Modelling Borehole Thermal Energy Storage of Renewable Resources as a Fluctuating Source for Charge

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Modelling Borehole Thermal Energy Storage using Curtailed Wind Energy as a Fluctuating Source of Charge

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ABSTRACT

Decarbonization of heating is essential to achieve net zero targets. As 80 % of heat in the UK is generated by combustion of natural gas, alternative renewable resources must be explored to meet this demand. Low enthalpy, shallow geothermal resources can contribute to space heating and cooling by utilizing ground sourced heat pumps, providing a low carbon energy supply. Borehole heat exchangers circulate heat transfer (working) fluid through a subsurface closed-loop system, to feed ground sourced heat pumps providing heating or cooling to adjacent buildings. Additionally, the temperate climate in the UK provides a promising setting for borehole thermal energy storage through coupling of seasonal sources of surplus heat or coolth (or even surplus low carbon electricity, e.g., wind or solar), with subsurface borehole heat exchangers. Yet, there has been limited uptake of borehole thermal energy storage systems in the UK, possibly due to a lack of familiarity or confidence in borehole thermal energy storage technology, high capital costs, lack of policy driving thermal energy storage or the widespread availability of gas boilers. This study investigates the potential use of shallow geothermal resources to supply heat to the King's Buildings Campus of the University of Edinburgh, Scotland, via modeling of a borehole heat exchanger array to meet heating demand. Energy generated from surplus curtailed wind was modeled as a fluctuating source of charge generated by air source heat pumps. As part of this study, 'whole systems' modeling was undertaken with TRaNsient SYStem simulation tool (TRNSYS), but the subsurface component of this software is not capable of modelling groundwater flow. Therefore, this paper aims to 1) compare a numerical model developed with OpenGeoSys to the data generated from TRaNsient SYStem simulation tool for any discrepancies, and 2) evaluate the subsurface thermal response using OpenGeoSys, with and without regional groundwater flow imposed on the model. Results indicate that there is a high potential for the use of such systems which incorporate curtailed wind, but the demand profile of the building and supply of heat for charge will impact the subsurface thermal balancing of the system. Initial comparison of the two modelling environments showed they have a strong match, with modeled outlet temperatures for the first year typically within 2 ºC of each other. Furthermore, detailed subsurface evaluation with OpenGeoSys showed groundwater flow has a strong impact on such systems, negatively inhibiting thermal performance. Whether the storage of surplus electricity, with recovery for thermal energy, is attractive from an economic or exergy point of view remains an open question.

1. INTRODUCTION

In the UK, net zero carbon targets have been set to reduce emissions of carbon dioxide and other greenhouse gases by 2050 (HM Government, 2008). Renewable sources of energy have the potential to contribute to this goal, particularly within the heating sector, but their energy supply fluctuates which does not coincide with peak periods of demand. Therefore, methods of thermal energy storage must be considered to allow the temporary storage of heat so that the thermal stores can be discharged when required. More specifically for this study, borehole thermal energy storage is a technology that allows the storage of heat in the subsurface, with less reliance on geological conditions than other subsurface storage technologies, such as aquifer and mine thermal energy storage (e.g., Lyden *et al.*, 2022). Thermal energy is stored underground via borehole heat exchangers (BHEs), where heating or cooling is achieved by circulating a working fluid in shallow u-tubes transferring or extracting heat from the subsurface via conduction at the BHE wall (**Figure 1**).

BHEs can contribute to spatial heating and cooling using ground sourced heat pumps (GSHPs) to tap into low temperature subsurface resources. In the UK, there are limited numbers of BHE systems designed specifically for borehole thermal energy storage (BTES), around the low 10's according to BEIS (2016). Usually, a heat source for charge is coupled to a BHE array using a GSHP which can raise the fluid temperature, although there are some high temperature systems which do not require heat pumps (e.g., Sibbitt *et al.*, 2012). In literature, the modeling and operation of BTES systems focus on using waste heat or solar thermal for charging (e.g., Ghoreishi-Madiseh *et al.*, 2019; Elhasmi *et al.*, 2020; Li *et al.*, 2021; Guo and Yang, 2021), with some investigating the potential of deeper systems seasonally (Xie *et al.*, 2018; Brown *et al.*, 2023). As a result of using solar thermal for the periods of charge, heat is stored in inter-seasonal cycles, corresponding to heat stored in the summer during low-demand periods and extracted in winter during high-demand periods. As far as the authors are aware, no BTES systems have been designed with the intention of using curtailed wind. BTES systems can provide low-cost, long-term storage of abundant thermal energy generated from wind using heat pumps that would otherwise be curtailed.

The drive to net zero carbon emissions and reducing associated costs is fueling a growth in installed capacity of wind power which is increasingly curtailed due to a mismatch with demand or network constraints. Electricity is traded through bilateral contracts and power exchange markets which do not explicitly include network constraints. The energy system operator (National Grid) then uses the balancing mechanism, and other ancillary services, to rebalance generation, demand, and storage in line with the physical requirements of the electrical transmission network. This is leading to curtailment of wind farm outputs, with increasing volumes of constrained power being forecast according to the operator's Future Energy Scenarios (National Grid, 2023). Curtailment increases for all scenarios to a peak in the years around 2035 to 2040, whereafter it falls due to increasing levels of flexibility technologies. For example, curtailment increases from ~1 TWh in 2021 to ~85 TWh by 2036 in the System Transformation scenario, so there is a significant opportunity forecast to store this excess energy using BTES.

The main constraints of the electricity network are limited to a few boundaries in the system. Typically, these are boundaries between areas of high renewable generation and high demand, with the network having insufficient capacity to transfer the power flow. A major constraint is the boundary between Scotland and England, indicated on **Figure 2** as SCOTEX and referred to by the National Grid as the B6 boundary. It is within this area that King's Buildings (Edinburgh) is located, which is the case study for this project. It is assumed that flexible operation of supply and demand above the SCOTEX boundary can utilize otherwise curtailed wind energy in this area.

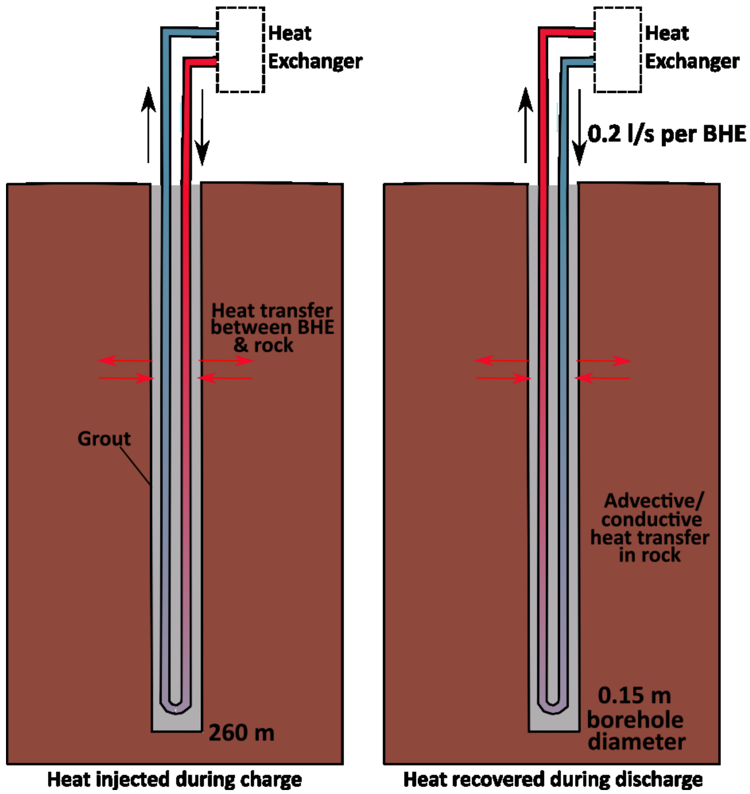

Figure 1: Schematic of BTES system during charge and discharge. Note that only one BHE of an array is shown and the array shape and dimensions can be found in Figure 5 and Table 1.

The King's Buildings, a large university campus, have significant demand for heat, comprising of 35 buildings, including a nursery and many laboratories, a district heat network with a supply temperature in excess of 85°C in winter, and a winter peak thermal demand predicted to reach 13 MWth by 2030. The available surface space is likely to limit the development of a BTES system. It has been shown that equidimensional (i.e., diameter is equal to the depth of the array), cylindrical arrays are most efficient at storing heat as the surface area-to-volume ratio is minimized (Skarphagen *et al.*, 2019) and the Drake's Landing scheme in Canada was developed with this criterion in mind (Wamboldt and Harrison, 2009). Due to the limited surface space available in the King's Buildings, the depth of the modelled BTES array was disproportionate to the diameter (i.e., not equidimensional). Therefore, this is unlikely to be an optimal design of the array, and future work will look into optimization using equidimensional cylindrical arrays with the TRaNsient SYStem simulation tool (TRNSYS).

The King's Buildings is underlain by Carboniferous strata that could include permeable sandstones, which present a possibility of groundwater movement in bedrock (and potentially superficial) aquifers in the subsurface (O Dochartaigh *et al.*, 2015a, b). This poses a risk to BTES, as it could advect heat away from the array, reducing the efficiency of the system's storage and subsequent recovery of the heat. In the literature, it has been suggested that groundwater flow in the subsurface can impact BTES when the Darcy velocity exceeds a value in the order of 1e-7 m/s (Ingersoll *et al.*, 1954; Van Meurs, 1985; Nordell, 1994; Banks, 2015; Emad Dehkordi *et al.*, 2015; Nguyen *et al.*, 2017). The potential influence of regional advection of heat to and from the array was therefore investigated to test the potential hydrogeological uncertainty. As it is not possible to model regional groundwater flow with TRNSYS, another numerical software is required such as OpenGeoSys (OGS).

In this study, the overall objective was to test the implications of using curtailed wind as a source of charge for the King's Buildings at the University of Edinburgh. As there are limitations in the approach to solving heat flux in the subsurface with TRNSYS, such as not having the capability to solve heat flux in the subsurface to include advection via groundwater flow, OGS was used to evaluate the subsurface. The key aims of this paper were to: 1) compare a 'whole systems' modelling approach using TRNSYS (i.e., model all components of the energy system) with a detailed subsurface model on OGS for potential discrepancy, 2) understand the thermal response in the subsurface when using short intermittent periods of charge sourced from curtailed wind, and 3) evaluate the impact of groundwater flow on the system and the implications on BTES. Preliminary results presented in this paper aim to show the compatibility of using OGS for detailed evaluation of the subsurface, before incorporating these results into a 'whole systems' approach. Future work will test the uncertainty of the subsurface further, before informing the 'whole systems' method with TRNSYS.

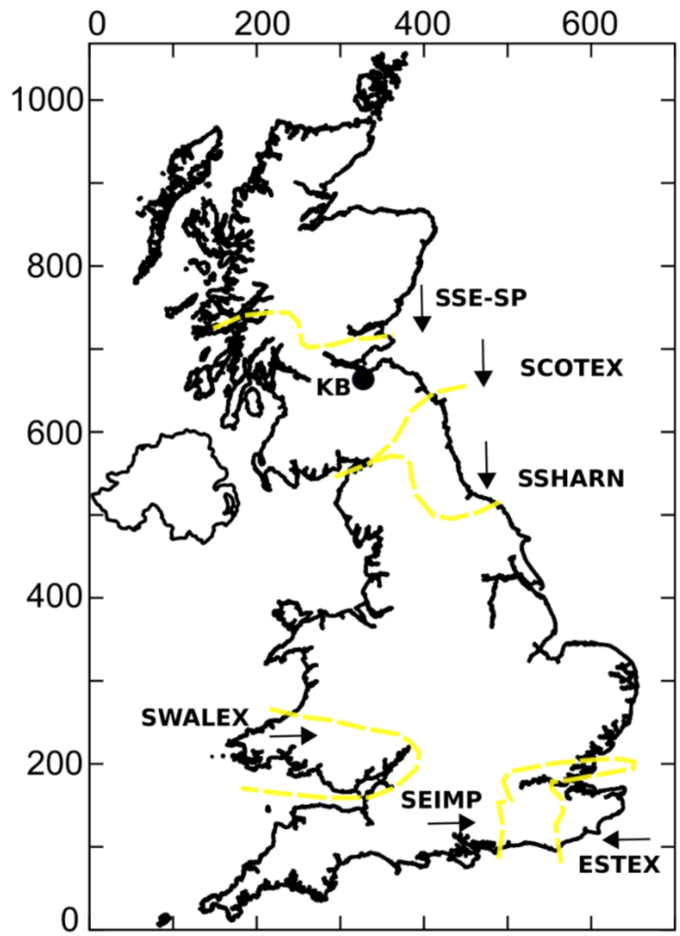

Figure 2: Map of constrained boundary areas in the transmission network with arrows indicating direction of constrained flow, including location of King's Buildings (KB) above the SCOTEX boundary (after National Grid ESO, 2023). X and Y axis correspond to Easting and Northing coordinates, respectively.

2. METHODS

In this section the methods for modelling the different components of the system are outlined, including the subsurface, surface supply from renewable sources of charge, and the demand. Initial 'whole systems' modeling was undertaken on TRNSYS, before further modeling was undertaken in OGS to determine the influence of the hydrogeological uncertainty (i.e., presence of groundwater) on the system. This is essential to the area of study as there is potential for groundwater movement and TRNSYS at present cannot solve for fluid flow in the subsurface.

2.1 'Whole Systems' Modeling

TRNSYS is a graphically based software used to simulate the behavior of transient systems and is most commonly applied to the modeling of electrical or, as is the case here, thermal systems. It has a large library of modules (such as HVAC, hydronics, hydraulic, and electrical components, various types of storage systems, solar and wind energy converters) which can be linked together allowing the whole system to be simulated. It is Fortran based, and lets the user create new modules and modify existing ones. Its kernel then iteratively solves the system using a differential equation solver to plot and output selected system variables (TRNSYS, 2023).

In particular, it has a Ground Heat Exchanger module (Type 557) which was used to model BTES in this study. In the corresponding numerical routine, the thermal transfer problem within the BTES was divided into a local problem, a steady-flux problem, and a global problem. The local problem was used to resolve short-term temperature variations around single ducts due to thermal transfers with the heat-carrier fluid circulating in the duct using the standard transient heat equation in the soil with a source term derived from a steady-state heat balance in the heat carrier fluid. The steady-flux problem resolves slower temperature variations at larger time scales to account for energy redistribution within the volume around the same duct. In the global problem, the standard transient heat equation is solved across the whole BTES volume accounting for conduction in the soil and with additional source terms transferred over from the local and steady-flux solutions. A finite difference method is used for the local and global problems, whereas an analytical solution was used for the steady-flux problem (Pahud and Hellström, 1996). The final temperature distribution was then the superposition of the resulting three temperature fields.

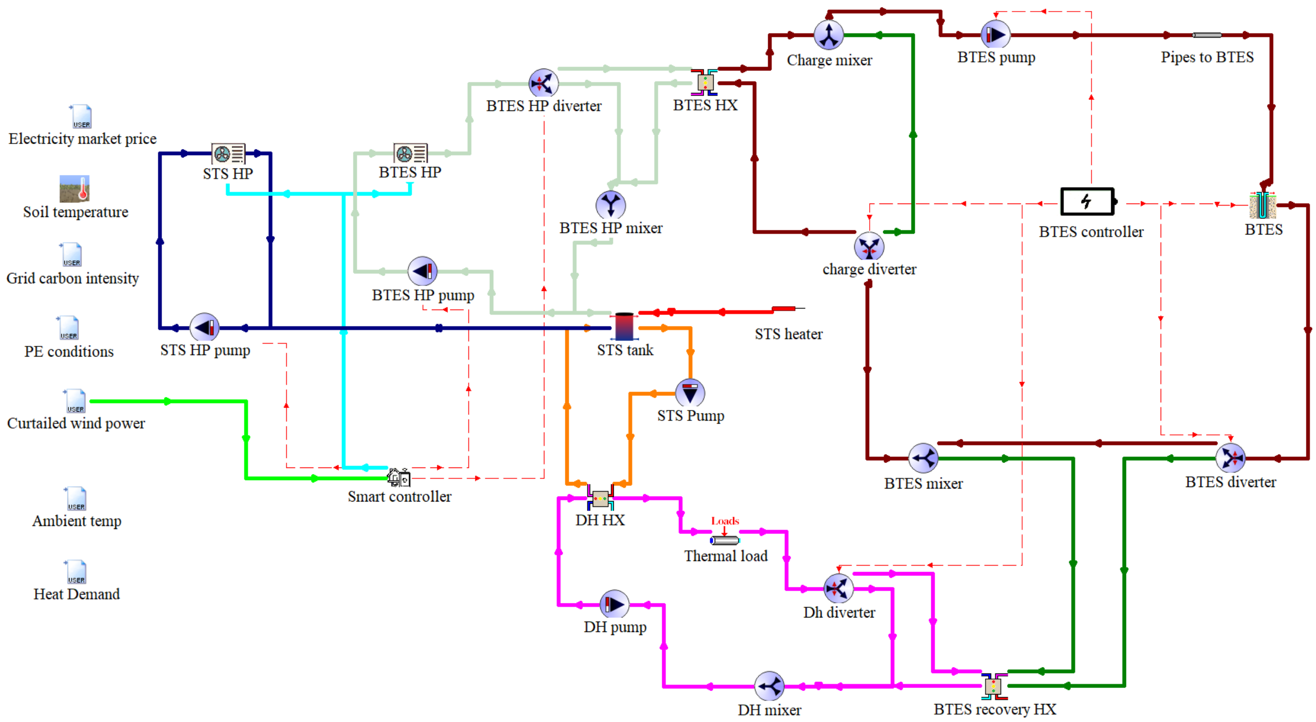

Figure 3: Simplified schematic of the TRNSYS model of the proposed energy system for King's Buildings. For clarity, only the main connections between different modules are shown and auxiliary components are omitted. "HP" stands for heat pump, "HX" for heat exchanger, "STS" for short-term store, and "DH" for district heating.

A simplified schematic of the TRNSYS model of the proposed energy system for the King's Buildings, which includes a BTES array, is shown on **Figure 3**. The short term storage (STS) tank, which is comprised of a hot water cylindrical storage tank with an immersed resistive heater (shown separately as "STS heater"), is the central hub which connects all other parts of the system; namely two heat pump loops (blue and light-green solid lines), the BTES charge and discharge loops (brown and dark green solid lines), and the district heating (DH) system (pink and orange solid lines). The smart controller and BTES controller regulate the power flows between the different components and operate all the diverter and mixer valves and pumps via control signals (red dashed lines). The smart controller sends operational orders to the heat pumps and resistive heater based on current and forecasted electricity market price, grid carbon intensity, level of curtailed wind power, STS charge level, and thermal demand to minimize the overall cost and emissions and to accommodate as much curtailed wind power as possible. All the corresponding inputs are represented on the far left of **Figure 3**: the electricity market price (Octopus 2018 Agile tariff, based on the day-ahead wholesale market price), the soil temperature (calculated by TRNSYS, based on the ambient temperature), the grid carbon intensity for southern Scotland, price and emissions (PE) conditions (price and cost statistics-based conditions which the smart controller uses to decide when and how much electricity to buy from the grid), amount of curtailed wind energy and heat demand (see below), and ambient temperatures (Weatherspark, 2023).

The operation of the system is as follows. At each timestep of 10 minutes, the "STS pump" and "DH pump" flowrates are adjusted based on the STS tank temperature and the target DH flow temperature (modeled at 65 °C) to meet the current heat demand. In parallel, if there is no curtailed wind power available, the smart controller decides how much electricity to purchase from the grid (if any). The STS heat pump (HP) (3.5 MWe air-source heat pump) is used first to heat up the STS tank (1,000 m^3 cylinder, constrained by space availability on site). If additional capacity is required, the BTES HP (2.5 MWe air source heat pump) may also be used for the same purpose. If curtailed wind power is available, the STS HP is used to charge up the STS tank to full power whilst meeting the current demand, and the BTES HP is used in parallel to boost the temperature of the water charging the BTES through the BTES heat exchanger (HX) up to 95°C. This ensures maximal BTES charging rates. The immersed heater (0.5 MWe) is used as back-up. The maximum electrical power drawn from the grid is 6 MWe at all times, as per the King's Buildings restricted connection to the distribution network. Discharging the BTES into the DH supply flow (i.e. upstream of the heat load) would be inefficient given the high DH flow temperature and moderate achievable discharge rates (around 1 MWth or less) in comparison to King's Building's large thermal demand (see **Figure 4a**). Therefore, the BTES discharges into the DH return flow (i.e. downstream of the heat load, target temperature of 45 °C) through the brown/dark green loop whenever it is not charging and is at least 2 °C hotter than the return flow, in which case the latter is directed to the "BTES recovery HX". Additionally, to further improve curtailed wind integration, the BTES outlet flow during charge is also directed to the BTES recovery HX if its temperature is at least 2 °C hotter than the return flow, before being routed back to the "BTES HX" to continue the charge. It should be noted that the BTES is only charged with curtailed wind energy (via a heat pump), which is first stored in the STS tank (acting as a fast-charging buffer), and later discharged it into the BTES at lower rates.

The heat demand hourly time series for the whole campus, shown on **Figure 4a**, based on metered data and which spans a year starting on 8th August 2018, reveals a strong seasonal pattern with a peak of 9.62 MWth in February, corresponding to a total of 157.52 MWh for that day, and totals 26.17 GWh over the whole year. It is larger in winter and spring, and consistently shows two daily peaks around 8 am and 11 am throughout the year.

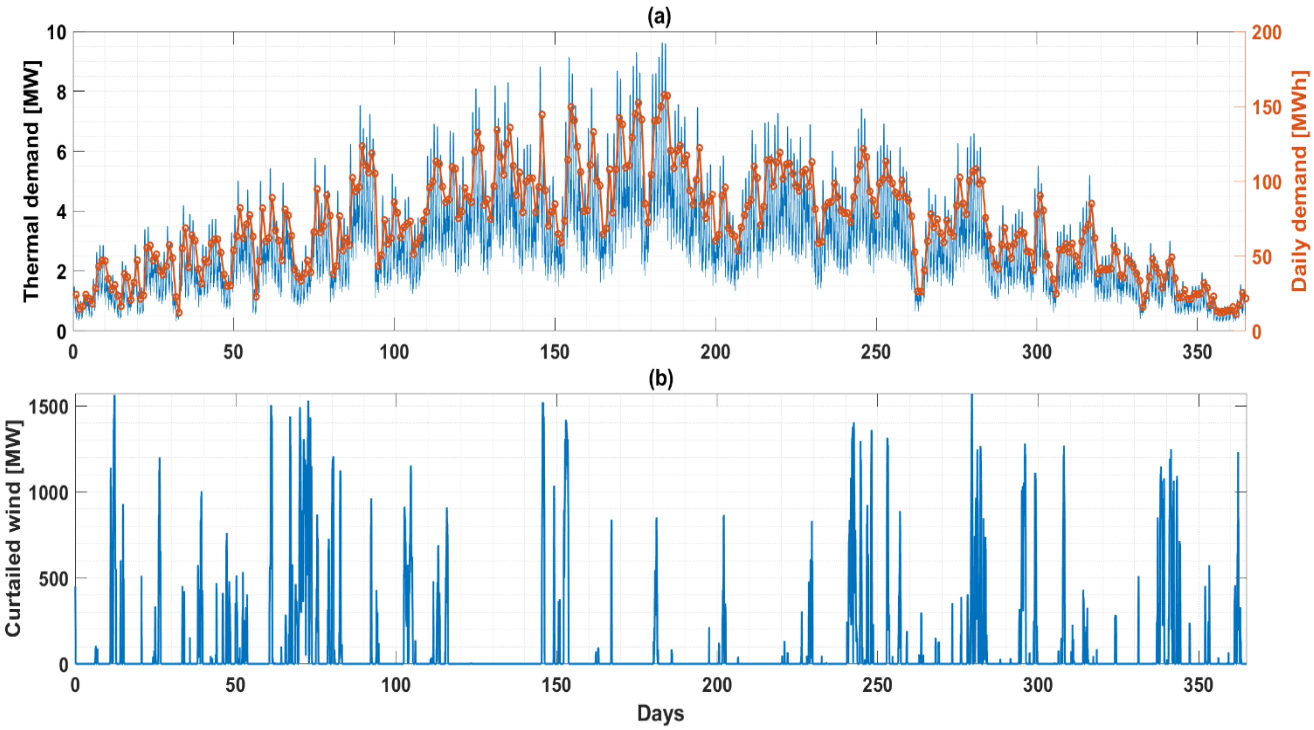

Figure 4: (a) King's Buildings thermal demand from 8th August 2018 to 8th August 2019 (b) Curtailed wind from 10 Scottish wind farms

The curtailed wind time series used in this study, as measured from 10 Scottish wind farms (Elexon, 2023), is shown in **Figure 4b** for the same period. With no clear seasonal pattern, it shows curtailed wind power available for a total of 1508 hours throughout the year, i.e., a cumulative 62.83 days, or 17.21 % of the year. Curtailment of these wind farms incurs costs for the energy system operator which are passed onto all electricity consumers. This highlights the necessity for flexibility in the energy system in order to integrate as much curtailed wind as possible.

The 'whole systems' modeling approach on TRNSYS serves as an overall method of coupling all aspects of the system; however, in comparison to some numerical software it is limited by simplistic assumptions of the subsurface around the BHE array. Therefore, to account for subsurface variations, data generated from TRNSYS was compared to that from OGS as a first step, before investigating subsurface uncertainty on OGS by incorporating groundwater flow within the system.

2.2 Subsurface Numerical Modeling

2.2.1 Modeling Tools

OGS was initially compared to TRNSYS, before being used to model transient conditions in the subsurface and hydrogeological uncertainty. OGS is a numerical model developed using the finite-element method for spatial discretization and the 'Dual Continuum' method for modeling BHEs (**Figure 5**) (e.g., see Al-Khoury *et al.*, 2010). This method treats the BHE as a 1D line source, while the surrounding rock is fully discretized in 3D (e.g., Chen *et al.*, 2019) which saves computational time whilst retaining the accuracy and details of the fully discretized models. In this model, the U-tube BHE configuration was used, with the average inlet temperature input as the boundary condition at the top of the BHEs. The governing equations for heat transfer was solved for 4 components: 1) the inlet section of the U-tube, 2) the outlet section of the U-tube, 3) the grout, and 4) the rock formation. Initially, when comparing the model to the TRNSYS 'whole systems' approach, only conduction in the subsurface was considered. For further simulations, when considering advection in the surrounding rocks, regional groundwater flow was modelled by setting a constant Darcy velocity across the domain. This was implemented as 1e-7 m/s through the x direction (i.e., horizontally in one direction) as it is often defined as the critical velocity influencing shallow BHE/BTES systems (Ingersoll *et al.*, 1954; Van Meurs, 1985; Nordell, 1994; Banks, 2015; Emad Dehkordi *et al.*, 2015; Nguyen *et al.*, 2017).

Table 1: Parameters used for the subsurface BTES simulations.

Parameter	Value	Units
Borehole diameter	0.15	m
Active heat exchanger length	260	m
Array radius	8	m
Number of boreholes	58	-
BHE spacing	2	m
Pipe diameter	0.025	m
Pipe wall thickness	0.0025	m
Distance between U-tube pipe (center to center)	0.0508	m
Pipe wall thermal conductivity	0.41	W/(m.K)
Grout thermal conductivity	0.89	W/(m.K)
Grout specific heat capacity	1222.22	J/(kgK)
Grout density	1800	kg/m^3
Ground thermal conductivity	2.25	W/(m.K)
Ground volumetric heat capacity	2.2×10^6	$J/(K\ m^3)$
Water flow rate (per borehole)	0.2	l/s
Water density	999	kg/m^3
Water volumetric heat capacity	4.17×10^6	$J/(K\ m^3)$
Water thermal conductivity	0.65	W/(m.K)
Porosity	20	%
Average ground temperature	10	°C

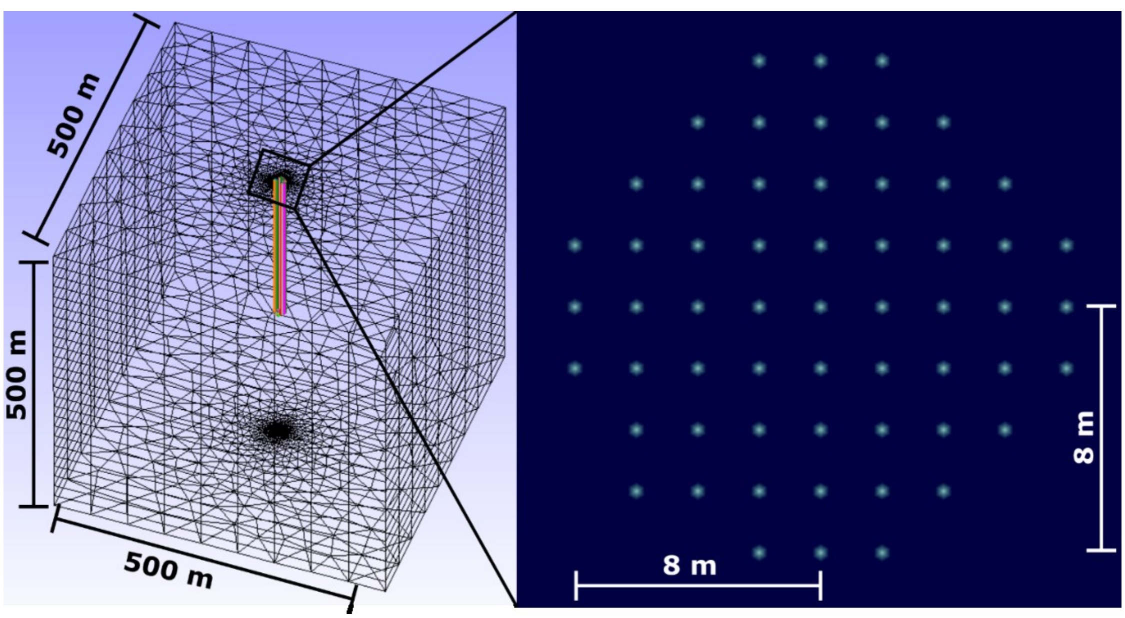

Figure 5: Example of the OpenGeoSys mesh used in the study; (left) in 3D and (right) the borehole spacing in 2D.

2.2.2 Model set-up, Boundary Conditions and Parameterization

Under initial conditions a constant temperature (10 °C) was assigned across the spatial domain, neglecting the influence of solar radiation or the geothermal gradient. This simplistic approach was used to match conditions from TRNSYS to OGS. The upper surface was fixed as a Neumann no-flow boundary condition with heat-flux set to zero to act as an insulating layer, similar to that modeled in TRNSYS. Although, this could be set as a fixed Dirchlet boundary, it does lead to a discrepancy between the models, particularly in periods with no charge or discharge (i.e., flow rate is set to 0 l/s). Lateral and basal boundaries were extended to minimize any thermal interactions with the boundaries and assigned Neumann no-flow boundary conditions. Homogenous subsurface parameters were implemented (see **Table 1**). Inflow temperature was prescribed as the same as that calculated in TRNSYS 'whole systems' modeling. This was then simulated to compare the models with conductive heat flux only in the surrounding rock, before testing the impact of groundwater. The domain size was set at 500 m x 500 m x 500 m (x, y, z), with a cylindrical/octagonal prism BHE array consisting of 58 BHEs (**Figure 5**). Spacing between BHEs was set at 2 m and all BHEs were in parallel. Dynamic time stepping was used on OGS with a maximum time step of 5 hours imposed on the model, and simulations were compared for a period of 2 years.

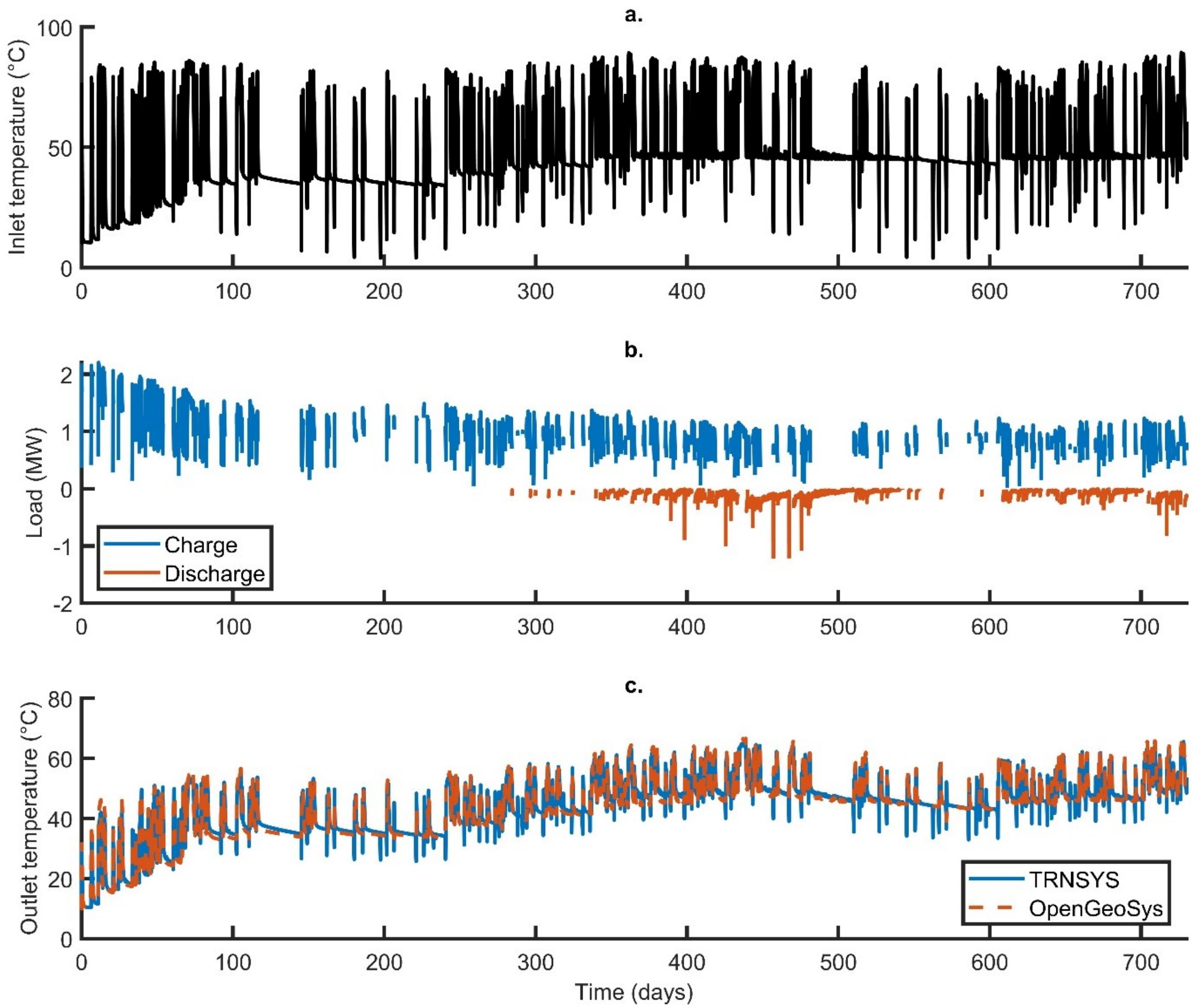

Figure 6: Comparison of OpenGeoSys with TRNSYS for the first two years of BTES operation. (a) is the inlet temperature across the BHEs with time, (b) is the varying loads during charge and discharge (note that when no load is present, there is no flow within the BHEs) and (c) the average outlet temperature for OpenGeoSys and TRNSYS.

3. RESULTS AND DISCUSSIONS

3.1 Model Comparison between TRNSYS and OpenGeoSys

An initial comparison between the two software was undertaken to test if there were any discrepancies between solutions. Generally, during charge and discharge periods, the models' outlet temperatures were closely aligned (**Figure 6**), with outlet temperature differences within 2 ℃ between the models. However, there were periods where there was a greater difference in outlet temperature between the modeling environments by up to ~4.5 ℃. This was associated with peak charging periods, with OGS providing hotter outlet temperatures, as seen in **Figure 7** at day ~13. There were also anomalous downward spikes in the TRNSYS data at timesteps where the iterative solver failed to reach convergence, as seen in **Figure 7** at day 689. The models provide strong comparative results for long time periods with varied intermittent periods of charge. OGS can therefore be used for further detailed modeling of the subsurface to incorporate parameters that TRNSYS cannot (such as groundwater flow and finer scale heterogeneity). It is worth noting that for other applications, the TRNSYS BTES model is computationally significantly faster than OGS, with simulations of 2 years of operation taking 4 minutes with a 10-minute timestep with TRNSYS compared to 36 hours with OGS. Admittedly, simulations were undertaken on different computers which could contribute to computational speed, but this would be unlikely to cause the observed variation in computational time. For the record, TRNSYS was modeled using an Intel Xeon CPU E3-1230 v5 at 3.4 GHz with 32 GB of RAM, whilst OGS was modeled using an Intel Core i7-10850H CPU at 2.7 GHz with 16 GB of RAM. There is also potential for a mismatch between parameters, specifically, the grout properties. TRNSYS does not require an input for the specific heat capacity or the density of the grout, so the values for these that are input to OGS may affect the results. Also, there is some uncertainty around the periods when there is no charge or discharge, whilst OGS assumed that conductive heat transfer is dominant in the BHEs, it is unclear how it is calculated in TRNSYS. Thus, within these no-flow periods, it is difficult to make a direct comparison between the models, but it appears that OGS slightly underpredicts outlet temperature.

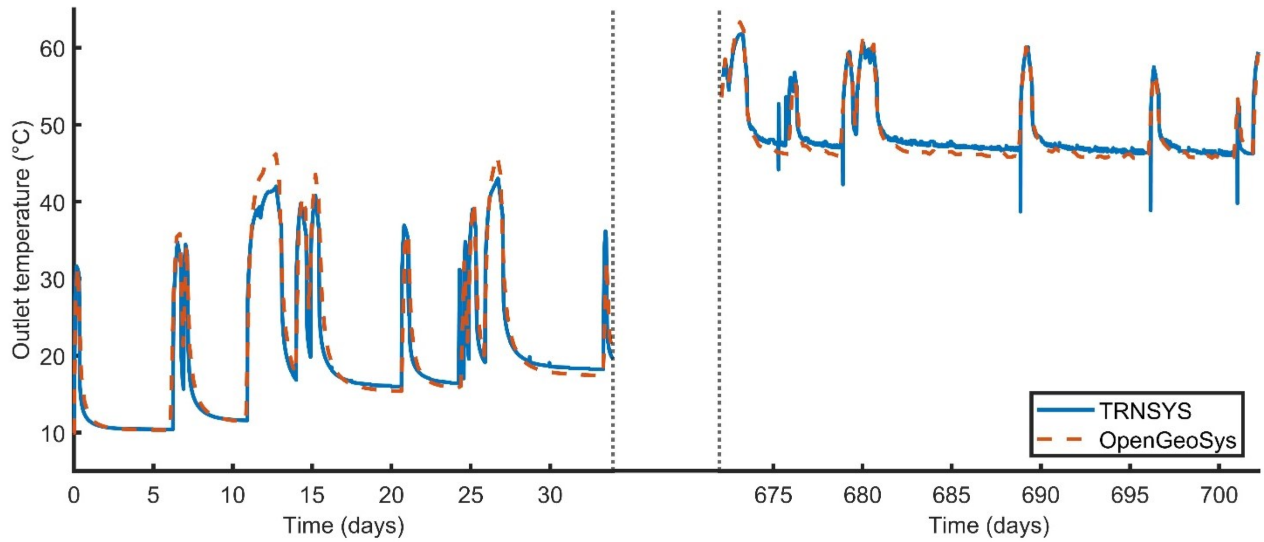

Figure 7: Comparison of TRNSYS and OGS for zoomed in intervals.

3.2 Temporal Thermal Evolution in the Subsurface

A more detailed evaluation of model results was then undertaken using OGS to understand the thermal evolution in the subsurface and BHEs. In the first year of operation, the model was dominated by subsurface charging with minimal discharge occurring until the end of the year at day 284. This was due to the limitation set in TRNSYS which prevented heat extraction until the return flow to the DH network was 2 ℃ higher than the 45 ℃ constraint. Within the first 100 days, curtailed wind was used to rapidly charge the BTES array with initial thermal loads reaching 2.18 MW. Average outlet temperature reached 33.4 ℃ on day 100, whilst the thermal field in the subsurface reached a maximum of 38 ℃ (towards the center of the array at surface level – see **Figure 8**). The temperature of the surrounding rock around the array decreased with depth (**Figure 7c**) as more heat was transferred to the subsurface from the BTES array immediately at the surface level (i.e., when depth = 0 m). This was due to the downward flowing heat carrier fluid cooling as it descends and dissipates heat to the surrounding ground, which results in it taking longer to warm the deeper intervals. After the first year, discharge rapidly increased between days ~350 and 550 as the peak loads reached a maximum of 1.2 MW of heat drawn from the thermal subsurface store (**Figure 6b**). With increased time, outlet temperatures exceeded the minima set for heat extraction, resulting in sporadic periods of charge and discharge, which is in contrast to how other cyclic seasonal thermal energy storage systems operate, such as solar thermal BTES.

Also, there were local subsurface variations of temperature associated with the inner and outer BHEs. The corresponding outlet temperatures highlighted in **Figure 9** show significantly more warming in the central BHE location in contrast to the outer, with differences in outlet temperature of up to 8 ℃. This is also apparent in the visualization in **Figure 8**. The greatest variation occurs within the charging periods, which is due to the cooler temperatures observed towards the outer regions of the model.

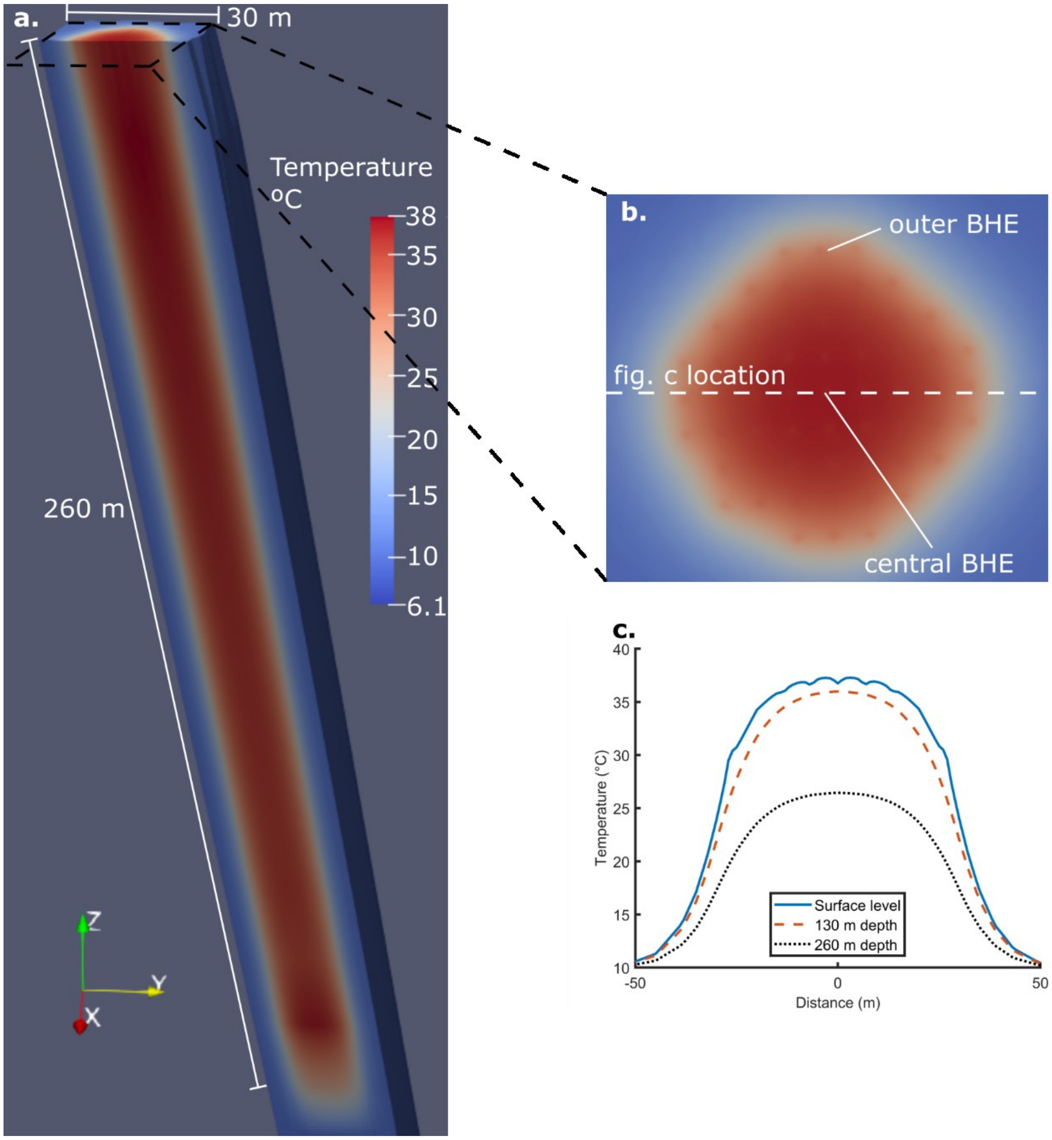

Figure 8: (a) 3D thermal plot at day 100, (b) 2D surface map of the rock (note the scale is symmetrical i.e., 8 m radius of array) and (c) rock profiles taken varying with depth.

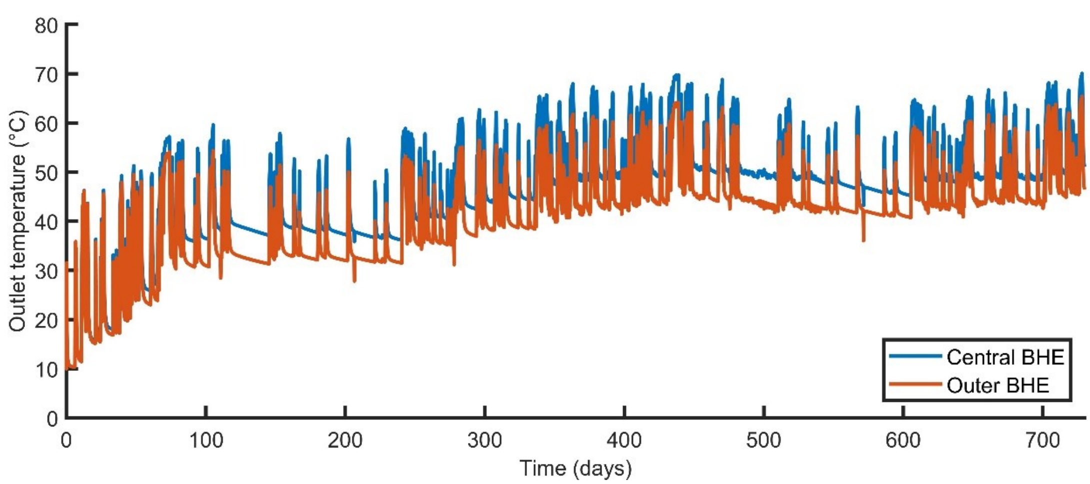

Figure 9: Comparison in outlet temperature between central and outermost BHEs. See figure 8b for locations of BHEs.

3.3 Influence of Groundwater on Performance

Groundwater flow was implemented with OGS by setting the regional Darcy velocity at 1e-7 m/s across the domain in the horizontal direction (highlighted in **Figure 10**). The results of this were compared to the 'conduction only' scenario simulated in the earlier sections.

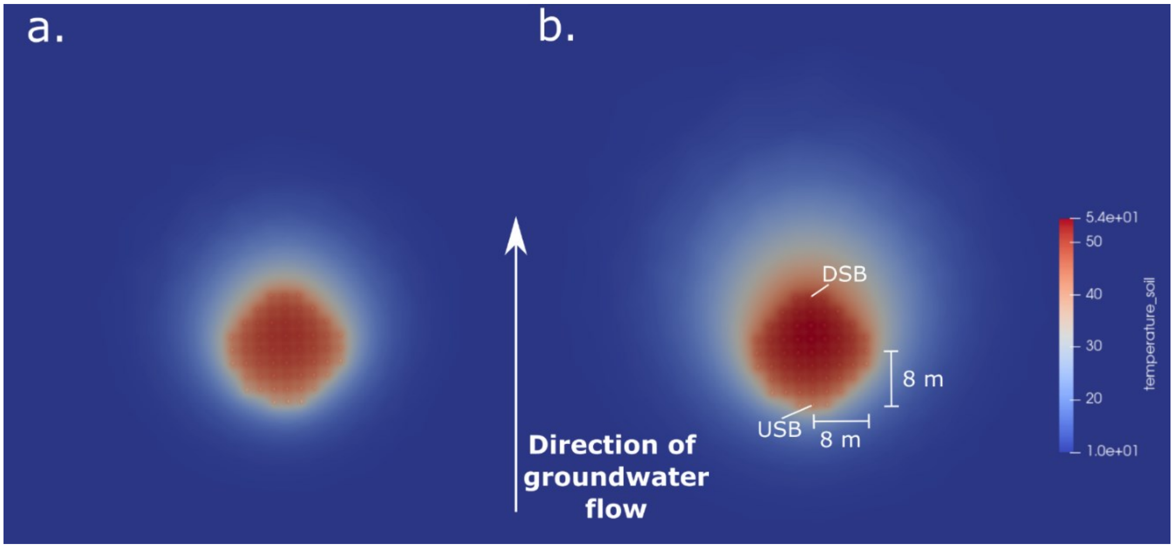

Figure 10: 2D model slice of the subsurface at ground level, when depth is set at 0 m (a) for the end of year 1 and (b) the end of year 2. DSB and USB denote the Downstream BHE and the Upstream BHE, respectively.

Groundwater flow resulted in advective transport of heat downstream of the array up to 40 m from the outer downstream borehole (DSB) (**Figures 10 and 11**). Subsequently, more heat was injected in comparison to the 'conduction only' scenario, but substantial amounts of this heat was lost and not recovered in the groundwater flow scenario. During injection and recovery of heat, outlet temperatures in the central and upstream boreholes (USBs) decreased by up to ~5 °C, whilst for the DSB they increased by up to ~3 °C (**Figure 12**). This effect appears to grow with time after the first year and is likely to be more prominent during the lifetime of the BTES system. The difference in outlet temperatures between the USB and DSB during the groundwater flow simulation reaches a maximum difference of 8.6 °C. This impacts the thermal power output per borehole by 7.2 kW which occurs at around 500 days during a discharge period. When considering the same point in time for the USB and DSB in comparison to the 'conduction only' case equivalent outer borehole, the maximum difference was -4.8 °C (-4 kW) and 4.1 °C (3.4 kW), respectively. During charge, there were similar differences in outlet temperature observed between the USB and DSB, but they were slightly lower (<7 °C or <5.8 kW).

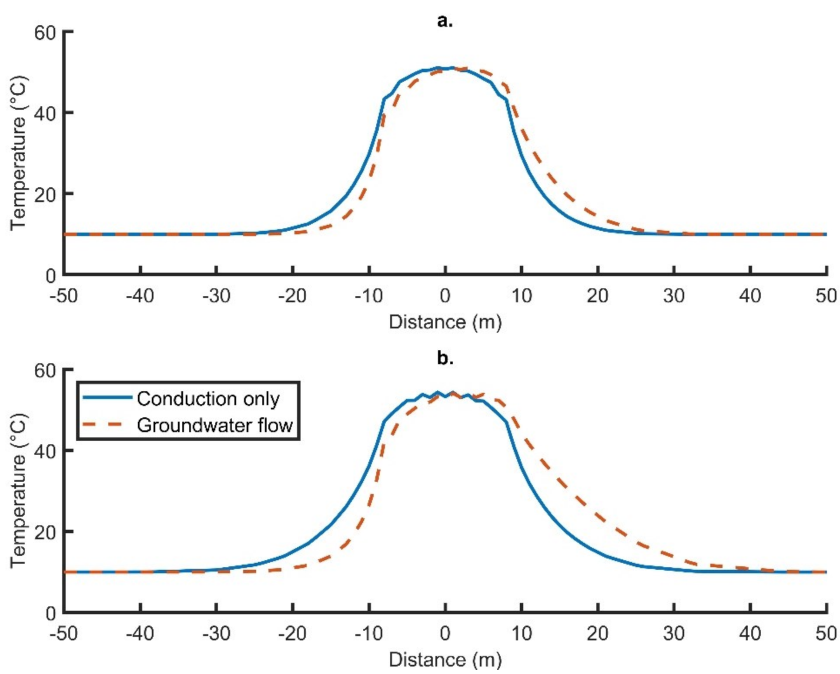

Figure 11: Corresponding thermal plots to Figure 10 showing the impact of groundwater flow on the thermal field at the surface level where depth = 0 m for (a) the end of year 1 and (b) the end of year 2. Direction of groundwater flow is from left to right.

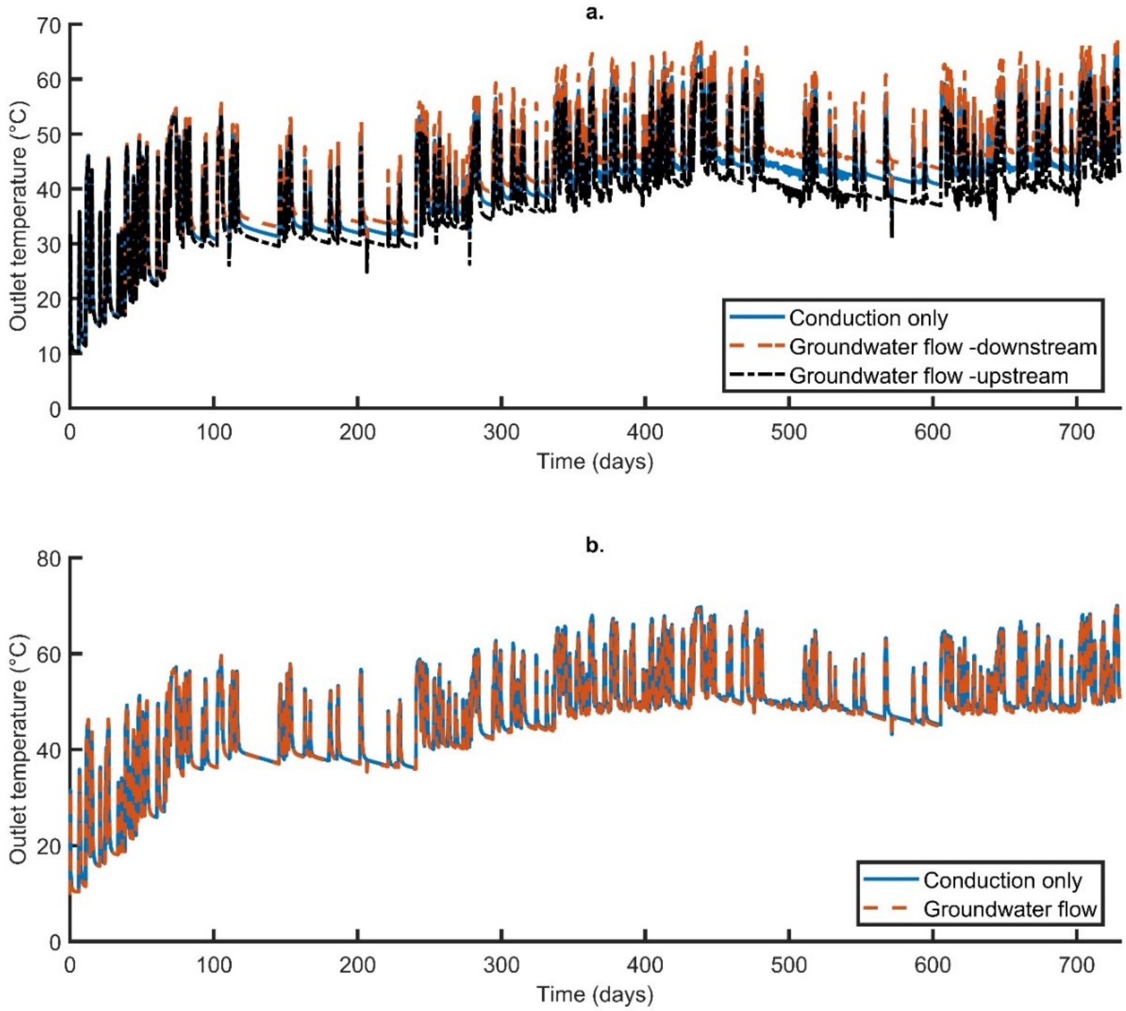

Figure 12: Comparison of inner and outer BHEs to test the influence of groundwater flow with a Darcy velocity of 1e-7 m/s in contrast to 'conduction only' in the subsurface. (a) is for the outer BHEs for upstream and downstream of the groundwater flow (see Figure 10 for locations) and (b) for the central BHE.

4. CONCLUSIONS

The results of this study highlight a potential for curtailed wind to provide a source of charge for BTES in the conductive geological regimes in the subsurface below the King's Buildings campus in the University of Edinburgh. It is likely that smaller scale systems could utilize the thermal stores earlier in the first year by using a heat pump, but periods of discharge occur only after 284 days of operation due to a minimum limit of 45 °C being set as the outlet temperature before use in the DH network. Furthermore, the utilization of OGS in addition to TRNSYS can be important for modeling further details of the system which are not accounted for in TRNSYS software. However, if there is no requirement to model parameters such as groundwater flow then it is better to use TRNSYS due to its faster computational time. The model comparisons appear to provide similar results with minimal discrepancy. The key conclusions of the study were:

- There is significant available curtailed wind energy within the SCOTEX boundary between Scotland and England (**see Figure 2**). Data from 2018 show curtailed wind energy was available from 10 Scottish wind farms for 1508 hours or ~17 % of the year, and this can be used to charge the BTES array. In one scenario, future projections of wind curtailed indicated substantial increases from around ~1 TWh in 2021 to ~85 TWh by 2036.
- Initial model comparisons between TRNSYS and OGS show minimal discrepancy and generally provide a close fit for outlet temperatures, typically within 2 °C, but there is a larger discrepancy for short periods where, during charge, outlet temperatures have a maximum difference of 4.5 °C.
- 'Whole systems' modeling can allow a thorough analysis of the system, whilst the integration with more detailed numerical models of the subsurface (such as with OGS) allows further geological and engineering constraints to be incorporated. These include groundwater flow, heterogeneity in the subsurface, and further specific properties of the wellbore materials (such as grout).

- Initial modelling of groundwater flow in the subsurface shows a maximum difference in outlet temperature of 8.6 °C (7.2 kW) between the USB and DSB. This was associated with a discharge period. Similar difference were observed for periods of charge, but these differences were slightly lower (<7°C or <5.8 kW).
- Groundwater negatively impacts the array and results in more energy being stored in the subsurface; however, most of it is transported away from the BHE array such that it cannot be recovered.
- Future work should focus on comparing OGS and TRNSYS for the lifetime of the BTES system, and incorporating further detail into the subsurface modelling on OGS, such as varying levels of heterogeneity and groundwater flow. There could also be coupling between the software, such that OGS could be directly used for the subsurface component of the TRNSYS model. There is also potential to look at optimization of the 'whole-systems' model on TRNSYS.

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