HEATSTORE: HIGH TEMPERATURE UNDERGROUND THERMAL ENERGY STORAGE

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ABSTRACT

Thermal energy storage 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 project HEATSTORE 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. It will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable geothermal energy production to reach its maximum deployment potential in the European energy transition.

HEATSTORE is a project under the GEOTHERMICA – ERA NET Cofund and contributes to achieving the several objectives 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, market, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The 3-year project started in 2018 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 HEATSTORE consortium brings together 23 contributing partners (mix of scientific research institutes and private companies) from 9 countries.

1. INTRODUCTION

The deployment of renewable energy sources (RES) for both power and heat production is accelerating in Europe, a trend that will continue. However, the variations in both the availability and demand of energy and their integration into the existing energy infrastructure raise challenges in terms of operational variability and balancing. Peak shaving and heat storage can help to balance demand and supply to make better use of infrastructure and assets (e.g. increase full load hours for geothermal heat sources). Thermal energy storage can, for example, be implemented in heating networks in the form of 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. UTES provides a smart and replicable solution for the 'bathtub challenge' for regions that have a seasonal dip and peak in heating demand. Underground thermal energy storage (UTES) provides large scale (potentially >10 GWh) storage capacity per site that is difficult to achieve with other heat storage technologies, and benefits from a typically lower range of storage costs (Persson et al.,2014).

Challenges highlighted for UTES technologies defined in the EASE-EERA energy storage technology roadmap towards 2030 include the need to assess the potential and suitability of the subsurface in Europe (EASE-EERA, 2017). This includes research and demonstration regarding high temperature storage systems and hybrid UTES systems to increase capacity, efficiency and alignment with renewable heat production technologies (solar heat, geothermal heat, biomass heat). Optimised control of heat networks with UTES can lead to energy savings and reduce the use of back-up systems. The Horizon 2020 STORM project indicates that the employment of a smart heat network controller can reduce peak demand with 20 to 30% (EASE-EERA, 2017). In combination with thermal storage capacity, demand side management in heating networks is an enabling technology for many renewable heat sources, including geothermal.

2. THE HEATSTORE PROJECT

The GEOTHERMICA HEATSTORE project aligns with these research and development needs described in energy storage and heat network roadmaps. The project has three primary objectives, namely, lowering cost, reducing risks, and optimizing the performance of high temperature (~25 to ~90°C) underground thermal energy storage (HT-UTES) technologies. These three objectives contribute to the goal of HEATSTORE, to advance the commercial viability HT-UTES technologies, so that geothermal energy, combined with and optimised through underground heat storage, can reach its maximum deployment potential in the European energy transition.

The three primary objectives will be achieved through the 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 are:

- 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 models to enhance prediction of site performance 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.

The objectives will be complimented by the introduction of adequate workflows and tools, and applying them – in collaboration with industry – in a portfolio of pilot demonstration sites across Europe (see Fig. 1 and Table 1).

Furthermore, HEATSTORE also draws lessons learned 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:

- Netherlands: ATES Koppert Cress high temperature (40°C) ATES at a greenhouse farm and the ATES pilot (45°C) at NIOO which has been in operation since 2012.
- Denmark: the performance of Pit Thermal Energy Storages in Marstal, Dronninglund and Gram, and Borehole Thermal Energy Storage in Brædstrup will be evaluated, as well as a number of shallow Aquifer Thermal Energy Storage plants.
- Azores Islands and Iceland: demonstrate innovative modelling tools to be used for resource assessment at the Caldeiras da Ribeira Grande geothermal area (Azores) and for pre-drilling scenario development for the development of supercritical resources (Iceland, Hengill area).
- Belgium: From 2002 till 2005 a high temperature (90°C) Borehole Thermal Energy Storage was operated and monitored at the site of VITO in Mol under the FP5 project TESSAS.

3. HEATSTORE IMPACT

HEATSTORE aims at accelerating the uptake of geothermal energy by 1) advancing and integrating several types of underground geothermal energy storage (UTES) and demand side management in the energy system and, 2) by providing a means to optimize geothermal heat production to support business cases associated with geothermal heat production doublets.

The business case for geothermal heat production doublets is highly influenced by the annual heat sales and full load hours, and thus limited by demand profiles that show a seasonal pattern (summer low, winter high). However, the low marginal production cost of geothermal heat sources offers a strong business case for seasonal heat storage, as storing surplus heat in the summer will allow the geothermal heat production to run baseload with high full load hours, improving the economics of the system. The combination of geothermal heat production, UTES and demand side management thus forms an important symbiosis to accelerate the uptake of geothermal energy in Europe at relatively low costs.

HEATSTORE will have short- and long-term impacts, and impacts on project (local), regional and European scale. The short-term impacts on the project level are expected to be:

- Improved performance (target efficiency of 75%) and economics of UTES technologies through improved reservoir characterisation and modelling, improved drilling technologies, innovative scaling and corrosion inhibitors and approaches, improved operational strategies and control, and efficient monitoring. These impacts can aid project development and operation, and can be applied to the whole spectrum of geothermal technology from UTES to high enthalpy power production.

- Advanced system integration using UTES and smart demand side management will improve the economics of the system as a whole and lead to lower costs of supplying energy to the end-user;

- Significantly higher integration of sustainable and surplus heat sources in heating networks (geothermal, solar and industrial surplus heat);

- Enhanced reliability and efficiency of the heating system in providing heat to the end-user;

- Bringing multiple underground thermal energy storage concepts and demand side management techniques further, potentially reaching market readiness (see TRL advancements in Table 1);

Key advancements in the science related to challenges identified in earlier pilot projects for the demonstrated concepts, including environmental impacts (hydrothermal effects, geo-chemical effects and effects on microbiological populations in the subsurface).

European wide impacts could also be significant. Currently there are more than 12.000 district heating networks in Europe, supplying more than 10% of total European heat demand with an annual turnover of €27-32 billion through 2.2 EJ (610 TWh) of heat sales. In the Heat Roadmap Europe 2050, the European District Heating sector evaluated the feasibility of increasing the use of geothermal heat as a renewable source for district heating from the current ~ 2 to 111 TWh/year in 2050. Such a large step can only be achieved if geothermal sources can be efficiently integrated into district heating networks. The UTES options in conjunction with the advanced heating network controllers demonstrated in HEATSTORE can facilitate such integration. Specifics in geology and surface restrictions may provide better conditions for specific UTES technologies and exclude others. Therefore, a portfolio of UTES technologies needs to be demonstrated and be technologically advanced to enable location specific needs to be identified and addressed.

4. HEATSTORE APPROACH

The research and demonstration objectives are translated into 7 work packages. Three consecutive phases can be discerned: **Design** phase, **Demonstration,** and finally the **Replication and scale-up** phase (see Fig. 3). In each phase synthesis and knowledge exchange between countries and partners is facilitated to prepare for the development of best practices. Work packages 1-3 are part of the **Design** phase. The general design considerations and detailed characterisation of the local subsurface for UTES technologies are provided in WP1. WP2 includes the development of a detailed and replicable toolset for system designers and modellers, which is verified and validated in demonstration projects, complimented with information from existing UTES projects. This allows pre-drilling scenario development for project risk minimization, assessing environmental impact, optimization of operational performance, reliability and sustainability, as well as providing input for energy system integration modelling. This includes TRL advancement of innovative reservoir simulation software for geothermal project development workflows and demonstrating their applicability in both UTES and other geothermal projects. WP3 aims to model in detail the performance of the UTES system, demand-side management and other flexibility options in an integrated local heat network, to determine optimal design and operational strategies for the UTES systems.

The **Demonstration** phase entails WP4 and WP5 where the application of the lessons learned from the Design phase are applied to the demonstrations to provide proof of concept. For these demonstration projects the most important objectives are:

- Provide detailed technical design specifications for the demonstration sites

- Realize demonstrations of UTES and demand side management in heat networks and monitor performance to provide proof of concept and validate the Design phase toolset(s).

- Overcome the reliability challenges faced by high temperature UTES, contributing to the advancement of the technologies' readiness from demonstration to commercial phase.

- Demonstrate an optimization algorithm to optimize design and operation of a future proof integrated smart district heating network.
- Develop best practice guidelines to reduce project risks and assess the potential for replication and scale-up of the concepts studied and demonstrated.

The **Replicate and scale-up** phase is covered by WP6, where the requirements are established necessary to move UTES and demand side management in heating networks from demonstration phase to commercial deployment, within 2 to 5 years on the European market, and provide an outlook towards 2030 and 2050. In addition, WP6 will identify favourable conditions for the replication of the developed technologies in Europe (with a focus on countries within HEATSTORE) and share these outcomes with relevant stakeholders in policy, science, industry and the general public. This work will involve addressing the fundamental technical, economic, environmental, societal, regulatory and policy aspects to support the efficient and cost-effective deployment of underground heat storage in Europe. Based on lessons learned from the Design and Demonstration Phases, a roadmap will be developed to provide a clear strategy for the immediate (2-5 years), medium term (2030) and long term (2035-2050) actions that need to be undertaken to implement the demonstrated and studied concepts within HEATSTORE. WP7 covers the project and knowledge management within HEATSTORE.

5. HEATSTORE DEMONSTRATION PROJECTS

The unique opportunity is present within HEATSTORE to apply lessons learned from case study pilot projects and develop high TRL (up to TRL 8 for UTES and TRL 9 for demand response) technologies in a wide variety of geological conditions. HEATSTORE facilitates learning from the demonstration projects across similar technology projects, across different UTES technologies, across sectoral and geographical borders.

In this section a detailed account of the national projects with their demonstration sites and case studies is presented.

Netherlands

ECW Demonstration project: the underground storage that is anticipated to be demonstrated in the Netherlands is an aquifer thermal heat storage (ATES) concept in combination with 2 km deep geothermal wells allowing for heat to be used directly for heating ~100 hectares of (agriculture) business. Three geothermal heat sources (doublets) are in operation A preliminary design for the ATES has been developed. The temperature level provided by the geothermal heat source is 92 °C. The geothermal wells have surplus heat in summertime which can be stored by using an ATES system. The ATES system pre-design constitutes two wells (1 doublet) storing heat in an aquifer at 300 to 400 hundred meter depth.

With the use of smart energy management and district heating design algorithms, the full potential of storage technologies in the ECW heat grid will be assessed and optimized on a system level.

Case study HT-ATES Koppert Cress greenhouse: Conversion of low-temperature ATES to high temperature (45°C) ATES. The heating demand of Koppert-Cress proved to be much higher than expected, which resulted in a very large imbalance in the ATES system towards the cold well. Now with solar heat collectors and heat recovery from the cool-well connected to the warm well more heat can be stored, which allowed minimization of having to run the heat pump. Monitoring results and experience from this current transition from low to high temperature ATES are used in HEATSTORE. Koppert-Cress is located in an area with high potential for geothermal mining, it is investigated in this case study to what it is possible and beneficial for them to extend their current transition to even higher temperature storage in combination with geothermal mining.

Case study NIOO KNAW**:** NIOO-KNAW has established a pilot HT-UTES facility for aquifer thermal energy storage at 45 °C at 300 m depth in collaboration with industrial partners and the Province of Gelderland, the Netherlands. This pilot is operational since 2012. NIOO-KNAW has acquired data for this facility for its subsurface effects on temperature, soil, groundwater and microbial composition through measuring technology and chemical and biochemical analysis, as well as data on above-ground – below-ground heating system integration. These studies have yielded datasets which can be analysed and used for establishing guidelines and basic assumptions for new designs and pilot facilities in the HEATSTORE project. NIOO-KNAW will share the existing data of its HT-UTES facility as well as to monitor and validate parameters of interest in the HEATSTORE project.

Switzerland

The Geneva project will allow the assessment of the heat storage potential for the development of a HT-ATES System connected to the waste-to-energy plant located in Cheneviers (Canton of Geneva). This plant uses domestic wastes to produce energy and emits about 50GWh/year of waste heat to the environment, which could potentially be stored in the Geneva subsurface. The subsurface conditions will be constrained by drilling and testing at two different locations where the potential reservoir in the Cretaceous limestone is located at 600 and 1000m respectively. In HEATSTORE the focus is on the technical, economical, regulatory, and social constraints, which will lead to a commercial implementation of the system in a future stage.

The pilot project in Bern aims to store waste heat from the nearby power generation site Bern-Forsthaus. The power generation site is operated by the local utility company Energie Wasser Bern (EWB) and contains a combined-cycle plant, waste-to-energy plant and wood-fired power station for electricity and heat production. For the pilot heat storage system an exploration well, ~ 500 m deep will be drilled to reach the Lower Freshwater Molasse USM. The goal of this project is to assess the feasibility of the ATES system and if the results are positives, to drill more wells to realize a fully functional heat storage system, which, in its final implementation is aimed to store lost heat at storing 7 – 10 MWth having a storage temperature of 120°C maximum.

Germany

The aim of the **German** project is to create a technically and fully functional seasonal mine thermal energy storage pilot plant for the energetic reuse of the abandoned coal mine Markgraf II, with the emphasis on a two year operating and monitoring phase during the project lifetime. The generated data can be exploited for the implementation and dissemination of future deep geothermal storage systems. The conceptual idea is based on the storage of seasonal unutilized surplus heat during the summer from solar thermal collectors within the mine layout and to use the stored heat during the winter for heating purposes of the institute buildings of the International Geothermal Centre (GZB).

France

The demonstration project will provide the heating needs for two administrative buildings of Storengy main natural gas storage facility located in Chémery (region Centre – Val de Loire) which represents 135 MWh. These needs will be addressed with 265 m^2 of solar panels combined with a BTES charged and discharged through 12 radial lines of 4 boreholes in series. The main objective of this project is to improve the overall efficiency of such coupled systems based on the combination of solar thermal and BTES.

Belgium

In 2015 -2016, VITO drilled the first deep geothermal doublet in Flanders at the Balmatt site in Mol, to a depth of 3,6 and 3,8 km. These wells will supply heat for an existing district heating network, heating the campus of VITO and neighbouring companies. Additionally, unused heat from the wells - mainly in summer when the heat demand is low - will be used to produce electricity by means of an ORC installation. According to the planning, the first geothermal heat will be delivered in the heating season 2018-2019.

The peak consumption of the existing heating network is almost 12 MW. According to the well tests however, the well will be able to produce a peak power of about 7 MW for the supply and return temperatures of the network. This means that about 186 hours per year, currently the gas fuelled peak boilers have to be active to cover these peak demands. The district heating network is currently operating at high return temperatures of 70°C in winter conditions and 60°C in summer conditions, resulting in injection temperatures of about 80°C to 70°C. For proper utilisation of the geothermal well, these temperatures should be reduced.

The research question in HEATSTORE is to assess to what extend the power peaks can be reduced by the installation of a smart district heating network controller, which benefits it will bring for the network, and if and how this controller can be replicated in other geothermal networks. Also, it is investigated in which extend the return temperature of the district heating network can be reduced, and which benefits this brings to the network operation.

In the context of HEATSTORE a self-learning DHC network controller will be implemented. After installation of the hardware, we will optimize and train the controller for conditions that are specific to geothermal DH. In addition, we will investigate the benefits of adding thermal storage options, including high temperature aquifer storage in fissured chalk deposits, high temperature storage at geothermal plant side, decentralised storage at building level, to the smart DH network. In a final step, the impact of demand side management and thermal storage on further extensions of the Balmatt geothermal DH network will be evaluated.

Denmark

The Danish case study will provide important knowledge necessary for the exploitation of the potential for UTES in Denmark through de-risking, cost reduction and optimization and thereby paving the way for commercial implementation of the technology.

Existing UTES projects in Denmark will be analysed in terms of subsurface conditions, design, system integration and performance evaluation and lessons learned will be translated into general specifications and design for ATES, BTES and PTES systems under Danish conditions as well as contributions to best practice guidelines.

Iceland

The Icelandic subproject of HEATSTORE will focus on using recent advances in academic/research reservoir modelling tools in conventional commercial field scale modelling schemes. Specifically advancing existing models to be used for simulating pre-drilling scenarios of different heat storage schemes for 1) storage of excess geothermal heat produced in base load co-generative geothermal power plants during summer time in geological formations located at a depth of 500-2000 m depth and 2) heat storage within superhot, deep geothermal systems (~ 5 km depth).

Simulating how different reservoirs respond to varying heat storage schemes provides important information on optimal energy storage and extraction methods. These in turn, provide essential criteria for future infrastructure development, such as well and piping designs, as well as the overall business case of utilizing heat storage in different geological conditions. This approach bears high innovation potential for pre-drilling resource assessment and targeting as well as robust scenario development for project development and decision making. Furthermore, linking the novel academic/research simulations of the superhot part to the existing conventional reservoir model will result in novel reservoir modelling approaches that will enhance our understanding of the subsurface.

Portugal

The Portuguese sub-project will also bring academic/research reservoir modelling tools forward to develop conceptual scenarios of a sparsely characterized, potentially high enthalpy geothermal resource, based on integrating geochemical data and preliminary well test information with subsurface process dynamics simulation. This is expected to significantly improve understanding of the potential for geothermal exploration of the selected research area: the Caldeiras da Ribeira Grande fumarolic field, Fogo Volcano, S. Miguel Island – Azores.

Following the pre-existent conceptual models, the geothermal reservoir, located in the north flank of Fogo Volcano, is a liquid-dominated system with temperatures more than 240 ºC and the flow is controlled by NW regional trends. Geochemical data that will be used to constrain conceptual models include gas composition from fumarolic emissions, water chemistry in thermal and cold CO_2-rich springs, diffuse degassing maps and altered minerals found out along the wells log (available rock samples from surface until 1300 m depth). Drilled wells temperature as well as geological mapping will be also used as inputs to model the reservoir conditions.

Spain

The Spanish participation in HEATSTORE concerns the development and application of numerical modelling tools of coupled Thermo-Hydro-Mechanical-Chemical (THMC) processes. Although during the project these techniques will be used for the demonstration pilot at Bern, it is expected that the project will improve the modelling tools and the experience of their use, which will be beneficial to applications to other UTES sites, both within and outside Spain.

6. CONCLUSIONS

Thermal energy storage technologies need to be developed and 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 this project are to lower the cost, reducing the risks and to optimize performance of high temperature (~25 to ~90°C) underground thermal energy storage technologies by demonstrating 6 distinct configurations of heat sources, heat storage, and heat utilization. Technical, economic, environmental, regulatory and policy aspects will be addressed that are necessary to support efficient and cost-effective deployment in Europe. The project will stimulate fast-track market uptake in Europe 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 2050.

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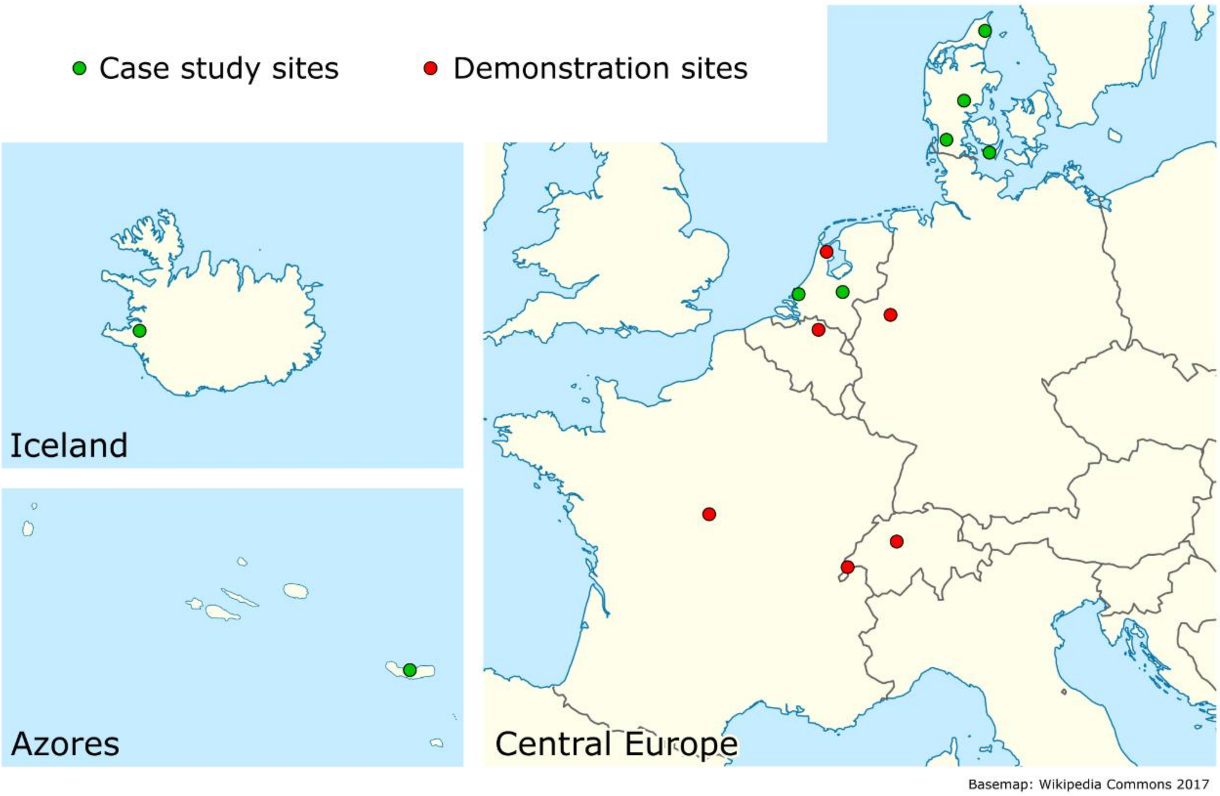

Figure 1: Overview of demonstration sites and case study locations in HEATSTORE

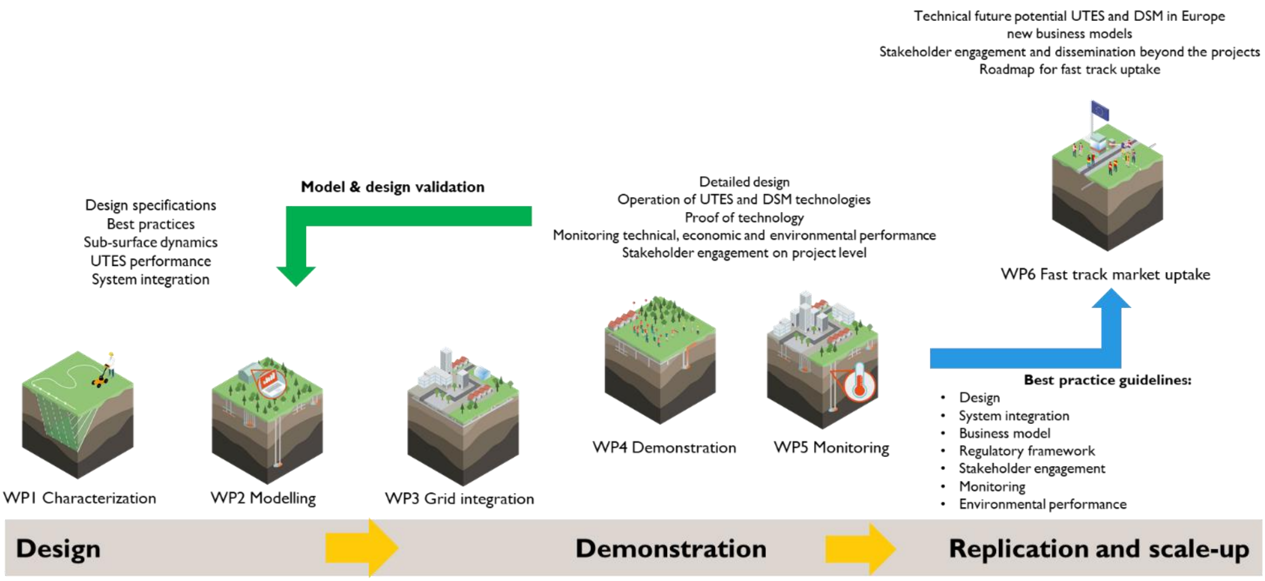

Figure 2: Graphic representation of the Design phase, Demonstration, and finally the Replication and scale-up phase in the HEATSTORE approach

Table 1: Summary of demonstration projects within the HEATSTORE project

Country	Concept of pilot demonstration	Storage capacity & volume	TRL* advance
Netherlands	Geothermal heat doublets combined with Aquifer Thermal Energy Storage (max 90°C) integrated into a heat network used by the horticultural industry	5-10 MW 20 GWh	7 to 8
France	Solar thermal combined with a Borehole Thermal Energy Storage (40˚C) with lateral heat recovery boreholes	kW range 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 reuse of summer surplus heat from Concentrated Solar Thermal (max. 80°C; Δt: 50-60 K) for heating buildings in winter.	45 kW 165 MWh	to 8
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