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Integrated Modeling of Geothermal Heat Pumps and Deep Coaxial Borehole Heat Exchangers

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ABSTRACT

Heat extraction performance and efficiency of Deep Coaxial Borehole Heat Exchangers (DCBHE) have been increasingly investigated in recent years. The DCBHE system is mainly used for heating of buildings, with most of the modeling studies in literature focused on analyzing the subsurface system by imposing a fixed inlet temperature or a constant power demand. However, the DCBHE system is likely to be coupled to a heat pump in real projects to maintain the supply temperature level to heated buildings. In this case, the system heating boundaries should come from the consumer building demand. The internal thermal load redistribution between the heat pump and subsurface DCBHE systems cannot be accurately simulated with independent subsurface DCBHE modelling, as this could underestimate the heat extraction capacity and sustainability of the DCBHE systems. In this work, a coupled DCBHE-heat pump model is developed and established based on the OpenGeoSys (OGS) and TESPy software, with the subsurface 3D DCBHE in OGS, and the thermodynamic heat pump model in the TESPy. The dynamic data exchange is achieved by a python interface implemented in the OGS software. Using the coupled model, the thermal performance of a well located in the Midland Valley of Scotland has been modeled to serve as a green resource for community/district heating for high density buildings located in the Midland Valley of Scotland. It is found that at least two wells need be repurposed as a DCBHE adding to the sources of low-carbon heat around Alloa for the planned Hallpark network with an estimated heating power of 856.3 kW. The numerical model also facilitates the techno-economic performance of repurposing oil and gas wells for geothermal utilization.

1 INTRODUCTION

Geothermal energy has been widely used all over the world for heating, cooling and power generation. Closed-loop Deep Coaxial Borehole Heat Exchanger (DCBHE) systems are increasingly implemented in recent years due to the wide applicability for all types of geothermal resources (Kolo et al. 2024). Nevertheless, the closed-loop systems have limited heat exchange area with the geothermal reservoirs and the dominant process is heat conduction, resulting in a limited heat extraction rate and less sustainability. Therefore, research and studies on the system heat capacity, performance, and sustainability have been significantly conducted based on either modeling tools (Chen et al. 2019, 2021) or pilot projects (Cai et al, 2025).

When using DCBHE systems, the surface heat pumps have to be coupled to the DCBHE to achieve high temperature for heating buildings as shown in Figure 1. This requires that the heat pump performance has to be considered to investigate the whole system performance and sustainability. In the operation of the DCBHE coupled heat pumps, the target temperature can be set on the heat pump, and the total heat load on the heat pump is from the building side, which are the boundaries in the reality. Basically, how much energy is extracted from subsurface remains unclear, since the heat pump itself also consumes electricity. In this case, the more realistic models will be the fully coupled DCBHE subsurface model with the heat pump thermodynamic model. With the coupled model, the evaluation of the long-term performance is more realistic and the heat load shift between the surface heat pump and the subsurface DCBHE can be quantified and clarified. Compared to the

constant heat load directly imposed as a boundary condition for heat extraction on the subsurface DCBHE model, the heat capacity can be underestimated without consideration of the dynamic performance of the coupled heat pumps (Chen et al. 2025). Zarrella et al. (2017) presented a numerical analysis of the variable flow pumping in a ground source heat pump (GSHP) system and examined control strategies of the circulation pumps in the ground loop. The performance of the heat pump was quantified using simplified curves without considering the off-design performance. Sun et al. (2025) investigated the performance of a GSHP system with energy piles and borehole heat exchangers (BHEs) that served a two-story building. They found that the COP of the heat pump is difficult to accurately quantify by a specific curve under different operations.

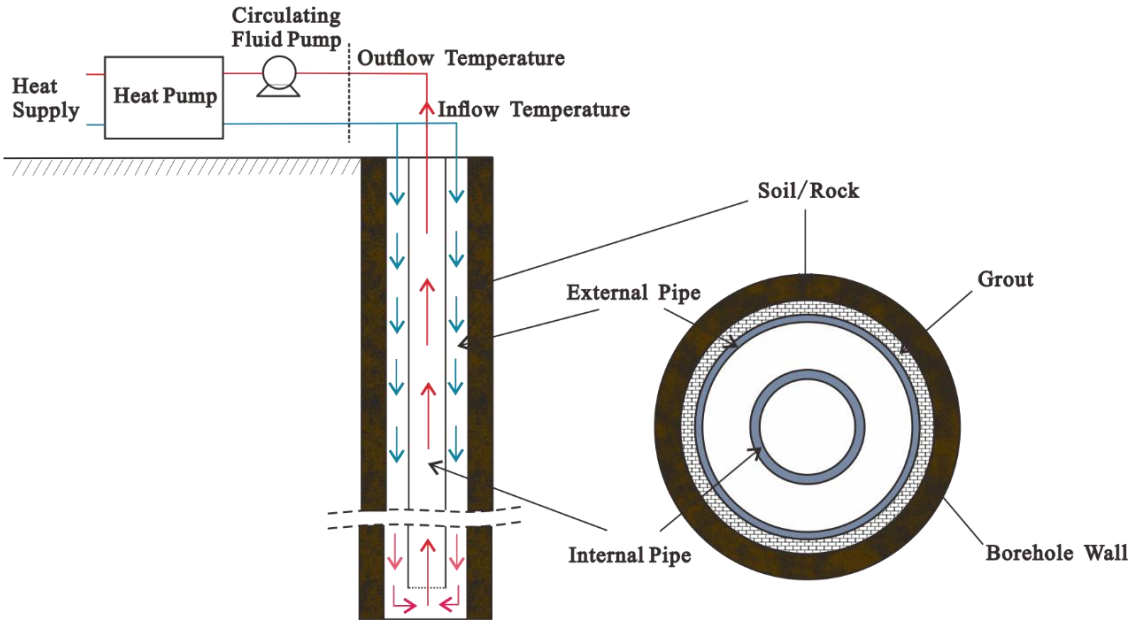


Figure 1. The schematic of the DCBHE subsurface system, and its utilization of coupling with the surface heat pump. (Kong et al, 2017)

In addition to many numerical studies on independent subsurface systems, Huang et al. (2025) integrated the subsurface BHE systems into the heat pump simulation using TRNSYS software. The heat pump performance and the subsurface system are significantly simplified in order to simulate larger scale of the heating network. Wang et al. (2022) presented a numerical study on the independent subsurface DCBHE model and the heat pump model, but the coupled interface and how the heat pump dynamically responds to the subsurface system remained unclear.

Therefore, in this study a detailed thermodynamic model of the heat pump was designed based on the initial subsurface heat source condition and it is fully coupled with a subsurface 3D DCBHE model, to investigate the transient response of the subsurface system to the heat pump off-design performance. The 3D DCBHE model was constructed based on the OGS software (Kolditz et al., 2012, Chen et al., 2019) and the heat pump thermodynamic model was constructed in the Thermal Engineering Systems in Python (TESPy) software (Witte and Tuschy, 2020). By integrating the heat pump thermodynamic model that was converged in TESPy into the subsurface model as the boundary condition during the iteration of the whole simulations in OGS, the converged model can make sure that the off-design performance of the heat pump is exactly the performance at the state of the subsurface performance. In this way, the heat load redistribution phenomenon was particularly investigated and the importance of the coupled model on the evaluation of the subsurface system.

2 METHEDOLOGY AND NUMERICAL MODELS

2.1 Subsurface DCBHE model

The DCBHE numerical model was implemented based on the dual-continuum method (Diersch, 2013). The borehole is represented using line elements and all the heat transport equations that correspond to each component inside the coaxial structure are solved in line element. The detailed implementations can be checked on the website of OGS (https://www.opengeosys.org/docs/benchmarks/heat-transport-bhe/3d_coaxial_deep_bhe/) and related reference (Chen, 2022). The depth of the DCBHE model in this work is 700 m, the geometry is the same as the verification case of the benchmark (Beier, 2024), the detailed parameters are listed in Table 1. In the numerical model, the initial BHE temperatures in the annulus pipe and centered pipe

are 25 ˚C, the initial formation temperature is the same as it in the analytical solution with the geothermal gradient of 0.03 ˚C/m and the surface temperature of 10 ˚C.

Table 1. Parameters of the DBHE benchmark with geothermal gradient.

Parameter	Symbol	Unit	Value
Borehole length	L	m	700
Borehole diameter	$2r_b$	m	0.25
Internal diameter of inner pipe	$2r_i$	m	0.0974
Wall thickness of inner pipe	t_{pi}	m	0.0063
Internal diameter of outer pipe	$2r_o$	m	0.150
Wall thickness of outer pipe	t_{po}	m	0.0045
Thermal conductivity of inner pipe wall	λ_{pi}	$Wm^{-1}K^{-1}$	0.24
Thermal conductivity of outer pipe wall	λ_{po}	$Wm^{-1}K^{-1}$	52
Soil/rock thermal conductivity	λ_s	$Wm^{-1}K^{-1}$	2.5
Heat capacity of soil/rock	$\rho_s c_s$	$Jm^{-3}K^{-1}$	2.1×10^{6}
Grout thermal conductivity	λ_g	$Wm^{-1}K^{-1}$	1.5
Heat capacity of grout	$\rho_g c_g$	$Jm^{-3}K^{-1}$	3×10^{6}
Thermal conductivity of circulation fluid	λ_f	$Wm^{-1}K^{-1}$	0.594
Heat capacity of circulation fluid	$\rho_f c_f$	$Jm^{-3}K^{-1}$	4.1767×10^{6}
Dynamic viscosity of circulation fluid	μ_f	$kgm^{-1}s^{-1}$	1.070×10^{-3}
Flow rate of circulation fluid	Q_f	m^3s^{-1}	3.005×10^{-3}
Surface ground temperature	T_s	˚C	10
Soil/rock temperature gradient	GG	$˚Cm^{-1}$	0.03

2.2 Heat pump thermodynamic model

The heat pump model was constructed in the TESPy software (https://tespy.readthedocs.io/en/main/). The schematic of the heat pump used in this work is shown below in Figure 2. The components in the heat pump include condenser, compressor, evaporator, and valve. The hot side of the evaporator is connected with the DCBHE system, the heat will be transported from the heat source from the subsurface to the working fluid in the heat pump. The working fluid chosen in the heat pump model is R410A. After the compressor, the working fluid in the heat pump will be condensed in the condenser and release energy to the target fluid that will supply heat to district heating networks.

When calculating the Coefficient of Performance (COP) of the heat pump, the electricity consumed by the feed pump in the DCBHE side is also considered besides the compressor. It is defined as below,

$$\mathrm{COP} = \frac{\text{heat output}}{\text{power input}} = \frac{Q_{\text{condenser}}}{Q_{\text{compressor}} + Q_{\text{pump, BHE}}} \tag{1}$$

As for the coupled interface between subsurface DCBHE and the heat pump model, it was implemented through python interface in the OGS, the detailed simulation coupling scheme and computational workflow can be referred to Chen et al. (2025). In addition, the detailed design parameters are listed in Table 2 to use the heat source temperature from the DCBHE system. The designed heat load of the heat pump was 30,000 W, the off-design performance would be simulated according to the heat source temperature and the actual heat load on the heat pump.

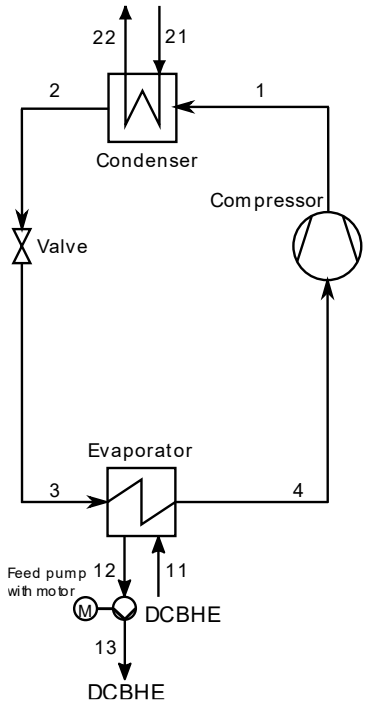


Figure 2. The design of the heat pump topological structure and the way of coupling with the subsurface DCBHE system.

Table 2. Process design parameters for the heat pump.

Parameter	Unit	Value
Isentropic efficiency of compressor	%	85
Isentropic efficiency of the feed pump	%	75
Lower terminal temperature difference of evaporator	˚C	5
Electric-mechanical efficiency of pump motor	%	97
Required feed flow temperature	˚C	65
Lower terminal temperature difference of condenser	˚C	3

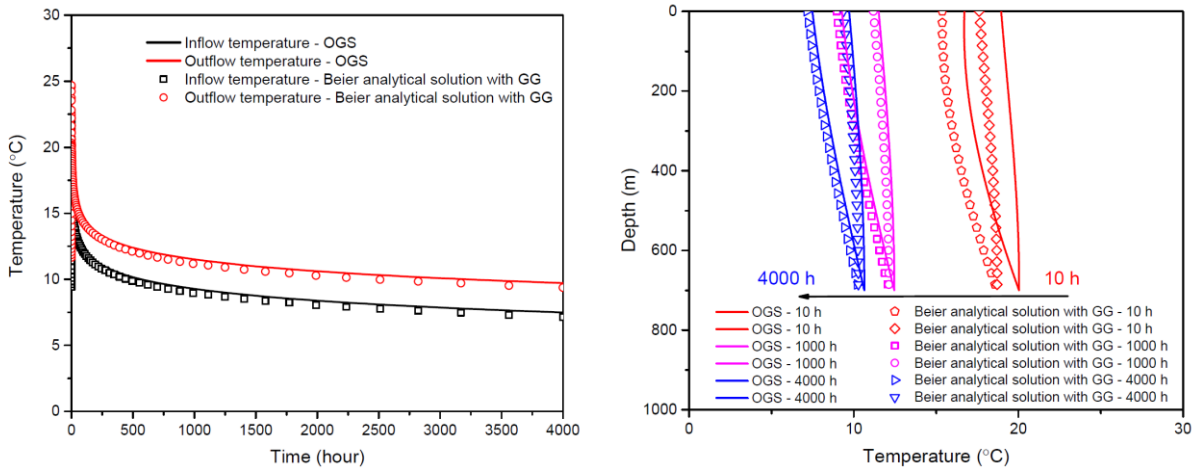
2.3 Model scenarios

The modelled scenarios in this work include (1) one DCBHE benchmark verification case for the operation of 4000 hours with the constant heat load of 28,000 W, (2) one 167-day heating season with the heat load of 28,000 W on the DCBHE directly, and (3) one 167-day extraction scenario coupled to the heat pump with the heat load of 28,000 W on the heat pump, and (4) the scenario with the heat load of 18,500 W on the DCBHE, which was translated according to the total heat load on the heat pump and the averaged COP value over the heating season.

3 RESULTS AND DISCUSSION

3.1 Model validation of the subsurface DCBHE

The benchmark was simulated by the analytical solution proposed by Beier (Beier, 2020) and OGS, respectively. The length of the coaxial DBHE is 700 m as listed in Table 1, and it is vertically buried in the surface with geothermal gradient of 0.03 ˚C/m. The heat extraction rate of 28,000 W is imposed on the system. The system is simulated for 4000 hours. The results comparison is presented in Figure 3(a) over the operational time, and in Figure 3(b) for the circulation fluid temperature distribution in pipes at different times.



(a) **(b)**

Figure 3. The comparison of the results between the analytical solution proposed by Beier and the OGS. (a) The change of inflow and outflow temperature from the 700-m DCBHE, (b) the temperature distribution in the coaxial pipes.

It can be seen from Figure 3(a) and 3(b) that both analytical solution and numerical results can match well, with outflow temperature difference of 0.3535 ˚C (relative difference of 3.77 %) after the operation of 4000 hours. The difference between the analytical solution and numerical results can be analyzed in three aspects. First, the influence of BHE initial temperatures in the numerical model, especially in the beginning of the simulation. In the numerical model, the circulation fluid with initial temperature in pipes needs to be drained out firstly after the operation, which is at non-equilibrium. However, the analytical solution assumed that it is at the equilibrium in the pipes and surrounding formation. Second, the different calculations of Nusselt number and other parameters related to the heat transfer coefficients in DBHE pipes lead to a difference on the overall heat transfer coefficients. The calculation of Nusselt in the analytical solution is based on the Gnielinski correlation (Gnielinski, 1975). Third, in the analytical solution, there is an assumption that the heat conduction along *z* direction is not taken into account.

It is worth noting that the difference between analytical solution and numerical results decreases as operational time progresses (see Figure 3(b)). This is because the BHE heat transport process is mainly dominated by the soil/rock heat conduction in long-term operations, which limits the system heat extraction capacity in comparison to open-loop systems. The DCBHE numerical model in OGS has also been successfully validated by Huang et al. (2020) through the results comparison with a field test in a 2044 m coaxial borehole heat exchanger in northern China. The DCBHE array model was also validated by monitoring data from a pilot project in Xi'an, China (Cai et al., 2021).

3.2 Heat Performance of the DCBHE with coupled heat pump

The inflow and outflow temperatures are depicted in Figure 4 in the scenarios (2) and (3), with the difference occurring due to the heat pump. It can be observed that the temperature difference between outflow and inflow is less when there is a heat pump coupled, when there is no heat pump considered in the system, the temperature difference is kept at 2.23 ˚C, while it ranges from 1.45 to 1.54 ˚C when the heat pump is included. The decrease in temperature difference from the subsurface was caused by the dynamic off-design performance of the heat pump. Specifically, after the operation of 167 days, the outflow temperature without coupled with the heat pump reaches 9.7 ˚C, while it is 13.6 ˚C in the scenario of considering dynamic performance of the heat pump. The inflow temperature is even lower when there is no heat pump coupled, it is approaching to 7.5 ˚C. Over

the whole operation, the outflow temperature decreases by 15.3 and 11.4 ˚C without and with the heat pump, respectively.

In general, the circulation fluid in the DCBHE system is water, to make the system working, the lowest temperature of inflow and outflow has to be higher than 0 ˚C. The heat load redistribution due to the variation of the heat pump performance slows down the speed of the inflow and outflow temperatures. Therefore, it will enhance the sustainability of the DCBHE system operation.

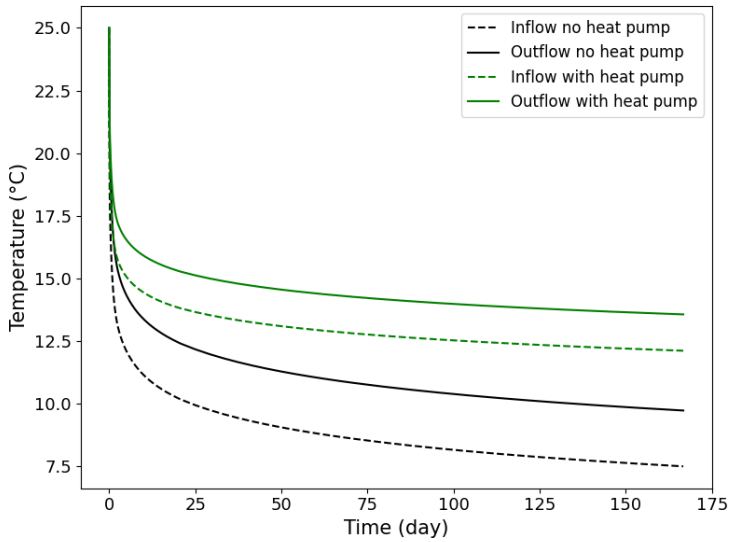


Figure 4. The evolution of the inflow and outflow temperature without coupling heat pump and with the dynamic off-design performance of the heat pump.

3.3 Energy analysis and the heat pump off-design performance

The detailed amount of the energy extracted from the subsurface is compared in Figure 5 in the scenarios (2) and (3). All the total heat load was added on the DCBHE system in the scenario (3), therefore, the heat extraction rate from the subsurface kept constant with 28,000 W over the whole operation time. However, when there is the heat pump coupled, the amount of heat extraction rate from the subsurface becomes various, which corresponds to the performance of the heat pump. The amount of heat extracted from the subsurface decreases from 19,350 to 18,190 W over the whole operation of 167 days. The heat extraction rate is decreasing by around 6 %, which is because the heat pump performance and efficiency becomes lower over the operation. Without considering the heat pump performance, the performance and sustainability of the DCBHE will be significantly underestimated.

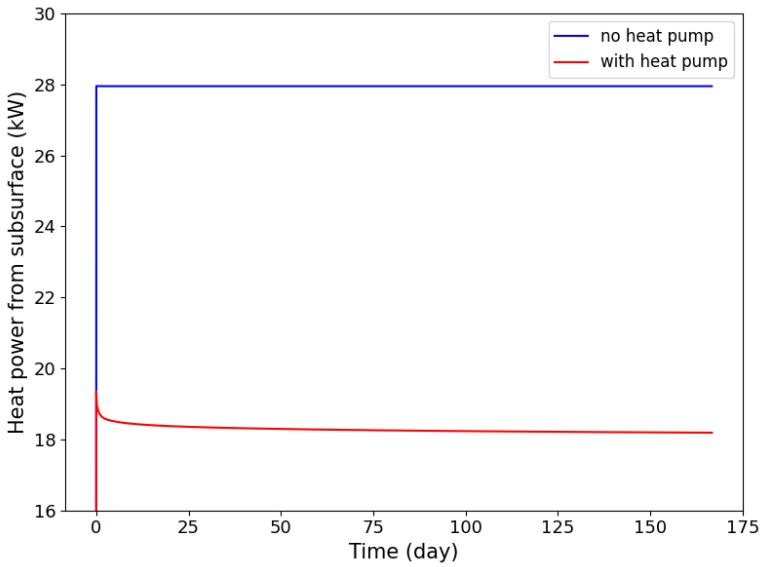


Figure 5. The amount heat power extracted from the subsurface in the two models.

When there is higher heat source temperature value, the heat pump has better performance, leading to a higher COP value. Therefore, more energy will be extracted from the subsurface according to Equation (1). The COP changes over time and the statistic distribution are plotted in Figure 6 over the whole operation period. It can be seen that the COP decreases from 3.14 at the beginning to 2.79 after the operation of 167 days, the averaged COP is around 2.95. most of the COP vales are distributed at the range from 2.86 to 3.06. The trend of the COP decrease and its distribution are significantly related to the outflow temperature of the DCBHE, which is the heat source of the GSHP.

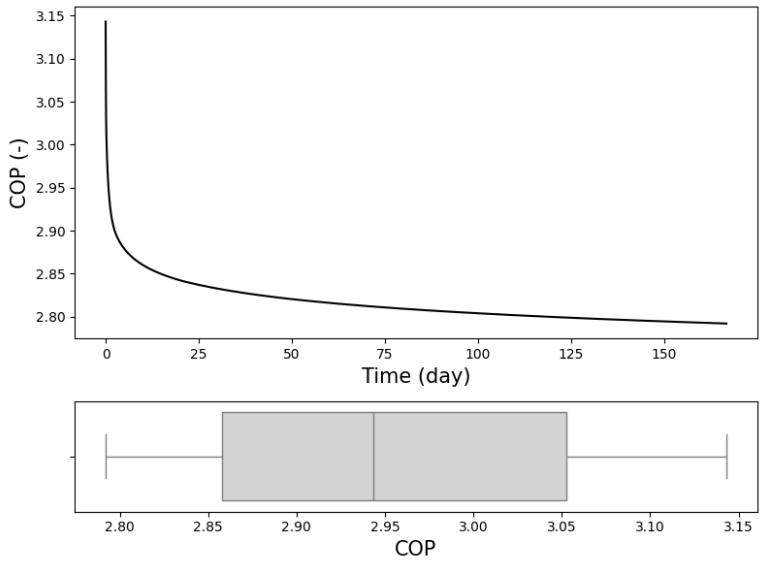


Figure 6. The COP evolution of the heat pump and the statistic distribution.

In order to investigate the difference of the subsurface performance with the dynamic heat pump performance or averaged COP value, the two models are simulated as introduced in scenario (3) and (4). The inflow and outflow temperatures are compared and it is found that the model with the coupled thermodynamic model of the heat pump has higher inflow and outflow temperatures. After the operation of 167 days, the outflow temperature difference is 0.1 ˚C higher when there is a heat pump coupled. Such difference will become more significant in the long operation when the heat load is dynamic with heat extraction and recovery period.

4 MODEL APPLICATION

4.1 Heat source for a planned heat network

In Scotland, the councils of Stirling and Clackmannanshire published their Regional Energy Masterplan at the end of 2023 outlining their aims in energy use and generation to transform their energy systems, tackle fuel poverty, and reach net-zero carbon emissions by 2045. The masterplan identified reduction in energy use through retrofit measures as an essential first step to net zero with potential to reduce carbon emissions from buildings by up to 20%. Heat management through decarbonization of heating is key as it has potential to reduce carbon emissions from the built environment in the region by 95%. The document investigated different technologies including heat pumps, electric resistive heating, bioenergy, low carbon mains gas and hybrid heat pumps (Stirling Council and Clackmannanshire Council, 2023). District heat networks also represent a low-cost heating approach especially in areas with heat demand concentration.

Investigation into possible heat networks identified 19 sites in Stirling and Clackmannanshire suitable for a heat network. Sites with predominantly social/council houses were chosen and the sites were ranked based on suitability of construction in the short-term considering factors like carbon emissions, fuel poverty, capital and operational cost and environmental impacts. The top sites in Stirling were in Raploch and Braehead while the top sites in Clackmannanshire were in Alloa Forthbank and Alloa Hallpark Healthcare Centre. For the proposed Clackmannanshire heat networks, the Alloa Forthbank site has a water treatment plant while there is no obvious source of low carbon heat for the Hallpark network (Stirling Council and Clackmannanshire Council, 2023). End-of-life oil and gas or otherwise abandoned wells can be repurposed as deep borehole heat exchangers to extract heat (Kolo et al., 2024). Next to Alloa, there is the Inch of Ferryton borehole which is the deepest onshore borehole in the Midland Valley of Scotland drilled to 2441.6 m depth. This well can be repurposed as a deep

borehole heat exchanger adding to the sources of low-carbon heat around Alloa for the planned Hallpark network with an estimated heat generation of 7500 MWh/year or 856.3 kW. Hence, the model developed in section 2 is adopted to estimate the heat supply from the Inch of Ferryton borehole.

4.2 Coupled surface-subsurface model

For the subsurface model, the composite logs from UK Onshore Geophysical Library were used to obtain well dimensions and lithology for the Inch of Ferryton well (UKOGL, 2025). Based on the composite log, L = 2441 m, $2r_b$ = 0.242 m, $2r_o$= 0.219 m and t_{po}=0.0089 m. The external pipe is made of steel while the internal HDPE pipe has dimensions $2r_i$= 0.1005 m and t_{pi} = 0.0068 m. A very simplified representation of the subsurface is adopted in this study. Based on the composite log, the stratigraphy was initially divided into three with the top section (1261.87 m) largely consisting of claystone, sandstone and a bit of siltstone. The middle section (167.64 m) consists of intrusive igneous rock while the bottom section (1012.24 m) consists of claystone, sandstone, conglomerate and siltstone. Properties were estimated based on the database in EED software (Blomberg et al., 2019) with properties of dolerite assumed for the intrusive igneous rocks (England et al., 1980; Waples and Waples, 2004). Further, using weighted average, the three sections of the subsurface were simplified to a homogeneous subsurface. A geothermal gradient of 25.9°C/km was assumed based on British Geological Survey (2024). The constructed subsurface 3D model is shown in Figure 7.

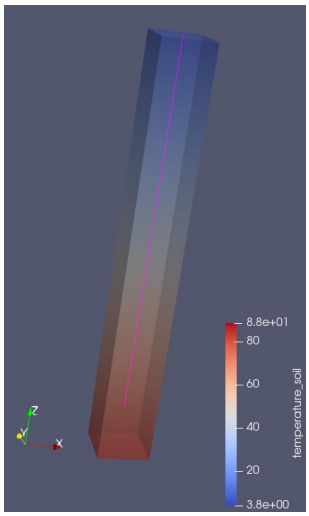


Figure 7. The 3D subsurface DCBHE model with the initial geothermal temperature.

4.3 Heat extraction performance analysis

The numerical model and the simulation results are shown in Figure 8. In the coupled heat pump, the total heat loads are imposed at 50 % and 60 % of the target full heating power (856.3kW), which are 428.15 and 513.78 kW, respectively. The change of inflow and outflow temperature are compared in Figure 8, along with the heat pump performance. For the heat load of 60 % of the full heating power, the inflow temperature is approaching 0 ˚C after the continuous operation of 100 days. The surface heat pump cannot use the heat source with the temperature below freezing point. Therefore, the system is even difficult to survive for 4 months. Due to the lower heat temperature from the DCBHE, the coupled heat pump has lower efficiency as shown in Figure 8 (right). The maximum COP difference is 0.2. When the heating power is decreased to 50 % of the full power, the outflow temperature can reach 9.6 ˚C, due to the higher outflow temperature, the heat pump also has better performance. Nevertheless, better heat pump performance leads to a higher heat extraction power from the subsurface as indicated in Section 3.

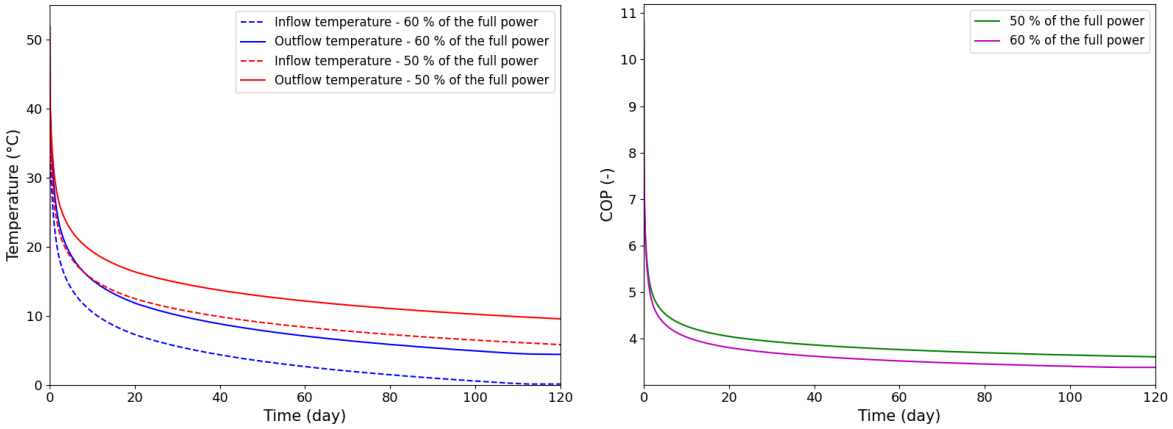


Figure 8. The simulated inflow and outflow temperature over 120 days (left) and the heat pump performance (right).

As for the energy extraction from the subsurface via the DCBHE, the evolution is depicted in Figure 9. In the operation time of 120 days, the maximum difference of the heat extraction power from the DCBHE is 80.327 kW in the two scenarios, while the total heating load difference on the heat pump is 85.63 kW. The increased heat load on the heat pump is not equivalently passed to the subsurface DCBHE system due to the different heat pump performance. The heat load redistribution by the heat pump is always happening in the coupled system, which will try to make the system sustainable as much as possible.

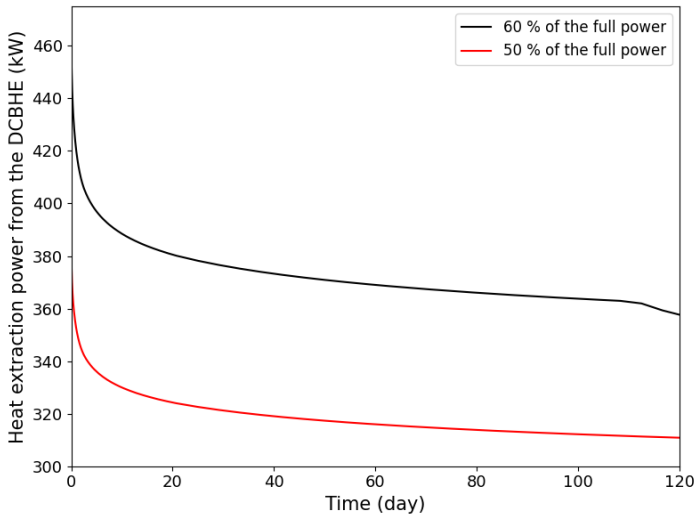


Figure 9. The amount of the energy extracted from the subsurface by the DCBHE.

5 CONCLUSIONS AND OUTLOOK

In this work, the heat pump thermodynamic model has been coupled with the subsurface 3D DCBHE model to achieve the transient interaction between the heat pump and the DCBHE. The total heat load will be automatically redistributed according to the transient off-design performance of the heat pump. In this case, the whole system performance and sustainability is found to be underestimated compared to the independent subsurface model. Even with the averaged COP imposed to translate the total heat load to the DCBHE, the results are similar, which prove the advances of the coupled model. Using the developed model, the heat extraction performance of a well located in the Midland Valley of Scotland has been investigated with an estimated heat generation of 428.15 kW. At least two DCBHEs are needed to meet the heat demand for the planned Hallpark network. Further techno-economic analysis will be conducted by accounting the cost of operation the DCBHE coupled heat pump systems.

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