HEATSTORE
Monitoring plans: demonstration projects and case studies

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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.

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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
2019.05.27	First version

Table of Content

1 Introduction

The overall objective of WP5 is to bridge the gap in terms of monitoring and validation of data for all possible types of HT-UTES (ATES, BTES, MTES, PTES) within the HEATSTORE project (**Table 1**) in order to facilitate the development of these smart and highly replicable technologies through de-risking, cost reduction, optimization and a controlled environmental impact.

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 (55˚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; ∆t: 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

The task 5.1 ‘‘Monitoring plans, demonstrations and case studies‘‘ consists in a joint effort of GZB, STY, BRGM, NIOO, GEUS, PE, IFT, TNO and SIG. This task aims to share the design and strategies of the monitoring plans considered for the HT-UTES demonstration projects and case studies (Figure 1). Different parameters are controlled in order to give a deeper knowledge of the system behaviour both at underground and at surface.

As it is summarized at the end of the report, all the projects are measuring a common basic set of data at minima to assess the overall system efficiency and its thermal impact in the surroundings. Depending on the specificities of the projects, some particular parameters are measured (InSAR surveys, microseismicity, ...).

Gathering these information is also of primary importance for the teams in charges of the modelling (WP2) to make sure there will have available a sufficient set of data to constrain their models. Thanks to an early collect of the relevant information for all the sites, this inter-disciplinary cross sharing was conducted during the WP2 workshop held in Geneva the 8th april 2019 before the diffusion of this report.

The following sections reminds the princicple of all the projects included in Heatstore with each time a description of the monitoring plans and objectives.

The final section consists in a synthesis of these information formatted in comparatives tables so that the reader can have a global view on the monitoring techniques covered for all the projects.

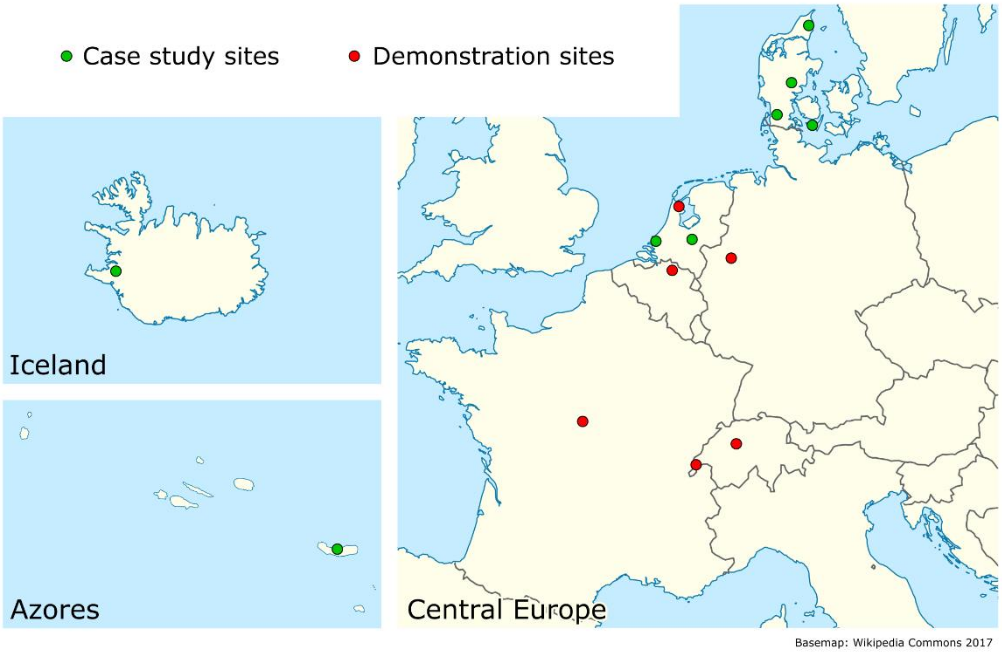

Figure 1: Overview of demonstration sites and case study locations in HEATSTORE

2 Netherlands:

Site name:	**Koppert-Cress**
Location:	**NL, Monster**
Operational since:	**2012**
UTES Type:	**HT-ATES**

This HT-ATES consists of 4 warm wells (Figure 1). In between the wells a specific monitoring well is completed in which a temperature logger is installed, logging temperature at the depth of the well screen at a 3hr interval. 2 separate DTS cables are installed at 5 and 18 m from one of the wells to monitor temperature profile along well depth. Current monitoring is only done for the upper aquifer (at 60-80 m depth).

Extended monitoring is planned for Q1 2019 (monitoring well and DTS locations) to get more insight in the temperature distribution in the subsurface over all depths (DTS) and to measure water quality changes due to heating of ground water (at 5m from warm well). The number of DTS locations can vary because of budget. The extend monitoring will go deeper and monitor up to 150m depth.

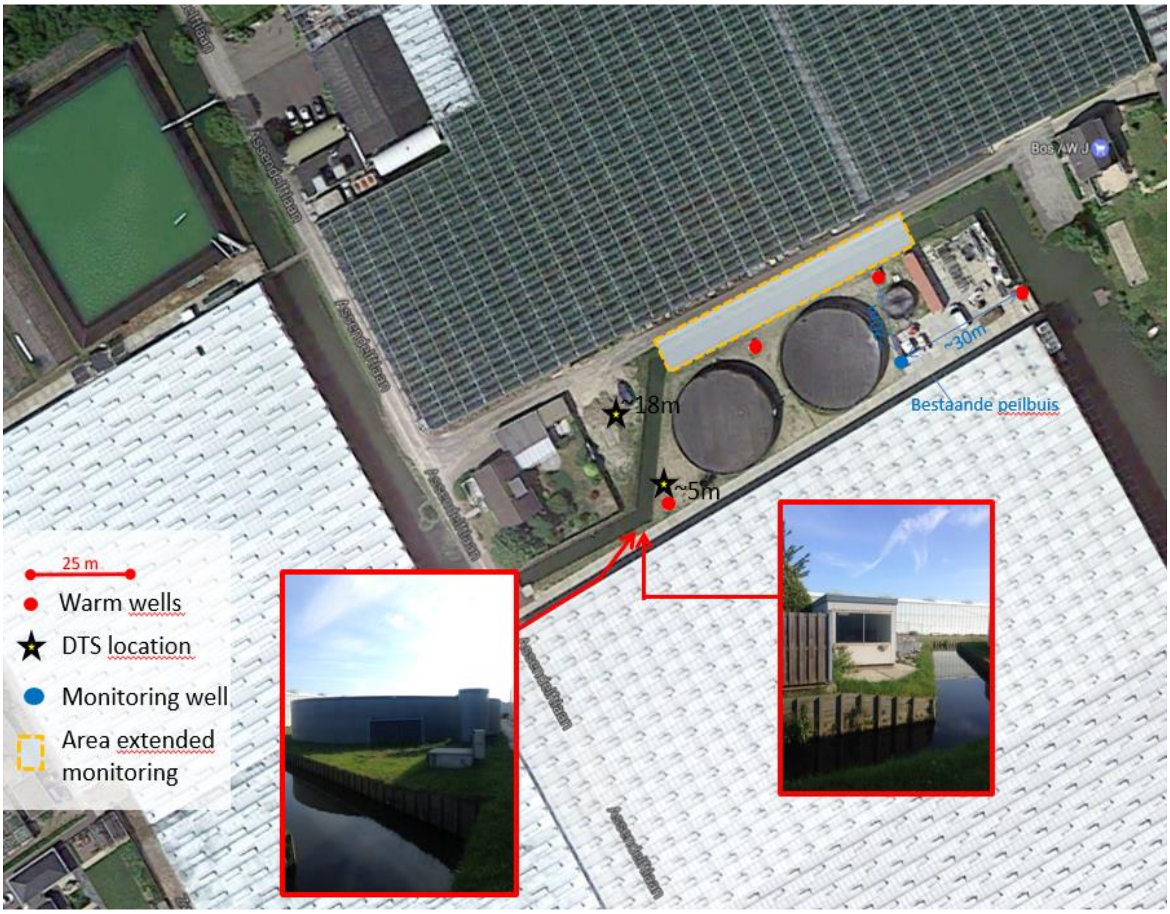

Figure 2: Top view of Koppert-Cress HT-ATES system

The climate installation of Koppert Cress is complicated and coupled to multiple sources of heat. Energy demand of the greenhouses can vary a lot, this results in intensive use of the stored energy in the subsurface (Figure 3). Multiple parameters are monitored to review all the possible energy and water flows. (flow rates of all wells, energy use of heat pump, pumps, boiler and energy input from other heat sources).

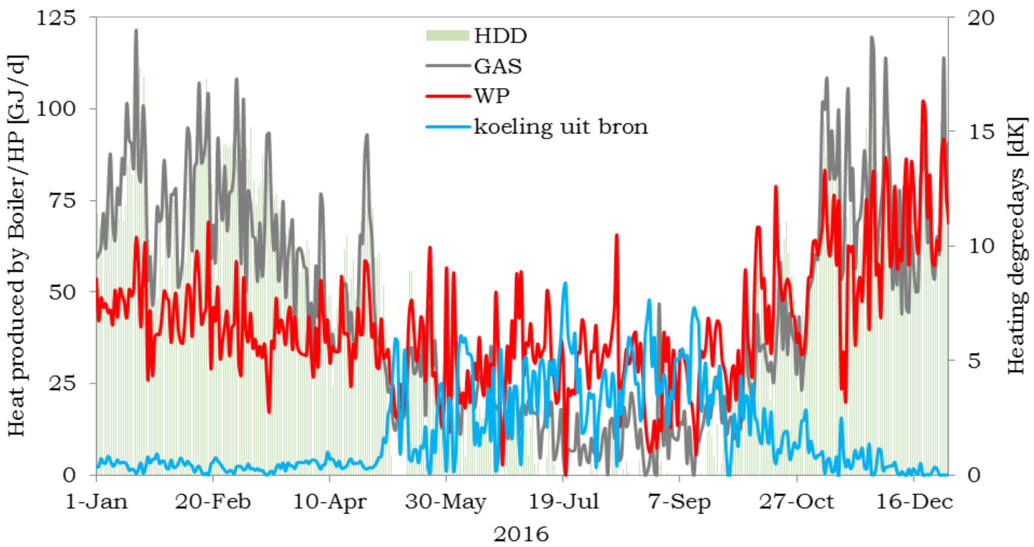

Figure 3: **Koppert-Cress heat demand – consumption profile during a typical year**

Site name:	NIOO-KNAW (Netherlands Institute of Ecology)
Location:	NL, Wageningen
Operational since:	2010
UTES Type:	HT-ATES

This HT-ATES consists of 1 hot (45°C) and 1 cold (26°C) well, and 1 monitoring well located 50m from the hot well (Figure 4). Temperature is measured along the full depth of the hot, cold and monitoring well, each half year (spring and autumn). Groundwater samples, at depth corresponding to the top of the filter, are taken twice a year for chemical and microbiological analysis. The hot well is sampled at the end of the warm season (i.e. in autumn) and the cold well at the end of the cold season (i.e. in spring). In addition to these samples, additional samples are taken at various depths along the hot and cold well, to measure chloride concentrations at various depths.

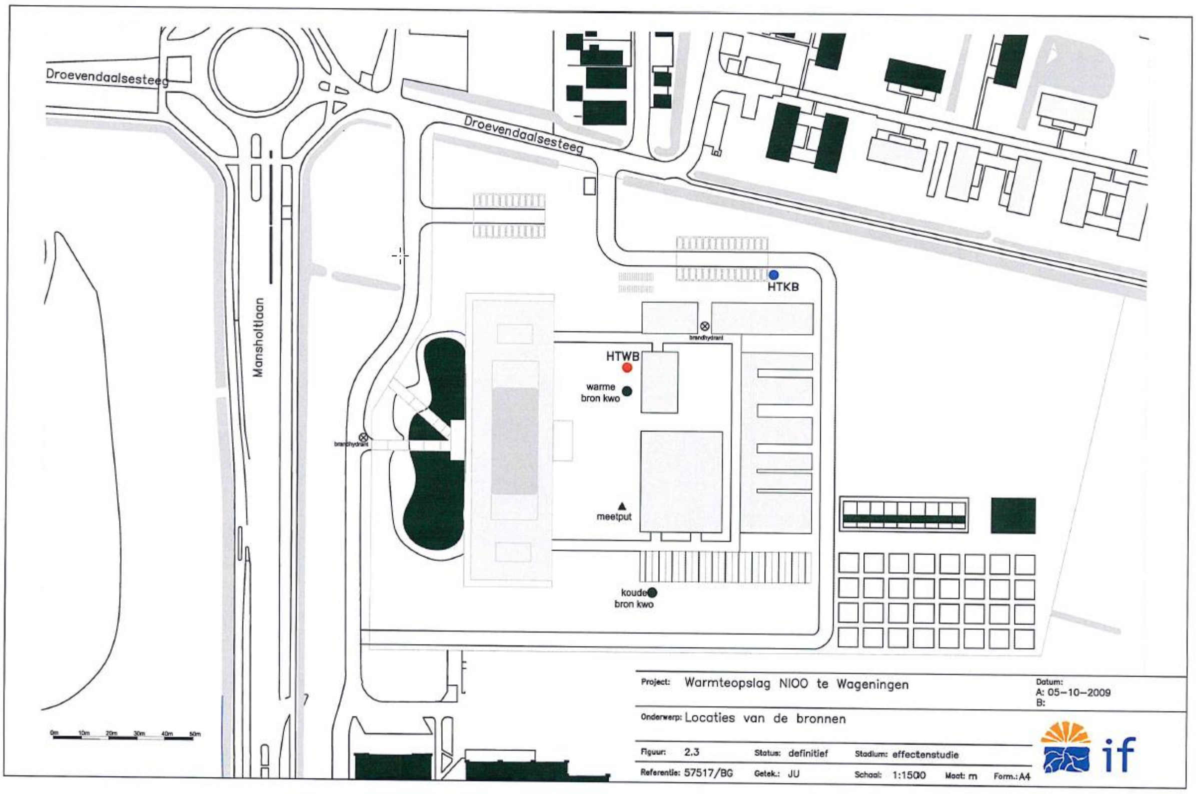

Figure 4 Bird-eye view at the NIOO site. Red and blue dots indicate hot and cold HT-ATES well respectively. The small triangle 'meetput' represents the monitoring well. The black dots indicate the locations where regular ATES is applied.

At NIOO, heat demand and supply is balanced between the different facilities located at the NIOO building complex. Heat is continuously exchanged between their (horticulture) buildings, the offices and laboratories. Surplus heat is stored in a regular ATES or in the HT-ATES system (Figure 5). The heat management system of the building registers heat flow between the facilities. It also registers the injected and produced water (and corresponding temperatures) from the HT-ATES wells.

Monitoringsrapportage provincie HTO
57517 NIOO HTO
kalenderjaar 2016

data compleetheid 100%

	waterhoeveelheden		energiehoeveelheden		gemiddelde onttrekking- en infiltratietemperatuur				spui-hoeveelheid	min/max infiltratie-temperatuur	
bedrijfstoestand:	warmtelevering	warmte opslag	warmtelevering	warmte opslag	warmtelevering		warmte opslag			minimaal	maximaal
eenheid:	m³	m³	MWht	MWht	°C	°C	°C	°C	m³	°C	°C
ontwerp:	45.000	70.000	578,0	1.283,0	40,0	26,0	24,0	45,0			
vergunning:	210.000				onttrekking	infiltratie	onttrekking	infiltratie	500		45,0
januari	2.100	0	3,7	0,3	26,8	26,2	20,1	31,0	0	20,3	30,0
februari	200	100	0,0	2,1	23,4	24,6	14,4	32,7	0	20,7	41,8
maart	1.000	400	0,1	7,1	25,0	27,4	19,7	36,0	0	20,1	45,2
april	600	800	2,7	20,1	31,0	27,5	20,4	43,5	0	20,1	46,8
mei	300	1.700	1,0	43,0	29,9	27,5	20,2	42,2	0	20,1	45,8
juni	0	1.500	0,0	41,3	26,6	26,9	18,6	42,7	0	20,2	45,9
juli	0	3.600	0,0	93,7	-	-	17,8	42,6	0	20,1	47,2
augustus	0	1.900	0,0	54,8	28,0	27,2	16,9	42,8	0	20,1	47,0
september	200	1.800	0,7	52,0	33,7	31,0	17,4	43,0	0	20,1	47,1
oktober	4.400	300	28,5	6,0	34,1	29,2	25,3	43,0	0	20,1	43,3
november	5.400	0	18,8	0,0	29,2	26,5	28,9	38,9	0	20,7	19,3
december	0	0	0,0	0,0	-	-	-	-	0	-	-
totaal 2016	**14.200**	**12.100**	**55,5**	**320,4**	**30,1**	**27,5**	**18,4**	**42,4**	**0**	**20,1**	**47,2**
	26.300										

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Figure 5 Yearly Monitoring report of the LIFT monitoring software, showing monthly information on pumped water volumes, average temperatures and energy supply to and demand from the HT-ATES.

3 France:

Site name:	**BTESmart**
Location:	**Chémery, France.**
Operational since:	**Not yet in operation.**
UTES Type:	**HT-BTES**

The HT-BTES strategy will consist in storing the heat generated by the solar panels when there is no heating needs in the buildings (and when available). At the beginning of autumn, when the storage is nearly full, they will be activated so as to bring their temperature level back to its initial value. The extracted heat will be either used for heating (if already needed), or reinjected in the BTES. During winter, the HP will be used to heat the buildings with the help of the existing boilers if needed. The system includes a belt of lateral boreholes to recover one part of the heat losses from the main field.

The subsurface monitoring system relies on 6 dedicated boreholes (Figure 6) with a temperature sensor every 5 m i.e. 5 temperature sensors per borehole. The boreholes cover different distances from the center of the BTES to beyond the lateral recovery boreholes and 2 directions. The measurements will be used to draw temperature profiles, see the potential impact of subsurface heterogeneities on it and adjust manually the flowrates allocated to each radius accordingly. They will then be used to calibrate the models.

The surface monitoring system includes temperature sensors and flowmeters for each circulation loop of the borehole and at several key parts of the surface facility (Figure 7). Global heat flow will be also measured.

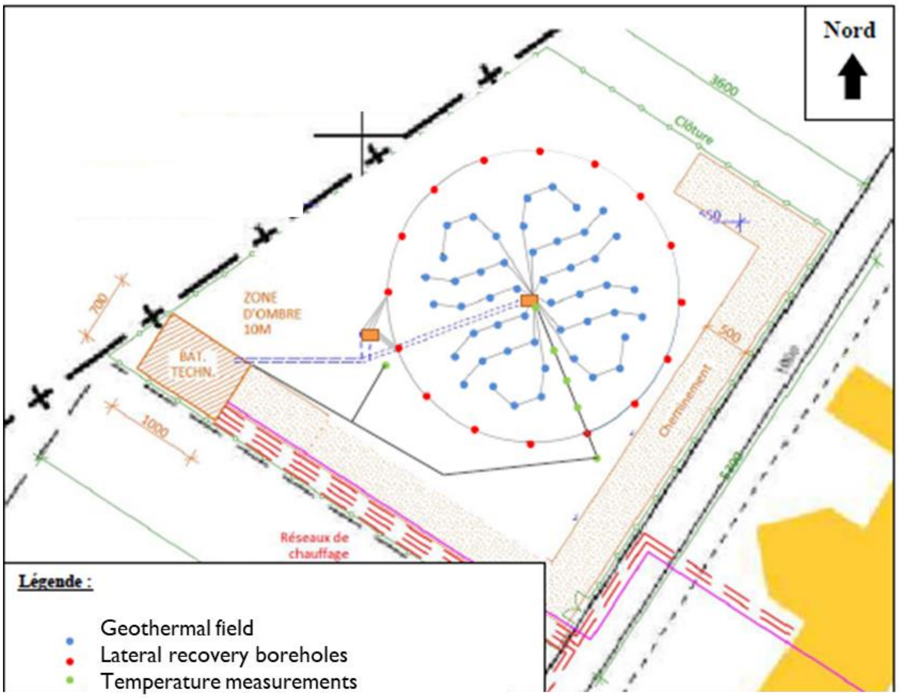

Figure 6 Top view of the HT-BTES BTESmart

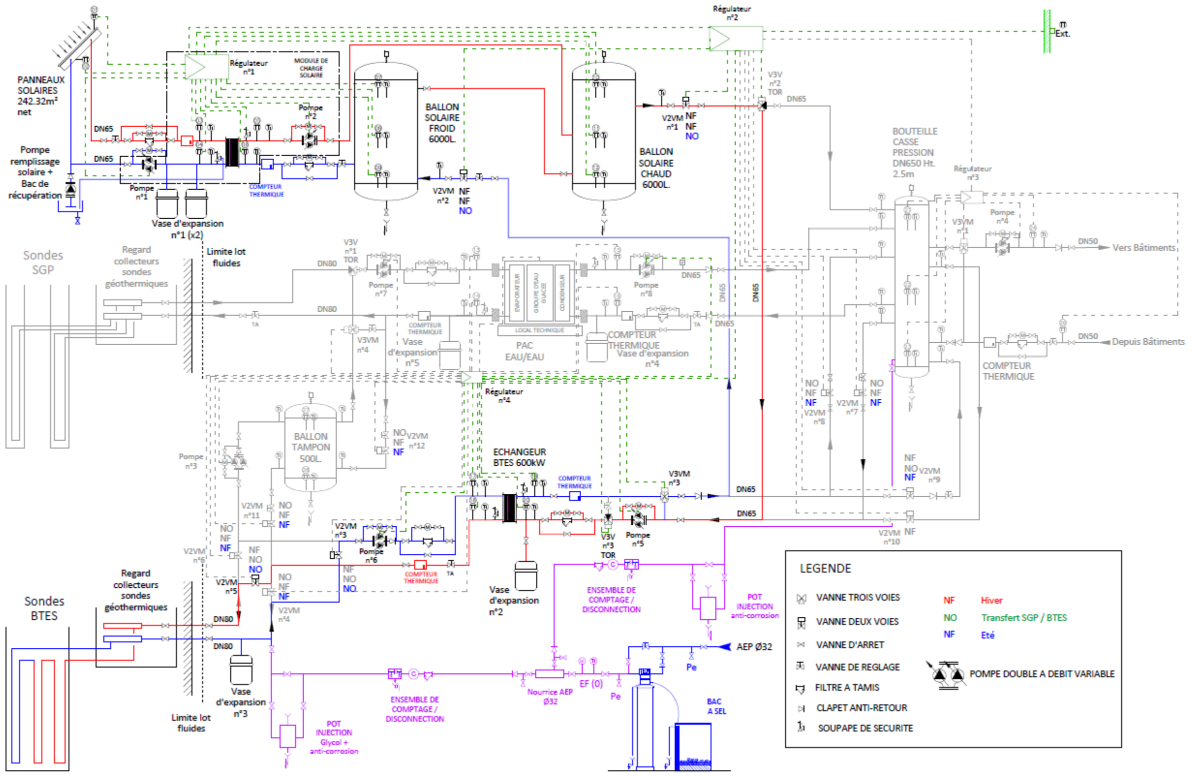

Figure 7 : Surface system of the HT-BTES BTESmart

4 Switzerland

Switzerland 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 or reef or faulted volumes)**

The GEo-01 well is providing a large amount of data for petrophysical characterization of the potential targets in the Upper Mesozoic Units (i.e. Lower Cretaceous and Upper Jurassic limestones). This well is characterized by a natural artesian flow. Water reaches the surface at 34˚C with a 50l/s flowrate and 8-10bars of wellhead pressure.

A water sampling campaign has been carried out by the University of Geneva and the results will establish the baseline to evaluate future variations in the geochemical compositions of the waters during production.
The main activity that will be carried out at the GEo-01 well is the long-term production tests. The production tests will last 6 months, and the planned protocol will follow two main phases:

- Step drawdown tests: This phase will last 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 tests (6 months). The well will be in production of 200m3/h for 6 months.

During production tests periodic water sampling campaigns will be carried out to monitor the variations in its composition. Additionally, temperature and pressure sensors will be installed in other wells in the region. This will allow 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.

Additionally, Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) equipment will be installed in a nearby well that will drill into the Tertiary molasse sediments, which overlie the Mesozoic reservoirs. These will be used as a monitor tool to assess if the two formations are hydraulically connected. The DAS equipment will also be used as sensor for a 3D VSP 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, having the DAS cable installed permanently, repeated 3D VSP surveys can be carried out in the future for time-lapse monitoring of the reservoir. S-Waves 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 well. These sediments host the main fresh-water resources which need to be carefully preserved.

The production tests design parameters are now being used by ETHZ to run some predictive THM modelling and assess whether the production can generate ground deformations.
Ground deformations are now proposed to be monitored by InSAR 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 if the production test will be associated to variations in the natural seismicity conditions.

The same protocol of monitoring methods will be applied to the GEo-02 well that will be drilled in Q3-Q4 2019 (Figure 8), but, at present, a detailed plan is not defined. At this well the potential target has beed defined in the Reef Complex formation in the Upper Jurassic, which is located at about 1000m in depth at the well location.

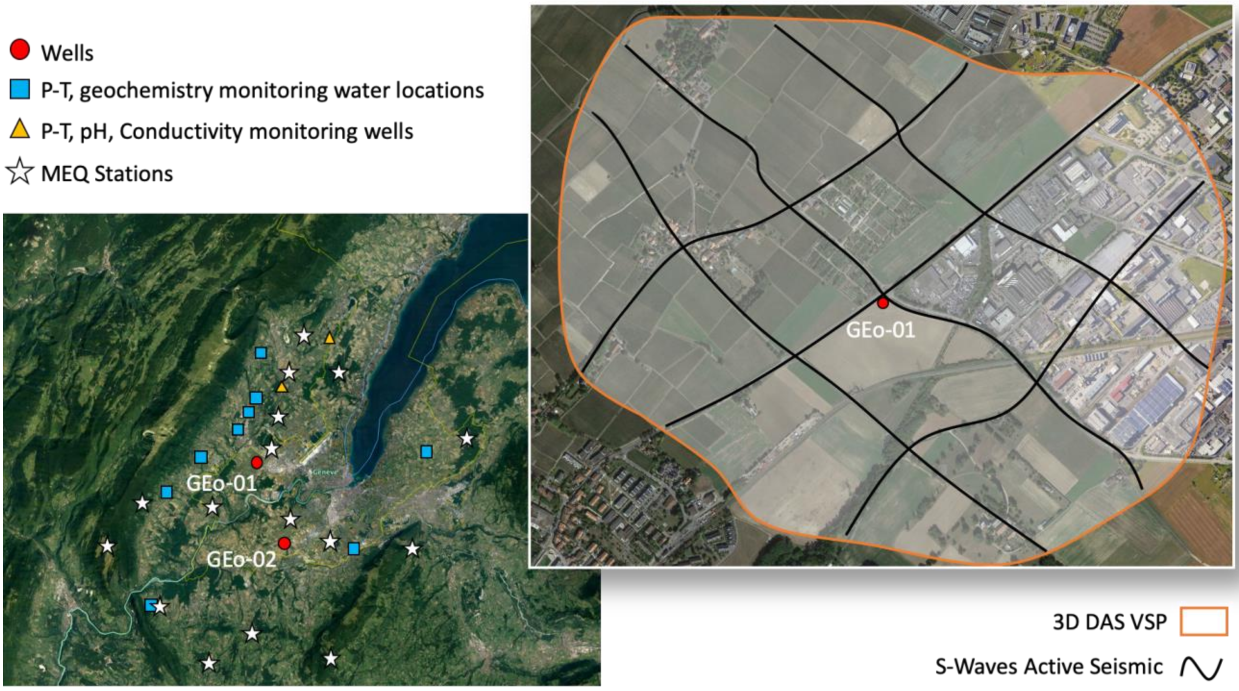

Figure 8: Top view of the HT-ATES in Geneva

Switzerland 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.**

Main well and auxiliary wells will be equipped with fiber optic cables monitoring temperature, pore-pressure and strain. There will be a monitoring well that is equipped with fiber optic cables as well, but this one is located in between the main and the auxiliary wells. This configuration allows monitoring temperature, pore-pressure and strain at the center, in between and at the periphery of the heat store reservoir (Figure 9). Temperature and pore-pressure are continuously monitored for reservoir engineering purposes. Continuously strain / deformation monitoring along the wells will deliver inputs for reservoir stability and surface deformation.

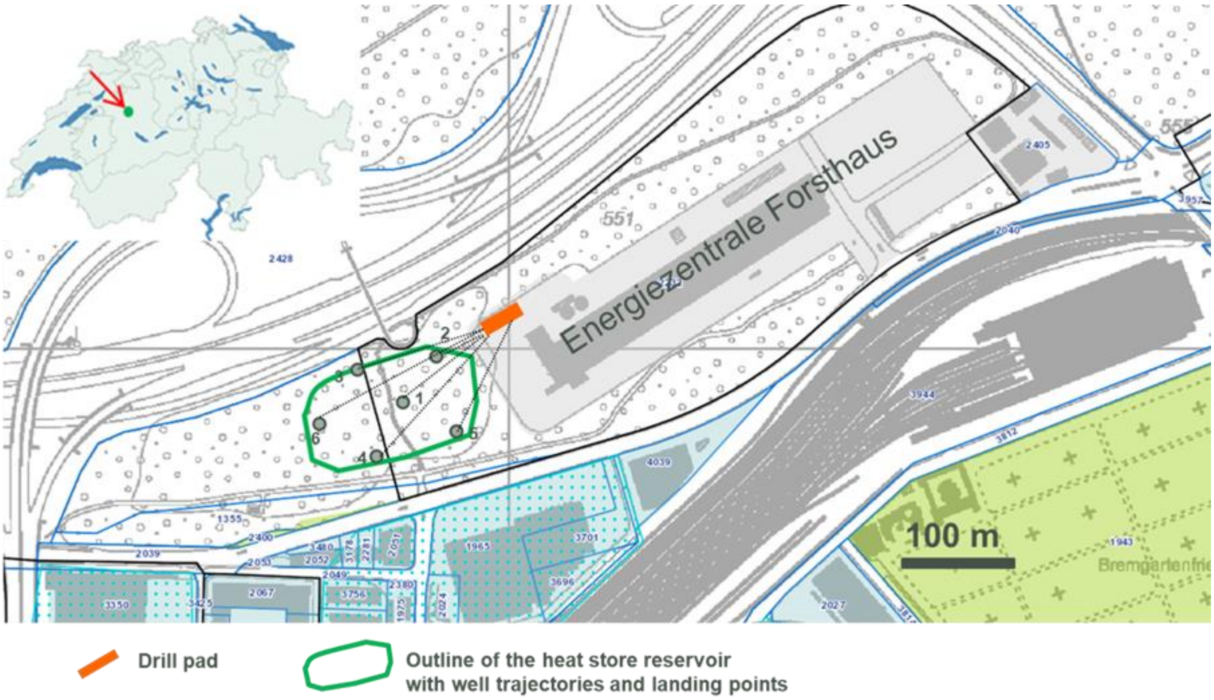

Figure 9 : Top view of the HT-ATES Forsthaus

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

The reservoir section will be entirely cored and slanted towards the target zone and total depth within the reservoir at 500m vertically. The cores will be stored in crates and will require immediate attention from the geologists. The coring and testing operations will be performed sequentially. When the cored section exhibits good reservoir properties, the specially 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 (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.

5 Germany:

Site name:	Markgraf II
Location:	Bochum, Germany
Operational since:	TBD
UTES Type:	HT-MTES

The existing monitoring wells will be the basis for the Markgraf II monitoring concept. Here the observation wells O1, O3 and O5 will play the most vital role (Figure 10). Further monitoring wells will be planned after more geophysical and hydrogeological information has been gathered (after the proposed exploration wells have been drilled). Suitable locations are indicated in yellow dots in Figure 11.

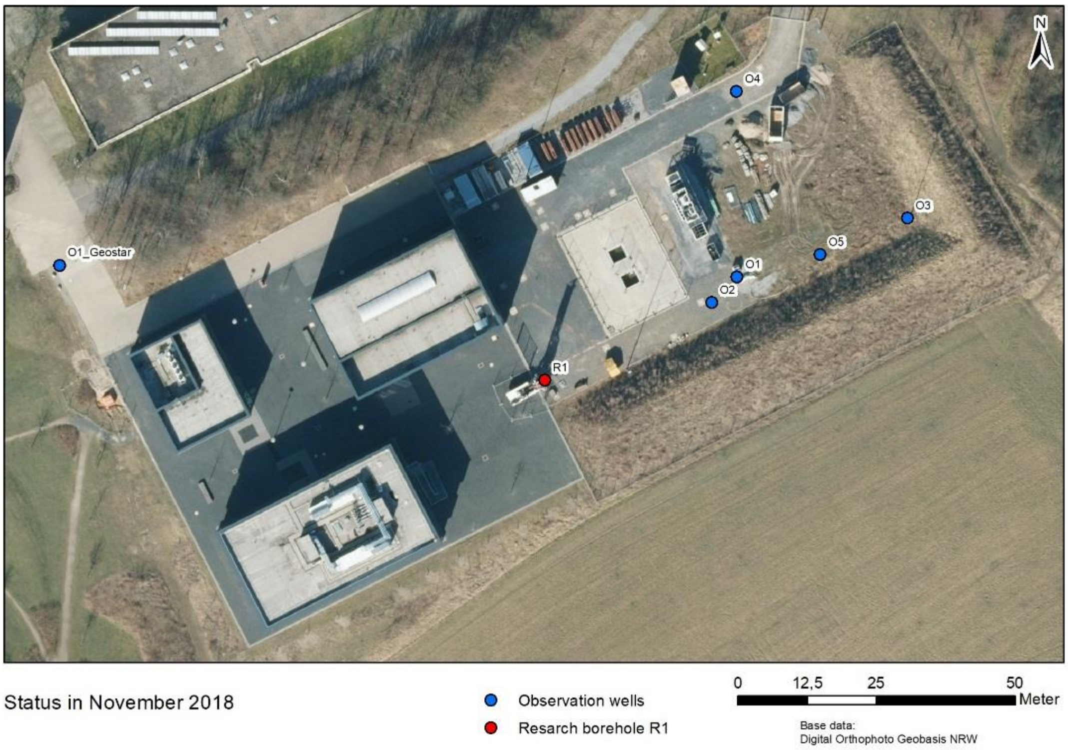

Figure 10 Location of existing monitoring wells at the GZB site

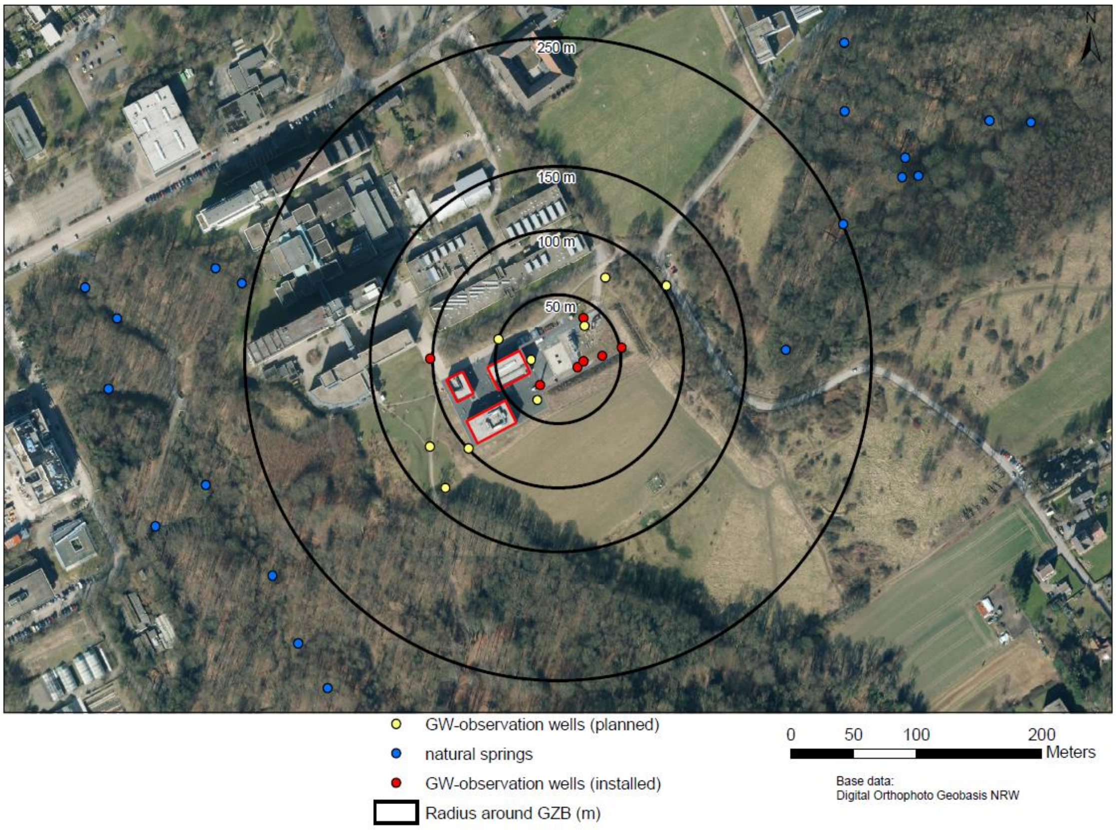

Figure 11: Enlarged top view including future monitoring wells at the GZB site

The well monitoring will include the following measurements on a continuous basis: temperature, pressure and flowrate for the injection and production wells. Every three month, standard water analysis along with EC, pH, redox, conductivity and oxygen level is foreseen. Three newly designed exploration wells will be also tested and submitted to pump and tracer tests. The overall design will be re-evaluated on the basis of these tests.

The general surface facility outline is depicted in Figure 12. The surface monitoring system will consist of temperature sensors and flowmeters in the main parts of the surface facility.

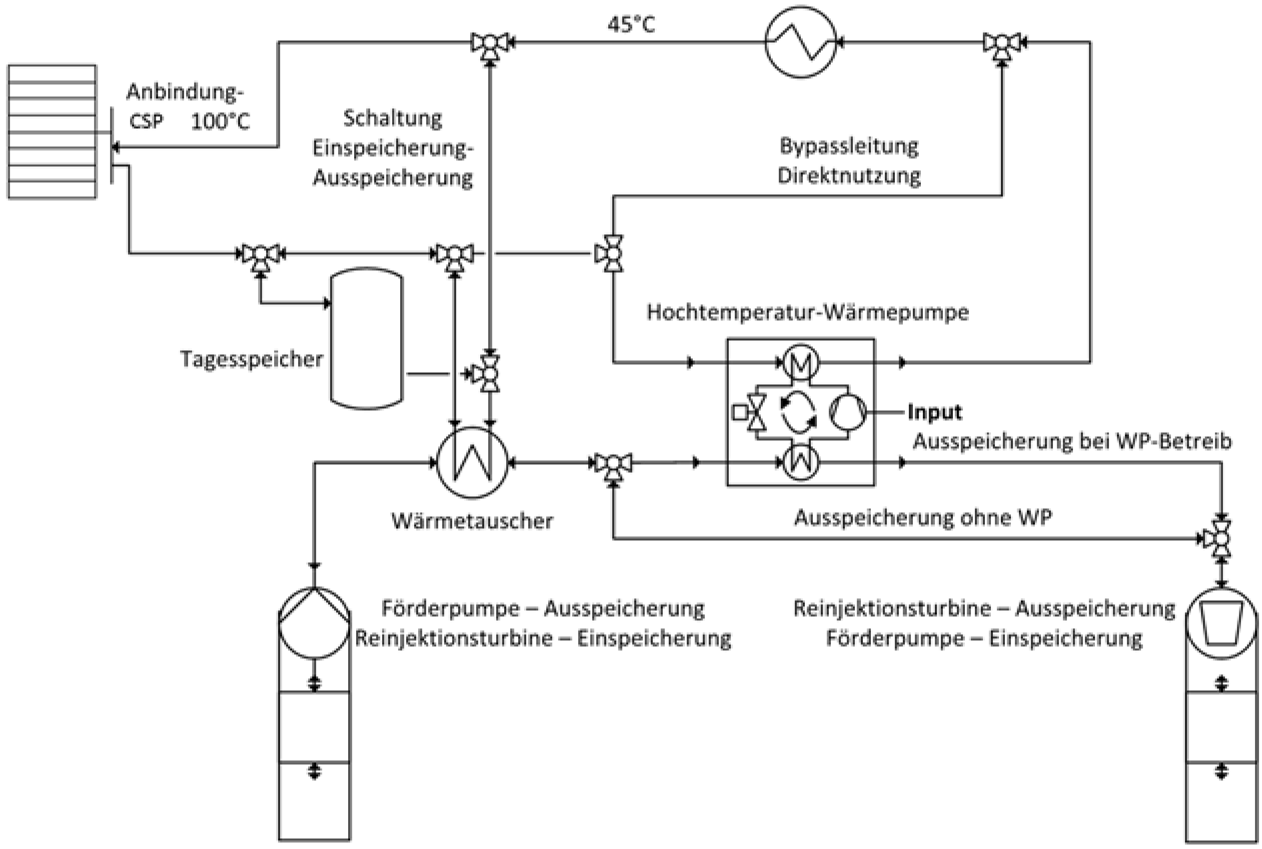

Figure 12: Surface system of HT-MTES Markgraf II

6 Belgium:

Site name:	**VITO, MOL**
Location:	**Boeretang 200, 2400 Mol, Belgium**
Operational since:	**District heating system > 15 years, geothermal system is in start up phase**
UTES Type:	**No UTES, we use building mass as storage**

A general schematic of the heating system at VITO Mol is given in Figure 13. The base heat load is provided by the geothermal doublet and a CHP unit (900 kW_e). The peak heat load is covered by three cascaded gas-fired boilers. From the production side the following parameters are monitored:

- Heat delivered by the geothermal doublet
- Gas consumption from the peak and back-up boilers
- Gas consumption from the CHP
- Electricity production from the CHP
- Supply and return temperature of the district heating system

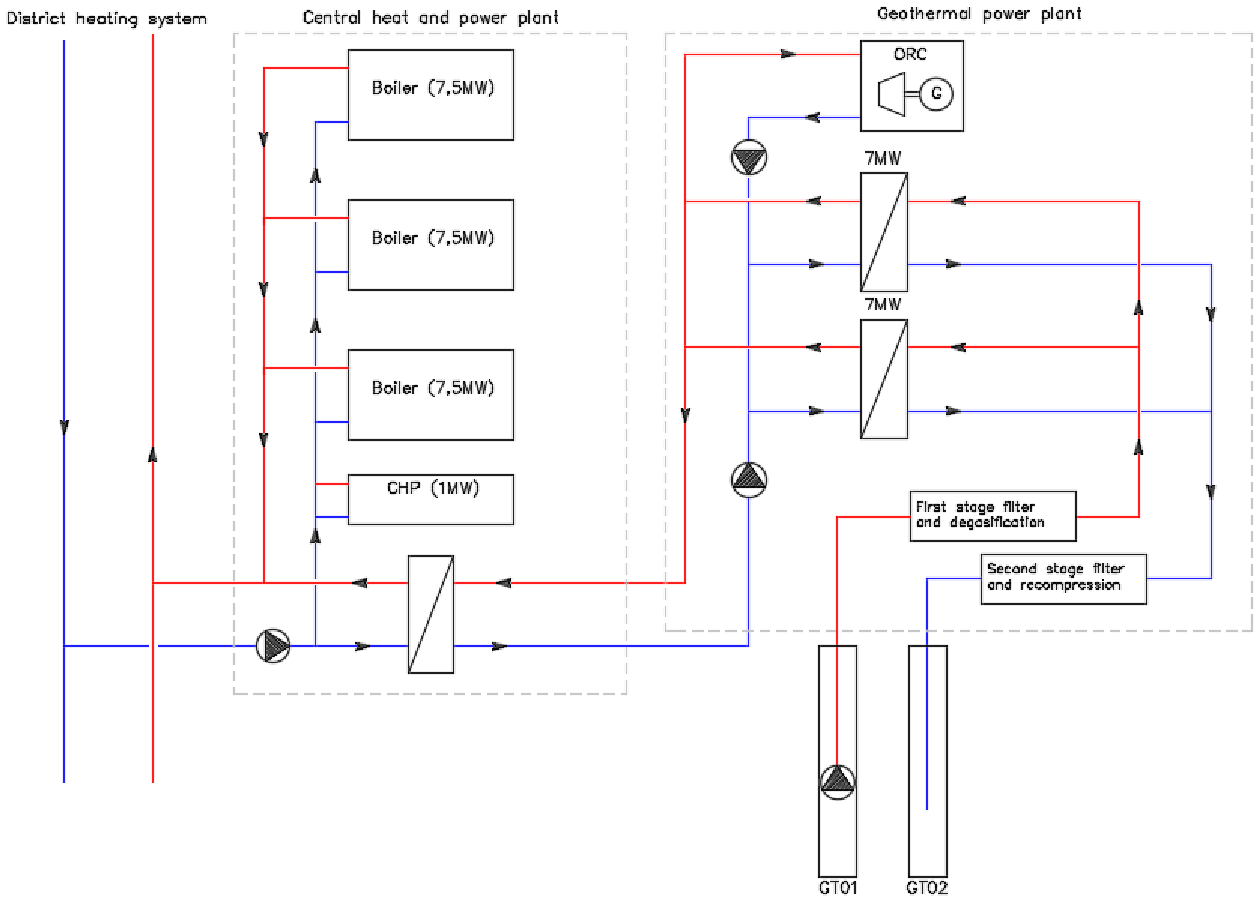

Figure 13: General P&ID of the heating system at VITO, Mol

Heat load data on building level can be monitored with an online platform called Energyview (Figure 14). The following parameters are monitored in each building where demand side management will be applied:

- Primary flow
- Primary supply and return temperature
- Secondary supply and return temperatures of the different heating circuits (radiators, underfloor heating, ventilation, domestic hot water, …)
- Outdoor temperature
- Indoor temperature

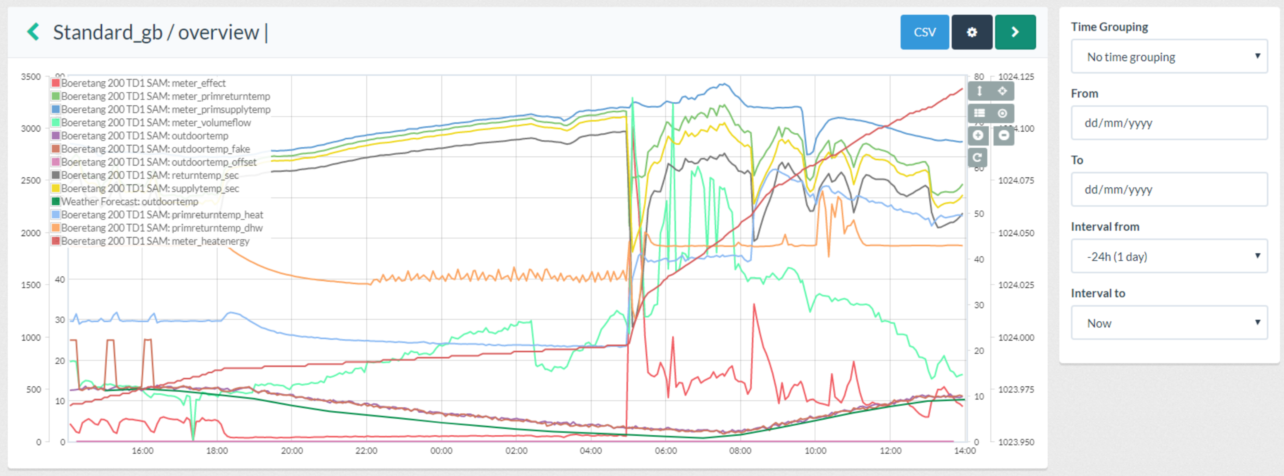

Figure 14: Example of the real time monitoring panel

7 Denmark:

Site name:	Braedstrup
Location:	Braedstrup, Denmark
Operational since:	2012
UTES Type:	HT-BTES

The main features related to this HT-BTES were summarized by Malmberg (2017)[1] and illustrated in Figure 17.

Table 2: Braedstrup HT-BTES subsurface characteristics

HT-BTES in Brædstrup			
Start of operation	2012-	Storage shape	Cylindrical
Storage volume [m3]	19 000	Ground type	Clay
Number of boreholes	48	Thermal conductivity [W/(m*K)]	1.42
Borehole depth [m]	45	Volumetric heat capacity [MJ/(m3*K)]	1.9
Total borehole length [m]	2 160	Insulated [Yes/No]	Yes
Borehole spacing [m]	3	Insulation material	Cockles
Borehole diameter [mm]	150	Insulation thickness [mm]	500
Collector type	Double U-tube	Source of charge	Solar thermal
Collector diameter [mm]	32	Energy charged [MWh]	444*
Collector material	RAUGEO PEXa	Energy discharged [MWh]	163*
Collector temperature resistance	95	Charging temp [°C]	80
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	60
Number of boreholes in series	6	Storage minimum temp [°C]	20
Total collector length in series [m]	540	HP for extraction [Yes/No]	Yes

* As of operation between May 2012 to February 2013 (PlanEnergi, 2013). **Heat loss estimated as 24% (Gehlin, 2016).

The project dimensions are :

- 22,000 m³ heated earth;
- diameter 24 m
- 48 boreholes

[1] Malmberg M.: "Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant", Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.

- depth 45 m

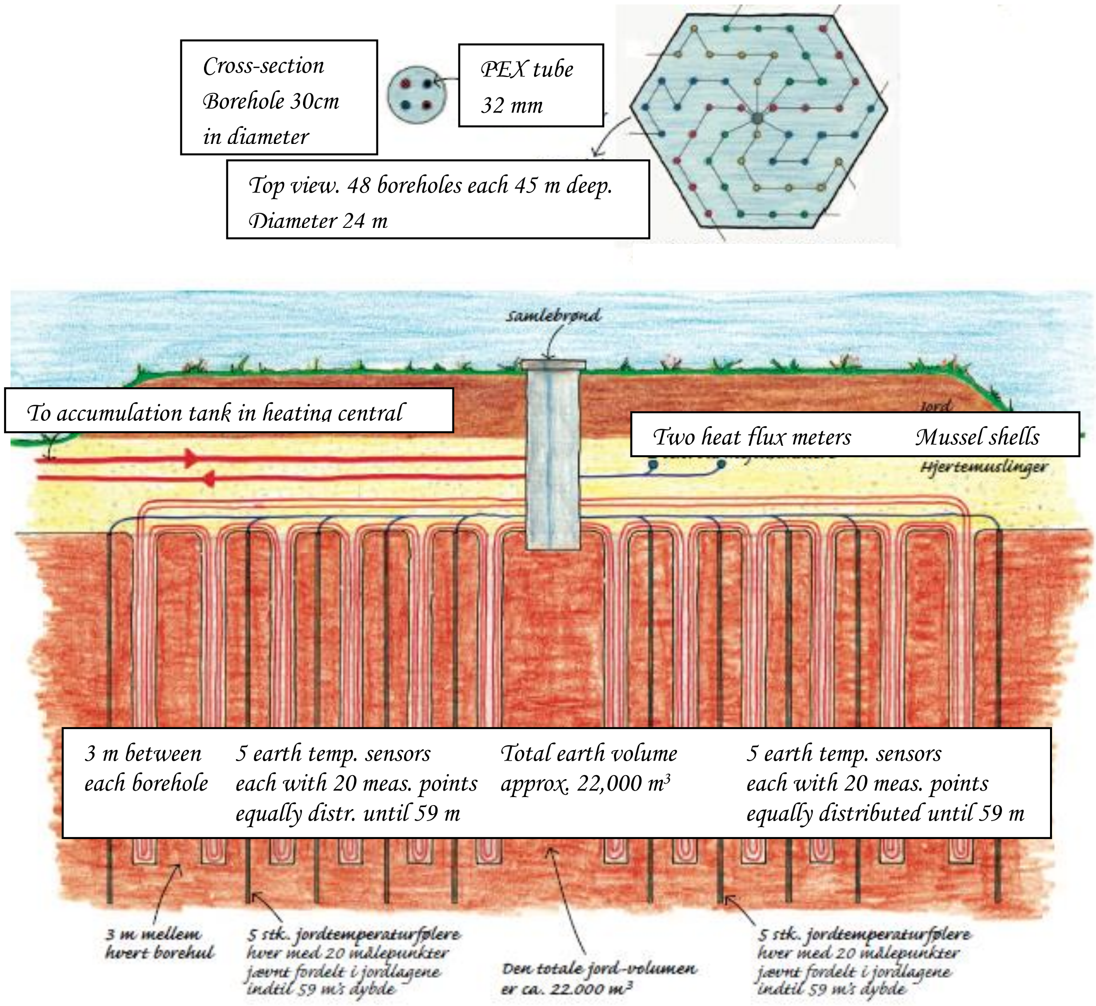

Figure 15 : Dimensions of HT-BTES Braedstrup project. Source: Braedstrup Fjernvarme.

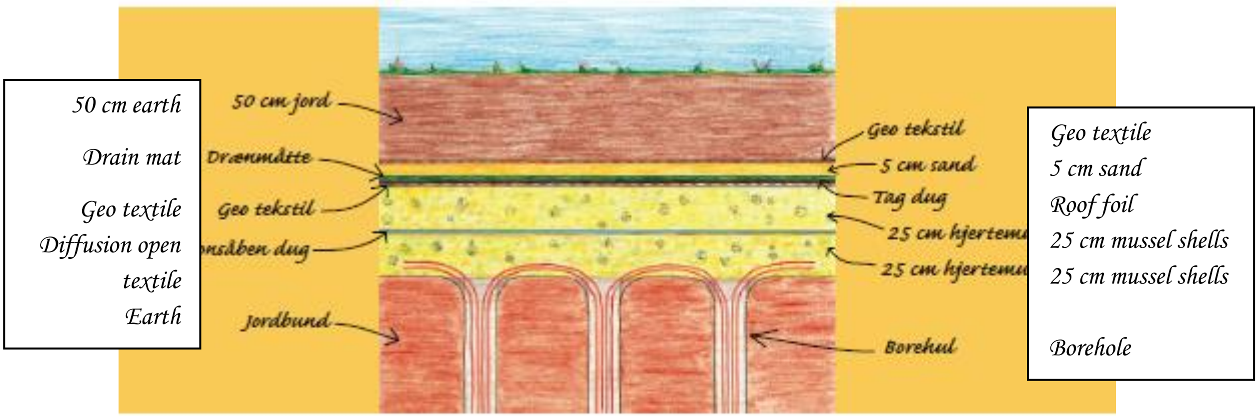

Figure 16 : Details of upper part of HT-BTES Braedstrup project. Source: Braedstrup Fjernvarme.

Figure 17 : Model view of the HT-BTES Braedstrup project

The main parameters monitored concerning the subsurface part are gathered in Table 3.

Table 3 : Braedstrup project subsurface monitoring plan

	Where	*Frequency*	*Accuracy*	*Type*
Temperature	Temperature sensors in BTES connection in-/outlet pipes	10 min	+/-0.1K	32 pcs. PT100 temperature sensors
Temperature	Ground temperature sensors inside and around the storage	30 min	+/-0.1K	5x20 pcs PT100 temperature sensors
Temperature	Temperature sensors below and above heat flux sensors	30 min	+/-0.1K	
Temperature	Air temperature in well and control box		+/- 0.5K	
Pressure	Supply and return pressure in manifolds	10 min	+/-3%	TPSA-E-1-E-B01C-T-V (2 pcs)
Hummidity	Hummidity in cover		+/-10%	Hygrometer (2 pcs)
Heat flux	Heat flux sensors for cover	30 min	+/- 10 %	Hukseflux HF05
Water level	Water level in storage	10min		Ultrasonic

The description of the surface system is provided in Figure 18. It consists in a solar district heating system with a collector area around 29 000 m2. The main parameters monitored concerning the subsurface part are gathered in Table 4. It concerns heat flows, electricity and climatic data.

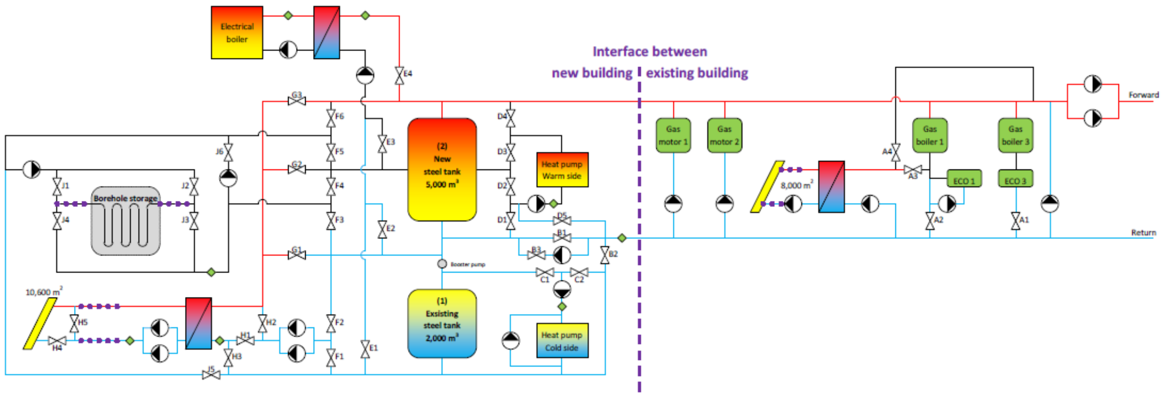

Figure 18 : Braedstrup project surface facilities principle

Table 4 : Braedstrup project surface monitoring plan

	Where	*Frequency*	*Accuracy*	*Type*
Heat flows				
Q1	Solar production primary side	1min	(+/-0.5%)	Inductive flow sensor
			+/-0.1K	2pcs. PT100 Temperature sensors
Q2/Q10	Solar production secondary side/Heat blow off and anti frost heating	10min	(+/-0.5%)	Inductive flow sensor
			+/-0.1K	2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Q3/Q4	Heat flow to/from BTES	10min	(+/-0.5%)	Inductive flow sensor
			+/-0.1K	2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Q5	Heat flow to HP cold side	10min	(+/-0.5%)	Inductive flow sensor
			+/-0.1K	2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Q6	Heat flow from HP warm side	10min	(+/-0.5%)	Inductive flow sensor

			+/-0.1K	2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Q7	Heat flow from Electrical boiler			Electricity meter
Q8/Q9	Heat flow to/from existing system	10min	(+/-0.5%)	Inductive flow sensor
			+/-0.1K	2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Electricity				
Σ(E1,E2,E10)	Solar circuit	10min	+/-0.2%	ABB, Danfoss VLT???
Σ(E3,E4)	Storage circuit	10min	+/-0.2%	ABB, Danfoss VLT???
Σ(E-HP,E5,E6)	Heat pump circuit	10min	+/-0.2%	ABB, Danfoss VLT???
Climatic data				
Solar radiation	Global irradiation in collector plane	10min	+/-3%	
Air temperature	Ambient temperature	10min	+/-0.1K	
Wind speed	Wind speed	10min		
Temperature	In and outlet temperatures for electrical boiler	10min	+/-0.1K	
Temperature	Temperaure sensors for steel tank	10min	+/-0.1K	20 pcs. PT100 temperature sensors
Temperature	Supply/return temperatures from selected collector rows	10min	+/-0.1K	16pcs. Wireless PT100 temperature sensors
Pressure	Pressure level in collector circuit	10min		Pressure transmitter 0-10bar

Site name:	**Marstal (SUNSTORE 4)**
Location:	**Marstal, Denmark**
Operational since:	**2014**
UTES Type:	**HT-PTES**

The general description can be summarized as follows with top and cross section views provided in Figure 19 and Figure 20:

- Dimensions: Top area 113 x 87,
- bottom area: 48 x 23,
- max height: 16 m.

Figure 19 : Top view of the Marstal HT-PTES project

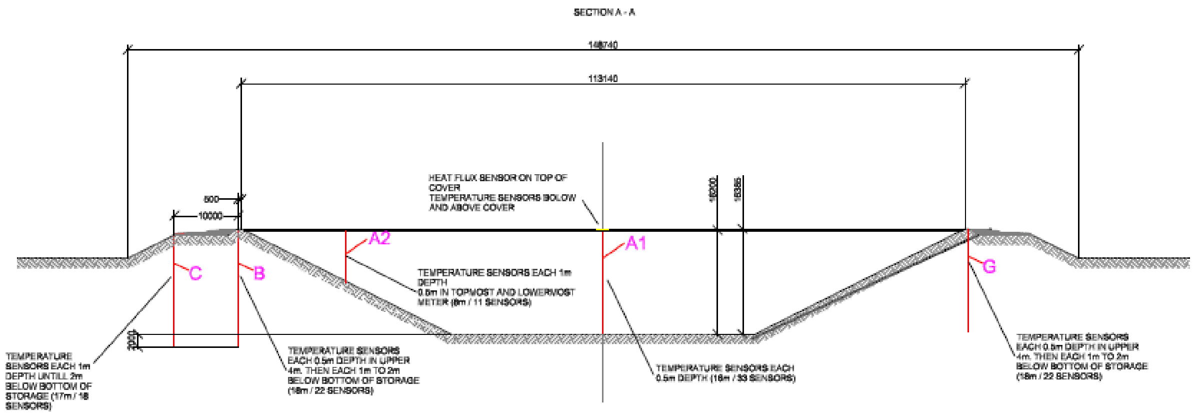

Figure 20 : Cross section of the Marstal HT-PTES project

The main parameters monitored concerning the subsurface part are gathered in Table 5.

Table 5 : Marstal project subsurface monitoring plan

	Where	*Frequency*	*Accuracy*	*Type*
Temperature	Temperatures inside the storage (center)	30min	+/-0.1K	PT100, cl.A, 3w (33sensors/16m)
Temperature	Temperatures inside the storage (North west)	30min	+/-0.1K	PT100, cl.A, 3w (11sensors8m)
Temperature	Temperature below insulated cover	30min	+/-0.1K	Pt100, cl.A, 3w
Temperature	Temperature above insulated cover	30min	+/-0.1K	Pt100, cl.A, 3w
Temperature	Ground temperature around storage	30min	+/-0.1K	2x13pcs. PT100 temperature sensors
Temperature	Ground temperature around storage	30min	+/-0.1K	9pcs. PT100 temperature sensors

Temperature	Ground temperature around storage	30min	+/-0.1K	2x3pcs. PT100 temperature sensors
Water level	Water level in storage	10min		Ultrasonic
Flowrate	(integrated in energy meters)			

The description of the surface system is provided in Figure 21. It consists in a solar district heating system with a collector area around 38 000 m2, adsorption heat pump, bio oil boilers, gas engines. The main parameters monitored concerning the subsurface part are gathered in Table 6. It concerns heat flows, electricity and climatic data.

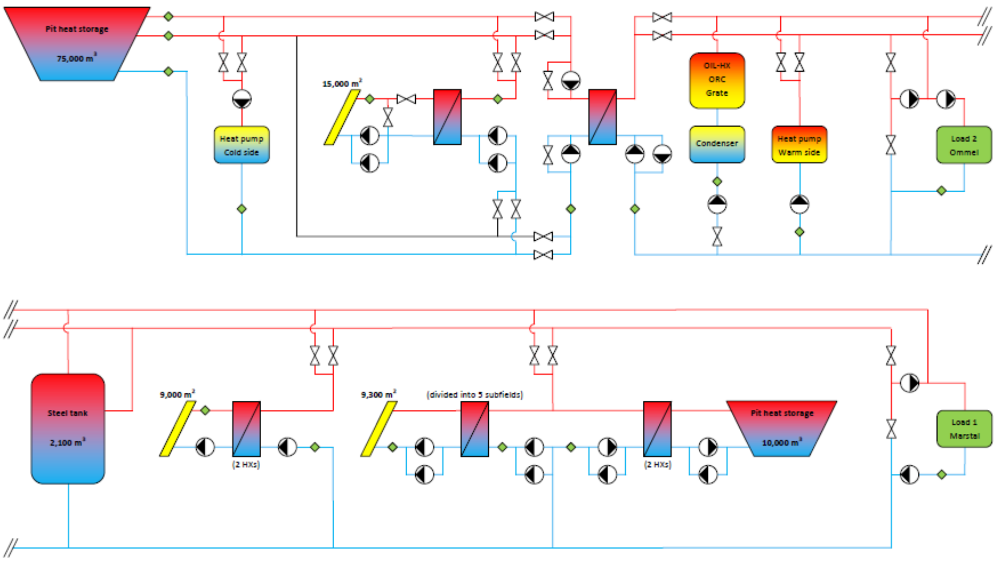

Figure 21: Marstal project surface facilities principle

Table 6 : Marstal project surface monitoring plan

	Where	***Frequency***	***Accuracy***	***Type***
Heat flows				
Q1	Fired biomass fuel	10min	+/-6%	Calculated from weight and moisture content in biomass fuel
Q2	Heat flow to ORC (Oil circuit)	10min	+/-6%	Vortex flow sensor
				2pcs. PT100 Temperature sensors
Q711	Heat flow from biomass boiler by grate	10min	+/-3%	Inductive flow sensor
				2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Q713	Emergency cooler, small	10min	+/-3%	Inductive flow sensor
				2pcs. PT100 Temperature sensors
				Integrator/Energy meter
Q714	Emergency cooler, large	10min	+/-3%	Inductive flow sensor
				2pcs. PT100 Temperature sensors

				Integrator/Energy meter
Q710	Condenser	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q712	Heat flow from ORC	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q110	Solar production primary side	1min	+/-6%	Inductive flow sensor 2pcs. PT100 Temperature sensors
Q210	Solar production secondary side/Heat blow off and anti frost heating	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q410	Heat flow to/from seaonal storage and collectors (Storage side)	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q510	Heat flow to/from seaonal storage and collectors (Consumption side)	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q310	Heat flow to heat pump (cold side)	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q311	Heat flow from heat pump (warm side)	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter
Q3	Heat flow from existing 18300m2 collectors	10min	+/-3%	
Q4	Heat Flow to Marstal district heating network (before biooil burner)	10min	+/-3%	
Q1010	Heat flow to Ommel district heating network	10min	+/-3%	Inductive flow sensor 2pcs. PT100 Temperature sensors Integrator/Energy meter

Electricity				
E-ORC-out	Electricity production, ORC-plant	10min		
Σ(E-ORC-in,E2,E722)	Electricity demand, ORC-plant	10min		Electricity meter
Σ(E1,E720,E721,E723,E724)	Biomass boiler circuit	10min		Electricity meter
Σ(E_SO.PU.01,E_SO.PU.02,E_SO.PU.03,E_LA.PU.01,E_LA.PU.02,E_LA.PU.03)	Solar circuit	10min	+/-0.2%	Electricity meter
Σ(E420,E421,E520,E521)	Storage circuit	10min	+/-0.2%	Electricity meter
Σ(E-HP,E320-1,E321)	Heat pump circuit	10min	+/-0.2%	Electricity meter
E3	Electricity demand, existing 18300m2 collector cirquit	10min	+/-0.2%	
E4	Electricity demand, Marstal district heating network	10min	+/-0.2%	
Σ(E1020-1,E1021-1)	Electricity demand, Ommel district heating network	10min	+/-0.2%	
Flow rates and temperatures integrated in energy meters above (and available from here)				
Climatic data				
Solar radiation	Global irradiation in collector plane	10min	+/-3%	Pyranometer
Air temperature	Ambient temperature	10min	+/-0.1K	Temperature sensor
Wind speed	Wind speed	10min		Anemometer
Other monitoring				
Temperature	Supply/return temperatures from selected collector rows	10min	+/-0.1K	16pcs. Wireless PT100 temperature sensors
Pressure	Pressure level in collector circuit	10min		Pressure transmitter 0-10bar

Site name:	**N/A**
Location:	**N/A**
Operational since:	**N/A**
UTES Type:	**HT-ATES**

In Denmark around ten[2] low temperature (< 22°C) ATES systems exists while some other tens of installations used only for heating or cooling (in combination with a heat pump) are typically also named ATES. Three deep geothermal plants are producing heat from 1.2-2.6 km of depths at 42-73 °C, but no deep or shallow high temperature ATES systems (HT-ATES) currently exist and both technical issues[3] and legal aspects[4] is currently regarded as barriers for HT-ATES deployment in Denmark.

For shallow ATES applications (< 250), the current regulation specifies the following monitoring activities:

- The installation must be equipped with a pressure-drop alarm and auto-stop device in case of leakage.
- The monthly average outlet temperature of the groundwater for re-injection must not be lower than 2ºC
- The outlet temperature of the groundwater for re-injection must not exceed 25ºC and the monthly average outlet temperature must not exceed 20ºC.
- Before start-up, the owner must provide a chemical analysis of the water in the aquifer used for production and re-injection, including temperature measurements.
- Three months after start-up, and then on a yearly basis, the owner must analyse the outlet water for agents that could potentially be dissolved from the system.
- An installation must be equipped with temperature sensors measuring the inlet and outlet temperature of the groundwater.
- The re-injection well must be equipped with temperature sensors connected to an automatic data-logging system and the logged outlet temperatures must be reported on a yearly basis to the municipality.
- The quantities of extraction and re-injection of groundwater must be monitored and reported on a yearly basis to the municipality.

Further recommended monitoring activities for future shallow HT-ATES systems in Denmark are outlined below.

As the actual performance of a HT-ATES in practice will differ from the prerequisites given in the design phase, proper monitoring is important for understanding the operational conditions and optimization of the performance. Thus, the monitoring data are an important source for[5]:

- Diagnosing issues that differ from design assumptions
- Optimizing the system (performance monitoring) to be able to deliver the energy efficiency it was designed for
- Preventing potential problems e.g. thermal leakage
- Scheduling maintenance operations

The temperature development in the storage aquifer around the hot well(s) should be monitored using (a) separate monitoring well(s) with temperature sensors or alternatively using fiber glass technique which can provide more detailed and continuous information[6]. Furthermore, the water quality in terms of water chemistry and microbiology in the storage aquifer should also be monitored by taking water samples from a separate monitoring well at regular intervals.

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[2] Danish Energy Agency. Udredning vedrørende varmelagringsteknologier og store varmepumper til brug i fjernvarmesystemet 2014
[3] Rosenbrand, E., Haugwitz, C., Jacobsen P.S.M., Kjøller, C. and Fabricius, I.L., 2014. The Effect of Hot Water Injection on Sandstone Permeability. Geothermics, 50, 155-166.
[4] Thomas Vangkilde-Pedersen, Anne Mette Nielsen, 2012: REGEOCITIES Deliverable 2.1: Denmark – National Report. Intelligent Energy Europe
[5] 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 – ERA NET Cofund Geothermal. 130 pp + appendices.
[6] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.

As the HT-ATES will interact with a more or less complex surface system, monitoring data from the demand side are also required in order to optimize the performance. This may include energy flow, the supply and return temperatures and electricity consumption of heat pumps and circulation pumps[7].

In order to detect any leakage in the loop, pressure monitoring of the system pressure is essential and already required in the current ATES regulation. Deterioration of the well because of e.g. clogging can be monitored by calculating the specific well capacity (yield in m³/h divided by drawdown in m) from monitoring data of the groundwater flow rate and the water level in the well[8].

8 Azores:

High enthalpy geothermal power plants run in the Azores in two of the nine volcanic islands, São Miguel and Terceira. In the São Miguel Island two power plants with a total of 23 MW installed capacity are located in the north flank of Fogo Volcano. In 2009 new geothermal wells were drilled in the Caldeiras da Riberia Grande area (Figure 22), but due to several technical problems the project was abandoned. The main goal of this monitoring case is to better model the geothermal reservoir conditions on this study site based essentially on geochemical data associated with the visible secondary manifestations of volcanism existing in the area (fumaroles, thermal and cold CO_2-rich springs), as well as the diffuse degassing structures. In addition, rock samples from the wells drilled in the area will be used to assess the temperature based on the minerals present at different depth. The integration of the data obtained based on the different geochemical approaches will contribute to better model the subsurface reservoir conditions in the Caldeiras da Ribeira Grande area.

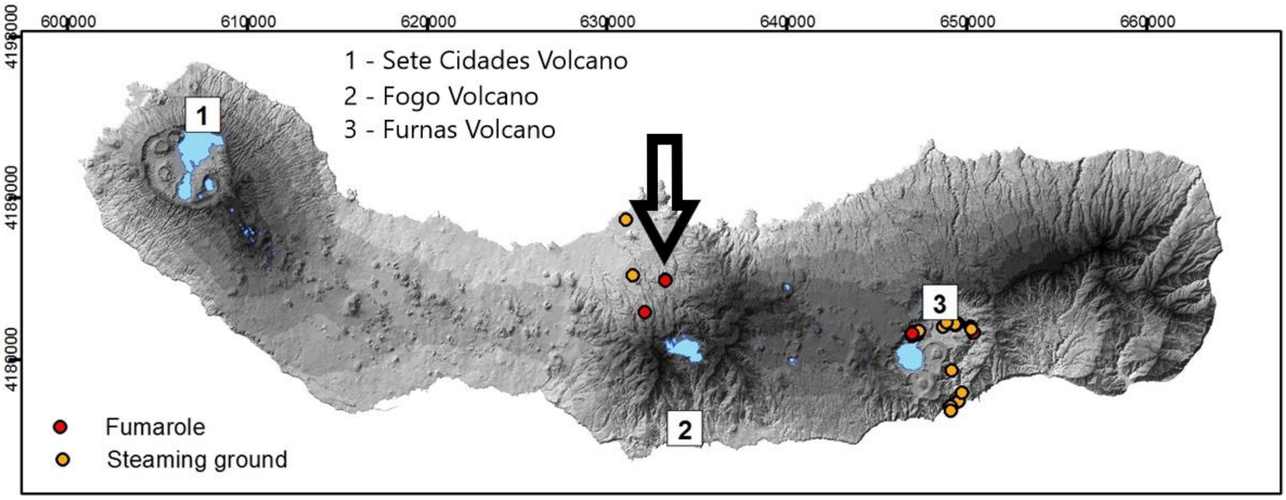

Figure 22 : Location of the Azores study site. The black arrow points Caldeiras da Ribeira Grande area, in the north flank of Fogo Volcano (São Miguel Island).

9 Iceland

Reykjavík Energy operates two geothermal power plants in the Hengill high temperature area in SW Iceland, in Hellisheiði and Nesjavellir. These fields have both production and reinjection wells. Below is a summary of regular monitoring done in these fields:

[7] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.
[8] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.

- TFT (tracer fluid test) measurements are done 2 times a year in each production well. These tests give information about the flow and enthalpy from each well. From the test results, productivity curves can be made which show the flow rate at a given pressure.
- Alongside of the TFT measurements, condensed steam and water samples are also taken to get pH and to do chemical composition analysis.
- Pressure and temperature profiles as a function of depth in specific wells are measured once a year, these measurements are done during production stops. They can be done more often if irregularties are seen in certain areas.
- The flow of water into injection wells and the temperature of the injected water is constantly measured, as well as the pressure at wellhead. The pressure at wellhead is also continuously monitored in production wells.
- To monitor seismicity, a local seismometer net is in place in the area.
- Tracer test have been done in the area to shed light on flow paths between reinjection and production zones.
- Groundwater samples are taken from shallower wells in the area to monitor any possible effect of the operation on shallower groundwater systems. Temperature profiles are also recorded in these wells annually.
- The data used to update the area´s large scale reservoir model is montly flow rate from production wells, montly injection into injection wells, enthalpy measurements and pressure drawdown measurements.

Reykjavík Energy also operates lower temperature fields that produce hot water for district heating. Monitoring in those fields consists of:

- Montly water level measurements in monitoring wells to monitor drawdown in the systems.
- Flow and temperature measurements at well head in all wells every 10 minutes.
- Total chemical analysis of water samples from all wells twice a year.
- Quality control on the water within the distribution system, every two weeks.
- The monitoring data used to construct and calibrate the simulation models for the lower temperature systems is initial rock temperature profiles, initial water level, montly flow rate from production wells, montly water level measurements and temperature measurements.

10 Comparison/Overview

A compilation of the monitoring plans conducted in the different projects and described in the above sections is provided hereafter in Table 7 and Table 8 per category. 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. This was confirmed by the feed back from the presentation of these results during the WP2 workshop held in Geneva the 8th april 2019. The nature, frequency and accuracy of the data monitored appear satisfactory to constrain the models build to reproduce the bahaviour of the energy systems.

Table 7 : Systems using doublet type architecture

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		Y		Y		Y	including EC, pH, Redox	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	10 min	Y	10 min	Y	10 min	Y	6-months	N		Y	Temp-profile	Well test & tracer test	N	Y

Table 8 : Systems based on HT-BTES and HT-PTES

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

It is 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.