protected areas, geological anomalies, etc.), to opportunities from heating grid connection (end of distribution, temperature levels, sources and demand nearby, etc.) and to legal challenges (ownership and legal framework).

Task 4.2 Demonstrator realization & verification for demonstration

The task 4.2 represents the summary report of the demo sites and case studies within the HEATSTORE project with a strong emphasis on the operational experiences during the project implementation. This task is enclosed within a combined report (D1.4&D4.2&D4.3), which is already depicted in task 1.4 “Best-practice guideline development for UTES”.

Within the HEATSTORE project six demo sites were planned, which covered a wide range of various underground storage technologies (ATES, BTES and MTES) and a demand side management of a geothermal heating network. Table 1 summarizes the status of the demo sites at the very end of the project in October 2021. Nearly all six demo sites faced deviations and delays during the implementation phase, which was drastically aggravated by the negative impacts of the Covid-19 pandemic.

Technology-independent aspects are elicited at the beginning of the report and focus on the crucial elements of the UTES integration into district heating networks, legal framework, social acceptance and local stakeholder involvement and the high importance of proper planning. This is followed by the demo sites and case study summaries, which utilized the following main description structure, in order provide a better comparison between the different sites and studies:

- Challenges and highlights during implementation
- Lessons learned from problems within the implementation phase
- Recommendation for further testing

Table 1. Pilot demonstration projects within the HEATSTORE project (status of October 2021).

Country	Concept of pilot demonstration	Storage capacity & volume	TRL* advance
Netherlands	Geothermal heat doublets combined with Aquifer Thermal Energy Storage (max 85°C) integrated into a heat network used by the horticultural industry	10-12 MW 20 GWh	7 to 8
France	Solar-assisted Borehole Thermal Energy Storage to avoid thermal depredation of the ground	100 MWh	5 to 8
Switzerland Geneva	The development of a deep Aquifer Thermal Energy Storage system (>50˚C) in Cretaceous porous limestone connected to a waste-to-energy plant	~4 MW	to 5 - 6
Switzerland Bern	Surplus heat storage underground (200 - 500m, max 120 ˚C) in existing district heating system fed with combined-cycle, waste-to-energy and wood fired plants.	~1.7 MW	to 5 - 6
Germany	Mine Thermal Energy Storage pilot plant for the energetic re-use of summer surplus heat from Concentrated Solar Thermal power plant (max. 60°C; Δt: 50-60 K) for heating buildings in winter.	20-30 kW 50-90 MWh	to 7
Belgium	Demand side management (DSM) of a geothermal heating network, including assessment of adding thermal storage	9,5 MW** 3 GWh/y***	DSM:7 to 9

*TRL = technology readiness level, ** Capacity of the geothermal source *** Additional annual heat supply due to smart control

Task 4.3 The demonstrator synthesis & best practice guidelines for replication

The objective of this task was the synthesis of the design and operation results of the different UTES systems (ATES, MTES, BTES and PTES), so that best practice guidelines for replication could be elicited.

For a better overview and enhanced comparability of the different UTES systems, the following framework for the replication of best practice guidelines was utilized:

- Pre-investigation and feasibility study
- Design and construction
- Operation, monitoring and maintenance

Based on the technical feedback and an analysis of the challenges faced by the demo sites, general recommendations for UTES implementation were given. Independent of the UTES system, it was highlighted that the performance of a test drilling is highly recommended, so that subsurface conditions and estimated drilling and construction costs could be verified. Also, the realization of a underground numerical model of the anticipated UTES system is strongly advised, which should also possibly be coupled with the surface energy system.

This task is also enclosed within the combined report previously mentioned (D1.4&D4.2&D4.3).

WP 5 Monitoring and validation to assess system performance and workflow

General summary

The overall objective of WP5 is to bridge the gap between the data collected on the demo site and the results of the modelling work for all the demo-sites, in order to adjust and validate our models to facilitate the development of future HT-UTES (ATES, BTES, MTES, PTES) projects.

Task 5.1 Monitoring plan demonstrations and case studies

The Task 5.1 (Monitoring plan demonstrations and cases studies) objective was to design and develop monitoring plans and strategies for HT-UTES demonstration projects. The related deliverable D5.1 Design and develop monitoring strategies for HT-UTES demonstration projects has been completed and delivered on schedule. This work was performed with a high level of exchanges between the different partners involved in the demo-sites of HEATSTORE, each partner bringing its own experience from its specific background and past experience on different projects.

The information to be collected on the demo-sites was also shared with the simulation teams in order to ensure that the monitored data will allow to properly constrain the models to make them predictive and adapted for the design of future HT-UTES at a larger scale.

A compilation of the monitoring plans was conducted in the different projects. One very good point illustrated from this work is that all the projects gather or will gather the minimum amount of data to enable assessing both the efficiency of the energy systems and their impacts on the environment.

HT-ATES systems	Pressure		Temperature		Flowrate		Water analysis		Bacteria		Monitoring well(s)		Specific tests	InSAR	Micro seismic
Koppert-Cress (NL)	Y	hourly	Y	hourly	Y	hourly	Y	3-months	N		Y	Temp-profile		N	N
Geneva (SWI)	Y		Y		Y		Y		N		N		Well test	Y	Y
Bern (SWI)	Y	min/hr	Y	min/hr	Y	min/hr	Y	Regularly	Y	Regularly	Y	Temp-profile	Well test	N	N
HT-MTES systems															
Markgraf II (DE)	Y	min/hr	Y	min/hr	Y	min/hr	Y	3-months	N		Y	Temp-profile	Well test & tracer test	N	Y
Deep doublet															
Mol (BE)	Y	min/hr	Y	min/hr	Y	min/hr	Y	Regularly	N		N		Well test & tracer test	N	N
Hengill area (IS)	Y	2 weeks	Y	2 weeks	Y	2weeks	Y	2 weeks	N		Y	Temp-profile	Well test & tracer test	N	Y

HT-BTES systems	Collector pressure		Temperature			Flowrate		Monitoring well(s)		Humidity in cover	Solar radiation	Air temp.	Wind speed
Braestrup (DK)	Y	10 min	Y	30 min	each line & global	Y	Heatflux : 10 min	Y	Temp-profile (probes) : 30 min	Y	Y	Y	Y
BETSmart (FR)	Y	min / hourly	Y	min/hourly	each line & global	Y	flow and heat : min/hourly	Y	Temp-profile (probes) : hourly / daily	N	N	Y	Y

HT-PTES systems	Collector pressure		Temperature			Flowrate		Profile		Water level in storage
Marstal (DK)	Y	10 min	Y	30 min	Various locations : inside & outside	Y	Heatflux : 10 min	Y	Every 0.5 m	Y

Figure 7. Compilation of the monitoring plan (from D5.1).

It is also interesting to observe that some projects will test innovative or advanced techniques like DTS (optic fibers), repeated InSAR, microseismic which will be helpful to investigate their added value and potential for future application in other, future sites.

Task 5.2 Monitoring results

This task presents the actual measurements performed on the demonstration sites, which can be compared to the initial monitoring plan: during the implementation of the projects, slight adjustments have been made to the initial monitoring plan on certain demonstration sites.

Task 5.3 Model validation for subsurface dynamics

Complex time-consuming numerical subsurface models are required for the design of Underground Thermal Energy Storage (UTES) systems. Such models imply large computation time and cost due to the large number of numerical evaluations required for each model. In the framework of the HEATSTORE project, UTES systems require to develop both (1) detailed numerical models of the subsurface dynamics requiring significant simulation time (WP2 – Modelization: Tools and processes to model underground flows), and (2) surrogate/proxy (simplified) models that can provide quick answers essential for the design optimization (WP3 – UTES Integration and optimization of the network) and monitoring (WP5 – Monitoring/Validation of the models for the system efficiency) of UTES systems.

Two important modeling efforts have been performed and published as part of the HEATSORE project:

- Development and benchmarking of detailed (3D) numerical models of subsurface heat storage dynamics fine characterization of UTES systems (with explicit account of heterogeneities) (Alt-Epping and Mindel, 2020); and
- Development and calibration of simplified (proxy) models that are analytical approximations of UTES systems for the design optimization and uncertainty analysis (with implicit account of heterogeneity) (Rohmer et al., 2020).

The deliverable of this task focuses on the validation of the detailed numerical models of the subsurface dynamics. It also provides definitions used in the literature about model validation, presents validation methods, and lists examples of validation studies relevant to UTES applications. Further, it presents validation tests and experiments conducted on numerical models used for the different HEATSTORE case studies. Finally, the deliverable summarizes and discusses the validation case studies.

Task 5.4 Model validation for system integration and optimization

Models are per definition simplifications of the systems that they represent. Model validation is the process of comparing the predictions to real world observations, and it is needed to confirm that the predictions are as accurate as needed for their purpose. If a model is not as accurate as needed, the model needs to be calibrated. Calibration (or model matching) implies the adaptation of model parameters to improve the comparison between model prediction and observations in an iterative approach.

The intention of the current report was to validate the system integration models developed in work package 3 of the HEATSTORE project using monitoring data from the demonstration sites. Unfortunately, the demonstration sites are not as advanced yet. Only one of the sites for which system integration modelling has been performed has become operational within the timeframe of the HEATSTORE project, which is the Dutch HT-ATES site in Middenmeer, The Netherlands. But even for this site, monitoring data relevant for the model validation is not yet available. The current report therefore describes the intended validation methodology for each of the demonstration sites.

Task 5.5 Uncertainty management

The design of complex systems such as Underground Thermal Energy Storage (UTES) requires not only the modelling of the whole installation and optimisation of the overall design but also to consider the large variety of different uncertainty sources that affect each stage of the modelling chain.

The Task 5.5 report provides an overview on the different methods that are available to deal with uncertainties, to discuss how they may be helpful for decision-making, and to highlight their advantages and limitations, focusing on an illustrative case study that consists in prior assessment of a go/no-go for a heat storage, depending on the storage efficiency.

These methods were deployed on real cases studies on the Bern demo site and at a more regional scale and with a generic storage case study in the Dogger Basin. For the Bern and Dogger case studies, we made the choice to represent the rock properties parameters by equivalent values but it constitutes a limitation of models, and some physical reservoir behaviours cannot be faithfully modelled without considering a complete representation of the reservoir properties such as porosity and permeability. Depending on the modelling objectives and on the availability of data, a more refined geological model may be key to move closer to reality. Uncertainties related to geological modelling may be assessed either by qualitative assessment or by quantitative assessment. A last case study was proposed to demonstrate how rock properties (porosity and permeability) could be predicted at unsampled locations for a demonstration site around Geneva, using geostatistics and machine learning. These techniques were successfully applied to elaborate rock properties maps.

Through a rapid overview on a fictive basic case study, and through 3 consistent case studies focusing on different specific bricks of uncertainty treatment, the Task 5.5 report proposes a number of advanced tools to deal with uncertainties in highly uncertain contexts that are expected in heat storage activities. Discussions concerning these different contributions between partners involved in WP5 were also the occasion to discuss limitations, strengths, possible improvements and perspectives of future work.

WP 6 Fast-track market uptake in Europe & dissemination

General summary

The HEATSTORE program proposed to achieve the following goals:

- Maps (GIS) showing the potential for implementation of the technology across Europe. The outcomes will help decision makers (local, national, regional) by describing the potential for flexible energy systems with UTES for countries under study based on GIS potential maps for UTES technologies.
- Improved understanding of societal acceptance of UTES technologies and sharing results and best practice experience from demonstration projects and case studies with relevant stakeholders and policy makers. Identification of heat storage project stakeholders and awareness of the possibilities offered by the subsurface supported by the feedbacks from the UTES demonstrators. And addressing the social engagement and acceptance of geological heat storage and demonstrating the potential environmental impact of UTES technologies.
- Overview of regulatory frameworks for a variety of UTES systems that may be developed throughout Europe. The regulatory guidelines should assist policy makers in issuing permits and drafting rules and laws in relation to flexible energy networks with UTES, thereby facilitating the introduction and deployment of the technology.
- Overview, evaluation and quantification of new business models for flexible energy networks with UTES.
- A roadmap for flexible energy networks with underground thermal energy storage in Europe. For quick and efficient deployment of this technique, it is important to communicate important barriers and key success factors and to see how these will interact on country specific circumstances.
- HEATSTORE will support industry and project developers by providing best practice guidance on technical, economic, and regulatory issues.

Task 6.1 Technical future potential for smart heat systems with underground thermal energy storage in Europe

Task 6.1 took results from WP1.3 and assessed the technical future potential for smart and integrated heating networks with UTES in Europe by using and updating existing data on district heating networks, power and heat sources, demand development and subsurface geological conditions.

Important outcomes were integrated in GIS maps for selected countries (at least including Netherlands, Switzerland and Denmark), mapping the technical potential. A web based platform (see screenshot below) has been developed and presents subsurface screening results and map themes to support stakeholders in the Underground Thermal Energy Storage (UTES) screening process. The partner countries have focused on specific technologies within the project, meaning that the national UTES screening is targeted differently. The tool provides quick access to national screening maps for UTES technologies that are valuable for national stakeholders. A thorough description of the used background data and the published maps in this storymap is found in deliverable D1.3. Metadata descriptions for the national published dataset can be provided to stakeholders upon request.

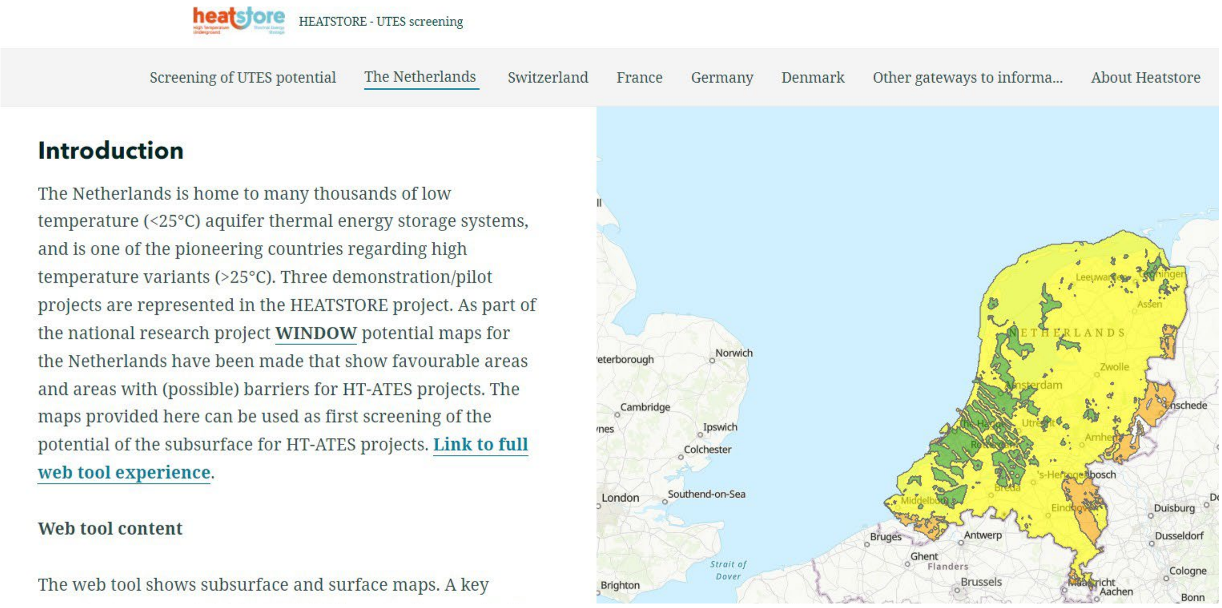


Figure 8. HEATSTORE GIS storymap (D6.1).

Task 6.2 regulatory and policy boundary conditions

Task 6.2 has been assessing how UTES technologies can be implemented within Europe by providing a detailed analysis of current regulations and standards. This report focuses on the existing regulatory frameworks associated with UTES technologies in a sample of several countries (Netherlands, France, Switzerland, Denmark, Germany) participating in the HEATSTORE project, specifically observing if enabling policy frameworks are already in place and identifying potential barriers for these technologies. The report also summarises information on best practice regulatory frameworks for the above listed countries (D6.2).

Task 6.3 Evaluation of new business models for flexible energy systems with underground thermal energy storage in Europe

The work in this task has yielded interesting insights in the market potential (e.g. drivers, barriers, volume, energy system development) for several UTES technologies in the participating countries (Netherlands, Germany, Switzerland and France). In addition, for several projects the business model has been analysed. This yields new insights that can be used for future commercial and demonstration projects to develop sustainable business models. The key lessons are: 1) that although projects are unique (due to geographical and geological circumstances) the projects can follow a structural approach to establish a robust business case model for UTES in early phase of project development; 2) The shown example projects indicate value stacking of value propositions adding to a positive business case. But in many situations requires (policy) incentives to achieve a positive business case. Decreasing financial risk for project developer and operators is therefore required.

This work has given future projects economic boundary conditions for business models and provides recommendations for replication of new business models for UTES in Europe (D6.3).

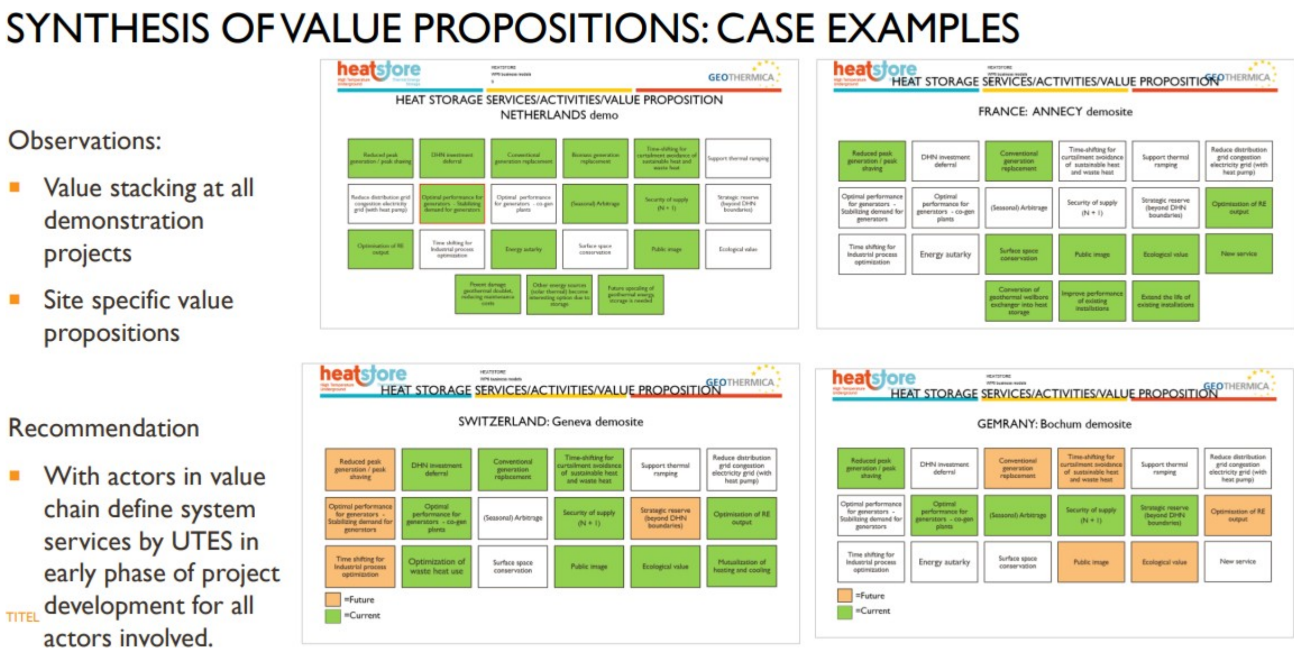
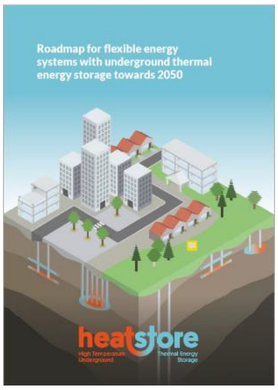


Figure 9. snapshot from the report indicating various business models value stacking for UTES (demonstration) projects.

Task 6.4 Roadmap for flexible energy systems with underground thermal energy storage in Europe



This Task has delivered a roadmap for the deployment of smart heat grids with UTES delivering flexibility to the European energy systems. The roadmap also forms a synthesis report of all the preceding tasks (technical potential, regulatory framework and economic potential). It has been created by summarising work done in HEATSTORE and by inviting partners and external stakeholder in a workshop series to identify barriers and drivers for UTES development and deployment. The roadmap delivered and overview of action points / recommendations for the immediate (2-5 years) and long term (2035-2050) that are needed to implement and fast track UTES concepts across Europe.In the webinar series in October 2021 the roadmap outcomes have been shared with a wider audience, including participants from DG ENER and EASE network (D6.4).

Task 6.5 Stakeholder engagement and dissemination

An internal HEATSTORE plan for communication and dissemination has been reported in deliverable D6.5.1 (confidential).

In Task 6.5.2 we studied the public acceptance (often referred to as social acceptance in the literature) of underground heat storage (UTES) and geothermal technologies. This was done partly as a literature review on public acceptance, and partly as a case study on UTES and geothermal technologies performed by partners within the HEATSTORE project. The work comprised analysis of 11 cases of UTES and geothermal technologies. For UTES technologies the main public concern has been economic risk and risk of negative consequences for groundwater and drinking water quality. For geothermal technology, the risk of induced earthquakes is likely the most important concern judging from previous experiences. Value perspectives of community acceptance have been identified and are related to economical, psychological, sociological, and environmental issues. Finally, an overview of recommendations on community acceptance have been presented based on reported perceived risk of the HEATSTORE cases combined with insights on community acceptance from comparable technologies (D6.5.2).

The scientific relevance of HEATSTORE is documented by the high visibility of project partners at various conferences and knowledge sharing events, and by the considerable number of publications in scientific journals (e.g., Applied Energy, Geothermics) and conference proceeding volumes.

Participation in scientific conferences include both small technical meetings as DECOVALEX, GET2020 or Enerstock2021 and European or global sector events as the European and World Geothermal Congresses or the European Workshop on Underground Energy Storage. HEATSTORE partners were involved in these conferences with oral and poster contributions.

Results of HEATSTORE were shared with the interested (scientific) public in a series of six webinars in September/October 2021. The webinar series consisted of general considerations of UTES and its applications, two examples of realized demonstration projects (HT-ATES project in the Netherlands, MTES project in Germany) and a table discussion on the role of UTES in the European future energy system.

A full list of dissemination activities (D6.5.3) is included as Appendix I to this report, see section 8.

Task 6.6 Environmental impact

In Task 6.6 a study aimed at identifying the environmental effects of the implementation of UTES systems has been performed. The overall approach was to highlight the effects rather than quantify the impacts also emphasising the potential positive effects such as the reduction of the CO2 intensity for each site. The results are based on the outcomes from the different activities carried out in WP2 (subsurface modelling), WP4 (Implementation of the UTES systems at the study sites) WP5 (Monitoring of the study sites). The challenges of the study are mostly related to the heterogeneity of the data available across the different phases of each UTES project due to the different level of maturity and advancement at each site. Additionally, the type of data collected might vary from site to site due technical requirements (e.g. for drilling operations), and country-specific regulatory framework constraints. We identified a set of potential common effects that would eventually allow to compare the performances among UTES types. Effects for both the subsurface and surface compartments have been identified, and then we looked if such effects were predicted, assessed and mitigated. Then we focussed on a fast-track risk assessment based on the correlation between probability and consequences of each effect to occur.

Risk / Effect	HT-ATES							MTES		BTES	PTES
	Koppert_Cress	NIOO	GEo-01		GEo-02		Bern	Bochum		Brædstrup	Marstal
	Operations	Operations	Drilling	Operations	Drilling	Operations	Operations	Drilling	Operations	Operations	Operations
Air quality	L	L	M	L	M	L		L	L	L	L
Noise and vibration	L	L	M	L	M	L		M	L	L	L
Formation water quality	M	M	L	H	L	H	M	M	M	L	M
Formation water temperature	M	M		M		M				L	
Surface clear water	L	L	M	L	M	L		M	M	L	L
Soil occupation	L	M	M	M	M	M		L	L	L	L
Wastes and dangerous substances	L	L	M	L	M	L		L	L	L	L
Environment	L	L	L	L	L	L				L	L
Nature	L	L	L	L	L	L				L	L
Soil mechanics	L	L		L		M		L	L	L	L
Seismicity	L	L	M	M	M	M		L	L	L	L
CO2 intensity redyction	H			H		H			H	H	H

Figure 10. Overview of the risk of environmental effects in several UTES projects studied in HEATSTORE (D6.6).

WP 7 Project management

General summary of Task 7.1 Project planning, monitoring and execution; Task 7.2 Legal support; Task 7.3 Financial support; Task 7.4 Project meetings

WP7 included all project management activities: operational, legal, and financial guidance of the consortium. It includes also reporting to the GEOTHERMICA office and to the national funding agencies in the participating countries.

After a positive evaluation procedure of the project and receipt of the invitation letter to prepare the contract, the implementation agreement between TNO as Coordinator and the GEOTHERMICA office was signed on 19 Apr. 2018 (TNO) and 3 May 2018 (GEOTHERMICA representative), respectively.

The final version of the Consortium Agreement, signed by all 23 consortium partners and being effective from 1 May 2018, was concluded on 12 June 2018.

In July 2020, the consortium submitted a extension request to the GEOTHERMICA office and requested an extension of HEATSTORE project by 6 months to 31 October 2021. Reasons for the request were a delay of many project activities due to the Coid-19 pandemic and a delay in the demonstration projects due to various technical, operational and legal challenges. The extension request was approved in April 2021.

The official kick-off meeting of HEATSTORE was organized on 17-18 Sept. 2018 at TNO in Utrecht. The kick-off had 34 attendants, 3 of them being representatives of the national funding agencies.

The 1st Annual Meeting with almost 50 participants was again organized at the TNO office in Utrecht on 3-4 July 2019 (meeting report is available). Meeting participants critically discussed the demonstration projects and case studies with a focus on the business cases and legal, operational and technical challenges.

The 2nd Annual Meeting with 64 participants was co-organized by ETHZ and TNO. It was a virtual meeting due to the travel restrictions related to the Covid-19 pandemic. Participants critically discussed progress of scientific activities and specifically the development of the demonstration projects.

The 3rd Annual meeting (the close out meeting) unfortunately could not be organized as physical meeting due to still prevailing travel restrictions across Europe related to the Covid-19 pandemic. Instead, the consortium organized a webinar series consisting of 6 webinars in September-October 2021. All webinars attracted ca. 60 participants mainly from European but also overseas institutions. The last webinar was a table discussion on future role of UTES in the European energy landscape with discussion partners from EASE and EC-DG Ener.

Operational control on the project was maintained by the Executive Board and Project Management Team (EB-PMT) which regularly had virtual meetings of approximately 1.5 h duration. The EB-PMT consists of the Coordinator, the 9 National Leads, and the WP Leads (5 National Leads are also WP Lead), altogether 11 members. Until October 2021, a total of 16 EB-PMT meetings were held. The EB-PMT discussed the operational progress, challenges and possible solutions, the status of the deliverables and workshops/meetings to be organized. Meeting minutes including an action list were always prepared by the Coordinator and made available to the consortium partners.

Operational activities also included the organization of topical workshops. In the entire project period, two international workshops have been organized:

- Workshop at IEG Fraunhofer in Bochum on 22-23 Nov. 2018 with 26 participants. Topics of the workshop included MTES (Mine Thermal Energy Storage) and activities and challenges in WP1 and WP3.
- Workshop at Univ. of Geneva in Genève on 7-8 April 2019 with 32 participants. This workshop focused on activities and discussion of activities and results WP2: modelling concepts for the demonstration projects.

The mandatory traffic light reports to GEOTHERMICA office, to be provided every 6 months, were sent on 9 Nov. 2018 (1 May 2018 – 31 Oct. 2018), 16 May 2019 (1 Nov. 2018 – 30 Apr. 2019), 7 Nov. 2019 (1 May 2019 – 31 Oct. 2019), 28 May 2020 (1 Nov. 2019 – 30 Apr. 2020), 3 December 2020 (1 May 2020 – 31 Oct. 2020), and 10 May 2021 (1 Nov. 2020 – 30 Apr. 2021).

Additional reporting and meetings took place on national level and were organized by the national leads of participating countries.

6. Utilisation of project results

The described technological and commercial results will be utilized by PlanEnergi when introducing PTES solutions in Denmark, because the screening instruments developed by GEUS is an excellent instrument when placing the storage. Also, the Roadmap will be used convincing Danish utilities about the readiness of PTES solutions.

Outside Denmark PlanEnergi have already been involved in 3 new PTES projects in Poland, Germany and France and more projects are in the pipeline. The market situation is better now compared to the project start because it is obvious, that DH utilities will have to reach carbon neutrality within a short period, and in many cities excess heat is available in the summer period. Also, flexibility in the district heating systems is more and more needed.

Until now competition in consultancy for PTES is very limited. This is expected to change, when foreign consultants will be more involved in large scale storage projects.

The barriers for realizing new PTES projects are still the price and also problems with the lid construction in some of the first Danish PTES storages. Especially German utilities want proven solutions. Thus, the PTES development has to be continued to demonstrate reliable and economically feasible solutions.

The improved GEUS heat storage web tool accessible for all stakeholders and the co-operation with Danish DH utilities on local subsurface characterizations have significantly boosted the maturity level of the technologies BTES and HT-ATES in Denmark. The project results have been, and will continuously be, communicated by GEUS to utilities, authorities, energy planners and consultancies to make early-stage awareness of these technologies in the process towards reaching the 2030 climate goals. The completed pre-feasibility studies in different geological settings and the connection to surplus heat has been a first step towards commercial BTES and HT-ATES systems.

Several Danish consultancies with expertise in water supply are today focusing more on groundwater-based energy systems like ATES than 3 years ago. And as good Danish business cases for LT-ATES are being documented and disseminated, also heat storage with ATES is receiving more attention and technical interest. Along with the Netherlands, the Danish stakeholders, especially the commercial players within the water business, have a unique opportunity to be a part of the development of UTES systems in a flexible European energy mix in the coming years, cf. the HEATSTORE Roadmap.

The main barriers regarding the commercialization of BTES and HT-ATES systems in Denmark are especially the lack of a demonstration pilots and regulative limitations on allowed injection/storage temperatures in the subsurface.

7. Project conclusion and perspective

The heating and cooling sector is projected to remain the largest energy sector in the long-term under both business-as-usual and decarbonisation scenarios and the transition of sector in Europe will depend strongly on the local, regional and national resources and priorities. A mix of solutions will be required: electrification with renewable power (wind, geothermal, PV, ambient heat and others), renewable or low-carbon gases (e.g. hydrogen, biogas, synthetic gas) and renewable and waste heat sources for heating and cooling networks and Underground Thermal Energy Storage (UTES) where excess heat is stored when available by heating the soil or a fluid in the subsurface and later retrieved has the potential to overcome short and long-term mismatch between demand and supply and therefore support the energy system by providing flexibility and adequacy in a sustainable way.

Thermal energy storage is already implemented in heating networks in the form of surface tanks storage and, although still highly limited, by Underground Thermal Energy Storage (UTES) to support the use of surplus heat from industry and the implementation of renewable heat sources such as bio-Combined Heat and Power (CHP), geothermal, and solar energy. It provides the opportunity to integrate variable renewables (wind, solar) and baseload thermal heat sources (geothermal, biomass, surplus heat, ambient heat). Herewith the application of UTES can help solve the problem of seasonality in heat demand and can reduce the carbon footprint of the energy sector. The application can be widely applied in energy infrastructures supplying sustainable and low carbon heat to industry, agriculture and district heating grids. It also provides a valuable coupling to the electricity sector allowing to absorb electricity surpluses through power-to-heat solutions.

Compared to other storage techniques UTES is economically competitive and it is compatible with many (local) renewable energy sources. Especially, synergy is possible when heat and electricity sources with low marginal costs are available (e.g. geothermal, solar thermal, waste heat, environmental heat with heat pumps). It is an environmentally friendly storage technique which requires a low use of rare or critical earth minerals and may, although technology dependent, help reduce the spatial footprint of the future energy system.

Globally, low temperature UTES systems provide already for several TWh of storage. The high temperature UTES options can best be defined as early commercial or in the pilot/demonstration phase, depending on technology. Over the next decades these technologies and project portfolio could grow towards tens or hundreds of TWh of storage capacity in Europe. UTES has then the potential to become the largest heat storage option and be an integrated part of the energy system in large parts of the EU, but this requires that hundreds to even thousands of large-scale UTES systems become operational in Europe in the next thirty years.

7.1 Current challenges for large scale implementation of UTES

In the HEATSTORE project the current challenges for ATES, BTES and PTES have been identified:

ATES

- Maximum injection temperature (20-25°C) in the regulation in some countries is a serious limiting factor
- General lack of clear regulation
- The "geological risk" regarding the aquifer/geothermal reservoir is significant – the deeper the reservoir, the higher the risk
    - In HEATSTORE TNO has been working in better subsurface characterization through reprocessing of existing seismic data
    - In HEATSTORE ETHZ and other partners in WP 2 have been working on improving models for characterization of reservoir dynamics
- Clogging of fines and calcite scaling are known problems
    - Ca/Na ion exchanges can be used to prevent precipitation of $CaCO_3$, but may cause clay swelling
    - HCl-treatment is effective, but expensive and subject to public acceptance
- Large initial investment for preinvestigations and modelling

BTES

- There is good business case for BHE systems for seasonal heating and cooling of buildings and there are several hundred of systems in Europe – but for heat storage alone, BTES can be an expensive solution, especially if a high thermal power is needed
- Large initial investment for drilling and top isolation
- A clear regulative framework is missing in many countries
- Risks of not getting a permit and/or a long permit procedure
- In HEATSTORE STORENGY is transforming an existing, but depleted (too cold), BHE system into a BTES for surplus heat storage

PTES

- Large space requirements – not ideal in urban areas
- Straight forward, but time-consuming permit procedure
- Generally, very successful systems with recovery efficiencies up to 60-90%
- One PTES system has experienced a leak from the basin which could be repaired after the unloading period
- Rainwater lakes/water ponds on the top lid can be a problem
- Some PTES systems has experienced problems with leaks in the insulating lid and wet insulation material
- In Denmark, focus in recent years has been to improve the construction of the lid
    - Sectioned lid constructions
    - Layering of insulation material
    - Better materials

7.2 Contributions to the development and deployment of UTES

The work in the HEATSTORE project have contributed broadly to the understanding of the various steps in the realization of UTES projects from the feasibility study and pre-investigation phase to construction and system integration:

- The geological conditions are of paramount importance and new characterization tools to better understand the subsurface and de-risk UTES projects have been developed as well as better maps of the UTES potential in the participating countries are provided.
- For HT-ATES, the subsurface reservoir dynamics are equally important and enhanced models to simulate the subsurface performance have been developed.
- For system integration UTES performance (proxy) modelling and demand side response control have been included in heat grid optimization software packages.
- New UTES projects have successfully been started up within the project duration and enhanced monitoring have taken place in existing UTES projects.
- HEATSTORE represents the start of an international UTES community for sharing learnings of successes and challenges in:
    - Pre-investigation and design
    - System integration and business models
    - Regulatory framework
    - Stakeholder perception and engagement
    - Monitoring and environmental performance

7.3 What is needed to progress Underground Thermal Energy Storage?

Although the HEATSTORE project has made significant contributions there are still many actions that are needed to progress the development and deployment of UTES across Europe.

Technology & Innovation

It is critical for UTES technologies to further reduce the subsurface and technological risks and improve the performance. The HEATSTORE project has proved that demonstration sites are crucial to ensure that tested technologies can be brought to market and valorised by the relevant stakeholders. Learning by doing is the best way to gain skills and improve the knowledge base and for this purpose, demonstration sites with extensive research programs are key. Another important lesson is that further innovation actions are needed to improve the efficiency of a UTES in the (first) operational years as this will enhance the business case and lower the financial risk. Some technology specific operational risks need attention and needs to be mitigated to enhance investments in UTES technologies. For all technologies improved insight in the subsurface suitability for the different UTES technologies is needed across Europe to lower the threshold for spatial planning agencies and for heat network developers to include UTES as part of their energy system design. Finally, any UTES project needs optimal integration in the heat grid in such a way that it improves the flexibility and sustainability of the heat network and increases its cost-efficiency.

Market & Economics

A key insight observed within the HEATSTORE project and in literature is that large-scale thermal storage solutions are very cost-effective. However, actions are needed to further lower the project costs and investment risks for large-scale market development of UTES in Europe. HEATSTORE has helped to recognize that every underground thermal energy storage project is unique, but that a common approach can help to establish a robust business case. A long-term learning curve to further drive down investment and operating cost of UTES technologies must be established. This requires research and innovation, but also learning by doing so that replication can help improve project economics (CAPEX and OPEX). As with other energy storage technologies it is critical to get the revenue pillar of the business model right. This is achieved by matching a revenue model for the value that a storage project provides to the system and to individual actors in the value chain. UTES projects have site specific value propositions and thus require an approach to identify, stack and valorise multiple propositions. In many situations the revenues are not sufficient and thus requires (policy) incentives to achieve a positive business case. Finally, the ownership model and market structure shapes the business model for UTES. This means that clarity of roles and responsibilities is required and to find ownership and contractual relationships between partners that optimally fit with the business case.

Society & Environment

Some environmental impacts of UTES systems are inevitable; the local extraction and injection of groundwater and the thermal effects induce per definition physical, chemical and microbial changes. The environmental impacts are highly case- and location specific and need to be evaluated in the early phase of a UTES project development. A key learning is that projects need guidelines to evaluate and mitigate environmental impacts and robust monitoring programs to support containment of risks. In order to build trust and engagement among stakeholders, including the public, it is important to create awareness in UTES development in general and in an early stage of UTES projects specifically. It is then needed to provide balanced information on environmental risks and benefits. One means to this end could be to draft a spatial planning for the subsurface to start raising awareness and to reduce competition of subsurface space in future plans.

Policy & Regulations

The key action is to start strategy formation on UTES in local, national and EU energy system planning. And facilitate the achievement of these strategies by the timely development of a supporting regulatory and policy framework. The integration of UTES technologies in future energy scenarios and energy system planning will allow the demonstration of the crucial role that UTES can play in the decarbonatization of the heat sector. This will support the development of local and national roadmaps for a sustainable heating and cooling supply.

Including UTES in energy and climate strategies of cities, industry clusters, regions, member states and Europe requires awareness and capacity building among stakeholders at different geographical levels and across industry, science, governments and the public. The local and regional governments are typically very important as heating and cooling networks span across their jurisdiction. This also requires early local public stakeholder engagement in specific UTES projects for successful, large scale deployment of the technology. And when included in a robust communication and engagement strategy towards all relevant stakeholders, this can be a crucial support in the creation of awareness.

UTES projects are an integral part of large and long-term infrastructure investment decisions that require investment certainty for project developers. Simple and clear support schemes and an enabling market framework are required to support stakeholders in the development of UTES systems.

Furthermore, The HEATSTORE research program studied existing regulatory frameworks of a sample of EU member states identifying existing regulatory frameworks and potential barriers. The recommendation is that clear regulations specifically for high temperature UTES technologies need to be developed to smoothen the large-scale deployment.

Short term specific actions for tomorrow

The need for progress and inclusion of thermal storage in a new comprehensive approach to energy storage has recently been highlighted by the European Parliament - a clear recognition of the demand for further actions on the short and longer term. Considering that the timeline from project idea and up to an operational system spans several years, large-scale deployment of UTES should start now. Specifics in geology and surface restrictions may provide better conditions for some technologies and exclude others. Therefore, a portfolio of different UTES technologies must be available and technologically advanced so location specific needs and possibilities can be identified and addressed. This requires as a minimum the following urgent actions:

1. Stronger awareness and strategy for UTES on local, national and European level
2. Help for early movers with the financial de-risking and support schemes for early commercialisation
3. Launch of a European Underground Thermal Energy Storage Alliance

8. Appendices

All public project reports can be downloaded from the HEATSTORE project website: www.heatstore.eu.

The HEATSTORE GIS tool can also be found on the HEATSTORE website: HEATSTORE UTES screening.

Appendix I: HEATSTORE, Record of dissemination activities: reports, papers, conference contributions and media articles

Appendix I

HEATSTORE

Record of dissemination activities: reports, papers, conference contributions and media articles

Prepared by: Holger Cremer, TNO

Checked by: Geoffroy Gauthier, PlanEnergi

Please cite this report as: Cremer, H. (2021): Record of dissemination activities: reports, papers, conference contributions and media articles. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 16 pp.

This report represents HEATSTORE project deliverable number D6.5.3.

HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.
This project has been subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117), from the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain).

About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority – 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA – ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
2021.11.11	Final edited version
2021.11.19	Revised final edited version

Table of Content

1 Introduction

Results generated in the HEATSTORE project were shared with stakeholders and various user groups via different channels. These include the project website on which most deliverable reports were published, scientific publications and conference contributions. HEATSTORE was prominently represented with various contributions from all work packages on two of the biggest geothermal conferences: the European Geothermal Congress (The Hague, June 2019) and the World Geothermal Congress (Reykjavik, April-October 2021). HEATSTORE also gained significant media attraction in various newspapers and branch magazines in all participating countries. The complete overview of disseminated results and information is presented below.

2 Dissemination activities

2.1 HEATSTORE website and storymap UTES potential

https://www.heatstore.eu/
HEATSTORE - UTES screening (arcgis.com)

2.2 HEATSTORE annual conferences

1st Annual Conference. 3-4 July 2019, Utrecht, The Netherlands (organized by TNO, 50 participants).

2nd Annual Conference. 26 May 2020, organized as web-conference (organized by TNO & ETHZ, 64 participants).

2.3 HEATSTORE webinar series

The HEATSTORE consortium organized a webinar series with 6 webinars in Sept.-Oct. 2021. The webinars were fully virtual, presentations are available on the HEATSTORE website.

Webinar 1 (7 Sept. 2021): Challenges in Underground Thermal Energy Storage. Presented by H. Cremer (TNO), P. Ramsak (RVO), T. Vangkilde-Pedersen (GEUS). 66 participants.

Webinar 2 (14 Sept. 2021): Advances in subsurface characterization and simulation. Presented by T. Driesner (ETHZ), L. Guglielmetti (Univ. Geneva), A. Daniilidis (Univ. Geneva). 53 participants.

Webinar 3 (21 Sept. 2021): Integrating UTES and DSM in geothermal district heating networks. Presented by K. Allaerts (VITO), P.A. Sørensen (PlanEnergi), M. Clarijs (TNO) and R. Octaviano TNO). 48 participants.

Webinar 4 (28 Sept. 2021): Abandoned coal mines – promising sites to store heat in the underground. Presented by I. Nardini (IEG Fraunhofer), F. Hahn (IEG Fraunhofer) and L. Oppelt (Bergakademie Freiberg). 39 participants.

Webinar 5 (5 Oct. 2021): The ECW Energy HT-ATES project in the Netherlands. Presented by W. Bos (ECW Energy), B. Godschalk, P. Oerlemans and N. Franco Pinto (all IF Technology). 56 participants.

Webinar 6 (12 Oct. 2021): The role of UTES in the future EU energy system – a moderated discussion. Presented by J. Koornneef (TNO), Jacopo Tosoni (EASE) and Gonzalo Fernández Costa (EC DG Ener). 51 participants.

2.4 HEATSTORE workshops on roadmap for underground thermal energy storage

HEATSTORE Workshop. Roadmap for Underground Thermal Energy Storage. Workshop I. 4 March 2021 (virtual workshop with the entire HEATSTORE consortium and representatives of the national funding agencies).

HEATSTORE Workshop. Roadmap for Underground Thermal Energy Storage. Workshop II. 25 March 2021 (virtual workshop with the entire HEATSTORE consortium and representatives of the national funding agencies).

HEATSTORE Workshop. Roadmap for Underground Thermal Energy Storage. Workshop III. 22 April 2021 (virtual workshop with the entire HEATSTORE consortium and representatives of the national funding agencies).

2.5 HEATSTORE national conferences and workshops

Danish knowledge sharing day. 18 June 2019. Aarhus, Denmark (organized by GEUS and PlanEnergi; with four presentations by GEUS and PlanEnergi staff).

“Hengill day” workshop. 6 December 2019, OR headquarters, Reykjavík, Iceland. With participants from Reykjavík Energy, the Iceland Geosurvey and the University of Iceland. Workshop included a presentation on the Hengill reservoir model and the HEATSTORE Icelandic high temperature case study collaboration.

Danish knowledge sharing day. 28 October 2020. Web-conference, Denmark (organized by GEUS and PlanEnergi; with 11 presentations by GEUS, PlanEnergi and external national and international stakeholders).

Webinar at UPC. 22 October 2020. Vidal, R., A Geothermal Energy Concept based on Heat Storage in Geological Media. Webinar cycle in Hydrogeology and geochemistry, October 22. Hydrogeology Group (Associated Unit CSIC-UPC, Barcelona).

Intégration de la géothermie dans le système thermique, Presentation to Geneva Cantonal Energy Office, Geneva, 23 November 2020.

Azores national Heatstore meeting. 15 December 2020. IVAR researchers organized a virtual meeting of the HEATSTORE – Geothermica Era-net. December, 15. Invited researchers and end-users of the FRCT, EDA Renováveis S.A. and CIVISA (virtual meeting in Portuguese with three presentations).

- Matias, D., Moreno, L., Viveiros, F., Silva, C., Oliveira, S. (2020). Aplicação de geotermómetros a emissões fumarólicas. Desafios e oportunidades. Reunião virtual projeto do HEATSTORE [In Portuguese]. Oral presentation.
- Pereira, M.L., Matias, D., Viveiros, V., Uchôa, J., Zanon, V. (2020). Contributo da petrografia para o estudo de sistemas geotérmicos. Reunião virtual projeto do HEATSTORE [In Portuguese]. Oral presentation.
- Uchôa, J., Viveiros, F., Matias, D., Pereira, L. (2020). Modelação de dados espaciais em Sistemas de Informação Geográfica. Estratégias e limitações. Reunião virtual projeto do HEATSTORE [In Portuguese]. Oral presentation.

Institute of Earth Sciences, University of Iceland. Reservoir simulations of the Hengill geothermal system – current model and efforts to incorporate greater depths and higher temperatures into the modeling scheme. A virtual presentation on the Icelandic high temperature case study within HEATSTORE, 7 May 2021.

University of Neuchâtel – Exploration & Development of Deep Geothermal Systems Program. Presentation on Geothermal utilization in the Hengill area and efforts to incorporate greater depths and higher temperatures into the modeling scheme as part of the HEATSTORE project. Virtual workhop, 7 May 2021.

Webinar: Explore the possibilities for geological heat storage in your area – June 16, 2021. Webinar organized by GEUS in Danish, presenting the web-tool developed by GEUS for HEATSTORE Task 6.1.

Danish knowledge sharing day. Heat storage and monitoring results. 27 October 2021. Aalborg and Dronninglund (organized by GEUS and PlanEnergi, 7 presentations and site visit).

Festive opening of the Dutch HT-ATES project in Middenmeer, The Netherlands. 29 October 2021. 100 participants form politics, industry and science. Several speeches and walking tours at the HT-ATES installations.

2.6 Deliverables for consortium-restricted use only (confidential)

D2.1: Driesner, T. (ed.) (2019) Initial report on tools and workflows for simulating subsurface dynamics of different types of High temperature Underground Thermal energy Storage. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. Unpublished report, 143 pp.

D3.1: Allaerts, K. (2019) Minutes of the first workshop on design and system integration. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. Unpublished report, 3 pp.

D3.2: Allaerts, K. (ed.) (2019) Technical report on the characteristics of heat demand and supply at the demonstrator sites. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. Unpublished report, 56 pp. + appendices.

D3.4: Vanschoenwinkel, J. et al. (2019) Design and execution of business case models for the demonstration sites. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. Unpublished report, 41 pp + appendices.

D6.5.1: Sørensen, P.A., Koornneef, J. (2019) HEATSTORE Plan for communication and dissemination. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. Unpublished report, 7 pp.

D7.1: Cremer, H. et al. (2019) Mid-term review report HEATSTORE. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. Unpublished report, 36 pp.

2.7 Deliverables published on project website (www.heatstore.eu)

D1.1: Kallesøe, A.J., Vangkilde-Pedersen, T. (eds.) (2019) Underground Thermal energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 130 pp. + appendices.

D1.2: Nielsen, J.E., Vangkilde-Pedersen, T. (eds.) (2019) Underground Thermal energy Storage (UTES) – general specifications and design. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 58 pp.

D1.3 Guglielmetti, L. (ed.) (2021) Screening of the national potential for UTES. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 87 pp.

D1.4/D4.2/D4.3

Hamm, V. et al. (2021): Synthesis of demonstration projects and case studies realized in HEATSTORE – Best practice guidelines for the development of UTES. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 61 pp.

D2.1 Driesner, T. (ed.) (2021) Final report on tools and workflows for simulating subsurface dynamics of different types of High Temperature Underground Thermal Energy storage. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 348 pp.

D2.2: Tómasdóttir, S. & Gunnarsson, G. (eds.) (2019): HEATSTORE – Interim report on UTES-type/site-specific simulators based on academic/research codes. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 55 pp.

D2.2 Tómasdóttir, S. & Gunnarsson, G. (eds.) (2021): HEATSTORE – Final report on UTES-type/site-specific simulators based on academic/research codes. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 58 pp.

D2.3: Alt-Epping, P. & Mindel, J. (eds.) (2020): HEATSTORE – Benchmarking and improving models of subsurface heat storage dynamics. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 104 pp.

D3.3: Allaerts, K. et al. (2021): UTES and its integration in the heating system - Defining optimal design and operational strategies for the demonstration cases. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 96 pp. Revised version published on 31 October 2021.

D3.6: Werkman, E. et al. (2019) Incorporation of a new generation smart energy management algorithm (HeatMatcher) in CHESS. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 21 pp.

D4.1: Hahn, F. et al. (2019) Feasibility assessment & design for demonstration projects – learnings of an international workshop. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 22 pp.

D5.1: Hahn, F. (ed.) (2019) Monitoring plans: demonstration projects and case studies. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 29 pp.

D5.2 Oerlemans, P. (ed.) (2021) Monitoring data availability of the UTES demonstration projects and case studies, status 2021. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 12 pp.

D5.2 Oerlemans, P., Drijver, B. (2021) Effects of HT-ATES on the subsurface – the NIOO case study. An evaluation of the effects of a HT-ATES system (45 °C) on the subsurface. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 78 pp.

D5.2 Guglielmetti, L., Houlié, N., Nawratil de Bono, C., Martin, F., Coudroit, J. (2021) Monitoring results for the Geneva HT-ATES case-study. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 33 pp.

D5.3 Diaz-Maurin, F., Saaltink, M.W. (2021) Model validation for subsurface dynamics. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 111 pp.

D5.4 Koenen, M., Tümer, C., Rey, C., Gauthier, G. (2021) Validation report of system integration modelling. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 21 pp.

D5.5 Armandine Les Landes, A. et al. (2021) Uncertainty management in underground thermal energy storage development and operation. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 73 pp.

D6.1 UTES Screening – Subsurface potential for heat storage. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. Web GIS platform accessible via https://www.heatstore.eu/and HEATSTORE - UTES screening (arcgis.com)

D6.2 Mirjolet, F. et al. (2021) Regulatory and policy boundary conditions for UTES. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 116 pp.

D6.3 Hahn, F. et al. (2021) Report on evaluation of new business models for flexible energy systems with UTES in Europe. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 116 pp.

D6.4 Koornneef, J. et al. (2021) Roadmap for flexible energy systems with underground thermal energy storage towards 2050. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 57 pp.

D6.5.2 Borch, K. (2021) Public acceptance of UTES and geothermal projects – best practice learnings. GEOTHERMICA – ERANET Cofund Geothermal. 17 pp.

D6.5.3 Cremer, H. (2021) Summary of dissemination activities: reports, papers, conference contributions and media articles. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 16 pp.

D6.6 Guglielmetti, L., Bloemendal, M. Hahn, F., Hilleke Mortensen, M., Koornneef, J, eds. (2021) Environmental effects of UTES in Europe. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 118 pp. Revised version published on 25 October 2021.

2.8 Other scientific reports published on project website (www.heatstore.eu)

Dijkstra, H. et al. (2020) Workflow to evaluate the risk of mineral scaling in a HT-ATES system and application to a potential site in Middenmeer, The Netherlands. TNO report 2020R10437. 56 pp.

Ditlevsen, C. (2021) Vurdering af potentialet for geologisk varmelagring (UTES) – Aarhus Kommune. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2021/26, 35 p. (in Danish with English abstract).

Griffioen, J. (2020) A literature review on the precipitation of Ca, Ca-Mg and Fe carbonates and its inhibition under HT-ATES conditions. TNO report 2020R11204. 63 pp.

Kallesøe, A.J., Mortensen, M.H. (2021) Vurdering af potentialet for geologisk varmelagring (UTES) – Esbjerg området. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2021/11, 29 p. (in Danish with English abstract).

Kallesøe, A.J., Mortensen, M.H. (2021) Vurdering af potentialet for geologisk varmelagring (UTES) – Odense området. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2021/12, 35 p. (in Danish with English abstract).

Kallesøe, A.J., Mortensen, M.H. (2021) Vurdering af potentialet for geologisk varmelagring (UTES) – Ringkøbing-Videbæk området. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2021/13, 36 p. (in Danish with English abstract).

Kallesøe, A.J., Mortensen, M.H. (2021) Vurdering af potentialet for geologisk varmelagring (UTES) – Guldborgsund området. Danmarks og Grønlands Geologiske Undersøgelse, Rapport 2021/14, 31 p. (in Danish with English abstract).

Koumrouyan, M. (2019). Geomechanical Characterization of Geothermal Exploration Borehole: Implication for the GEO-01 Well in Geneva. Master Thesis, University of Neuchatel.

Van Unen, M. et al. (2020) HEATSTORE risk assessment approach for HT-ATES applied to demonstration case Middenmeer, The Netherlands. TNO report 2020R10192. 34 pp.

Gauthier, G. (2020) Benchmarking and improving models of subsurface heat storage dynamics. Comparison of Danish PTES and BTES installation measurements with their corresponding TRNSYS models. HEATSTORE project report, GEOTHERMICA – ERANET Cofund Geothermal. 47 pp. This report is a contribution form the Danish team to D2.3.

2.9 Milestone reports published on project website (www.heatstore.eu)

MS1.2 Mortensen, M.H. & Ditlefsen, C. (2020) National screening process for Underground Thermal Energy Storage (UTES) sites in Denmark. 9 pp.

MS1.3 Boullenger, B. et al. (2020) Seismic reprocessing for shallow structure of aquifers. 18 pp.

MS5.5 Rohmer, J. et al. (2020) Theoretical framework for the representation of uncertainties. 14 pp.

2.10 Scientific journal papers

Birdsell, D.T., Adams, B.M., Saar, M. (2021) Minimum transmissivity and optimal well spacing and flow rate for high-temperature aquifer thermal energy storage from economic and reservoir engineering constraints. *Applied Energy*, 289, https://doi.org/10.1016/j.apenergy.2021.116658.

Mindel, J. and 16 others (2021) Benchmark study of simulators for thermo-hydraulic modelling of low enthalpy geothermal processes. *Geothermics* 96: 102130 (https://doi.org/10.1016/j.geothermics.2021.102130).

Viveiros, F., Chiodini, G., Cardellini, C., Caliro, S., Zanon, V., Silva, C., Rizzo, A.L., Hipólito, A, Moreno, L. (2020). Deep CO_2 emitted at Furnas do Enxofre geothermal area (Terceira Island, Azores archipelago). An approach for determining CO_2 sources and total emissions using carbon isotopic data. *Journal of Volcanology and Geothermal Research*,401: 106968.

Viveiros, F., Silva, C., Moreno, L., Pacheco, J.E., Ferreira, T. (2020) Secondary manifestations of volcanism – an open window to understand geothermal resources in the Azores archipelago. *Comunicações Geológicas* 107, Especial I, 89-91.

2.11 Conference proceedings papers

European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June 2019

Beernink, S., Hartog, N., Bloemendal, M., van der Meer, M. (2019) ATES systems performance in practice: analysis of operational data from ATES systems in the province of Utrecht, The Netherlands. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019.

Bloemendal, M., Beernink, S., Hartog, N., van Meurs, B. (2019) Transforming ATES to HT-ATES, insights from Dutch pilot project. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019.

Drijver, B., Bakema, G., Oerlemans, P. (2019) State of the art of HT-ATES in The Netherlands. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019.

Hahn, F., Jagert, F., Bussmann, G., Nardini, I., Bracke, R., Seidel, T., König, C. (2019) The reuse of the former Markgraf II colliery as a mine thermal energy storage. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019.

Koornneef, J., Guglielmetti, L., Hahn, F., Egermann, P., Vangkilde-Pedersen, T., Aradóttir, E.S., Allaerts, K., Viveiros, F., Saaltink, M. (2019) HEATSTORE: high temperature underground thermal energy storage. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019.

Koumrouyan, M., Sohrabi, R., Valley, B. (2019) Geomechanical characterization of geothermal exploration borehole for Aquifer Thermal Energy Storage (ATES) development in Geneva, Switzerland. Proceedings European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June, 2019.

InSAR - Radar satellite interferometry and ground deformation workshop, Geneva, Switzerland, 3 April 2019

Birdsell D and Saar M.O. (2019) Predicting Surface Deformation for Geothermal Energy with a Thermo-Poro-Elastic Model, Oral Presentation, InSAR - Radar satellite interferometry and ground deformation workshop, Geneva, Switzerland, 3 April 2019.

AAPG 3rd Hydrocarbon - Geothermal Cross Over Technology Workshop, Geneva, Switzerland, 9 - 10 April 2019

Birdsell, D. and Saar, M.O. (2019). Use of a coupled thermo-hydro-mechanical model to constrain the risk of ground surface deformation due to subsurface energy storage and production, Poster Presentation, AAPG 3rd Hydrocarbon - Geothermal Cross Over Technology Workshop, Geneva, Switzerland, 9 - 10 April 2019.

World Geothermal Congress 2020, Reykjavik, Iceland, 26 April - 2 May 2020. Conference postponed to April-October 2021 due to Covid-19 pandemic. Organized as virtual conference 'WGC 2020+1' on several dates in 2021.

Birdsell, D., Saar, M. (2021): Modelling Ground Surface Deformation at the Swiss HEATSTORE Underground Thermal Energy Storage Sites. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Eruteya, O., Guglielmetti, L., Makhloufi, Y., Moscariello, A. (2021): 3-D Static Model to Characterize Geothermal Reservoirs for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Geneva Area, Switzerland. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Ferreira de Oliveira, G., De Haller, A., Guglielmetti, L., Makhloufi, Y., Moscariello, A., (2021): Application of Chemostratigraphy and Petrology to Characterize the Reservoirs of the Mesozoic Sequence Crossed by the GEo-01 Well: Potential for Direct Heat Production and Heat-Storage. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Godschalk, B., Provoost, M., Schoof, F. (2021) Netherlands country update. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Guglielmetti, L. and 22 others (2020) HEATSTORE SWITZERLAND: New opportunities of geothermal district heating network sustainable growth by High Temperature Aquifer Thermal Energy Storage development. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Hahn, F., Jagert, F., Bussmann, G., Nardini, I., Bracke, R., Seidel, T., König, C. (2021) The reutilization of a small coal mine as a Mine Thermal Energy Storage. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Kallesøe, A.J., Vangkilde-Pedersen, T., Nielsen, J.E., Bakema, G., Egermann, P., Maragna, C., Hahn, F., Guglielmetti, L., Koornneef, J. (2021) HEATSTORE – Underground Thermal Energy Storage (UTES) – State of the Art, Example Cases and Lessons Learned. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Koornneef, J., Guglielmetti, L., Hahn, F., Egermann, P., Vangkilde-Pedersen, T., Aradóttir, E.S., Allaerts, K., Viveiros, F., Saaltink, M. (2021) HEATSTORE Project Update: High Temperature Underground Thermal Energy Storage. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Mindel, J.E. & Driesner, T. (2021) HEATSTORE: Preliminary design of a High Temperature Aquifer Thermal Energy Storage (HT-ATES) system in Geneva based on TH simulations. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Moscariello, A., Guglielmetti, L. and 15 others (2021) Heat production and storage in western Switzerland: advances and challenges of intense multidisciplinary geothermal exploration activities, an eight year progress report. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Rey, C., Maragna, C., Egermann, P., Perreaux, M. (2021) Modelling of an innovative HT-BTES(smart) design with lateral recovery boreholes to reduce heat losses : development and preliminary result. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Sohrabi, R., Valley, B. (2021) Thermo-Hydraulic-Mechanical (THM) Experiments and Numerical Simulations to Quantify Heat Exchange Characteristics of Fractured Limestone Reservoirs for Aquifer Thermal Energy Storage (ATES). Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Tómasdóttir, S., Gunnarsson, G., Aradóttir, E.S.P. (2021) Possible seasonal injection of surplus hot water from the Hengill Area into a low temperature system within Iceland's capital area. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

Viveiros, F., Silva, C., Matias, D., Moreno, L., Driesner, T., Zanon, V., Uchôa, J., Cruz, J.V., Freire, P., Pereira, M.L., Pacheco, J. (2021). Geochemical tools as a contribution to improve geothermal potential on the Azores archipelago. Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, April-October 2021.

GET2020 – 1st Geoscience & Engineering in Energy Transition Conference, 16-18 November 2020, Strasbourg, France

Drijver, B., Oerlemans, P., Bos, W. (2020) Full-scale HT-ATES tests demonstrate that current guidelines considerably overestimate sand production risks in deeper unconsolidated aquifers-concept. Proceedings GET2020, Strasbourg, France, November 16-18, 2020.

18th Swiss Geoscience Meeting, Online, Hosted by ETH Zurich, 6-7 November 2020

Birdsell D. et al.(2020) Determination of minimum transmissivity for high-temperature aquifer thermal energy storage from reservoir-engineering and economic constraints, Contributed Talk, 18th Swiss Geoscience Meeting, Online, Hosted by ETH Zurich, 6-7 November 2020.

2.12 Conference participations

European Geothermal Congress 2019, The Hague, The Netherlands, 11-14 June 2019

Beernink, S. et al. (2019) ATES systems performance in practice: analysis of operational data from ATES systems in the province of Utrecht, The Netherlands. Oral presentation.

Bloemendal, M. et al. (2019) Transforming ATES to HT-ATES, insights from Dutch pilot project. Poster presentation.

Drijver, B. et al. (2019) State of the art of HT-ATES in The Netherlands. Oral presentation.

Hahn, F. et al (2019) The utilization of the former Markgraf II colliery as a mine thermal energy storage. Oral presentation.

Koornneef, J. et al. (2019) HEATSTORE: high temperature underground thermal energy storage. Oral presentation.

DECOVALEX 2019 Symposium – DEvelopment of COupled models and their VALidation against Experiments, Brugg, Switzerland, 4-5 November 2019.

Birdsell, D.T., Saar, M.O. (2019) Coupled Thermo-Hydro-Mechanical Model of Ground Surface Deformation at Swiss Heat Storage Sites. Oral presentation.

SCCER-SoE Annual Conference 2019: Hydropower and Geo-Energy in Switzerland: Challenges and Perspectives, Lausanne, 3 & 4 September 2019

Birdsell, D. and Saar, M.O. (2019). Modeling Ground Surface Deformation at the Swiss HEATSTORE Underground Thermal Energy Storage Sites. Poster Presentation.

Guglielmetti L. et al. (2019) HEATSTORE SWITZERLAND: New Opportunities for District Heating Network Sustainable Growth by High Temperature Aquifer Thermal Energy (HT-ATES) Storage. Oral presentation.

European Workshop on Underground Energy Storage, Paris, France, 7-8 November 2019

Koornneef, J. et al. (2019) HEATSTORE – High Temperature Underground Thermal Energy Storage. Oral presentation.

De Oliveira Filho, F. et al. (2019) District heating and thermal energy storage. Oral presentation.

Vangkilde-Pedersen, T. et al. (2019) Lessons learned from existing and past underground thermal energy storage systems. Oral presentation.

NRW Geothermiekonferenz, Bochum, Germany, 3 September 2020

Hahn, F. et al (2020) Die Erschließung eines Altbergbaus für die thermische Nachnutzung am Standort Bochum. Oral presentation.

Symposium Bodem Breed – 3 June 2021, Digital congres, the Netherlands

Oerlemans, P.J.A., Drijver, B., Pittens, B. (2019) Hoge Temperatuuropslag (HTO) bij ECW, Middenmeer; Een toelichting op het demonstratieproject van HEATSTORE. Oral presentation.

World Geothermal Congress 2020, Reykjavik, Iceland, 26 April -2 May 2020 (all listed contributions are submitted to the conference secretariat). Conference postponed to May 2021, and due to Covid-19 pandemic organized as virtual conference 'WGC 2020+1' on several dates in 2021. HEATSTORE was also represented at the on-site event in Reykjavik from 24-27 Oct. 2021, at the joint GEOTHERMICA booth.

Guglielmetti, L. et al. (2020) HEATSTORE SWITZERLAND: New opportunities of geothermal district heating network sustainable growth by High Temperature Aquifer Thermal Energy Storage development. Oral presentation.

Eruteya O., Guglielmetti L., Makhloufi Y., Moscariello A. (2020). 3-D Static Model to Characterize Geothermal Reservoirs for High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Geneva Area, Switzerland. Oral presentation.

Ferreira De Oliveira G., De Haller A., Guglielmetti L., Makhloufi Y., Moscariello A. (2020). Application of Chemostratigraphy and Petrology to Characterize the Reservoirs of the Mesozoic Sequence Crossed by the Geo-01 Well: Potential for Direct Heat Production and Heat-Storage. Oral presentation.

Hahn, F. et al. (2020) The reutilization of a small coal mine as a Mine Thermal Energy Storage. Poster presentation.

Kallesøe, A.J. et al. (2020) HEATSTORE – underground Thermal Energy Storage (UTES) – State of the Art, Example Cases and Lessons Learned. Oral presentation.

Koornneef, J. et al. (2020) HEATSTORE Project Update: High Temperature Underground Thermal Energy Storage. Oral presentation.

Mindel, J.E. & Driesner, T. (2020) HEATSTORE: Preliminary design of a High Temperature Aquifer Thermal Energy Storage (HT-ATES) system in Geneva based on TH simulations. Oral presentation.

Moscariello et al. (2020) Heat production and storage in Western Switzerland: advances and challenges of intense multidisciplinary geothermal exploration activities, an 8-year progress report. Oral presentation.

Quiquerez et al. (2020) Scenarios for Integration of Medium-Depth Geothermal Energy in an Evolving District Heating System: Case Study in Geneva (Switzerland). Oral presentation.

Rey, C. et al. (2020) Modelling of an innovative HT-BTES(smart) design with lateral recovery boreholes to reduce heat losses: development and preliminary result. Oral presentation.

Sohrabi, R., Valley, B. (2020) Thermo-Hydraulic-Mechanical (THM) Experiments and Numerical Simulations to Quantify Heat Exchange Characteristics of Fractured Limestone Reservoirs for Aquifer Thermal Energy Storage (ATES). Oral presentation.

Tómasdóttir, S. et al. (2020) Possible seasonal injection of surplus hot water from the Hengill Area into a low temperature system within Iceland's capital area. Oral presentation.

Viveiros, F., Silva, C., Matias, D., Moreno, L., Driesner, T., Zanon, V., Uchôa, J., Cruz, J.V., Freire, P., Pereira, M.L., Pacheco, J. (2020). Geochemical tools as a contribution to improve geothermal potential on the Azores archipelago. Oral presentation.

14th CCVG Workshop, Hokkaido, Japan, 29 May – 5 June 2020

Silva, C., Viveiros, F., Carmo, R. (2020) Radon soil diffuse degassing at caldeiras da Ribeira Grande (São Miguel, Açores) – new degassing area. CANCELLED DUE TO COVID-19 PANDEMIC.

Viveiros, F., Cardellini, C., Chiodini, G., Silva, C., Moreno, L., Matias, D. (2020) After three decades of soil CO2 flux studies on volcanic areas - challenges and potentialities. CANCELLED DUE TO COVID-19 PANDEMIC.

IEA REWP Workshop, The role of storage beyond electricity. Virtual meeting by the International Energy Agency, 29 September 2020

Godschalk, B. (2020) HEATSTORE project pitch.

Joint Programming Conference – Smart Energy Systems, Virtual meeting by the JPP SES and Geothermica program Cooperation Scoping group, 16 October 2020

Cremer, H. (2020) HEATSTORE project pitch.

7th Geothermal get-Together, TU Delft, 4 November 2020

Guglielmetti, L. (2020). HEATSTORE High Temperature Underground Thermal Energy Storage. Oral presentation.

Der Digitale Geothermiekongress 2020, German Geological Society, Virtual, 9-13 November 2020.

Hahn, F. et al. (2020) HEATSTORE – Die Erschließung eines Altbergbaus für die thermische Nachnutzung am Standort Bochum. Oral presentation.

Jagert, F. et al. (2020) Die Erschließung eines Altbergbaus für die thermische Nachnutzung im Rahmen von HEATSTORE: Status update. Oral presentation.

AGU Fall Meeting, online everywhere, 1-17 December 2020

Birdsell, D.T. et al. (2020) Minimum transmissivity for high-temperature aquifer thermal energy storage. Oral presentation.

ENERSTOCK2021 – 15th International Conference on Energy Storage, 9-11 June 2021, Ljubljana, Slovenia

Skov, C.K., Sørensen, P.A. (2020) Development and implementation of PTES in Copenhagen. Oral presentation.

British Geological Survey event 2021: Mine water heating and cooling: A 21st Century resource for decarbonization, Virtual, 10-11 March 2021

Hahn, F. et al. (2021) The Reutilization of a Small Coal Mine for Mine thermal Energy Storage. Oral presentation.

Virtual event by The Geological Society London – The role of subsurface research labs in delivering net zero – realising the potential of UKGEOS, 3-4 February 2021.

Koornneef, J., Goetzl, G. (2021) Heat storage. Oral presentation.

1st CCVG Virtual Workshop, 24-26 May 2021.

Viveiros, F., Cardellini, C., Chiodini, G., Silva, C., Moreno, L., Matias, D. (2021) After three decades of soil CO_2 flux studies on volcanic areas – challenges and potentialities. Poster presentation.

GeoKarlsruhe 2021 – Sustainable earth from processes to resources, 19-24 September 2021 (virtual conference)

Godschalk, B., Oerlemans (2021) First results of the full scale HT-ATES project in greenhouse area Middenmeer in the Netherlands. Oral presentation.

2.13 Media visibility

This section summarizes news reports in the media per country.

Europe

European Association for Storage of Energy website report entitled *Underground thermal energy storage facilitates the low-carbon transition of the heating and cooling sector* published on 1 Jan. 2018 about the HEATSTORE project (Link).

Belgium

www.energiesparen.be website report entitled *Extra steun voor onderzoek naar diepe aardwarmte* on 15 June 2018 (in Dutch; Link).

www.architectura.be website report entitled *Zomerwarmte opslaan om in de winter te gebruiken* published on 10 October 2018 (in Dutch; Link).

www.vito.be article in scientific magazine from VITO entitled *Flatten the curve en verschuif de energievraag met FLEXharvester/STORM District Energy Controller* published in December 2020.

www.vito.be Online info meeting / presentation for residents of the municipality of Mol and Dessel regarding the status and restart of the geothermal energy system. Link with Heatstore project is also explained, 31 March 2021 (in Dutch; Link).

Denmark

www.energiforskning.dk website report entitled *Højtemperatur varmelagring i undergrunden* (in Danish, Link).

www.planenergi.dk website report entitled *PlanEnergi deltager sammen med GEUS i EU GEOTHERMICA projektet HEATSTORE* (in Danish, Link).

www.geus.dk website report entitled *Grøn omstilling: Snart kan vores varme være geotermisk* (in Danish, Link).

www.pro.inch.dk website report entitled *Stort potentiale for varmelagring i grundvandsmagasiner* (in Danish, Link).

Germany

Geothermische Energie journal report (ed. 93) by the "Bundesverband Geothermie" published in Sep. 2019 (in German).

Bundesverband Geothermie webinar on 3 July 2020 includes the contribution 'Grubenwasser als Wärmelieferant – Kann aus Ewigkeitslasten ein Ewigkeitsnutzen generiert werden?' (in German).

The **Westdeutsche Allgemeine Zeitung** published an article entitled *Bochumer Projekt könnte für Wärmewende im Ruhrgebiet sorgen* on 04 Sep. 2020 (in German, Link).

The **Süddeutsche Zeitung** published an article entitled *Tief im Westen* on 19 Dec. 2020 (in German, Link).

The Netherlands

In **VPRO television** documentary on Energy Storage "De race om de super batterij" Heat storage a.o. was highlighted. 7 February 2021 (in Dutch, Link).

In **BodemenergieNL Nieuwsbrief** an article entitled HEATSTORE – op weg naar hoge temperatuuropslag in de ondergrond on 12 February 2021 (in Dutch, Link).

In **Noordhollands Dagblad** an article entitled *Miljoenen in aardwarmte* published on 2 Feb. 2021 (in Dutch, Link).

Energeia published an online article entitled *Experiment met seizoensopslag aardwarmte binnenkort van start in Middenmeer* on 7 Sept. 2020 (in Dutch, Link).

In **Noordhollands Dagblad** an article entitled *Mooi om koploper te zijn* published on 2 Sept. 2020 (in Dutch, Link).

Energeia published an online article entitled *Ondergrondse thermosfles voor seizoensopslag aardwarmte tuinders* on 30 Oct. 2019 (in Dutch, Link).

In **Noordhollands Dagblad** an article entitled *Project grootschalige opslag warmte van ECW in Middenmeer grootste in Europa* published on 23 Oct. 2019 (in Dutch, Link).

In the **ThinkGeoEnergy** Newsletter of 9 Sept. 2019, the HEATSTORE deliverable report 'Underground Thermal energy Storage (UTES) – state-of -the-art, example cases and lessons learned' is discussed and promoted.

HEASTORE is mentioned in the **Dutch national climate agreement** (in Dutch: Het Klimaatakkoord), released on 28 June 2019. In Chapter C1.11 'More sustainable heat' under d) Development & innovation agenda, the report says: "Additionally to the European project HEATSTORE, the heat sector engages in the development of seasonal high temperature storage".

Cobouw website report entitled *TNO: 'Prijs warmtenetten halveren met bodenwarmte'* published on 11 Oct. 2018 (in Dutch; Link).

Engineeringnet website report entitled *Europees consortium demonstreert ondergrondse seizoensopslag zomerwarmte* published on 11 Oct. 2018 (in Dutch; Link).

Utilities website report entitled *Doel: 20 procent minder kosten voor opslag en gebruik zomerwarmte* published on 4 Oct. 2018 (in Dutch; Link)

FluxEnergie.nl website report entitled *Schaalvergroting voor bodemopslag warmte in Kop van Noord-Holland* published on 4 Oct. 2018 (in Dutch; Link).

Vlaanderen is energie website report entitled *Extra steun voor onderzoek naar diepe aardwarmte* published on 15 June 2018 (in Dutch; Link).

Portugal

IVAR website reports the 2nd Year Annual Meeting mentioning the work performed by IVAR. The title is "*Investigadores do IVAR participam em reunião virtual do projeto Heatstore – Geothermica Era-net*", published on the 26 May 2020 (in Portuguese, Link).

IVAR website reports the HEATSTORE project highlighting the main objectives of the national project (in Portuguese; Link).

IVAR website reports that *IVAR participa em projet europeu que pretende desenvover tecnologias para armazenar calor no subsolo*, published on 10 October 2018 (in Portuguese; Link).

Correio dos Açores newspaper reports *Os Açores vão ser caso de estudo de criação de tecnologias para armazenar calor no subsolo*, published on 11 October 2018 (page 9, in Portuguese).

Açoriano Oriental newspaper report *Geotermia 'detetada' por modelos informáticos*, published on 23 January 2021 (in Portugese)

IVAR website reports the virtual HEATSTORE national meeting "Investigadores do IVAR organizam reunião virtual do projeto HEATSTORE – Geothermica Era-net", published on the 23 December 2020 (in Portuguese, http://www.ivar.azores.gov.pt/noticias/Paginas/all-news.aspx?a=2).

Broadcast on the local Azorian television, with 5 min on geothermal energy and HEATSTORE, broadcasted on 17 November 2021, in Portugese, https://www.rtp.pt/play/p9378/e580094/acores-cons-ciencia.

Switzerland

Geotermia Svizzera website report entitled *Stockage thermique à haute température dans les aquifères profonds*, published on 10 October 2018 (in French, Link).

Geothermie Suisse website report entitled *Le premier rapport HEATSTORE à été publié*, published on 24 September 2019 (in French, Link).

Geo-Energie-Suisse AG company website project description entitled *HEATSTORE* (in French, Link and German, Link).

Iceland

OR website reports the HEATSTORE project as one of current research projects and describes the main objectives of the project (in Icelandic, Link and English, Link).

OR website reports on the two Icelandic case studies within HEATSTORE, the international collaboration within the project and the recent annual meeting. Entry entitled *OR þátttakandi í alþjóðlega verkefninu HEATSTORE*, published on 5 June 2020 (in Icelandic, Link).