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Modelling of an Innovative HT-BTES (Smart) Design with Lateral Recovery Boreholes to Reduce Heat Losses: Development and Preliminary Result

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ABSTRACT

HT-UTES (High Temperature Underground Thermal Energy Storage) systems are very attractive solutions to match the heat availability from various heat sources (waste, process, solar, district heating network, …) with heat demands. One drawback of these solutions is their inherent heat losses, especially under high temperatures. The BTESmart pilot was developed to tackle this problem. In addition to a standard BTES field, outer (lateral) recovery boreholes are installed at the field periphery to capture heat losses from the field heart. The heat to be stored into the BHE field will come from thermal solar panels. The system will cover the heating needs for the administrative buildings of Storengy main natural gas storage facility located in Chémery (region Centre Val-de-Loire, France), i.e. 211 MWh/year. The BTES will be charged at 40°C through 12 radial lines of 4 boreholes in series. The project should be under construction end 2019 and operations should start in June 2020.

For HT-BTES applications, analytical models are more suitable for routine use than fully discretized models. They can run over reasonable time frames, i.e. performing relevant simulations over decades with hourly time step. As this innovative design is not available in the standard modelling suites like TRNSYS, a specific BTES module need to be developed to assess the added value of this innovative design and optimize its operation.

As the BTESmart project is not yet in operation, it cannot produce already the necessary monitoring data to validate the developed module. Therefore, a fully discretized numerical model is built in FEFLOW to deliver an independent and relevant set of numerical results to validate the new analytical module. FEFLOW enables to accurately take into account the design of BTESmart and to simulate the complete and detailed temperature field and circulating fluid temperatures.

Only the first part of the modelling work and the cross-validation between the fully discretized and the semi-analytical models of a BTES with no active recovery boreholes will be presented here.

Several conclusions can however be already listed from the work done:

- Analytical approach is definitely the way to go to simulate accurately and rapidly the BTES behavior along several cycles;
- Temperatures from the new analytical module are compared to the numerical outputs from FEFLOW and the domain of validity of each model is presented;
- The influence of design parameter such as boreholes number, location, and operation strategy over the unloaded energy per volume and BTES efficiency is discussed.

1. INTRODUCTION

In France, according to the French Energy Environment and Energy Management Agency, residential and tertiary sectors account for 45% of national final energy consumption and 20% of total greenhouse gas emissions. The French Parliament has promulgated the energy transition law for a green growth in August 2015. This law targets a 40% reduction of greenhouse gas emissions between 1990 and 2030, and renewable energy covering 32% final energy consumption in 2030. The development of UTES and in particular, HT-UTES will definitively help to meet these objectives.

The first HT-BTES projects carried out enabled the IEA to make available a first methodological guideline for design and construction (Sibbit, B., & Mc Clenahan, D., 2015). Nevertheless, as it can be seen from the review of existing projects, major scientific and technical issues which concern both soil and surface to improve the overall efficiency of the system in order to obtain sufficient profitability to multiply their use in the context of the energy transition, remain. From an underground perspective:

- Efficiency is penalized by heat losses, which are more important because of the high storage temperature (70°C at Braestrup and Crailsheim, 55°C at Drake Landing). If the installation of surface insulating materials helps to limit losses with the atmosphere, lateral losses in the warmer soil at the border of the storage remain significant as evidenced by the instrumentation of the Braestrup and Crailsheim sites. Reducing thermal losses is therefore a major area of scientific and technical developments.
- The efficiency of such systems also depends on the history of use of the underground because the operating regime is continuously transitory due to load and discharge cycles. Because the underground is inherently heterogeneous, these cycles can also cause temporary hysteresis effects (non-reversibility of behavior). For this type of system, it is therefore important to monitor and simulate the behavior of the underground with adapted tools and approaches in order to derive

the quintessence in terms of performance. A second major area of scientific and technical development is representative modelling of subsurface heat exchanges.

The BTESmart project aims to address all these issues and to provide solutions that can be applied more broadly in order to support the development of this type of projects. The BTESmart pilot will be located in Chémery (region Centre Val-de-Loire, France). It will cover the heating needs for the administrative buildings of main Storengy natural gas storage facility. In addition to a standard BTES field, outer (lateral) recovery boreholes will be installed at the field periphery to capture heat losses from the field heart.

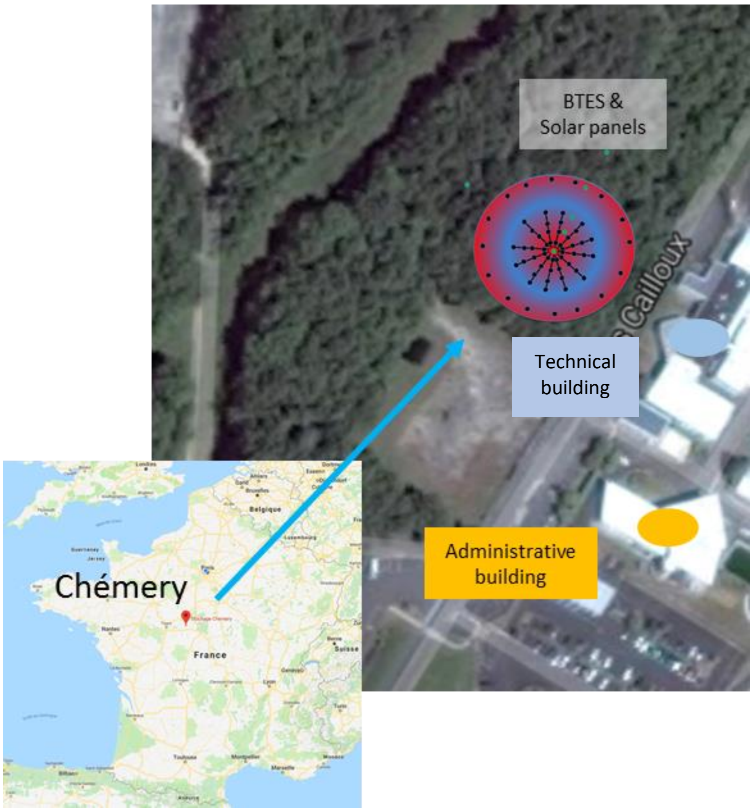

Figure 1: Location of BTESmart pilot – Chémery, region Centre Val-de-Loire, France.

This work is conducted in the frame of the Geothermica HEATSTORE project which aims at promoting the development of HT-UTES solutions (http://www.geothermica.eu/projects/heatstore/). The BTESmart pilot is one of the 6 demonstration sites involved in this project.

2. MODEL DEVELOPMENTS AND CROSS-VALIDATION

2.1 Fully discretized model

The fully discretized model will be made using FEFLOW (Diersch, H.-J.G., 2005). The BTES described here is strongly inspired by the design of the BTESmart project even if there are some differences. The BTES will consist in 48 double 20 m deep double U-tube BHE installed on a circular area (diameter of 21 m). 16 lateral boreholes with the same depth will be installed at 5 m around the central boreholes (cf. Figure 2). The local geology is supposed to be, horizontally and vertically homogeneous. The BTES is covered with soil and heat insulation (Table 1). No underground water flow is considered in the simulations.

The whole system has axes of symmetry and only ¼ of the model will be simulated, to maintain the simulation time within reasonable durations.

The properties of the used BHE are given in Table 1. Within FEFLOW's BHE configuration dialog, the Eskilson and Claesson's analytical solution BHE was chosen, as it is a better alternative to the general Al-Khoury *et al.'s* numerical strategy for long term-predictions in terms of accuracy. Only one iteration is performed per each time, but a stronger RMS error tolerance of 10^{-6} concerning the FE/BE automatic time-stepping control was selected. The streamline upwinding option was also preferred to the default no upwinding (Galerkin-FEM) option.

The linkage of a single BHE within its BHE array is shown in Figure 2. The central boreholes are connected in series of 4, with 3 parallel radii in a ¼ of model, forming the first BHE array. 4 lateral recovery boreholes are connected in parallel to form the second BHE array, hydraulically independent.

Table 1: reference parameters (used for the benchmark).

Stratigraphic columns				
Description	Top depth [m]	Bottom depth [m]	Thermal conductivity [W.K^{-1}.m^{-1}]	Heat Capacity [MJ.K^{-1}.m^{-3}]
Soil	0	0.5	0.25	1.50
Insulation	0.5	1.0	0.20	2.00
Rock	1.0	Inf.	1.90	2.30

BHE characteristics							
Borehole depth	Grout thermal conductivity	External pipe radius	Internal pipe radius	Spacing between pipes	Pipe thermal conductivity	Fluid heat capacity	Fluid Thermal conductivity
20 m	2.0 W.K^{-1}.m^{-1}	16.0 mm	13.1 mm	40.0 mm	0.40 W.K^{-1}.m^{-1}	4 000 kJ.K^{-1}.kg^{-3}	0.48 W.K^{-1}.m^{-1}

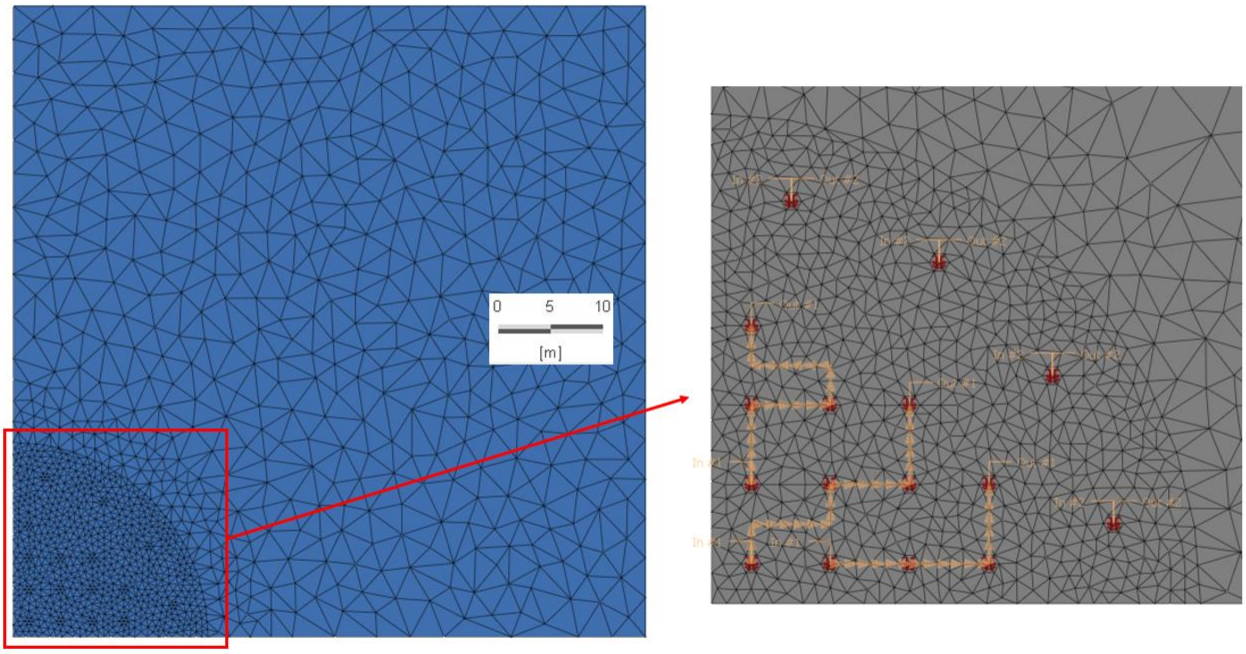

Figure 2: Mesh used in FELOW and hydraulic connections between boreholes. Only one quarter of the BTES simulated, with 48/4 = 12 inner boreholes and 16/4 = 4 lateral boreholes.

For the finite element meshing of the BHE arrays, additional point add-ins were introduced. This was particularly done to attain an optimal nodal distance Δ around each single BHE. According to FEFLOW White Paper Vol. V (Diersch, H.-J.G., 2005), an optimal BHE nodal distance of 0.38 m (by using n = 6) was chosen for the unstructured mesh. An additional circular polygon was defined in the supermesh design to allow a finer mesh around the heart of the system. Finally, the total study area of 60 m x 60 m was discretized in 1,500 triangular prismatic element per layer. In the vertical direction, the used finite element mesh consists in 28 layers with a thickness between 0.5 and 10 m; within the BTES the slice thickness is 1 m.

2.2 Semi-analytical model

Numerical simulations with fully discretized model as described in section 2.1 are useful to understand the influence of heterogeneity for instance or underground water flow but are rarely practical for routine applications. On the contrary, analytical models can run over reasonable time frames, i.e. performing simulations over 30 years with hourly time step, without resorting to cluster computing.

Here we develop a semi-analytical (SA) models based on the theory of the *g*-functions (Eskilson, P., 1987). However, such models rely on simplifying assumptions, which are worth being checked against fully discretized models. In what follows the assumptions are:

(i) All elements (ground, grout, insulation layer) are regarded as homogenous media.
(ii) Physical properties of these materials do not depend upon temperature.
(iii) Underground water flow is neglected. Heat is transferred through conduction, advection is negligible.

(iv) The initial, non-disturbed temperature T_0 is constant in the whole domain and remains constant far away from the BTES.
(v) The insulated top layer is of infinite radial extent.

g-functions, also called step responses, account for the evolution of the mean fluid temperature T_{fl} in a single BHE under a constant linear power *p* applied per meter of borehole:

$$T_{fl} = \frac{T_{in} + T_{out}}{2} = T_0 + \frac{p}{\lambda_m} g(t^*) \tag{1}$$

where T_{in} and T_{out} accounts for the BHE inlet and outlet temperatures, λ_m is the ground thermal conductivity [W.K^{-1}.m^{-1}] and t^* is a dimensionless time factor (Fourier number) defined by:

$$t^* = \frac{\lambda_m}{(\rho C_p)_m {r_b}^2} t \tag{2}$$

with $(\rho C_p)_m$ the ground thermal capacity [J.K^{-1}.m^{-3}] and r_b the borehole radius. When the heat load changes with time, the fluid temperature can be computed with the superimposition principle:

$$T_{fl}{}^n = T_0 + \frac{p}{\lambda_m}\left[p^1 g^n + \sum_{l=1}^{n-1}(p^{l+1} - p^l) g^{n-l}\right] \tag{3}$$

Let us assume that all the BHE are merged into a single BTES. The mean fluid temperature $T_{fl,1}$ at time step *n* is given by:

$$T_{fl}{}^n = \frac{T_{in}{}^n + T_{out}{}^n}{2} = T_0 + \frac{1}{\lambda_m N_1 H}\left[{P_1}^1 G^n + \sum_{l=1}^{n-1}({P_1}^{l+1} - {P_1}^l) G^{n-l}\right] \tag{4}$$

In eq. (4), T_{in} and T_{out} accounts for the inlet and outlet fluid temperature, *G* the step response and *P* the power exchanged:

$$P^n = \dot{M} C_{fl} (T_{in}{}^n - T_{out}{}^n) \tag{5}$$

Assembling eq. (4) and (5) leads to:

$$T_{out}{}^n = \frac{T_0 + \frac{\tilde{P}}{\lambda_m N H} + \left(\frac{\dot{M} C_{fl} G^1}{\lambda_m N H} - \frac{1}{2}\right) T_{in}{}^n}{\frac{1}{2} + \frac{\dot{M} C_{fl} {G_{11}}^1}{\lambda_m N H}} \tag{6}$$

G is defined by:

$$G(t^*) = g(t^*) + \frac{1}{N}\sum_{\substack{i=1 \\ j\neq i}}^{N} g_{j\to i}(t^*) \tag{7}$$

In eq. (7), $g_{i\to j}(t^*)$ accounts for the step response from borehole *i* to borehole *j*. $\tilde{P}$ is the "convoluted" power:

$$\tilde{P} = \begin{cases} 0 \; if \; n = 1 \\ P^1 G^n - P^1 G^1 \; if \; n = 2 \\ P^1 G^n + \sum_{l=1}^{n-2}(P^{l+1} - P^l) G^{n-l} - P^{n-1} G^1 \; if \; n > 2 \end{cases} \tag{8}$$

Many step-responses have been published, depending on assumptions on geometry and boundary conditions. This includes the *infinite line source* (*ILS*) model (Ingersoll, L. R., & Plass, H. J., 1948), the *finite line source* (*FLS*) model (Eskilson, P., 1987), the *hollow infinite cylindrical source* (*HICS*) (Carslaw, H. S., & Jaeger, J. C., 1947) and the *hollow finite cylindrical source* (*HFCS*) (Maragna, C., & Loveridge, F., 2019). For this work we used the *moving finite line source model with Cauchy-type top boundary conditions* since it deals with the heat exchange at the surface (Rivera, J. A., Blum, P., & Bayer, P., 2016):

$$\begin{aligned} g(t^*) = \lambda_m R_b + \frac{1}{8\pi}\int_{\frac{1}{4t^*}}^{\infty} \frac{1}{\varphi} \exp\left[-\varphi - \frac{1}{\varphi}\right]\Big\{4\,\mathrm{erf}\big(H^*\sqrt{\varphi}\big) - 2\,\mathrm{erf}\big(2H^*\sqrt{\varphi}\big) \\ + \frac{1}{H^*\sqrt{\pi\varphi}}\left[4\exp\left(-\varphi {H^*}^2\right) - \exp\left(-4\varphi {H^*}^2\right) - 3\right]\Big\} d\varphi + \frac{1}{h^* H^*}\int_{\frac{t^*}{4}}^{\infty} \frac{1}{\varphi}\exp[-\varphi]\,\psi(h^*, H^*, \varphi)\, d\varphi \end{aligned} \tag{9}$$

Note that (Rivera, J. A., Blum, P., & Bayer, P., 2016) assumes a constant underground water flow through a Peclet number *Pe*. Since there is no underground water flow in our study, *Pe* has been set to zero in eq. (9). The term $\lambda_m R_b$ has been added to account for the heat transfer inside the borehole. H^* and h^* are normalized expressions for the BHE depth *H* and heat transfer coefficient at the surface *h* [W.K^{-1}.m^{-2}]:

$$H^* = H/r_b \tag{10}$$

$$h^* = (h\, r_b)/\lambda_m$$

$h \to 0$ and $h \to \infty$ respectively correspond to an adiabatic condition (perfectly insulated surface) and no insulation at all. h can be estimated through:

$$h = \frac{1}{\left(\frac{e}{\lambda}\right)_{layer\ 1} + \left(\frac{e}{\lambda}\right)_{insulation}} = \frac{1}{\frac{0.50}{0.25} + \frac{0.50}{0.20}} = 0.222\ \mathrm{W.K^{-1}.m^{-2}} \tag{11}$$

In eq. (9), ψ is a function defined by:

$$\psi(h^*, H^*, \varphi) = 2\,\mathrm{erf}\left(H^*\sqrt{\varphi}\right) - \mathrm{erf}\left(2H^*\sqrt{\varphi}\right) + \kappa(h^*, H^*, 0) - \kappa(0,0,0) - \kappa(h^*, H^*, H^*) + \kappa(h^*, 0, H^*) \tag{12}$$

$$\kappa(h^*, \mu, \nu) = 2\sqrt{\frac{\varphi}{\pi}} \int_0^\infty \exp\left[-\left((\nu + \mu + \varepsilon)\sqrt{\varphi}\right)^2 - h^*\varepsilon\right] d\varepsilon$$

2.3 Benchmark and cross-validation

The SA model has been benchmarked against the FEFLOW model with a synthetic case (see data in **Error! Reference source not found.Error! Reference source not found.**) in the case there is no circulation in the lateral boreholes. The BTES geometry and hydraulic connections have been described in section 2.2. The borehole resistance R_b has been estimated to 0.080 K.m.W^{-1} by FEFLOW based on geometrical and thermophysical properties. The initial temperature is T_0 = 13 °C in the whole domain. Heat is stored for 214 days by circulating fluid at 40 °C and unloaded for 151 days by circulating fluid at 13 °C, so a full cycle is 1 year, and 10 cycles are simulated. Each branch of the inner core is fed with a volume flow-rate Q = 0.5 m.h^{-3}, so that 6 m.h^{-3} circulates in the inner core. Note that as the discharge temperature is low, a heat pump will be necessary to increase the fluid temperature to a level usable for heating (e.g. 35-30 °C).

For the case with no lateral BHE activated, both models are in good agreement (see Figure 3), though the error on the BTES outlet temperature is about 0.9 °C after 10 h of operation. The influence of the FE mesh on the result quality must be further investigated. The error on the energy exchanged between the fluid and the ground over the 10 years of operation is 0.25% (energy in absolute value). If one defines the BTES efficiency η as the ratio of unloaded to stored heat, the BTES reaches a pseudo-periodic state after a few years of operation and η converges towards 67.0 % at the 10th year of operation.

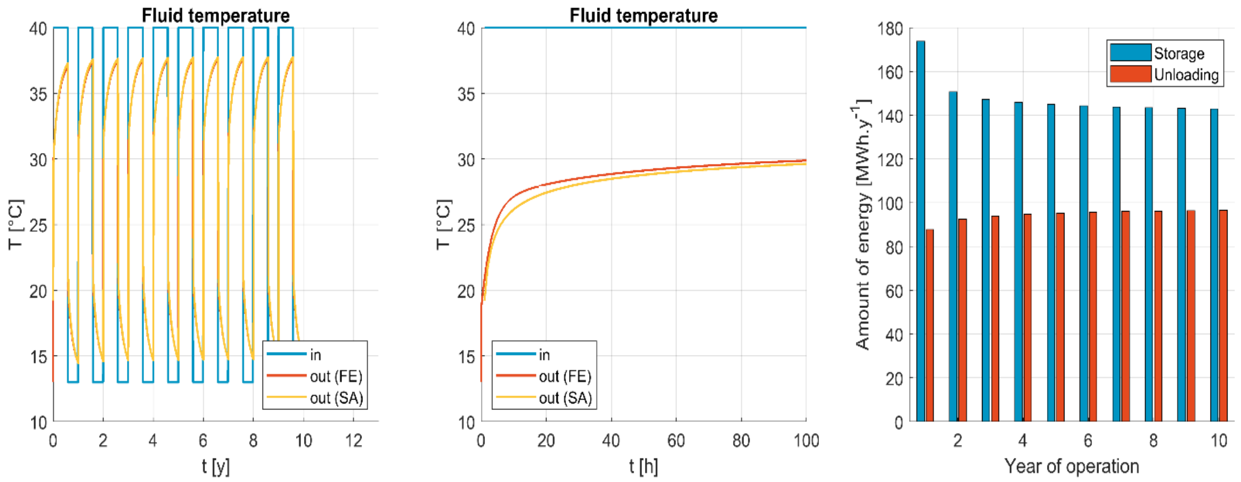

Figure 3: Benchmark: Evolution of the fluid temperature for 10 years (left) and at the early stage (middle). Yearly energy stored and unloaded (right), as computed by the SA model.

3. PARAMETRIC ANALYSIS

The influence of several design parameters has been investigated (see section 3.1), and the shape optimisation is discussed in section 3.2. To compare the performed simulations, two indicators have been chosen:

- The mean energy that can be unloaded during one cycle from the ground divided by the BTES volume V, e_{ul} [kWh.m^{-3}.y^{-1}],
- The BTES efficiency η, i.e. the ratio of unloaded to stored heat [-].

Note that the amount of energy loaded into the BHE E_{ul} is related to both indicators through:

$$\eta = \frac{E_{ul}}{E_l} = \frac{E_{ul}/V}{E_l/V} = \frac{e_{ul}}{e_l} \tag{13}$$

Both indicators e_{ul} and η are computed based on the heat balances established on 10 years of simulation, not only the 10th one. For the reference case, e_{ul} = 110 kWh.m^{-3}.y^{-1} and η = 63.9 %. The latter value is lower than the above mentioned 67.0 % efficiency, since this value was computed on the 10th year, once a periodic regime is reached.

Note that when the volume *V* is changed, a new optimal, compact plan filling a circle is generated. Every borehole is in the middle of a square cell of top surface d^2 (ref. value: 3×3 = 9 m^2) and depth *H* (ref. value: 20 m). The flowrate is adjusted too, so that it remains the same per borehole length.

3.1. Sensitivity analysis

Eight parameters have been varied around the benchmark case defined above (see Figure 4). The following conclusions can be drawn:

- Increasing the BTES volume *V* slightly increases the unloaded energy e_{ul}, and tremendously increases η. Indeed, the heat losses are decreased due to better shape factor, i.e. higher ratio of storage volume to surface,
- Long charging durations result in increased heat losses. The storage cannot be fully depleted during the too short unloading phase. For our set of parameters, a (flat) optimal charging duration would be 150 – 170 days rather than 214 days.
- Ground thermal capacity and flowrate have a limited influence.
- High thermal conductivities increase the unloaded energy at the expense of higher losses: Boreholes are more responsive, but the heat diffuse further away and cannot be fully retrieved.
- If the upper surface was perfectly insulated (h = 0), η would reach 70.0 % instead of 63.9 %.
- Borehole spacing has a tremendous effect on both unloaded energy and efficiency. From an energy point of view, boreholes should be as close to each other as possible.
- Finally, there is an optimal depth for the borehole depending on the volume. This is further investigated in section 3.2.

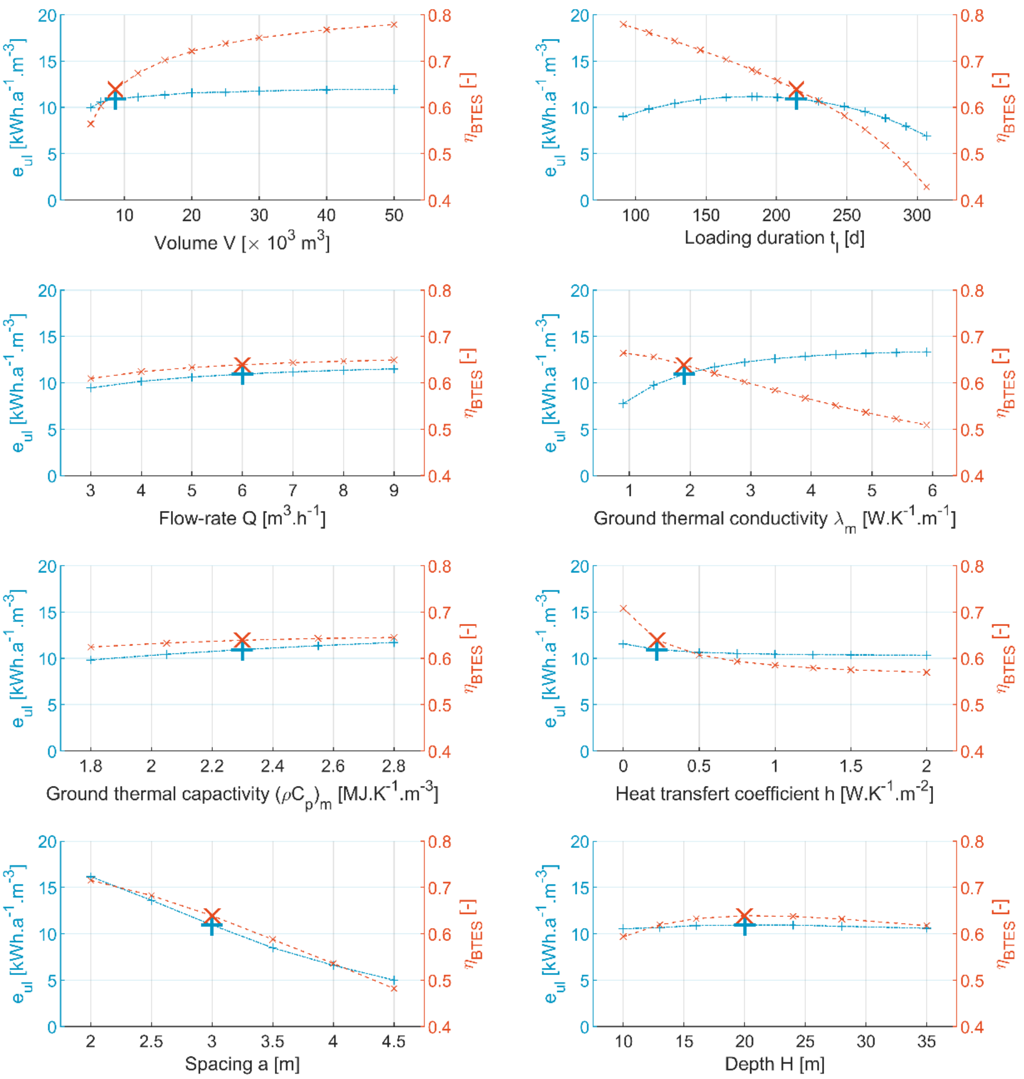

Figure 4: Sensitivity of unloaded energy per volume eul and BTES efficiency ηBTES, with no recovery boreholes. Both indicators are computed on 10 years. Larger markers accounts for the reference scenario (benchmark case).

3.2. Shape optimisation

For every volume *V*, there is an optimal borehole depth *H* that minimizes the heat losses and maximizes the efficiency. When the surface is perfectly insulated, the optimal depth is $(V/\pi)^{1/3}$ (Nguyen, A., Pasquier, P., & Marcotte, D., 2017). Here, as the surface is not perfectly insulated, higher efficiency is achieved through drilling deeper boreholes. However, drilling much deeper boreholes than the optimal depth has little influence on the efficiency, especially for large BTES (cf. Figure 5), and allows saving on the top insulation costs.

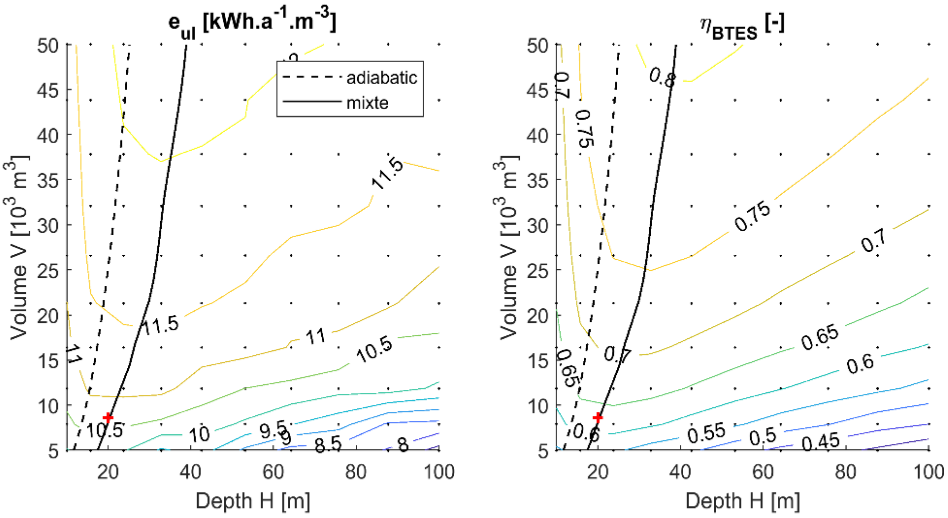

Figure 5: Energy per volume e_{ul} and BTES efficiency η_{BTES} as a function of volume and depth. Red crosses account for the reference scenario and black points are the sampling points, where the model was evaluated. The dotted black line accounts for optimal shape when the surface is perfectly insulated ("adiabatic condition") while the continuous line ("mixt condition") is for the reference value h = 0.222 W.K^{-1}.m^{-2}.

4. CONCLUSION AND FURTHER STEPS

Analytical approach is definitely the way to go to simulate the BTES behavior along several cycles, as it as accurate than using a fully discretized model in the case of a pretty homogeneous underground and a lot faster.

The studied BTES design showed quite high amounts of energy that can be unloaded during one cycle from the ground per storage cubic meter and efficiency, of respectively 110 kWh.m^{-3}.y^{-1} and 63.9 %. The parametric analysis demonstrated that the efficiency can further be improved by increasing the volume of the heat storage or decreasing the load duration.

From the shape optimisation, drilling much deeper boreholes than the optimal depth has little influence on the efficiency, especially for large BTES. Increasing the depth results is reduced insulation cost, which is far from being negligible. Therefore, the available surface and cost reduction should be the design criteria, much more than fulfilling an optimal, theoretical depth.

Some simulations were carried out with FEFLOW activating the lateral boreholes during the first 3 months of the discharging period, with an inlet temperature of 13°C and a flowrate per borehole of 0.125 m3/d. The figures below show that on the 9th cycle, the lateral BHE slightly increase the amount of injected heat from 145.6 MWh/y to 152.4 MWh/y. (+4.9 %). The amount of heat retrieved changes from 94.2 MWh/y to 107.1 MWh/y. (+13.6 %). Through an independent network, the circulation of a heat carrier fluid in the periphery increases the depletion of the storage in unloading phase, which is the targeted behaviour.

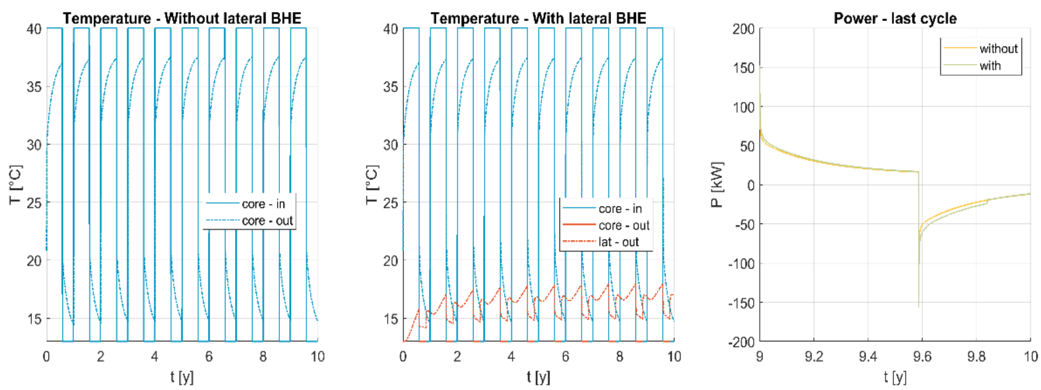

Figure 6: Evolution of the fluid temperature for 10 years without (left) and with lateral recovery boreholes (middle). Extracted/Injected power during last cycle (right), with or without lateral boreholes.

Further steps will now consist in developing an analytical module, able to represent the behaviour of the lateral recovery boreholes, to be able to quickly find the best design (depth, spacing, distance from the inner core) and operational strategy of such systems. However, the study will not be complete without the integration of this module in TRNSYS to allow a global technical economic-optimization on the whole system (under and above-ground parts), including the solar panels, BTES, heat pumps and backup boilers.

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NOMENCLATURE

Latin Letters		***Subscripts***	
a	thermal diffusivity [m.s^{-2}]	0	undisturbed conditions
$\dot{m}$	flow rate [kg.s^{-1}]	w	water
r	radius	fl	heat-carrier fluid
R	thermal resistance [K.m.W^{-1}]	m	media (ground)
p	power per meter of borehole [W.m^{-1}]	in	BTES inlet
T	temperature [°C]	out	BTES outlet
t	time [s]	b	borehole wall
t^*	normalized time (Fourier number)	l	loading heat (storage phase)
h	heat transfer coefficient at the surface [W.K^{-1}.m^{-2}]	ul	unloading heat (depletion phase)
H	borehole depth [m]		
d	borehole spacing [m]		
Greek letters		***Superscripts***	
λ	thermal conductivity [W.K^{-1}.m^{-1}]	n	time step
ρC_p	volume-specific heat capacity [J.K^{-1}.m^{-3}]	*	normalized value
η	BTES efficiency (ratio of unloaded to loaded heat)		
Acronyms			
BHE	Borehole Heat Exchanger		
BTES	Borehole Thermal Energy Storage		
FE	Finite Elements		
SA	Semi-Analytical		

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