Design and analysis of a sustainable energy application Ground Source Heat Pump

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Abstract

This report explores the design and analysis of a sustainable energy application, specifically focusing on a Horizontal Ground Source Heat Pump (GSHP). It delves into the background theory of GSHPs, emphasising the coefficient of performance and heat exchange mechanisms. The design is made in Simulink which encompasses subsystems such as the House Thermal Network and Ground Loop Piping System, with detailed components like the accumulator, compressor, condenser, thermostatic expansion valve, and evaporator. MATLAB code is provided for system simulation and performance evaluation. The analysis reveals a positive correlation between energy consumption and higher heat loads, emphasising the system's efficiency across varying thermal conditions. The report discusses scope, and limitations, and concludes with recommendations for future enhancements.

1 - Introduction

This study explores the sustainable use of ground-source heat pumps, focusing on the design and analysis of a horizontal system. Ground source heat pumps efficiently tap into stable ground temperatures, offering a solution to fuel poverty in the UK. The report covers theoretical foundations, heat pump types, potential applications and a Simulink model of GSHP simulating it COP.

1.1 - Ground Source Heat Pump

1.1.1 - What is it?

Ground source heat pumps use a heat pump to move heat to or from the ground. The system maximises unvarying temperatures maintained in the earth across seasons (Hou et al., 2022). These systems are noted for their highly efficient energy use for HVAC and water heating (Yerdesh et al., 2022). The energy efficiency levels offered by these systems exceed the energy efficiency available through the combustion of fuel in a boiler or furnace (Moya et al., 2018).

1.1.2 - Background Theory

1.1.2.1 - Coefficient of Performance

The efficiency of a ground source heat pump (GSHP) is typically expressed by the coefficient of performance (COP). The COP is a ratio that represents the amount of heat energy delivered by the heat pump to the amount of electrical energy it consumes (Mustafa Omer, 2008). The equation for the COP is given by Equation 1:

$$COP = \frac{Heat\ Output\ (Q)}{Electric\ Input\ (W)} \quad (1)$$

Heat Output (Q) is the amount of heat energy delivered to the building or system. Electric Input (W) is the electrical energy consumed by the heat pump.

The COP essentially tells you how much heat energy the heat pump can provide for each unit of electrical energy it consumes. A higher COP indicates a more efficient system.

1.1.2.2 - Heat exchange

Ground-source heat pumps leverage temperature disparities between the surface and various underground depths, as outlined by the thermal characteristics of near-surface ground (Kalogirou et al, 2004; Williams G. and Gold L, 1977). In the surface layer (up to 1 metre), temperature is influenced by sunlight and weather. In the shallow layer (8–20 metres, depending on soil type), temperature variations decrease exponentially with depth, peaking six months after surface peaks. Deeper layers have relatively constant temperatures, increasing about 0.025 °C per metre following the geothermal gradient. The "penetration depth" (Williams G. and Gold L, 1977) is where temperature variation is less than 0.01 of the surface variation, contingent on soil type.

Ground-source heat pumps exchange heat with the ground through a crucial component in the system's design—the ground heat exchanger (Hellström, 1991). Typically made of high-density polyethylene pipework, this heat exchanger circulates a mixture of water and antifreeze, such as monopropylene glycol. As the fluid circulates through the buried loop, it absorbs heat from the ground in winter or dissipates excess heat into the ground in summer. Precise system design is crucial to avoid freezing or inefficiency, ensuring optimal heat exchange and overall performance.

1.1.3 - Types of heat pumps

1.1.3.1 - Horizontal

A Horizontal Ground Source Heat Pump utilises a closed-loop system of pipes arranged in a trench below the frost line. U-shaped or slinky coils within the trench form a horizontal heat exchanger (Hou et al., 2022). This system undergoes seasonal temperature cycles influenced by solar gains and ambient air losses. The heat exchanger's thermal inertia results in temperature lag, enabling the pump to extract heat accumulated from the sun months earlier. While providing efficient heating, it faces challenges in late winter and spring as it carries the burden of accumulated winter cold. Overall, the system capitalises on the Earth's stable temperature for sustainable and eco-friendly heating.

1.1.3.2 - Vertical

A Vertical Ground Source Heat Pump utilises boreholes spaced at least 5–6 metres apart, reaching depths of 50 to 400 feet. U-shaped pipe pairs, thermally fused HDPE tubes, or integrated foundation piles with heat-carrying fluid circulation form the system (Li & Lai, 2015) (Hellström, 1991). The space between borehole walls is often grouted, fostering heat migration from surrounding geology. These systems, suitable for limited land spaces, recharge during surplus heat periods. For instance, a 10 kW heating capacity for a detached house might require three boreholes, each 80 to 110 metres deep. Vertical geothermal systems efficiently tap into the Earth's subsurface for sustainable heating and cooling solutions and are typically used where there is insufficient available land for a horizontal system.

1.1.4 - Potential for Use

Fuel poverty, a term introduced in 1973, is the incapacity to maintain a comfortable home temperature without compromising on essentials like food or water due to exorbitant heating costs (Grey et al., 2017). In the UK, it is widely acknowledged as a distinctive manifestation of social inequality and injustice (Roberts, 2008; Walker and Day, 2012).

Within the British academic landscape, there exists a substantial corpus of literature on fuel poverty, predominantly fixated on space heating as the primary or exclusive energy concern. Recent investigations by Anderson et al. (2012), Christman and Russell (in press), Walker and Day (2012), and Middlemiss (2015), coupled with earlier contributions by Bradshaw (1983) and Boardman (1991), underscore the enduring significance of the affordable warmth or cold homes motif across various studies through the years.

Ground source heat pumps offer a promising solution to alleviate winter fuel poverty in the UK. Particularly prevalent during the colder months, fuel poverty becomes a pressing concern. Ground source heat pumps tap into stored warmth in the ground from the summer, efficiently providing heating in winter. This sustainable technology minimises reliance on expensive conventional heating methods, ensuring homes stay comfortably warm without compromising essentials like food and water. By addressing the root cause of exorbitant heating costs, ground-source heat pumps contribute to combating social inequality and promoting affordable warmth, aligning with the imperative to mitigate fuel poverty in the winter months.

2 - Design of Horizontal Ground Source Heat Pump

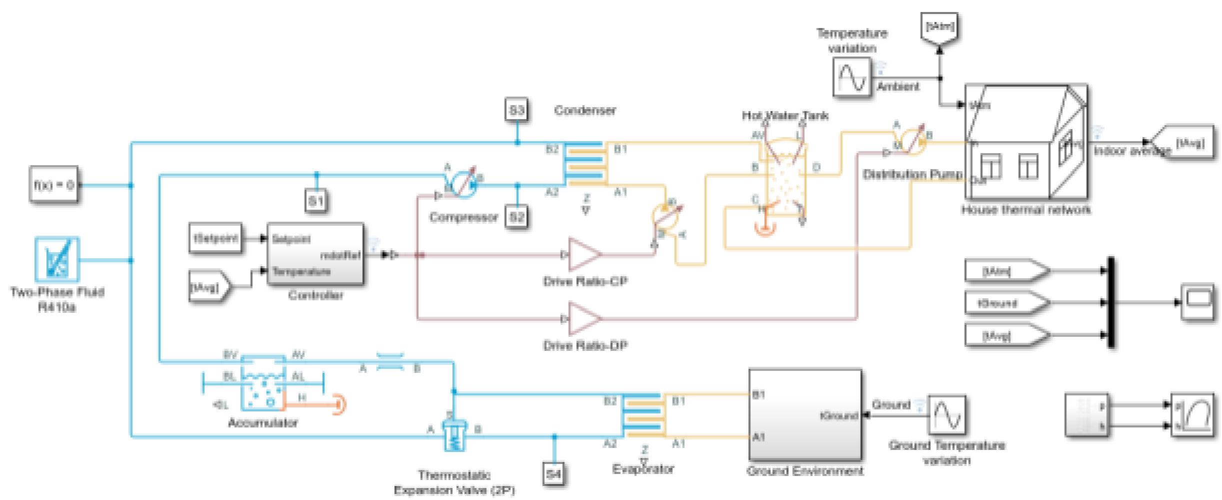

Figure 1: Simulink model of a Horizontal Ground source Heat Pump

The Simulink model shown in Figure 1 represents a horizontal ground source heat pump system using R410a refrigerant to extract heat from the ground for residential heating. The subsystems include the House Thermal Network, Radiator, Room, Controller, Temperature Controller, Ground Environment, and Ground Loop Piping. The system comprises a compressor, condenser, expansion valve, and evaporator, with an accumulator ensuring only vapour enters the compressor. A buried ground loop with a mixture of water and antifreeze absorbs heat from the ground. Circulation pumps drive fluid through the loop and evaporator, while a PI controller adjusts the refrigerant flow for temperature maintenance. The model accommodates ambient and ground temperature variations for optimal performance.

2.1 - Subsystems

2.1.1 - House Thermal Network

This subsystem as shown in Figure 2 simulates the thermal dynamics of a residential building with hot-water radiators. Four rooms (each having its own subsystem) exchange heat with the environment through walls, roofs, and windows, considering thermal convection, conduction, and mass. Internal heat transfer between rooms is neglected. Initial indoor temperatures are 5°C, and the ground temperature is 10°C.

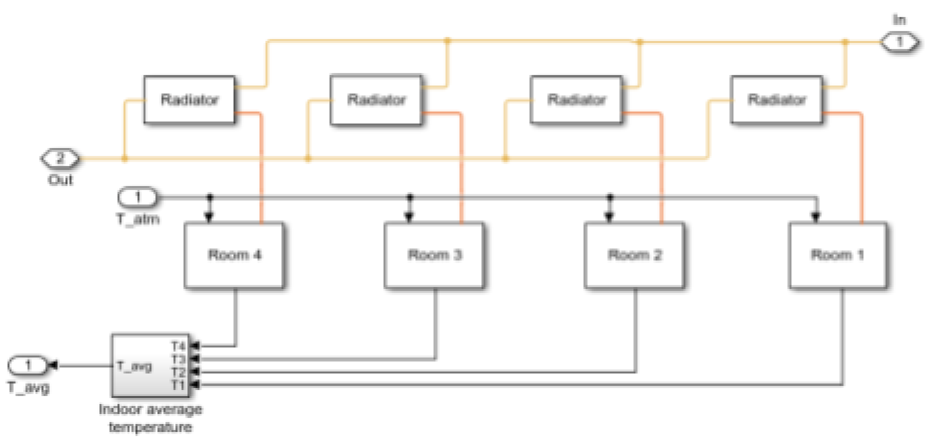

Figure 2: House Thermal Network Subsystem

2.1.2 - Ground Environment

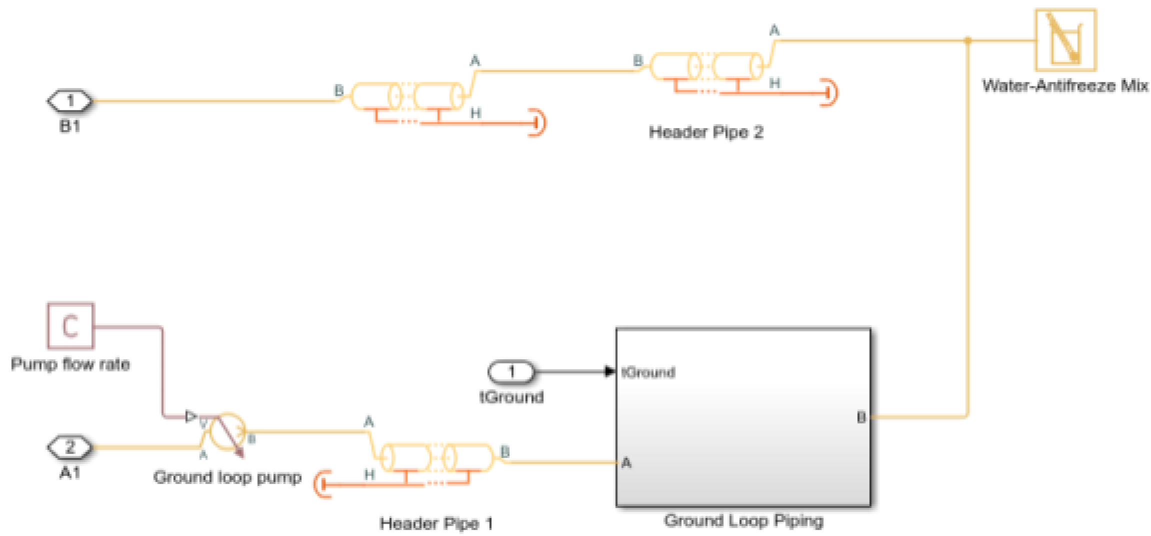

Figure 3: Ground Environment Subsystem

Figure 3 represents a Ground Environment Subsystem with an input A1 (from the evaporator) and output B1. A pump, controlled by a volumetric flow rate through port V, ensures constant flow from A1 to B1 regardless of pressure. Ground temperature, modelled as a sinusoidal wave, serves as an additional input. A1 is connected to a subsystem for ground loop piping, capturing the thermal dynamics of the system.

2.1.3 - Ground Loop Piping System

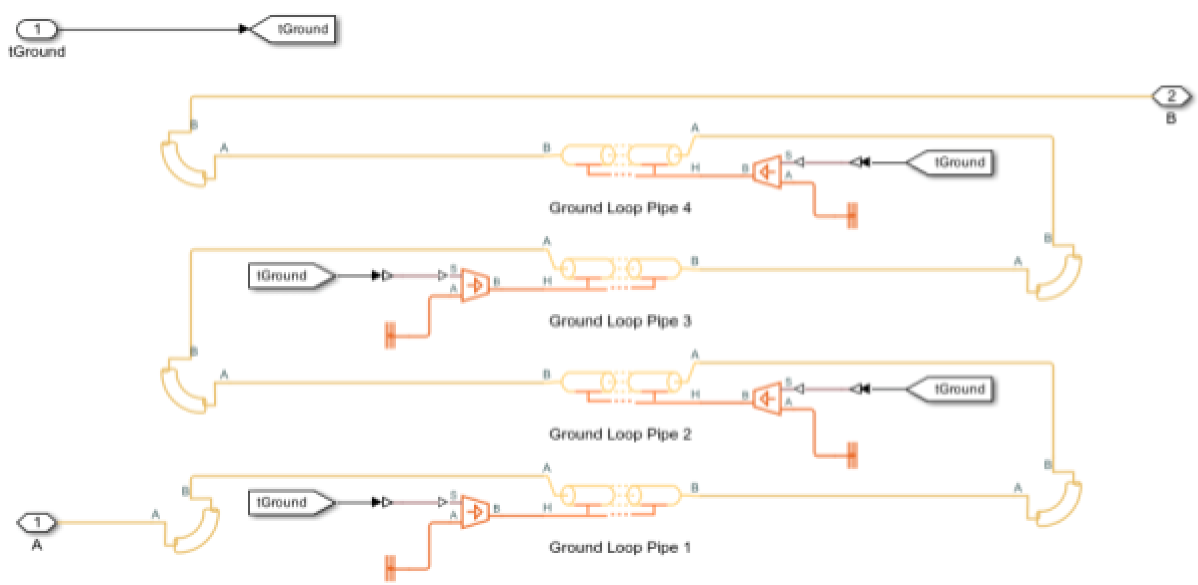

Figure 4: Ground Loop Piping Subsystem

Figure 4 represents a Ground Loop Piping System for a horizontal ground source heat pump. With an input of ground temperature, the system features four ground loops circulating water and Propylene Glycol. These loops absorb heat from the soil, transferring it through the pipes. Inlet (A) and outlet (B) points indicate the flow direction. The model captures the thermal exchange process, essential for simulating the efficiency of a ground source heat pump in extracting heat from the ground.

2.2 - Components of the model

2.2.1 - Accumulator

This block as shown in Figure 1 represents a two-phase fluid container with distinct liquid and vapour ports. The fluid inside can exist as entirely liquid, entirely vapour, or as a combination of both. Mass and energy exchange occurs between the liquid and vapour volumes due to evaporation and condensation. Port L provides the liquid volume fraction of the total container volume.

Ports AV and BV connect to the vapour volume, and unless the container is fully liquid, fluid leaving these ports will be vapour. Similarly, ports AL and BL connect to the liquid volume, and unless the container is fully vapour, fluid leaving these ports will be liquid.

Port H represents the thermal conserving port associated with the container wall, modelling heat transfer between the container wall and the fluid.

2.2.2 - Compressor

This block as shown in Figure 1 represents an ideal mechanical energy source in a two-phase fluid network that can maintain a controlled mass flow rate regardless of the pressure differential. There is no flow resistance and no heat exchange with the environment. The mass flow rate is set by the physical signal port M [kg/s]. A positive mass flow rate causes fluid to flow from port A to port B.

2.2.3 - Condenser

This block as shown in Figure 1 models a heat exchanger between a thermal liquid network and a two-phase fluid network. Heat transfer between the Thermal Liquid 1 side and the Two-Phase Fluid 2 side is calculated based on the effectiveness-NTU method. It is typically used as a chiller in a liquid cooling system, but heat transfer can occur in either direction.

The Two-Phase Fluid 2 side models up to three zones of fluid along the length of the tubes with different heat transfer coefficients. They are the liquid zone, mixture zone, and vapour zone. The zone length fractions vary between 0 and 1.

Ports A1 and B1 are the thermal liquid conserving ports associated with the Thermal Liquid 1 inlet and outlet. Ports A2 and B2 are the two-phase fluid-conserving ports associated with the Two-Phase Fluid 2 inlet and outlet. Physical signal port Z outputs a vector of the liquid, mixture, and vapour zone length fractions.

2.2.4 - Thermostatic Expansion Valve

This block as shown in Figure 1 models a thermostatic expansion valve (TXV) in a two-phase fluid network. It produces the pressure drop between the condenser and the evaporator in a refrigeration system. A sensing bulb measures the superheat at the evaporator outlet. The TXV adjusts the valve area to maintain the nominal superheat at the nominal evaporator capacity. When the superheat decreases, the valve closes to reduce flow into the evaporator and vice versa. The valve is closed at the static superheat and is fully open at the maximum evaporator capacity.

Ports A and B are the two-phase fluid-conserving ports associated with the valve inlet and outlet, respectively. Port S is the two-phase fluid-conserving port representing the bulb sensor measurement. When internal pressure equalisation is selected, port B provides the equalisation pressure. When external pressure equalisation is selected, port E becomes visible to measure the equalisation pressure. Ports S and E are both typically connected to the evaporator outlet. There is no mass or energy flow rate through ports S and E.

2.2.5 - Evaporator

This block as shown in Figure 1 models a heat exchanger between a thermal liquid network and a two-phase fluid network. Heat transfer between the Thermal Liquid 1 side and the Two-Phase Fluid 2 side is calculated based on the effectiveness-NTU method.

The Two-Phase Fluid 2 side models up to three zones of fluid along the length of the tubes with different heat transfer coefficients. They are the liquid zone, mixture zone, and vapour zone. The zone length fractions vary between 0 and 1.

Ports A1 and B1 are the thermal liquid-conserving ports associated with the mixture of water and antifreeze inlet and outlet. Ports A2 and B2 are the two-phase fluid-conserving ports associated with the Two-Phase Fluid 2 inlet and outlet. Physical signal port Z outputs a vector of the liquid, mixture, and vapour zone length fractions.

2.3 - MatLab Code

This MATLAB code shown in Figure 5 simulates and plots the performance of a residential ground source heat pump system. The system consists of a compressor, condenser, evaporator, and radiator. The plots show various parameters such as compressor power, heat flow rates, and the Coefficient of Performance (COP) over time. In this case, the COP is calculated as COP = heatCondenser / pwrCompressor, where heatCondenser is the heat flow from the condenser, and pwrCompressor is the compressor power.

```
% Call the function to plot simulation results
plotFuel(simlog_sscfluids_residential_ground_source_heat_pump)

% Function to plot simulation results
function plotFuel(simlog)

   % Get simulation results
   t            = simlog.Compressor.M.series.time/3600; % Time in hours
   pwrCompressor  = simlog.Co% mpressor.power.series.values('kW'); % Compressor power
   heatCondenser  = -simlog.Condenser.Q.series.values('kW'); % Heat flow from condenser
   heatEvaporator = -simlog.Evaporator.Q.series.values('kW'); % Heat flow from evaporator
   pwrRadiator1   = simlog.House_thermal_network.Radiator1.Convective_Heat_Transfer.Q.series.values('kW');
% Heat flow from radiator 1
   pwrRadiator2   = simlog.House_thermal_network.Radiator2.Convective_Heat_Transfer.Q.series.values('kW');
% Heat flow from radiator 2
   pwrRadiator3   = simlog.House_thermal_network.Radiator3.Convective_Heat_Transfer.Q.series.values('kW');
% Heat flow from radiator 3
   pwrRadiator4   = simlog.House_thermal_network.Radiator4.Convective_Heat_Transfer.Q.series.values('kW');
% Heat flow from radiator 4

   % Total heat flow rate through the radiators
   pwrRadiators = pwrRadiator1 + pwrRadiator2 + pwrRadiator3 + pwrRadiator4;

   % Coefficient of Performance (COP)
   COP = heatCondenser./pwrCompressor;

   % Plot results
   handles(1) = subplot(2,1,1);
   plot(t, pwrRadiators)
   hold on
   plot(t, heatCondenser)
   hold on
   plot(t, heatEvaporator)
   hold on
   plot(t, pwrCompressor)
   hold off
   grid on
   xlabel('Time (hrs)')
   ylabel({'Thermal'; 'power (kW)'})
   legend({'Radiators','Condenser','Evaporator','Compressor'}, 'Location', 'northeast')
   title('Heat Transfer Rate & Compressor Power')

   handles(2) = subplot(2,1,2);
   plot(t, COP)
   grid on
   xlabel('Time (hrs)')
   ylabel('Coefficient of Performance')
   legend('COP', 'Location', 'best')
   title('Coefficient of Performance')

   linkaxes(handles, 'x') % Link x-axes for synchronized time axis
end
```

Figure 5: Matlab Code of computation of COP

3 - Analysis

3.1 - Results

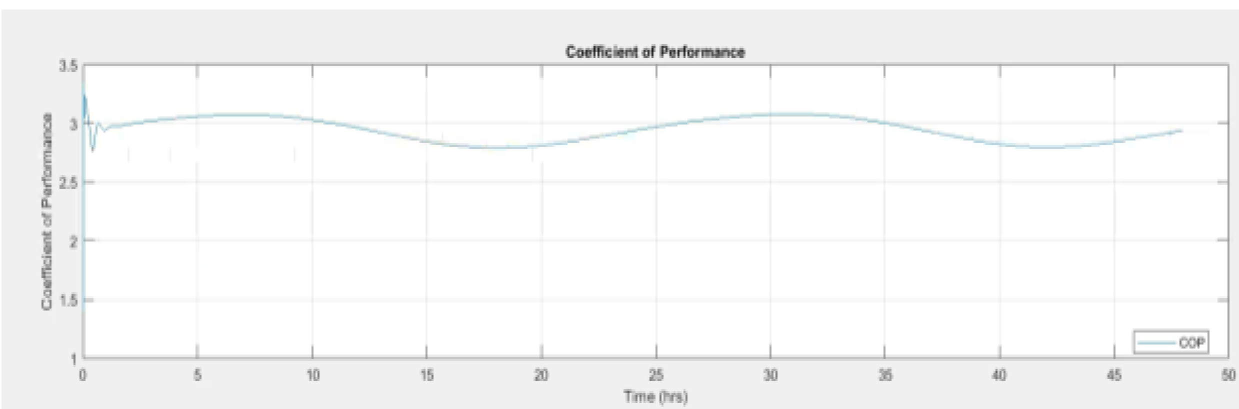

Figure 6: Plot of Coefficient of Performance

Figure 6 depicts the coefficient of performance (COP) in relation to the heating load and power consumption ratio. Notably, as the heat load increases (associated with lower ambient temperatures), energy consumption rises, while it decreases with lower heat loads (higher ambient temperatures). Despite these variations, the COP remains relatively constant at around 3, signifying the system's consistent efficiency. The COP consistently exceeds 1, indicating that the system produces more heat output than the electricity inputted, affirming its effectiveness in converting energy to provide ample heating with minimal electrical consumption across varying thermal conditions.

4 - Discussion

4.1 - Scope and Limitations

The report on ground-source heat pumps is constrained by its reliance on a single set of thermal fluids, limiting the comprehensiveness of its findings. Moreover, the omission of climate change considerations raises concerns about the report's applicability in evolving environmental conditions. The absence of parametric modelling undermines precision, and the oversight of vertical heat pump modelling hampers completeness. The reliance on a singular metric overlooks crucial aspects, such as CO2 measurements, detracting from a holistic assessment. Furthermore, the absence of a comparative model diminishes the report's ability to provide nuanced insights. Future enhancements should address these limitations to bolster the report's credibility and relevance.

To enhance the report's robustness, future iterations should diversify thermal fluid sets, incorporating a broader range for comprehensive analysis. Integration of parametric modelling techniques would refine accuracy, ensuring a more nuanced understanding of ground-source heat pump performance. Considering the pressing issue of climate change, future assessments should incorporate its impact, making the report more forward-thinking. Additionally, modelling vertical heat pumps, introducing CO2 measurements, and incorporating a comparative model would yield a more comprehensive and impactful evaluation, strengthening the report's applicability and relevance.

4.2 - Conclusion

In conclusion, this study offers a thorough exploration of the design and analysis of a Horizontal Ground Source Heat Pump (GSHP) for sustainable energy applications, demonstrating its efficiency through Simulink modeling and MATLAB simulations. The consistently above-1 Coefficient of Performance (COP) is a noteworthy finding, indicating that the system produces more heat output than the electrical energy inputted. This not only affirms the GSHP's effectiveness in converting energy but also underscores its potential to alleviate fuel poverty during the winter months. By tapping into stored warmth in the ground from the summer, GSHPs provide a reliable and cost-effective heating solution, reducing reliance on conventional, expensive methods and contributing to affordable warmth for households in need.

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