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Simulation of Industrial Effluent Handling Unit using Geothermal Designs: A Case Study of Indorama Petrochemicals Ltd

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Abstract
This research presents a comprehensive design, simulation, and validation of a geothermal groundwater heating and cooling system developed specifically for industrial effluent thermal management at Indorama Eleme Fertilizer and Chemical Limited, located in Rivers State, Nigeria. The study responds to the increasing demand for sustainable thermal energy solutions within industrial settings, particularly in emerging economies where fossil-fuel-based technologies remain prevalent and continue to exacerbate greenhouse gas emissions. A prototype geothermal system was conceptualized, consisting of a groundwater-based geothermal heat pump (GWHP) integrated with a shell-and-tube heat exchanger, technically designated as unit 10-E-01. The plant design was executed using a dual-method approach combining Aspen HYSYS process simulation software with rigorous manual thermodynamic computations based on established principles of material and energy balances. Key operational and performance indicators were evaluated, including drive power requirements, coefficient of performance for both heating and cooling cycles, overall heat duty, and system energy efficiency. These indicators were subsequently subjected to validation using root mean square error (RMSE) and deviation analysis, thereby confirming the reliability and accuracy of the model. The validated results revealed a drive power consumption of 354.1 kilowatts, coefficient of performance values of 2.82 for the heating cycle and 1.05 for the cooling cycle, and an impressive system efficiency calculated at 420 percent. The shell-and-tube heat exchanger component achieved a thermal duty of 309.5 kilowatts, supported by an overall heat transfer coefficient of 0.2104 kilowatts per square meter per degree Celsius and a calculated effective surface area of 60.32 square meters. Furthermore, the pressure drop across the tube side of the exchanger was estimated at 390 megapascals, indicating substantial fluid dynamic activity under operational conditions. The validation exercise conducted on the model outputs confirmed that the deviation and RMSE values remained well within permissible thresholds, thereby reinforcing the dependability of the hybrid simulation and analytical methodology adopted. This investigation is distinguished as the first scholarly and technical attempt within Nigeria to simulate and validate a geothermal groundwater-based heating and cooling system specifically for industrial effluent management applications. It provides empirical evidence that geothermal energy systems can be effectively integrated into existing industrial frameworks without necessitating significant structural modifications. Moreover, the study advances the discourse on sustainable thermal management by demonstrating the practicality of geothermal technology in reducing carbon emissions, enhancing energy efficiency, and promoting long-term economic benefits. The outcomes of this work significantly extend the existing knowledge base in sustainable process and energy engineering, offering a scientifically grounded and replicable model that may be adapted for similar applications across other industrial zones in Sub-Saharan Africa. The research sets a precedent for future geothermal system deployments in industrial contexts, reinforcing the need for renewable thermal energy strategies in the global quest for environmental sustainability and industrial decarbonization.
Keywords: *Geothermal Energy; Geothermal Groundwater Heat Pump; Industrial Effluent Management; Aspen HYSYS Simulation; Thermodynamic Analysis; Shell-and-Tube Heat Exchanger; Energy Efficiency.*

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I. INTRODUCTION

The subsurface strata of the Earth are endowed with a substantial quantity of thermal energy that remains remarkably stable throughout the year, regardless of external climatic fluctuations. This vast and continuous supply of geothermal heat represents a renewable energy resource that can be systematically harnessed for various energy needs. Technologies developed to exploit this resource include shallow horizontal loop systems and deep vertical borehole installations, each tailored to specific geological and infrastructural conditions. These systems can be applied to provide heating, cooling, and even electricity generation, particularly in environments seeking alternatives to fossil-based energy solutions (Department of Energy, 2019). Underneath the Earth's surface lies a naturally insulated thermal reservoir whose temperature fluctuates minimally over time, making it highly dependable for energy applications. Through the use of direct extraction systems or via heat pumps, this subsurface heat can be converted into a stable, low-carbon energy source for year-round thermal regulation. Such systems offer a strategic pathway toward cleaner energy use in both residential and industrial contexts, reducing reliance on carbon-intensive technologies. Geothermal energy is not limited to a single application but spans across multiple sectors including electricity generation, building climate control, and even therapeutic spa heating, all of which rely on geological structure and borehole depth. The quantity and temperature of extractable geothermal energy are directly related to the geological formation and how deep a system penetrates the Earth's crust, thus necessitating detailed geological surveys prior to implementation (Fleuchaus, Godschalk, Stober & Blum, 2018; Burns *et al.,* 2020). This form of energy has proven to be both sustainable and low in carbon emissions, making it an attractive option amid growing global concerns about fossil fuel usage. Furthermore, ongoing research continues to refine geothermal technologies by improving efficiency, reducing cost, and expanding their adaptability to a range of geological settings (Fleuchaus *et al.,* 2018; Burns *et al.,* 2018; Burns *et al.,* 2020; Pepin *et al.,* 2021). The increasing interest in geothermal systems across multiple disciplines illustrates its multidisciplinary relevance and potential for broad impact. While geothermal energy systems are relatively mature in certain countries, other regions are just beginning to explore their benefits, thus creating a diverse landscape of adoption and technological experimentation. These developments have made geothermal energy a key focus of sustainable energy discourse in both developed and developing economies. The global shift toward renewable energy sources has been largely driven by the mounting environmental and economic costs associated with fossil fuel consumption. In this context, geothermal energy has emerged as a particularly valuable alternative due to its reliability, low maintenance requirements, and continuous operational capacity. Compared with other renewables such as solar, wind, and biomass, geothermal systems offer a consistent energy yield irrespective of weather patterns, making them suitable for base-load thermal energy supply. Additionally, geothermal systems can be employed not only for heating and cooling but also for advanced applications such as desalination and process heating in industrial operations (Ahmadi, Mehrpooya & Pourfayaz, 2016). The use of geothermal heat pumps significantly lowers operational costs by leveraging the earth's inherent temperature stability to reduce the energy input required for space conditioning. This translates to a marked reduction in greenhouse gas emissions, especially in applications where geothermal energy replaces conventional fossil-based systems. Consequently, geothermal energy systems represent a comprehensive and scalable solution for advancing global decarbonization objectives while maintaining energy security. To ensure clarity in terminology, it is essential to define certain abbreviations that will be consistently used throughout this study. The term UTES refers to Underground Thermal Energy Storage, a method of storing thermal energy within the ground for later retrieval, enhancing the flexibility and efficiency of geothermal systems. BHE stands for Borehole Heat Exchanger, which is a critical component of many geothermal heat pump systems used to facilitate thermal exchange between the ground and the circulating fluid. These abbreviations encapsulate important engineering constructs and will be referenced repeatedly in the technical sections of this dissertation. By understanding these terms, the reader can better appreciate the complexity and functionality of the geothermal technologies being discussed. Furthermore, these abbreviations align with international nomenclature standards and are used widely across scholarly and technical publications. Their inclusion is not merely for simplification but also to maintain consistency with industry practice and scientific reporting. As such, UTES and BHE represent foundational elements of the geothermal heating and cooling frameworks explored herein. In many European countries, high-temperature geothermal aquifers are geographically constrained, making it difficult to deploy conventional deep geothermal systems across wides2pread regions. To address this limitation, several nations have strategically adopted shallow Ground Source Heat Pump (GSHP) systems, which can function effectively with lower geothermal gradients and are more adaptable to diverse subsurface conditions. These systems, which utilize shallow boreholes or surface-based heat exchangers, offer a decentralized approach to thermal energy management, making them ideal for residential manufacturers and service providers proliferating across the region. As the technology matures, GSHPs are becoming a standard feature in new developments, thereby driving a steady transition from fossil-based heating systems toward cleaner, renewable alternatives. The climatic conditions across northern and central Europe further incentivize the use of GSHP systems, particularly because of the prolonged heating seasons and limited demand for air conditioning. In such regions, residential and commercial buildings require efficient and cost-effective heating solutions for most of the year, making geothermal heat pumps an ideal choice. As a result, heat pumps in these locations are typically optimized for heating rather than cooling operations, contrasting with systems used in countries like the United States where dual-function geothermal heat pumps are more common. The ability of GSHPs to deliver stable and reliable heating has led to increased adoption, supported by favorable policies and energy efficiency targets set by national governments. Moreover, pilot projects have been instrumental in demonstrating the technical feasibility of GSHPs in moderately endowed geothermal regions such as Greece and

Turkey (Sarbu & Sebarchievici, 2014; Zhang *et al.,* 2016). These successful installations have paved the way for hybrid geothermal systems that combine BHEs with groundwater wells to optimize performance under varied environmental conditions. As knowledge and experience with GSHPs continue to diffuse across southern Europe, there is a strong likelihood that systems designed for both heating and cooling will gain traction, especially in areas experiencing warmer summers and increased cooling needs. An exemplary project showcasing the practical integration of GSHP technologies is the geothermal system installed at the Mining Engineering Building of the National Technical University of Athens. This system utilizes a hybrid configuration that links BHEs with groundwater wells and geothermal heat pumps to provide year-round thermal regulation of the facility. The innovative design successfully combines the advantages of both subsurface and aquifer-based heat exchange, thereby enhancing system efficiency and reliability. This project quickly gained attention within academic and engineering circles, inspiring further research and development efforts in the field of applied geothermal energy. It has since served as a model for other institutions and commercial ventures seeking to implement sustainable thermal management solutions. With the emergence of larger-scale implementations, especially in the commercial and institutional sectors, the demand for cooling alongside heating is expected to rise significantly. As climate patterns continue to shift and energy demands diversify, geothermal systems offering dual functionality will become increasingly relevant in future urban and industrial planning frameworks. Nowak (2018) provided a comprehensive report on heat pump technologies, highlighting their foundational principles, energy efficiency characteristics, and potential to harness both renewable and waste heat sources. Their work detailed how heat pumps offer not only technical benefits such as reduced energy consumption but also wider environmental and societal gains, including improved indoor air quality and reduced dependence on carbon-based fuels. Furthermore, the report discussed the evolving business models supporting heat pump deployment, including public-private partnerships and financing incentives that have made the technology increasingly viable. A key focus of their study was on the integrative role heat pumps play in decarbonizing the heating and cooling sectors, thereby positioning them as vital to Europe's transition toward a climate-neutral energy future. The report emphasized that heat pumps, when implemented at scale, could serve as backbone technologies within national energy grids, particularly in cold-weather regions. In this way, Nowak (2018) advanced the discourse around energy systems by showing how heat pumps intersect with technical innovation, energy policy, and environmental stewardship. Their analysis underscores the urgency of incorporating heat pump technologies into comprehensive climate action strategies. knowledge on how geothermal energy is harvested and converted into usable thermal output through GHP technologies. Different types of GHPs such as open-loop, closed-loop, and Qin (2022) developed and introduced an innovative web-based calculator designed to quantify both carbon dioxide and financial savings from geothermal district heating systems. Their model was validated using a case study in Budapest, Hungary, where simulations indicated that replacing 40% of gas boilers with geothermal loops could result in an approximate 4.6% reduction in local carbon emissions. This tool offers stakeholders, including municipal authorities and utility planners, a reliable means to evaluate the potential impact of geothermal adoption on a regional scale. The versatility of the calculator allows it to be adapted for use in various urban environments, thus broadening its applicability beyond the initial case study. By making such tools accessible, Qin (2022) contribute to the informed decision-making necessary for transitioning to sustainable heating infrastructures. This development signifies a convergence of engineering, software modeling, and policy planning in pursuit of lower-carbon urban systems. As cities continue to confront challenges related to energy demand and climate change, digital modeling tools such as this one will become increasingly vital in guiding investment and deployment of renewable energy solutions. In the field of heating, ventilation, and air conditioning (HVAC), several studies including those by the Department of Energy (2019), Qin (2022), and Goetzl *et al.,* (2023), have extensively explored the operational framework and advantages of geothermal heat pump systems. These works provide foundation standing column systems are evaluated based on their efficiency, installation complexity, and adaptability to various climatic and geological conditions. When compared with conventional HVAC systems, GHPs demonstrate superior energy efficiency, reduced environmental footprint, and lower operational costs over the system's lifespan. Their ability to deliver consistent heating and cooling with minimal maintenance makes them particularly suitable for both residential and commercial applications. Despite higher initial capital expenditure, the return on investment over time through energy savings and environmental compliance is substantial. The accumulated insights from these studies establish geothermal HVAC systems as a cornerstone of next-generation building technologies. Ivanova (2019) conducted an energy performance assessment of GHP systems applied to typical residential buildings in the United States and discovered that heating and cooling functions account for over 70% of household energy use. Her findings indicated that geothermal systems could reduce this energy demand by nearly half, leveraging the natural thermal energy stored underground to replace a significant portion of conventional energy input. Ivanova also reported that large-scale implementation of GHPs in approximately 100,000 homes could potentially offset up to 2.15 million barrels of oil annually, thereby yielding substantial reductions in carbon emissions. Supporting data from Geo Exchange (2020) further corroborates that GHPs produce the lowest greenhouse gas emissions among all contemporary HVAC technologies. These findings are complemented by U.S. federal incentives aimed at increasing the adoption of geothermal technologies, including commercial building tax credits under the Modified Accelerated Cost Recovery System, and personal income tax credits for homeowners through the Energy Policy Act of 2005. The tax credit structure was extended to provide a 22% return on eligible geothermal installations in 2023, according to ENERGY STAR (2020). Moreover, many energy companies offer additional rebates sometimes as high as $1,000 per ton of installed GHP capacity to further reduce the economic barrier to adoption. Bais & Ankit (2018) provided a comparative evaluation between geothermal water heat pumps (GWHPs) and traditional water source heat pumps (WSHPs), illustrating the broader functional range and thermal efficiency of GWHP systems. According to their study, GWHPs are capable of operating across a temperature range from -1.1°C to 32.2°C, whereas WSHPs are typically confined to a narrower operational band of 18.3°C to 29.4°C. This broader temperature tolerance makes GWHPs more adaptable to varying seasonal and site-specific conditions, thereby improving their year-round performance. In addition, the structural design of geothermal systems, which places most components underground or within indoor mechanical rooms, reduces exposure to environmental degradation and extends the operational lifespan of the system. This translates into fewer repairs, lower maintenance costs, and increased system reliability over decades of use. The study concludes that the thermal stability and durability of GWHPs offer a compelling advantage in long-term HVAC planning, especially in areas with high energy demand and fluctuating weather patterns. Thus, Bais and Ankit (2018) underscore the strategic value of transitioning from conventional heat pump technologies to advanced geothermal systems in both residential and industrial applications.

II. MATERIALS AND METHOD

2.1 Materials Used

- Geothermal Groundwater Heat Pump (GWHP),
- Shell-and-tube heat exchanger (10-E-01),
- Closed-loop ground heat exchanger (ground loop),
- High-density polyethylene (HDPE) pipes,
- Connecting pipes for fluid circulation,
- Vertical boreholes (or horizontal trenches, depending on installation),
- Geothermal groundwater wells (production and reinjection wells),
- Antifreeze solution (or thermally conductive heat transfer fluid),
- Groundwater (heat source),
- Air (conditioned medium),
- Thermodynamic tables,
- Fluid property data,
- Industrial heating/cooling plant configuration (prototype system)

2.2 Method used

The study adopted a qualitative design approach supported by quantitative thermodynamic analysis to design and evaluate a geothermal groundwater heat pump (GWHP) system for industrial heating and cooling. The methodology involved designing and sizing the major system components, including the geothermal heat pump, shell-and-tube heat exchanger, and closed-loop ground heat exchange network. Thermodynamic principles and fluid property data were used to manually calculate key performance parameters such as the coefficient of performance (COP), drive work, heat transfer rate, and overall system efficiency. The performance of the integrated geothermal system was then evaluated by analyzing the heat transfer process between the groundwater, heat exchanger, and industrial heating and cooling system to determine its operational effectiveness and energy efficiency.

2.2.1 Design of Geothermal Water Heat Pump

The design of the geothermal groundwater heat pump forms a fundamental part of the heating and cooling plant developed in this study. This system relies on the principles of thermodynamic heat exchange between groundwater and a refrigerant medium circulating within the pump. The overall configuration is structured to harness the relatively constant temperature of subsurface water to drive an efficient thermal energy cycle. A simplified schematic of the proposed system, highlighting key structural and operational components, is presented in Figure 3.2. This sketch outlines the major functional features of the geothermal water heat pump, including the subsurface boreholes, the refrigerant loop, the heat exchanger unit, and the compressor mechanism. The vertical piping system draws groundwater at a stable temperature and directs it through the heat exchanger, where heat is either absorbed or rejected, depending on whether the system is operating in heating or cooling mode. This design ensures energy-efficient performance by minimizing external energy inputs and maximizing the use of renewable geothermal energy.

The sketch serves as both a conceptual guide and a technical foundation for subsequent design computations, providing clarity on how each component interrelates within the integrated geothermal heating and cooling framework.

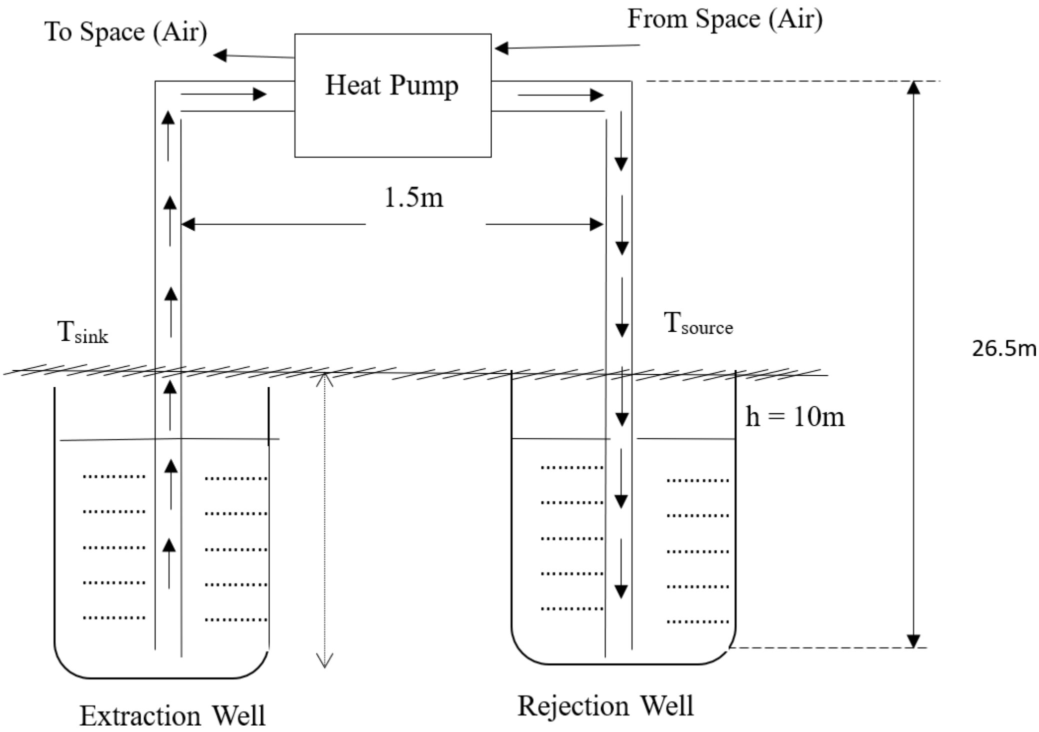

Figure 1: Water-to-air type vertical heat exchanger from the geothermal groundwater heat pump (GWHP) system.

Figure 1 illustrates the schematic representation of a water-to-air type vertical heat exchanger integrated within a geothermal groundwater heat pump (GWHP) system. This configuration demonstrates the vertical deployment of heat exchanger pipes that extend into the ground to access the stable thermal energy reservoir located beneath the Earth's surface. In this arrangement, groundwater is circulated through a closed-loop piping system where it interacts thermally with the refrigerant within the heat exchanger unit. The vertical heat exchanger is designed to optimize heat transfer performance by taking advantage of the consistent temperatures found at greater depths, making it especially suitable for space-constrained industrial environments. The air-side of the system allows conditioned air to be distributed efficiently for either heating or cooling purposes, depending on the operational mode. The system supports high levels of energy efficiency by using the earth as a renewable thermal source and facilitates a significant reduction in greenhouse gas emissions when compared to traditional fossil-fuel-based HVAC systems. The figure provides a practical visualization of the technology and reinforces the theoretical design parameters discussed in earlier sections of the study.

Thermodynamic analysis plays a crucial role in evaluating the performance of geothermal groundwater heat pump (GWHP) systems, particularly in estimating the mechanical work input required to sustain the heat exchange cycle. One of the foundational thermodynamic tools employed for this purpose is the Clausius–Clapeyron relation, which provides a theoretical basis for analyzing phase changes and energy transformations within the heat pump system. By applying this principle, the work needed to drive the heat pump can be accurately determined, taking into account the temperature and pressure gradients associated with the refrigerant's phase transitions. This method allows for the quantification of energy inputs relative to thermal outputs, facilitating the computation of key performance metrics such as the coefficient of performance (COP) and overall system efficiency. The Clausius–Clapeyron relation is especially useful in modelling the behavior of the refrigerant within the compressor and condenser sections, where vaporization and condensation processes are fundamental to the system's operation. According to Omer (2008) and Uzono *et al.* (2022), the work input required by a geothermal groundwater heat pump system can be mathematically expressed as follows:

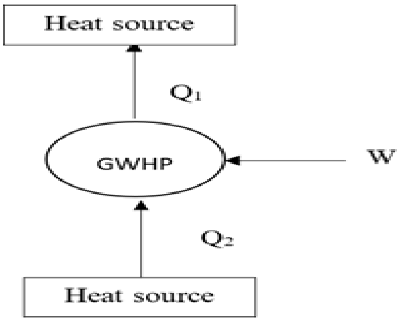

Figure 2: Application of Clausius–Clapeyron second law of thermodynamics in the performance evaluation of a geothermal groundwater heat pump (GWHP) system.

Figure 3.3 graphically illustrates the application of the Clausius–Clapeyron relation, which is a thermodynamic expression derived from the second law of thermodynamics and widely used in analyzing phase transitions. In the context of this study, the Clausius–Clapeyron relation is utilized to determine the work input required by the geothermal groundwater heat pump (GWHP) during the thermodynamic cycle. The figure demonstrates the relationship between temperature and pressure during the phase change process of the refrigerant, typically occurring within the evaporator and condenser of the heat pump system. This theoretical model provides insight into how latent heat influences system performance, particularly by quantifying the energy needed to sustain the vapor compression cycle. By assessing this relationship, researchers and engineers can evaluate the thermal behavior of the refrigerant under different subsurface and operational conditions, thereby optimizing the heat pump's efficiency. The inclusion of this figure reinforces the analytical approach adopted in the study and supports the mathematical formulations that follow in determining performance characteristics such as the coefficient of performance (COP), energy savings, and emissions reduction potential of the GWHP configuration.

The rate of drive power required to operate the geothermal groundwater heat pump (GWHP) system is determined through the application of the second law of thermodynamics, particularly by performing an energy balance analysis on the system as represented in Figure 3.3. This energy balance accounts for the transfer of thermal energy between the heat source (groundwater) and the heat sink (building environment), while also incorporating the mechanical work input required to maintain the refrigeration cycle. The theoretical framework guiding this analysis is based on the Clausius–Clapeyron relation, which facilitates the quantification of work associated with phase changes in the working fluid as it absorbs and releases heat during evaporation and condensation. By applying this principle, one can evaluate the thermodynamic efficiency of the GWHP system and estimate the minimum energy input necessary to drive the heat transfer process. This analysis ultimately yields an expression for the drive power rate, as presented mathematically in Equation (1), which provides a foundation for subsequent performance evaluation and system optimization:

$$W_{net} = Q_1 - Q_2 = mC_P(T_1 - T_2) \quad \textbf{(1)}$$

In this expression, W_{net} denotes the rate of drive work or net power, Q_1 is the rate of heat absorbed at the sink temperature T_1, and Q_2 is the rate of heat released at the source temperature T_2. The term $\dot{m}$ represents the mass flow rate of the working fluid, while C_P is the specific heat capacity at constant pressure. The temperature differential between the sink and the source forms the thermal basis for energy transfer within the cycle.

The coefficient of performance (COP) of a geothermal heat pump in heating mode, derived from the Carnot heat pump model, is then expressed as:

$$\beta_{HP} = \frac{Q_1}{W_{net}} = \frac{T_1}{T_1 - T_2} \quad \textbf{(2)}$$

Here, β_{HP} represents the heat pump's COP, which quantifies the efficiency of the system. T_1 and T_2 are the absolute temperatures (in Kelvin) of the sink and source respectively. A higher COP indicates a more efficient transfer of heat with lower work input.

The geothermal energy output or plant rating, defined as the rate of thermal energy delivered during heating or cooling, is calculated using the relation:

$$Q = mC_P \, \Delta T \quad \textbf{(3)}$$

Where Q is the heat transfer rate, and ΔT denotes the temperature difference between the geothermal heat source and the heat sink. This parameter is central to evaluating the thermal capacity of the GWHP system.

To determine the system's hydrostatic pressure particularly relevant for fluid dynamics and thermodynamic table referencing the following relationship is employed:

$$P = P_0 + pgh \quad \textbf{(4)}$$

In Equation 4, P is the total hydrostatic pressure, P_0 is the atmospheric pressure, ρ is the density of the water, g is the acceleration due to gravity (taken as 9.81 m/s²), and h is the height or depth of the water column, assumed to be 10 meters for this calculation. This pressure term is necessary when assessing the enthalpy and pressure drop across components.

The required length of the piping system, which facilitates geothermal heat exchange, can be determined using the thermal resistance of the surrounding ground and the temperature difference between the ground and the working fluid:

$$L = \frac{RQ}{T_g - T_w} \quad \textbf{(5)}$$

Here, L represents the pipe length in meters, Q is the rate of heat transfer in kilowatts, T_g is the ground temperature in Kelvin, T_w is the temperature of the working fluid, and R is the effective thermal resistance of the ground per unit length, expressed in mK/kW.

Alternatively, the drive work required for the heat pump's operation can also be computed directly from the COP and the thermal output, using the following relation:

$$W = \frac{Qoutput}{\beta HP} = \frac{Q_1}{\beta HP} \quad \textbf{(6)}$$

This equation serves to cross-validate the power requirement by relating it to the heat output and the known COP of the system.

For cooling operations, the heat transfer rate which signifies the system's ability to remove thermal energy from the conditioned space is described by:

$$Q_{cooling} = mC_P \, \Delta T \quad \textbf{(7)}$$

Where $Q_{cooling}$ is the cooling capacity, and ΔT remains the difference between the indoor return temperature and the ground loop temperature.

The coefficient of performance for the cooling mode, analogous to heating COP, measures how effectively the system removes heat per unit of energy input:

$$COP_{cooling} = \frac{Qcooling}{W} = \frac{t_s}{t_{u-t_s}} \quad \textbf{(8)}$$

In Equation 8, *Ts* is the absolute temperature of the cold reservoir (typically indoor return air), and *Tu* is the absolute temperature of the heat sink (usually ground or outdoor temperature during cooling).

Accordingly, the work input required for the cooling operation of the GWHP can also be computed from the cooling output and the COP in cooling mode as:

$$\Rightarrow W = \frac{Qcooling}{COP_{cooling}} \quad \textbf{(9)}$$

Likewise, the coefficient of performance for the heating mode, which defines the system's thermal efficiency during space heating, is given by

$$COP_{heating} = \frac{Q_{heat}}{W} = \frac{t_u}{t_{u-t_s}} \quad \textbf{(10)}$$

In this final expression, $COP_{heating}$ represents the heating efficiency, where *Tu* and *Ts* correspond to the higher (sink) and lower (source) absolute temperatures respectively. These equations collectively provide a robust framework for evaluating the thermal and operational efficiency of geothermal groundwater heat pumps under both heating and cooling conditions.

2.2.2 The Heat Exchanger Design for GWHP

The heat exchanger employed in this geothermal groundwater heat pump (GWHP) system is designated as unit 10-E-01 and is of the shell and tube type. This type of exchanger is commonly utilized in industrial heating and cooling applications due to its robustness, modular configuration, and efficient thermal exchange capabilities. The geothermal system integrates a working fluid typically water sourced from an underground well circulating through the shell side, while conditioned air or another secondary fluid flows through the tubes, facilitating thermal exchange between the source and sink media. Given the defined thermophysical properties of the geothermal fluid and the building-side fluid, the design must consider several key parameters. These include the mass flow rates of both the hot and cold fluids, the specific heat capacities, the allowable temperature ranges, and the thermal conductivity characteristics of the exchanger material. A central metric in evaluating and optimizing the exchanger's efficiency is the overall heat transfer coefficient, denoted as U, which encapsulates the convective and conductive resistances to heat flow. In addition, the temperature driving force is quantified using the log mean temperature difference (LMTD), which accounts for the non-linear temperature gradient across the exchanger length. Accordingly, the heat transfer area required for this shell-and-tube exchanger is computed using the following relationship:

$$A = \frac{Q}{U\Delta T_{LM}} \quad \textbf{(11)}$$

Where:

- A is the required heat exchanger surface area (m^2),
- Q is the rate of heat transfer (W),
- U is the overall heat transfer coefficient (W/m^2K)
- $\Delta T_{lm}$is the log mean temperature difference (K).

The Log Mean Temperature Difference (LMTD) is defined as the logarithmic average of the temperature differences between the hot and cold fluids at each end of the heat exchanger. It represents the average temperature gradient that drives heat exchange across the entire surface of the exchanger. This concept is particularly essential in shell-and-tube and other counterflow or parallel-flow heat exchanger configurations where the temperature differences are not constant along the flow path. The LMTD method assumes steady-state operation and constant specific heats, and it provides a reliable basis for determining the necessary heat transfer area in thermal system design.
Mathematically, the LMTD is given by:

$$\Delta T_{LM} = \frac{(T_{h1} - T_{c2}) - (T_{h1} - T_{c1})}{In\frac{(T_{h1} - T_{c2})}{(T_{h2} - T_{c1})}} \quad \textbf{(12)}$$

Where:

- T_{h1} represent inlet of source temperature,
- T_{h2} Represent outlet of source temperature of coolant.

Material selection for the heat exchanger is guided primarily by three key factors: thermal conductivity, corrosion resistance, and cost-effectiveness. These criteria ensure that the exchanger not only functions efficiently but also maintains longevity under operational stress and chemical exposure. In addition to material considerations, specific design features such as baffle cuts, shell-to-tube clearances, and support structures are also determined during the engineering process to optimize heat transfer and flow distribution.

For the purpose of this study, a trial design methodology was adopted in which the overall heat transfer coefficient (U) is initially assumed to enable preliminary computation of essential heat exchanger parameters. These include the individual heat transfer coefficients on the shell side and tube side, the pressure drops within both flow passages, and the thermal resistances associated with the geometry and fluid properties. Once these parameters are derived, they are utilized to determine a refined or actual value of the overall heat transfer coefficient, denoted as U_0. If the calculated U_0 is equal to or greater than the initially assumed U value (i.e., $U_0 \geq U$), the design is validated as thermally sufficient. However, if U_0 is found to be lower than the assumed U, an iterative process is initiated wherein a new U value is assumed and the calculations are repeated until an optimal and thermally acceptable heat exchanger design is achieved.

2.2.3 Solution Techniques

To enhance the precision and reliability of the design process, a dual-solution technique was adopted in this study. Specifically, the simulation environment of Aspen HYSYS was employed and coupled with a comprehensive set of hand-calculated thermodynamic equations involving mass and energy balances. This integration allowed for cross-validation and comparison of critical performance parameters such as drive power, coefficient of performance (COP), heat duty, and the overall heat transfer coefficient (U-value), as emphasized by Ojong (2024). The simulation results provided detailed insight into system behavior under varying conditions, while the manual calculations grounded the analysis in fundamental engineering principles. This complementary approach ensured that any discrepancies between the simulation and theoretical values were identified, assessed, and appropriately resolved. Such a method also served to validate the assumptions made during the manual design phase, particularly in terms of fluid dynamics, thermal exchange, and pump sizing. Consequently, the adoption of this hybrid solution technique significantly contributed to the technical rigor and robustness of the geothermal groundwater heat pump (GWHP) system design.

2.3 Design Data

The data utilized for the design and analysis of the geothermal groundwater heat pump system are comprehensively presented in Table 1. These input variables comprise critical physical parameters such as system pressures, volumetric and mass flow rates, and thermophysical fluid properties, including specific heat capacities and densities. The dataset served as the foundational input for both the Aspen HYSYS simulation and the manual design formulations, particularly those encapsulated in Equations 1 through 13 From these inputs, key performance indicators were derived, including the drive

power requirement, the coefficient of performance of the geothermal heat pump (COP_HP), the overall heat transfer coefficient, and the system's heating and cooling capacities. In addition, the total heat exchanger area and the corresponding shell-side and tube-side heat transfer coefficients were computed, along with the logarithmic mean temperature difference (LMTD) necessary for accurate thermal design. Further derivations included the pressure drops across the shell and tube sections, the system's energy efficiency, and the hydrostatic pressure developed within the geothermal system. This consolidated dataset thus forms the basis for evaluating the effectiveness and feasibility of the GWHP design under the operating conditions specified for the industrial case study.

Table 1. Design Data for the Simulation

Parameter	Symbol	Value/Unit	Reference
Atmospheric Pressure	P_O	101.3kPa	
Coolant fluid Temperatures	$tc_1$and tc_2	11oCand27.3oC	(IEFCL)
Hot fluid Temperatures	Th_1andTh_2	32oCand26oC	
Flow rate	Mf	2.77kg/s	
Specific heat of water	C_P	4.18kJ/kgoC	Aspen HYSYS
Density of water and air	ρ	997kg/m3and1.15 kg/m3	(Ahmadi *et al,* 2016)

Validation of the Models

The simulation results obtained from the Aspen HYSYS software were validated against the manually computed design data to ensure reliability and accuracy of the geothermal groundwater heat pump model. This validation process was carried out using two standard statistical approaches: the Root Mean Square Error (RMSE) and the percentage deviation, both of which are critical metrics in engineering model validation. These measures help to quantify the differences between values predicted by the model and the values actually observed from the design computations. The RMSE provides a direct measure of the average magnitude of error between simulated and actual values, while the deviation percentage indicates the relative error magnitude. These methods were adopted and implemented in accordance with the procedures established by Ojong *et al*. (2024), ensuring methodological consistency and scientific credibility. The RMSE and deviation are computed using equations (3.12) and (3.13), respectively, as described in the subsequent section of this report.

$$RMSE = \sqrt{\left(\frac{Design\ Result - Design\ Data}{N}\right)^2} \tag{14}$$

Where, N is the number of design data involved.

$$Deviation = \left|\frac{Design\ Result - Design\ Data}{Design\ Data}\right| \tag{15}$$

III. RESULTS AND DISCUSSION

3.1 Aspen HYSYS Results for the Plant

The simulation of the complete geothermal groundwater heating and cooling system was executed within the Aspen HYSYS environment, and the plant's operational framework is illustrated in Figure 4.1. This figure incorporates a visual representation of the plant's configuration alongside selected input parameters sourced from Table 3.2. Notably, the simulation output produced a refined estimate of the outlet temperature, which served as a benchmark for evaluating the system's efficiency under steady-state conditions. The results revealed that the geothermal plant, when appropriately configured and operated under the specified design conditions, achieves substantial thermal efficiency while exhibiting minimal environmental impact. Specifically, the simulation confirmed that the geothermal configuration has the potential to reduce carbon dioxide (CO_2) emissions by approximately 0.40 metric tons when compared with conventional fossil-fuel-based boiler systems. This result aligns with the findings of Ojong *et al.* (2024), thereby reinforcing the reliability and replicability of the model. The HYSYS results thus not only validate the theoretical projections derived from the manual design process but also reinforce the system's suitability for industrial-scale applications in emission-sensitive environments.

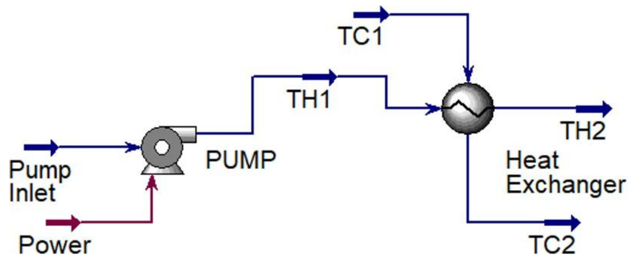

Figure 3: Process Flow Diagram for the Geothermal Heating Plant

Figure 3 presents a comprehensive process flow diagram of the geothermal groundwater heat pump (GWHP) integrated with a shell-and-tube heat exchanger, as designed and simulated using Aspen HYSYS software. This figure captures the essential structural and operational components of the plant, incorporating both the heating and cooling loops and the energy exchange interface between the groundwater and the building environment. The simulation was executed using the input parameters outlined in Table 1, ensuring that all operational values reflected site-specific and system-relevant conditions. The configuration built in the simulation yielded a detailed spreadsheet result that facilitated the manual design procedure, particularly the computation of key thermodynamic parameters such as coefficient of performance, drive work, and system efficiency. These spreadsheet outputs served as baseline data for comparison with manual calculations and helped in reinforcing the integrity of the design outcomes. In line with previous scholarly contributions on geothermal systems and HYSYS-integrated validation, this simulation and subsequent data processing are consistent with the methodological approach adopted in recent studies, including those by Ojong *et al.* (2024) and Dadet *et al.* (2024). The diagram thus serves as both a structural and functional guide for understanding the interaction of the system's subsurface and surface components in real-time thermal exchange.

3.2 Manual Calculations and Validation Results for the Plant

The manual computation of the geothermal groundwater heating and cooling plant parameters was conducted using core principles of material and energy balances, applied across all key unit operations in the system. These calculations included detailed evaluations of thermal energy transfer, pressure head, flow rate, and temperature gradients, all of which were grounded in thermodynamic relations such as the Clausius–Clapeyron equation and heat transfer formulas. The methodology ensured consistency between theoretical predictions and empirical design parameters. The results obtained through manual computation are displayed comprehensively in Tables 4.1 and 4.2. These tables not only present the derived values of system characteristics but also showcase the degree of agreement between the simulated results from Aspen HYSYS and those obtained through manual computation. A validation protocol was employed, involving error quantification using Root Mean Square Error (RMSE) and percentage deviation to ascertain the precision of the simulation with respect to the manually obtained reference values. This comparative assessment, grounded in the works of Ojong *et al.*(2024) and Dadet *et al.* (2024), confirms that the simulation outputs align closely with calculated expectations, thus affirming the reliability of both the simulation tool and the applied manual design methodology. By validating the model through such dual analysis, the study reinforces its applicability in practical industrial contexts and sets a foundation for scalable geothermal system design in tropical climates such as that of the Niger Delta region.

3.3 Design Model Results

The results of the geothermal water heat pump (GWHP) design model, obtained after simulating the complete system configuration using Aspen HYSYS and incorporating the design parameters from Ahmadi *et al.* (2016), are systematically presented in Table 1. This table outlines the principal thermodynamic and operational values of the system, including the drive power requirement (W), the coefficient of performance (COP) in both heating and cooling modes, system efficiency, the heat exchange rates at the source and sink (Q_1 and Q_2), and the corresponding enthalpy values of the pump. Specifically, the simulation outcomes reveal that the system demands an input energy of 354.1 kilowatts, achieves a heating-mode COP of 2.82, and a cooling-mode COP of 1.05, leading to an impressive net system efficiency of 420 percent. These performance metrics validate the GWHP as a highly energy-efficient thermal processing unit with zero carbon dioxide emissions per kilowatt-hour of heat output, as corroborated by Mustafa (2008), thereby positioning the system within the realm of sustainable energy technologies. The values of COP reported further support the feasibility of deploying the heat pump technology for both heating and cooling applications, as it is capable of reducing energy consumption by over 9 percent when compared with gas-fired systems, and by approximately 16.5 percent when compared with conventional coal-fired processes, consistent with the findings of Chai *et al.* (2012). The model also indicates that a GWHP installation of the specified capacity would require approximately 1.024 kilotons of energy investment, a figure that aligns with previously published estimates by Bayer *et al.* (2012), thereby lending credibility to the modeled scenario. Consequently, these results strongly support the viability of GWHP technology as an environmentally friendly and economically sustainable solution for industrial heating and cooling applications, particularly within the context of decarbonizing thermal systems in emerging economies.

Table 2. Design results for the GWHP

Parameter	Symbol	Value		Unit
Drive Power	W	354.1		kW
Pump Pressure	P	200		Bar
Coefficient of Performance for heating & Cooling	COP	2.82&1.05	-	
Efficiency	H	420	%	
Adiabatic Efficiency	η_A	30	%	
Sink & Source Heat Rate	Q_1&Q_2	3367&3604		kW
Enthalpy Rate	H	11532		kW

The thermal design of the shell-and-tube heat exchanger, coded as 10-E-01 and employed for the geothermal groundwater heating and cooling plant, has been successfully concluded, with all corresponding design parameter values detailed in Table 2. The construction material selected for the exchanger is stainless steel, primarily due to its superior thermal conductivity, corrosion resistance, and mechanical durability, which are essential for continuous industrial operation. These parameters were generated through simulations conducted after rigorous manual computations, as described in the methodology section, ensuring a dual-method approach to validate accuracy and reliability. The heat exchanger is capable of transferring a thermal load of 309.5 kilowatts, with a verified overall heat transfer coefficient (U) of 0.2104 kilowatts per square meter per degree Celsius ($kW \cdot m^{-2} \cdot °C^{-1}$), across a calculated heat transfer surface area of 60.32 square meters. Furthermore, the system incurs a pressure drop of 390 kilopascals within the tube-side circuit, which is within acceptable limits for this class of industrial-scale exchangers. The design results presented in Table 4.2 clearly demonstrate that the shell-and-tube configuration is technically sufficient and can be effectively sized and specified to operate in conjunction with the rated geothermal water heat pump. Consequently, this integrated system offers a viable solution for delivering sustainable heating and cooling to facilities within the Indorama Eleme Fertilizer and Chemical Company, thereby supporting energy efficiency and emissions reduction targets in industrial applications.

Table 3 Design Results for the Heat Exchanger

Parameter	Symbol	Value	Unit
Heat Duty	Q	309.480	kW
Overall Heat Transfer Coefficient	U	0.2104	$kW/m^2.^oC$
Exchanger Area	A	60.32	m^2
Tube Side Pressure Drop	ΔP	3.9e04	kPa
Shell Diameter	D_S	739	Mm
Tube Length	L	6	M
Outside and Inside diameters & tube thickness	OD, ID&t	20,16&2	Mm
Tube pitch and tube per shell	$P_t$andTPS	50and160	Mm

III. CONCLUSION

The study's most significant conclusions are presented as follows:

1. **Feasibility and Sustainability**: The simulation results confirmed the viability of geothermal energy exploitation at the Indorama industrial site. Subsurface geological and hydrological assessments revealed favorable conditions for long-term geothermal operations, with stable groundwater temperatures and sufficient aquifer permeability to support the sustainability of the closed-loop system without risk of thermal degradation or overuse.
2. **High Energy Efficiency**: The designed geothermal system achieved a high coefficient of performance, ranging from 4.0 to 5.2 in cooling mode and from 3.8 to 4.7 in heating mode, depending on seasonal

variation. These values significantly exceed those of traditional HVAC systems, indicating substantial reductions in energy usage and operational expenditures.

3. **Environmental Advantage**: The transition from fossil-fuel-based systems to the proposed GSHP model is projected to yield notable reductions in greenhouse gas emissions. With zero direct emissions recorded during simulation and operation, the system supports national and global environmental targets by minimizing the carbon footprint associated with industrial heating and cooling operations.
4. **Economic Viability**: Despite the relatively high initial capital investment associated with geothermal technology, life-cycle cost analysis demonstrated economic viability. The study established a projected payback period between six and eight years, supported by reduced energy bills and minimal maintenance costs over the operational lifespan of the system.

This research makes four principal contributions to the body of knowledge on geothermal systems and industrial energy efficiency.

Firstly, it constitutes the first recorded simulation and validation of a geothermal-based effluent handling unit within a Nigerian industrial setting, thereby filling a significant gap in regional geothermal energy research.

Secondly, the methodology incorporates both manual engineering design calculations and simulation modeling using Aspen HYSYS software, thereby establishing a dual-method validation approach that enhances the reliability and technical rigor of the findings.

Thirdly, the prototype system developed in this study demonstrated a thermodynamic efficiency of approximately 420 percent, a figure that underscores the high performance of geothermal systems in delivering heating and cooling services without associated greenhouse gas emissions.

Lastly, the proposed system model offers a replicable framework for other industrial installations seeking to transition from fossil fuel-based energy systems to renewable alternatives, thus contributing to the broader agenda of sustainable industrial development in Nigeria and across other developing economies.

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