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HEATSTORE

Swiss Consortium Annual Meeting

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heatstore

High Temperature Underground Thermal Energy Storage

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Summary

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, and 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 24 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 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. The Swiss consortium (4 university and 2 industry partners) is working on two pilot demonstration projects located in Geneva and Bern, respectively.

Table 1 - Proposed pilot 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

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1 Introduction

1.1 Background of the project

The HEATSTORE Switzerland project aims at assessing the feasibility and the potential of High Temperature Aquifer Thermal Energy Storage (HT-ATES) systems at two sites located in the Cantons of Geneva and Bern, respectively.

The goal of the Geneva project is the assessment of the heat storage potential for the development of an HT-ATES system connected to the waste-to-energy plant operated by Services Industriels de Genève (SIG). This plant uses domestic wastes to produce energy and emits excess heat to the environment, which could potentially be stored in the Geneva subsurface and delivered to final users during seasons of high heat demand. The overall goal of the project is the subsurface characterization and energy system integration constrained by drilling and testing at two different locations where two potential reservoirs in Cretaceous and Jurassic limestones are located at depths between 500 m and 1100m. At this stage, the work is focused on the technical, economical, regulatory, and social constraints, which will lead to a commercial implementation of the system in a future stage, potentially in 5 years.

A modular and holistic approach is developed addressing the following aspects:

- Resource assessment and reservoir characterization by drilling of two deep wells, collecting well data, running laboratory experiments, developing and running in-situ test protocols in the exploratory boreholes and an analogue test site adapted for determining key reservoirs parameters in the context of an HT-ATES, and running production/injection tests reproducing the envisaged full-scale future operating conditions.
- Reservoir & development scenario modelling in order to provide industrial developers with the necessary background knowledge to assist their decision-making process.
- Energy system scenario modelling to integrate an HT-ATES system into the existing network.
- Economic modelling aiming at reducing the risk and the costs of running an HT-ATES system focusing on the sustainable development of the project.

The pilot project in Bern aims to store waste heat from the nearby power plant Bern-Forsthaus. The power plant 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 sandstone layers of the Lower Freshwater Molasse (USM). The goal of this first well is to assess the feasibility of the HT-ATES system and, if the results are encouraging, more wells will be drilled after the HEATSTORE project, to realize a fully functional heat storage system with an injection temperature of max. 120 °C and an expected output of 7 – 10 MWth.

The main drivers of this project are:

- Energie Wasser Bern (EWB) is a strong industry partner and the local utility company in the region of Bern.
- An increasing heat demand and a planned expansion of the existing district heating network in the city of Bern.
- The commitment of the city of Bern, owner of EWB, to support renewable energy technologies; to improve overall efficiency in energy production and to reduce CO_2-emissions.

The Technology Readiness Level (TRL) of both projects advances to a maximum of TRL 5 – 6.

1.2 Justification of the project

The deployment of renewable energy sources (RES) for both, power and heat production is accelerating in Switzerland. This trend will continue thanks to the passing of the 2050 Swiss Energy Strategy on May 21st, 2017. The new energy strategy aims at gradually phasing out nuclear power by reducing the energy consumption and increasing electric and heat generation from renewable energy sources.

In Switzerland the total energy consumption decreased by -0.4% between 2016 and 2017, reaching 849’790 TJ. More than 60% of the energy consumed was supplied by fossil fuels, 12% by renewable energy sources and 24.8% was covered by electricity. Of the energy consumption, 27.8% was for households, 18.5% for industrial activities, 16.4% for services and 36.3% for mobility.

UTES systems and more specifically ATES systems can provide a modular and flexible solution to contribute to the 2050 Swiss Energy Strategy by storing waste heat into to aquifer formations and then deliver it in high demand seasons.

1.3 Objectives of the project

In the framework of HEATSTORE we intend to develop a workflow focusing on the following objectives:

- Integration of subsurface characterization and surface energy systems. This will allow evaluating the overall technical feasibility of ATES projects in Switzerland.
- Definition of business models to assess the profitability of ATES systems. The main focus will be the valorisation of ATES systems in complex energy systems.
- Improvement and adaptation of the current Swiss legal framework to ATES application. This will be an important goal to be achieved as it will facilitate the future development of ATES systems.

Finally, the application of this approach to two sites characterized by different subsurface conditions (e.g. lithologies, depth intervals, structural constraints, formation water chemistry) and energy system configurations is setting up a baseline for replicability to other potential implementations across the entire Swiss territory.

2 Methods

2.1 Workflow

Data collected in the framework of the industrial geothermal exploration and development activities driven by SIG and EWB will be combined to produce a number of predictive integrated models that will allow evaluating the technical-economical-legal-social feasibility of HT-ATES projects within Switzerland.

The starting data to be evaluated are the energy system configuration in terms of waste heat availability and heat demand, and the subsurface conditions that will be used to develop energy system scenario models and 3D subsurface petrophysical models. The combination of both models will be used as inputs for predictive thermal-hydraulic-mechanical-chemical (THMC) dynamic models. Such models allow assessing the technical feasibility of HT-ATES systems at the two pilot sites. These models will be calibrated and validated when new data becomes available during subsurface prospection and exploration phases and from small scale analogue test sites. Once the THMC models will be validated, they will allow assessing the economic feasibility, which will also be linked to the improvement and adaptation of the existing Swiss legal framework. Dissemination and communication/outreach activities aim to improve public acceptance.

The overall workflow is summarised in Figure 1.

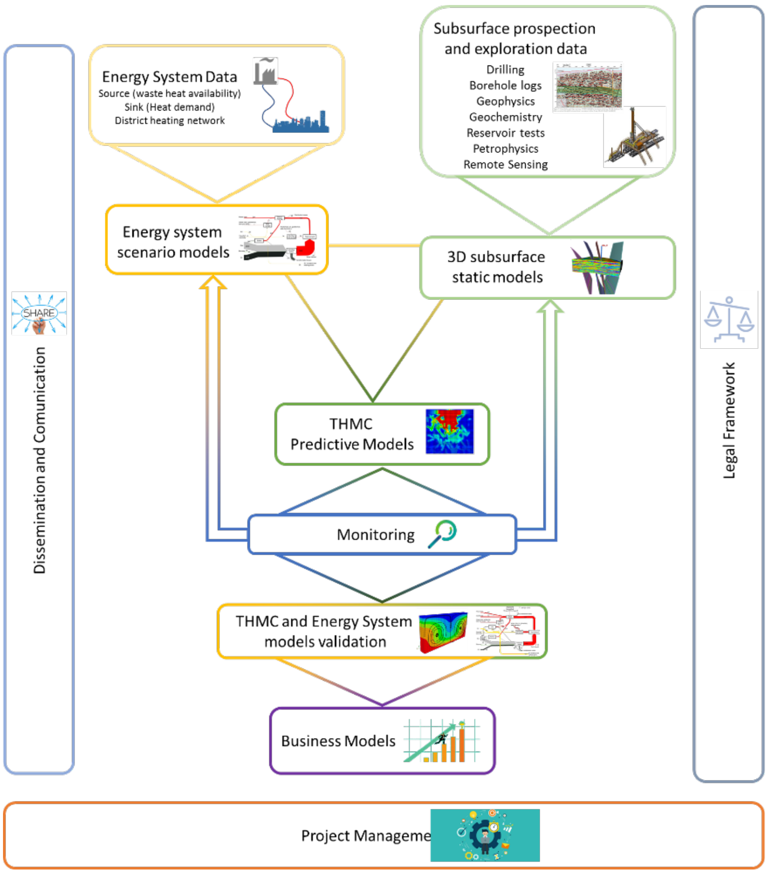

Figure 1 – Workflow for WP integrations

2.2 Monitoring

Geneva:

Site name:	**GEo-01 and GEo-02 wells**
Location:	**Geneva / Switzerland**
Operational since:	**not in operation; still in planning phase**
UTES Type:	**HT-ATES (the heat storage is located within the Upper Mesozoic Units, characterized by local high porosity and permeability conditions located in karstified volumes or reef complexes or faulted volumes)**

The GEo-01 well reaches the Lower Cretaceous and Upper Jurassic limestones and is providing a large amount of data for subsurface characterization of these potential target units. The well is characterized by well-head natural artesian flow of 50 L/s, temperatures of 34˚C and wellhead pressure of 8 – 10 bars.

Long-term production test at GEo-01 will last 6 months, and the planned protocol will follow two main phases:

- Step drawdown tests: This phase will last for 5 days. The flow rate will be increased by 5 steps of 24h until the maximal artesian flowrate observed (200m^3/h).

- Long-terms production test (6 months max). The well will produce up to 200m^3/h.

During production tests, periodic water sampling campaigns will be carried out to monitor compositional variations. Additionally, temperature and pressure sensors will be installed in other wells in the region. This allows to monitor the aquifer response at a larger scale to better understand the hydrodynamic behaviour of the aquifer during and after the end of the production tests. A water sampling campaign has been carried out by the University of Geneva in November 2018 and the results will establish the hydrogeological baseline to evaluate potential variations in the geochemical compositions of the waters during production.

In addition, Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) equipment will be installed in a nearby well that will be drilled in summer 2019 into the Tertiary Molasse sediments, which overlie the Mesozoic units (Figure 2). This well will be used as a monitoring tool to assess if the two formations are hydraulically connected. The DAS equipment will also be used as sensor for a 3D VSP (Vertical Seismic Profiling) survey that will be carried out in summer 2019. The goal of this acquisition is to resolve, in high resolution, the fracture network of the Lower Cretaceous formation and characterize the lithological heterogeneities within the Molasse sediments. Additionally, with the DAS cable installed permanently, additional 3D VSP surveys can be carried out in the future for time-lapse monitoring of the reservoir. S-Wave active seismic data will be also be collected in summer 2019 with the goal to better define the geometry of the Quaternary deposits around the wells. These sediments host the main fresh-water resources, which need to be carefully protected.

The production tests design parameters are now being used by ETHZ to run some predictive THM modelling and assess whether the production can produce ground deformations. It is also planned to monitor ground deformations using the InSAR (Interferometric synthetic aperture radar) method. This will help validating the THM predictive modelling.
A Micro-Earthquake (MEQ) monitoring network is installed across the whole Geneva area and nearby France. Data from the MEQ will be used to monitor potential seismicity induce by the production tests.

The same protocol of monitoring methods will be applied to the GEo-02 well that will be drilled in Q3-Q4 2019. The detailed monitoring plan is currently being developed. At this second well, the target formation is the Upper Jurassic Reef Complexes, which are located at about 1000m in depth at the location of GEo-02.

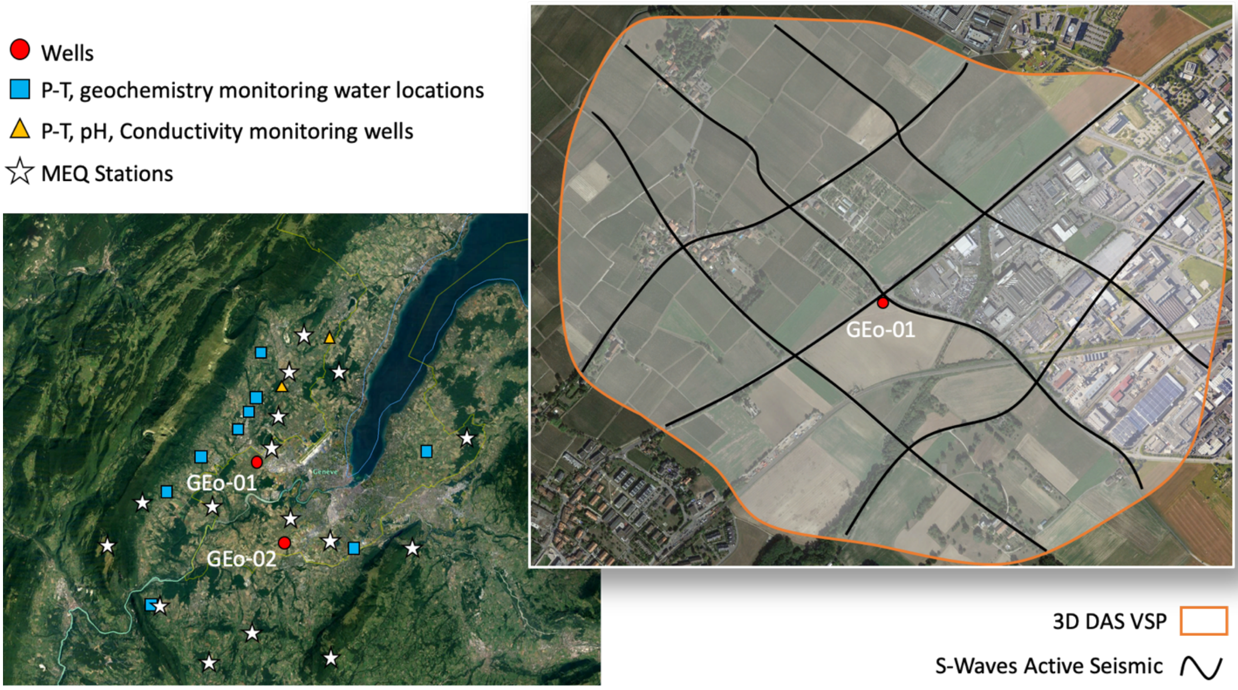

Figure 2 Satellite view of the Geneva Basin and top view of the GEo-01 area

Bern:

Site name:	**Geospeicher Forsthaus (Bern)**
Location:	**Bern / Switzerland**
Operational since:	**not in operation; still in planning phase**
UTES Type:	**HT-ATES (the heat storage is located within the Lower Freshwater Molasse (USM). USM as a whole is considered as an aquitard with some conductive layers.**

The main and auxiliary wells will be equipped with fibre optic cables, monitoring temperature, pore-pressure and strain. There will be an additional monitoring well, equipped with the same fibre optic cables, but located in between the main and the auxiliary wells. This configuration allows monitoring of temperature, pore-pressure and strain at the centre, in between and at the periphery of the heat store reservoir (Figure 3). Temperature and pore-pressure are continuously monitored for reservoir engineering purposes. Continuous strain / deformation monitoring will deliver inputs for reservoir stability and surface deformation.

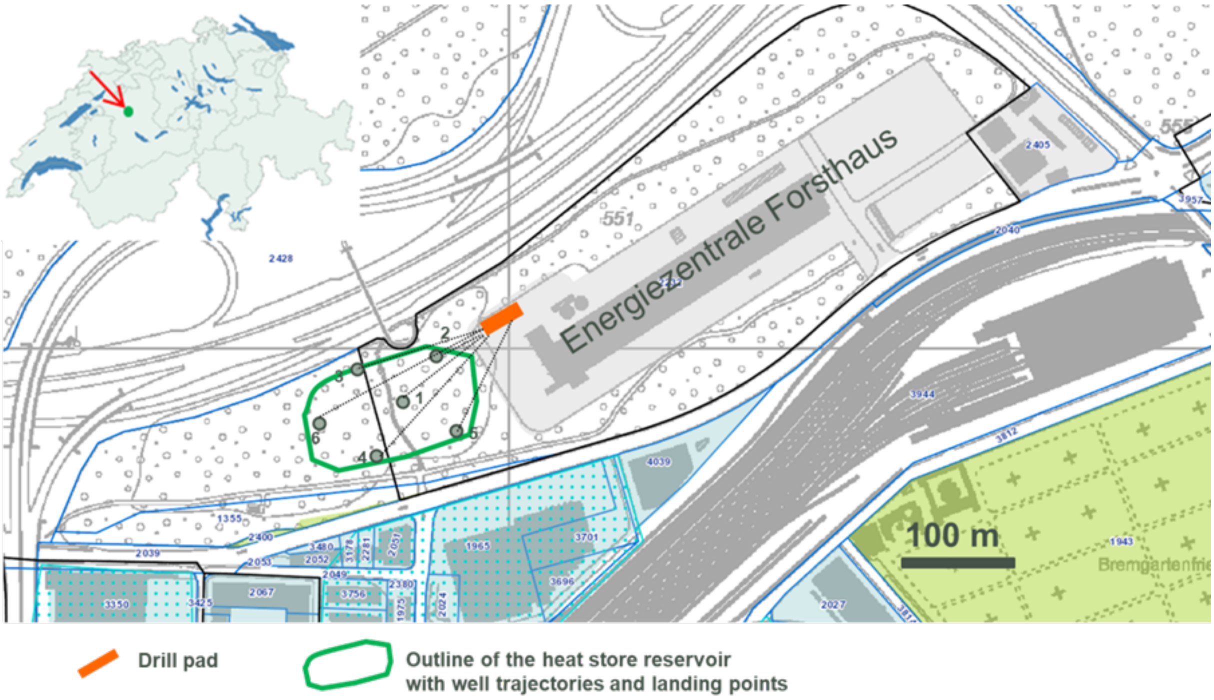

Figure 3 Top view of the HT-ATES Forsthaus

Periodical levelling (detailed elevation measurements) of control points will be executed during the course of drilling and testing in order to monitor potential surface lift or subsidence. The control points are distributed on top of the heat store reservoir and the nearby infrastructure (buildings, roads).

The well will be drilled to a depth of 500 m vertically but will be drilled at an angle so the total length of the well will be longer. The entire reservoir section will be cored, with the cores requiring immediate attention from geologists. The coring and testing operations will be performed sequentially. If the cored section exhibits good reservoir properties, the specifically designed testing equipment (wireline packer system) will be run across that section through the coring bit, and a selective hydraulic test will be performed in order to characterize the test interval with respect to in-situ formation pressure, transmissivity, hydraulic boundaries and, as soon as more than one well is available, wellbore interconnectivity will be determined by hydraulic tomography. The procedure will allow establishing a geology and transmissivity profile for the entire reservoir section. This profile will be later used to select the zones to be perforated and used for the heat storage volume.

3 Ongoing Activities and Results

3.1 SIG

SIG is the leading industrial partner for the Geneva site and in charge of all the operations of subsurface characterization and target identification.

The main focus has been directed on the following activities:

- Design of pumping tests at GEo-01: See Chapter 2
- Cores collection in the Reef Complex Units at La Plagne Quarry: 247m of cores have been collected and are available for other partners for studies. UniGe and UniBe already collected cores for mineralogical-petrographic-diagenetic-geochemical studies
- Design of GEo-02 well: The GEo-02 well will reach a depth of 1130m. A casing will be installed down to 832m and the open-hole section will reach the bottomhole with a 6-1/2" diameter. The main target for Heat storage has been identified on the Reef Complex located at the base of the well
- Definition of the monitoring plan at GEo-01: See Chapter 2
- Energy system scenarios modelling: See section 3.3

3.2 EWB

EWB developed a conceptual reservoir model for the UTES Bern-Forsthaus, which has been used as basis for the development of the following models:

- TH Model 2D, radial symmetric, 6/12 conductive layers
- TH Model 3D, 1 main well, 4 aux. Wells
- TH Model 3D, 1 main well, 4 aux. Wells, 4 hor. Wells (radial jetting)
- TH Model 2D, aquifer plume
- TH Model results for a variety of different layouts and boundary conditions

The models and a selection of simulation results have been presented on the WP2 Progress Meeting in Zurich 2019-02-11.

Further achievements are:

- Analysis of economic feasibility
- Risk management. Technical report on environmental impacts.
- Pre-Design of wells, testing and monitoring

3.3 University of Geneva

UniGe is the national coordinator of the project. On the project management side UniGe organised regular meetings with Swiss project partners:

- 2018-10-08: Kick-Off Meeting Swiss Consortium (Geneva)
- 2018-11-19: WP2 Meeting (Geneva)
- 2019-01-10: WP2 Meeting (Neuchatel)
- 2019-02-11: WP2 Meeting (Zurich)
- 2019-05-22: Annual Meeting (Bern)

Additionally, UniGe in collaboration with ETHZ and UniBe organised and hosted the following meetings at the international consortium level:

- 2019-04-08: WP2 Meeting (Geneva)

And attended the following workshops:

- 2018-09-17: Kick-off Meeting (Utrecht)
- 2018-11-22: WP1 Meeting (Bochum)

On the technical side, UniGe has been focussing on the subsurface 3D static modelling at the GEo-01 site. The Geneva Basin 3D model available from the GEOMOL project has been improved in terms of data accuracy and resolution over a volume of 2x2x2km surrounding the GEo-01 well. Stratigraphic and geophysical well data provided by SIG have been interpreted to produce a geological and structural 3D model which has been populated with petrophysical data (porosity and permeability) according to the following studies (Figure 4):

- Interpretation of seismic data to reconstruct the fault architecture and improve the identification of the main potential targets
- Diagenetic characterization of Lower Cretaceous and Upper Jurassic Units based on cuttings analysis
- Mineralogical and petrographic characterization of Lower Cretaceous and Upper Jurassic Units based on cuttings analysis and correlation with surrounding wells
- Fracture network modelling to produce a discrete fracture network model using geomechanical (in collaboration with UniNe) and stochastic methods

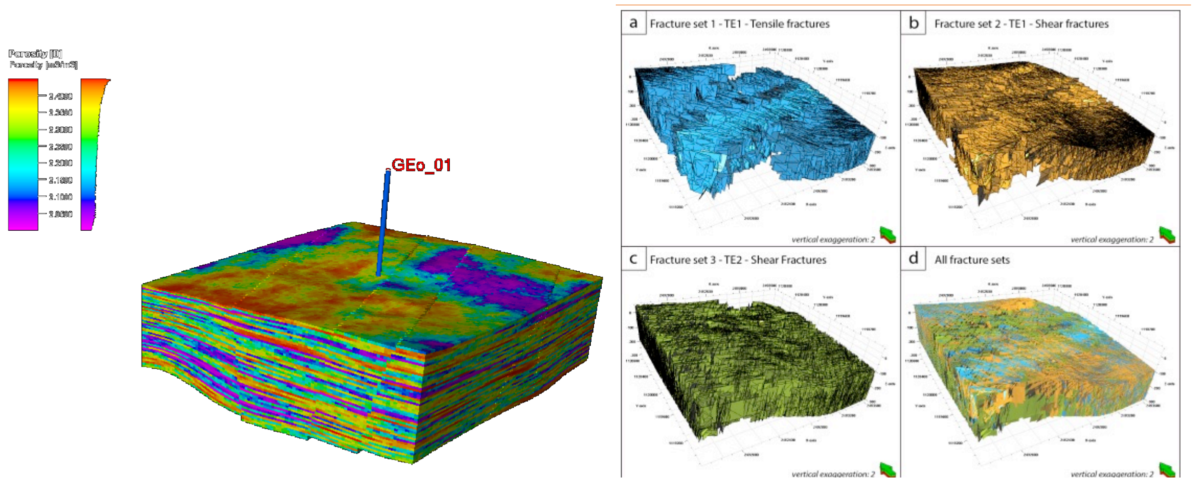

Figure 4 (left) Porosity model and (right) simulated discrete fracture network at the GEo-01 well

Additionally, a water sampling campaign across the Geneva area was carried out in November 2018 to improve the understanding of the hydrogeological processes controlling water circulation in the study area.

UniGe started working on the GEo-02 well where the main potential target has been identified in the Reef Complex unit at the base of the Upper Jurassic. This formation, which was not reached by the GEo-01 well, is known to present favourable conditions in terms of porosity and permeability. Its vertical extent can reach up to several tens of meters and its lateral continuity is discontinuous but can reach up to 1km in width. This unit is potentially very promising also thanks to the presence above and below it of impermeable formations that might prevent flow away from the reservoir. At the moment the information available are scarce but UniGe carried out two studies on outcrop analogues:

- Drone photogrammetry on a selected outcrop to assess the vertical and horizontal extent of the Reef unit. Data have been processed to produce preliminary porosity and permeability 3D models. This study will continue in summer 2019-2020 on other outcrops in the Geneva area and will then be validated and calibrated by GEo-02 data (Figure 5).

- Diagenetic, mineralogical and petrographic characterization of core samples collected in the La Plagne Quarry (France).

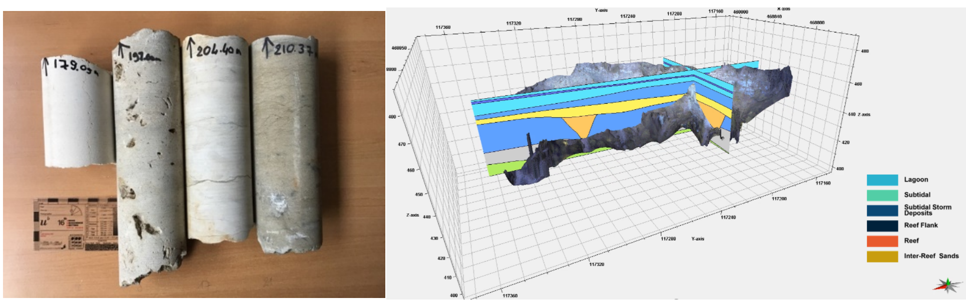

Figure 5 (left) Cores from La Plagne quart and (right) 3D model from photogrammetric survey

UniGe, in collaboration with SIG, in the definition of the energy system scenarios to 2035 according to the expected waste heat availability, heat demand, and district heating development and configuration (Figure 6). Such scenarios coupled to the 3D static model have been developed to provide realistic input for predictive TH-THM-THC dynamic modelling.

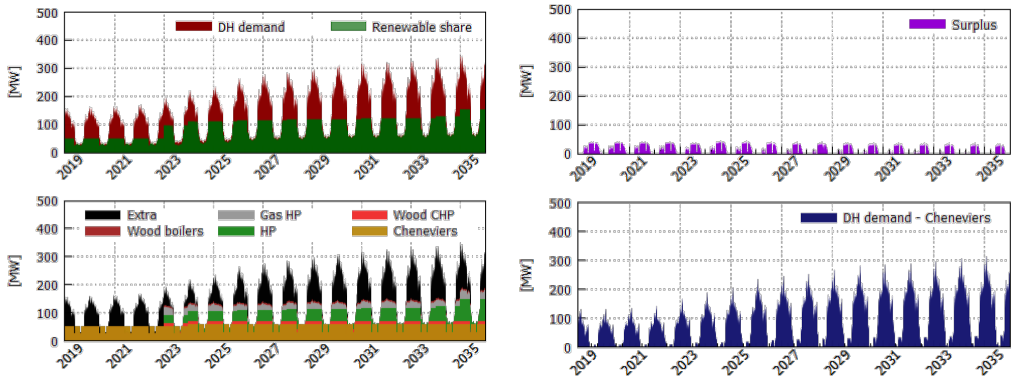

Figure 6 - Charging/discharging provisional profiles to 2035 from the waste incineration plant in Geneva

3.4 University of Neuchatel

UniNe is performing Geomechanical characterisation of the geothermal exploration borehole GEo-01. This is achieved by the analysis of the logging data collected during drilling operations at the GEo-01 well. The study focusses on the assessment of the fracture distribution, the stress field, and the mechanical properties of the fractured limestone present around the borehole. We plan also to evaluate the relation between fracturing and inflows in the well, although the available logging data on this aspect are at the moment incomplete for Geo-01. The realisation of a local-scaled geomechanical model is a required step to develop an understanding of the geomechanical conditions prevailing in the Geneva basin. Geomechanical parameters are also required as inputs for THM modelling (see Section 3.4.2). More largely the geomechanical characteristics of the subsurface will impact groundwater flow and heat transport and drive possible interactions with the fracture and fault system.

UniNe compute several numerical simulations for fractured limestone rock to highlight relevant processes for ATES in Switzerland. The calculations give a first idea of the scale and size which has to be investigated afterward.

UniNe has performed a test site selection for different thermo-hydro-mechanical test experiment to initiate and build a thermo-hydrogeological research site with properties that are relevant for ATES in Switzerland, but at shallow depth so that experimental work can be performed easily. This site should act as an analogue for Geneva heat storage with conditions comparable with the one encountered in the GEo-01 well. For that we target the same formation that in Geneva but at shallower depth.

The principal scientific objectives of current experiments and monitoring studies performed at the site are the following:

- Test new methods for characterizing the environment (in boreholes) that can be used for understanding highly heterogeneous environments.
- Acquire the data required for testing and validating thermo-hydrogeological modelling methods designed for fractured environments.
- Develop methods for quantify underground flows and measuring flow velocities in highly heterogeneous environments
- Study the environment's heat reactivity and especially changes in the heating quality of the waters as extraction proceeds
- Measure the distribution of residence times and estimate the distribution of travel times.

Short- and medium-term programs

- Transport parameters
- Reactivity of the environment one of the features of the site is the reactivity of the environment
- Water tracing and residence times
- Flow measurements and hydraulic: efforts to characterize and model flows at various scales will also be pursued.
- Hydro-geophysical monitoring: new methods of inversion coupled with hydrogeological measurements (pressure, tracing, etc.) and geophysical measurements (electrical, etc.). Application of these methods in fractured environments poses conceptual problems related to the very strongly channelled nature of the flows. The UniNe-HEATSTORE site will be used to test and develop hydro-geophysical characterization methods for imaging fractured/karstic media. New hydro-geo-thermophysical experiments will be conducted there.
- Coupling of measurements and modelling: in parallel with the acquisition of these data, modelling studies should be undertaken as part of the various activities being conducted. This should lead to better definition of certain missing data, both to constrain the processes, and to model the site itself.

UniNe has initiated a collaboration with the Swiss Competence Center for Energy Research – Heat and Electricity Storage (SCCER-HaE) to characterize thermal conductivity and heat capacity of rock properties for storage.

3.5 ETHZ

ETHZ has been in charge of the development of simulator applications as well as the development and analysis of individual simulation scenarios based on site-relevant parameters. In particular, two simulator-based assessments are being made, and thus two main simulators were developed based on framework libraries of different origin (Nexus-CSMP++, and MOOSE). The first one is aimed at addressing Thermo-Hydrological (TH) modelling aspects of the Geneva site, while the second one is aimed at addressing Thermo-Hydro-Mechanical (THM) aspects through ground stress and deformation for both the Geneva and Bern sites.

3.5.1 TH modelling

A TH simulator application was built using Nexus and CSMP++ libraries, allowing for an object oriented, flexible, and modular design. Specific parameters were requested from and provided by UniGe and SIG for the Geneva site. Simulation models were then built with incremental levels of complexity for the purpose of assessing the major factors that may influence HT-ATES design without incurring excessive computational cost.

The focus was centred on important aspects as presented, discussed, and decided in the regular meetings arranged by UniGe. In an effort to reach beyond a simple parameter sensitivity study, ETHZ proposed that the main factors at play be considered, and thus modelled features should include buoyancy, groundwater flow, multiple aquifer storage, and faults/fractures/reef structures. Simulation assessment increments were then defined through a series of ongoing and iteratively-improved scenarios. Based on the WP2 Bern meeting in May 22, 2019, and provided input data, a simplified list of scenarios, including some of the variants within, consists of the following:

- **Scenario 1:** A “flat” model (i.e. no dip angle on any layer), synthetic but with characteristics relevant to the interpretation provided by UniGe, simulated with and without groundwater flow.

- **Scenario 2:** Based on Scenario 1 but introducing 15-degree dip angle on all layer surfaces, simulated with and without groundwater flow.

- **Scenario 3:** Based on Scenario 1, introducing reef structure in aquifer layer(s) of variable permeability, with and without groundwater flow.

- **Scenario 4:** Based on Scenario 1, introducing a synthetic single fracture only on the aquifer region with varying permeability and within $100\ [m]$ from the well, simulated with and without groundwater flow.

- **Scenario 5:** Based on Scenario 1, introduce faults of different types. In contrast to Scenario 4, this scenario may require more involved meshing depending on the type of fault (e.g. thrust, strike-slip with dilational step-overs)

- **Scenario 6:** Based on Scenario 1, introduce auxiliary re-injection well at a variety of distances (i.e. $50\ [m]$, $100\ [m]$, $200\ [m]$, directly upstream in terms of groundwater flow from the location of the main injector well.

- **Scenario 7:** Based on interpreted data provided by UniGe and SIG with a certain degree of simplification, introduce the final accepted geometries of horizons and faults as well as petrophysical parameters distribution. This scenario will essentially be a more geometrically/geologically detailed and complex version of all combined scenarios above, focusing on the possibility of a fault/fracture flower structure existing in the vicinity of the main operating well. This scenario's final definition (i.e. there may be more than one) will likely be a moving target depending on results from other scenarios.

Considerable progress has been made by ETHZ in simulating Scenarios 1, 2, 3 and 4 thus far. A sample of the results obtained for Scenarios 1 and 2 can be observed in Figure 7.

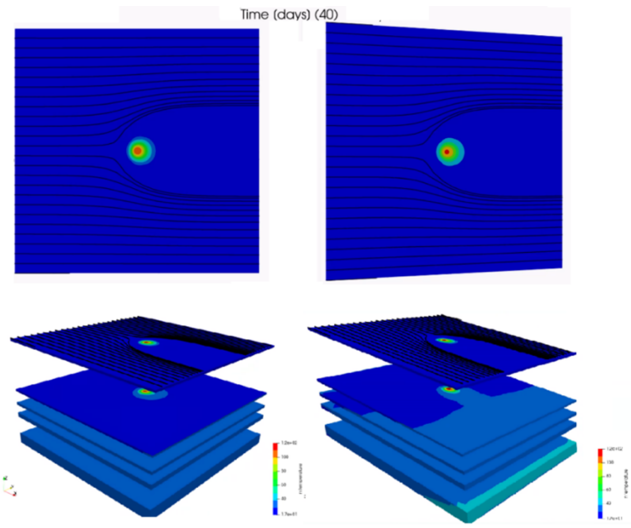

Figure 7: Snapshot of temperature results from Scenarios 1 (left) and 2 (right). The black lines represent the streamlines present due to groundwater flow. A slight drift can be observed in the top figures for the temperature signature established by the injector well present in the centre of the domain. The well penetrates all five aquifer layers shown in the bottom figures. These aquifers are also surrounded by other heat conductive layers of lower permeability (not shown).

Progress towards simulating each one of these scenarios will yield the necessary risk valuation and thus allow for assessing:

1. Feasibility of an HT-ATES system in Geneva.
2. If performed sufficiently ahead of time, improved drill site selection.
3. Operational strategy selection and optimization, including multiple aquifer usage.

3.5.2 THM modelling

The THM modelling is motivated primarily by a desire to understand and constrain ground surface deformation, which is important due to the proximity of the HT-ATES sites to infrastructure and urban centres in Geneva and Bern. The THM modelling group is focused primarily on the Geneva project but was also asked to consider Bern. The simulations are performed with the Multiphysics Object Oriented Simulation Environment (MOOSE), which is a massively-parallel finite element solver. MOOSE is capable of using both structured and unstructured meshes, including externally-generated meshes, which will facilitate incorporation of site-specific stratigraphy and material properties from the 3D subsurface static models.

Early results have focused on two aspects of the project: (a) the uplift due to the first loading/injection stage of heat storage, and (b) the subsidence due to the planned pumping test of GEo-01. The subsidence simulations were motivated by a desire to inform the monitoring activities during the pumping test. These pumping test simulations will be useful for calibration of the THM model once the pumping test is complete. Two-dimensional THM simulations have been performed for relatively simple geological conceptual models. Three-dimensional hydromechanical (HM) simulations have also been conducted, using more information about material properties and stratigraphy provided by UniGe. These simulations will be expanded to include thermal coupling in the near future. Fluid is either injected or extracted at 50 L/s for six months to represent the loading stage of heat storage or the pumping test of GEo-01, respectively. The base case scenario, which does not include an auxiliary well to balance pressure, shows that substantial surface deformation occurs. For the injection scenario, a simple sensitivity analysis shows that uplift is diminished marginally for stiffer rock and/or if a deeper target formation is selected. Uplift is substantially diminished if auxiliary well(s) are included to balance the reservoir pressure. Figure 8 shows example results for a scenario with and without an auxiliary well. Based on these preliminary results, the placement and operation of auxiliary well(s) is very important and needs to be carefully considered as the project progresses. When selecting the reservoir(s) for heat storage, rock properties (e.g. transmissivity and elastic parameters), should also be considered to ensure that the reservoir(s) can store the desired amount of heat and fluid without resulting in excessive pore pressure or surface deformation. Future work involves expanding the THM model to include more site information from the static geological models and simulating multiple loading and unloading cycles based on feedback from the energy system scenario modelling team. This future work can further clarify site-selection and operational decisions about HT-ATES in Geneva and Bern.

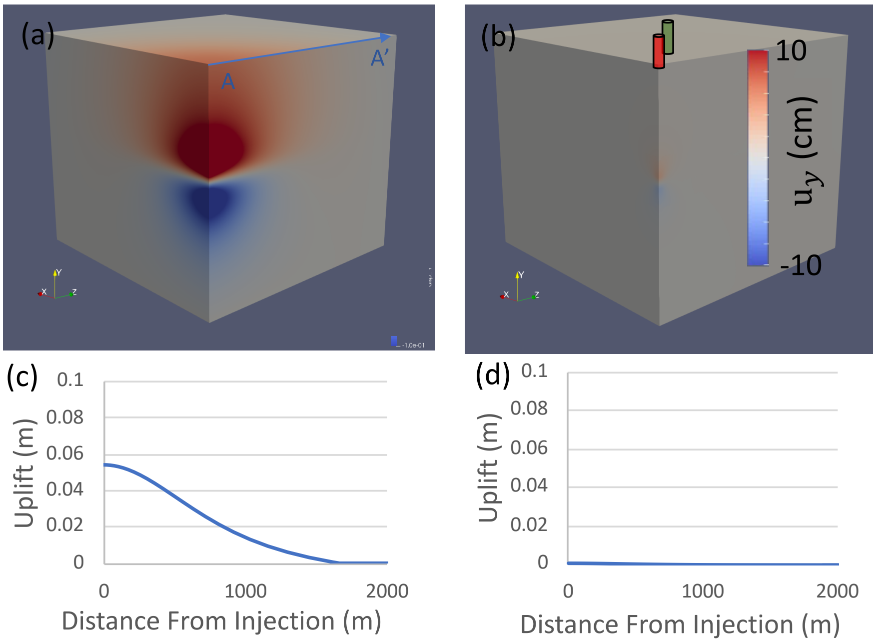

Figure 8: THM model results. Figures (a) and (b) show the vertical displacement for the base case scenario and a scenario where auxiliary wells balance the pressure. The approximate surface location of the main well (red) and auxiliary well (green) are shown in (b). The simulations take advantage of symmetry. Figures (c) and (d) represent the surface uplift along line AA' shown in (a).

3.6 University of Bern

The UniBe Team is assessing the impact of mineral reactions on the successful operation of a HT-ATES system by combining experimental work and THC modelling for both the Geneva and Bern sites. For the laboratory work, we have designed and are currently installing the setup needed to run kinetic mineral dissolution/precipitation experiments. The rock samples needed for the experiments have already been chosen:

- Different cores from the Kimmeridgian reef complexes at the Geneva site (core samples from a borehole in the La Plagne Quarry, France), which is the primary target lithology of current exploration efforts.

- Several sandstone cores from the Lower Freshwater Molasse representing the target lithology at the Forsthaus site, Bern. In anticipation of drilling at Forsthaus, the samples have been taken from stratigraphically higher levels (less than 20 m b.s.l. compared to a maximum depth of 500 m b.s.l. at Forsthaus) at a location approximately 2 km east of the Forsthaus site.

The carbonate samples for the Geneva project have already been characterised in detail (mineralogy, porosity and permeability) by UniGe and SIG, while we performed the same analyses on the sandstone cores at the University of Bern. In addition, one fluid–rock equilibration experiment has been started under the expected elevated P-T conditions using a synthetic pore water.

We have also compiled data from other wells and outcrop locations in the regions of Geneva and Bern, respectively, to assess the variability of geological characteristics (mineralogical composition, porosity, permeability etc.) of the target lithologies as they are strongly heterogeneous. In addition, we are developing a regional hydrogeological model together with UniGe, based on their sampling campaign of wells and springs in December 2018. The hydrogeology of the Forsthaus site will be investigated once drilling has started. Knowledge of the range of mineralogical, petrophysical and hydro-chemical conditions is crucial in order to develop a range of different geochemical scenarios (e.g. different carbonate mineral content or formation water chemistry) which can then be tested once our experimental setup is functional.

In addition to the experimental work, we have compiled an initial THC model of the Bern site which will be used as a THC-benchmark problem (distributed to UPC Barcelona and BRGM). This model predicts mineral dissolution/precipitation reactions both in the subsurface (reservoir) as well as in the surface installations. It will be expanded to a site model as in-situ data is obtained from the Forsthaus site during drilling. A similar model can be developed for the Geneva site if a specific site is developed as part of HEARSTORE.

The results are resumed in Table 2

Table 2 - Synthesis of the results:

	Result
SIG	Design of pumping test at GEo-01
	Cores samples collection at la Plagne Quarry
	GEo-02 well design
	Definition of monitoring plan at GEO-01
	Energy System scenario models 2035
EWB	Definition of monitoring methods at drilling site
	TH Reservoir Modelling
	Definition of drilling targets and strategy
UniGe	3D static petrophysical model GEO-01
	Mineralogical and petrographic characterization Mesozoic GEO-01
	Fracture modelling GEO-01
	Hydro-geochemical sampling and analysis across the Geneva area
	Re-interpretation of existing seismic lines
	Diagenetic characterization of Mesozoic units
	Photogrammetric characterization of Reef Complex outcrops
	State-of-the-art of UTES in Switzerland
	Energy system scenario models 2035
ETHZ	Predictive TH synthetic model for GEo-01 Well
	Predictive THM synthetic model for GEo-01 Well
UniBe	Reef Complex core sampling in Geneva
	THC predictive models at Bern Site
UniNe	Fracturing characterisation of GEo-01
	Mechanical parameter evaluation of GEo-01
	Stress model development for Geo-01
	Mechanical Earth Model compilation as input for THM modelling of ETH
	Literature review of thermo-hydraulic well testing
	Identification of analogue site for drilling wells for testing protocols for thermo-hydraulic investigation
	Predictive thermo-hydraulic simulations for analogue test site evaluation

4 Results evaluation

The following activities have been carried out during the first year of the project.

Table 3 – Activities carried out at the two study sites

<table>
<tr><td rowspan="23">Year 1</td><td>Geneva</td></tr>
<tr><td>State-of-the-art of existing UTES in Switzerland (UniGe)</td></tr>
<tr><td>3D Geologic Static Modelling set-up at GEo-01 (UniGe)</td></tr>
<tr><td>Water sampling in the Geneva area (UniGe)</td></tr>
<tr><td>TH Modelling based on the location of GEo-01 (ETHZ)</td></tr>
<tr><td>THM Modelling set-up at GEo-01 (ETHZ)</td></tr>
<tr><td>THC Modelling set-up at GEo-01 (UniBe)</td></tr>
<tr><td>Water-rock interaction rock sampling (UniBe)</td></tr>
<tr><td>Energy System scenario 2021-2035 set-up (UniGe-SIG)</td></tr>
<tr><td>Design of the GEo-02 well and test/logging program (SIG)</td></tr>
<tr><td>Definition of the monitoring activities at GEo-01 (SIG-UniGe)</td></tr>
<tr><td>State-of-the-art of legal framework in Switzerland (SIG)</td></tr>
<tr><td>Geomechanical characterization of the geothermal exploration borehole GEo-01 (UniNe)</td></tr>
<tr><td>Test site selection for thermo-hydro-mechanical experiment (UniNe)</td></tr>
<tr><td>Bern</td></tr>
<tr><td>Compilation of information on geology, hydrogeology, heat excess & demand, heating network at EZF</td></tr>
<tr><td>Development of a conceptual reservoir model for the UTES Bern-Forsthaus</td></tr>
<tr><td>TH Modelling set-up 2D, 3D (multiple configurations including horizontal wells (radial jetting)</td></tr>
<tr><td>TH Modeling set-up 2D, aquifer plume</td></tr>
<tr><td>TH Modelling, Simulation of a variety of scenarios for different temperatures, flow rates, injection and withdrawal times</td></tr>
<tr><td>THM Modelling of uplift (ETHZ)</td></tr>
<tr><td>Planning of Well Design and Testing</td></tr>
<tr><td>Planning of Monitoring</td></tr>
</table>

The following table shows the traffic light report of the different activities.

Table 4 – Traffic light indicators

Progress in:		Green	Yellow	Red
WP1	Subsurface modelling and well engineering optimization for ATES implementation	X		
WP2	Models and tools for subsurface dynamics for optimal/efficient heat storage.	X		
WP3	Drilling, logging, in-situ & laboratory tests	X		
WP4	Heating system integration design and optimization for future commercial implementations.	X		
WP5	Fast-track market uptake and dissemination	X		
WP6	Project Management	X		
Critical path		X		
Financial progress		X		
HSE		X		

5 Following activities

The following operation are planned to for the two sites in the second year of the project:

Table 5 – Planned activities for YEAR 2 of the project

Year 2	**Geneva**
	3D Geologic Static Modelling refining at GEo-01 (UniGe)
	3D Geologic Static Modelling set-up at GEo-02 (UniGe)
	Reservoir characterization via production tests at GEo-01 (SIG)
	TH Modelling refinement at GEo-01 (ETHZ)
	THM Modelling refinement at GEo-01 (ETHZ)
	THC Modelling refinement at GEo-01 (UniBe)
	Water-rock interaction laboratory experiments (UniBe)
	Energy System scenario 2021-2035 refinement according to subsurface modelling results (UniGe-SIG)
	Drilling at GEo-02 (SIG)
	Definition of the monitoring activities at GEo-02 (SIG-UniGe)
	Run thermo-hydro-mechanical experiment at the selected site (UniNe)
	Geomechanical characterisation of the geothermal exploration borehole GEo-02 (UniNe)
	Bern
	Engineering & Design GES
	Drilling, Testing & Instrumentation
	Geochemical monitoring (Uni Bern)
	Reservoir Analysis & Modelling (GES)
	Thermo-Hydraulic models (TH) (UPC)
	Thermo-Hydro-Chemical models (THC) (UPC)
	Thermo-Hydro-Mechanical models (THM) (UPC)
	Thermo-Hydro-Mechanical-Chemical models (THMC) (UPC)
	Thermo-Hydro-Chemical models (THC) with special focus on rock-water interaction (Uni Bern)
	Thermo-Hydro-Mechanical models (THM) with special focus on surface uplift and thermo-poro-elasticity (ETH Zürich)

6 National and international cooperation

On the international level several collaborations have been established and in the first year resulted in the participation to the first workshop on design and system integration in Bochum (Germany) and the organization of the first workshop on WP2 – Models and tools for subsurface dynamics in Geneva (Switzerland).

Strong international collaboration is particularly ongoing in the WP2 "Models and Tools for Subsurface Dynamics:

- ETH Zürich has the overall WP lead and coordinates Task 2.1 "Modelling toolsets and workflows for optimal and efficient HT-UTES of different types" that acts as an umbrella of all modelling activities. The first outcome of this WP lead is assembling the month 9 version of Deliverable 2.1 (Report on tools and workflows for different types of HT-UTES), which is close to completion (ca. 180 pages) and outlines the conceptual approaches and simulation techniques. We took particular care to force the contributors to think about conceptualisation, understanding subsurface system behaviour and how these will benefit operators through meaningful qualitative and quantitative results.

- For the Bern/EWB project the University of Catalunya is one of the subsurface dynamics modelling partners, they bring their internationally highly reputed expertise in modelling coupled subsurface thermo-hydro-mechanical (+/- chemical) processes into the project.

- UniBE is leading Task 2.3 on "Benchmarking and improving tools of subsurface heat storage dynamics. In the WP2 meeting in Geneva in April, a set of benchmarks was laid out and has now mostly be defined in detail. The international partners collaborate intensely on benchmark design, comparison, and implications for model improvement and validation in collaboration with other WPs (e.g., 3 and 5)

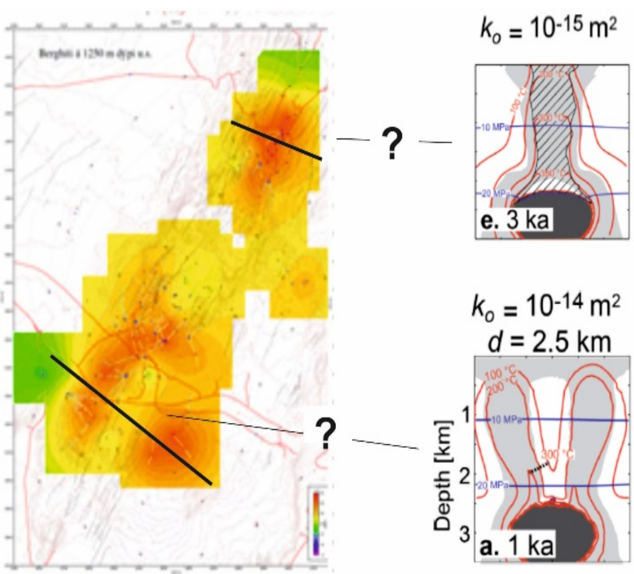

Figure 9 - Left: Temperature distribution at 1250 m depth in the Hengill area where the IDDP-3 well will be drilled. Right: Two ETH simulations (Scott et al., Geothermics, 2016) that offer possible interpretations for different parts of the field. In the South there exists the possibility that the two hot zones represent upflows from a single magmatic heat source (dark grey); counterintuitively, drilling to target a supercritical resource would have to be done between the two thermal plumes. However, in the North, the hot zone may represent a single upflow and a supercritical zone is likely located vertically below. Our ambition is to integrate such numerical modelling, the existing data on the thermal structure and geochemical signals for magmatic input to aid optimal well-sting for IDDP-3.

- In Task 2.2 "Integrating advanced academic simulation codes into diverse geothermal project development workflows, ETHZ is collaborating intensely with Reykjavik Energy (Iceland) and the partners from the Azores on translating the modelling capabilities to broader geothermal applications beyond heat storage. Collaboration with Iceland has been quite intense and focuses on (a) utilizing ETH's unique simulation capabilities to identify the optimal location for the next superhot IDDP well (see figure above) (b) integrating the existing reservoir model and the newly introduced modelling capabilities to derive optimal utilization scenarios for IDDP-3 (Figure 9). The Azores collaboration is still in its initial stages and will likely provide generic models of geothermal flow in an island topography that can be matched by field observations in order to constrain possible scenarios of actual reservoir style.

EWB is collaborating with Universitat Politecnica de Catalunya, University of Bern and ETH-Zürich. The three different modelling groups have their own focus and approach:

Modelling group	**Focus**
Universitat Politecnica de Catalunya (UPC)	Thermo-Hydraulic models (TH) Thermo-Hydro-Chemical models (THC) Thermo-Hydro-Mechanical models (THM) Thermo-Hydro-Mechanical-Chemical models (THMC)
University of Bern Rock-Water Interaction group	Thermo-Hydro-Chemical models (THC) with special focus on rock-water interaction
ETH Zürich Geothermal Energy and Geofluids (GEG)	Thermo-Hydro-Mechanical models (THM) with special focus on surface uplift and thermo-poro-elasticity

7 Annexes

- Deliverables HEATSTORE Europe
  - D1.1: Existing UTES systems and lessons learned
  - D2.1 Initial report on tools and workflows for simulating subsurface dynamics of different types of High Temperature Underground Thermal Energy Storage
  - D3.1: Minutes of the first workshop on design and system integration
  - D5.1: Monitoring plans: demonstrations and case studies
- Minutes of the first workshop on WP2 – Models and tools for subsurface dynamics (Geneva, CH), 8 April, 2019 (Geneva)
- Slides of the presentations of the HEATSTORE Switzerland 1st meeting on 22 May, 2019 (Bern).
- Minutes of the HEATSTORE Switzerland 1st meeting on 22 May, 2019 (Bern).