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Hydraulic-Thermal Evaluation and Maintenance Prioritization for a District Geothermal Network in Berkeley, California

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Abstract: District geothermal systems require reliable and efficient pressurized circulation and limited thermal dissipation in buried piping, yet design studies often report hydraulic or thermal behavior separately and rarely translate results into maintenance priorities. This study develops a one-way hydraulic-thermal screening workflow aiming to enhance the geothermal energy sustainability by designing a cyber-physical systems baseline. In the district closed-loop geothermal network, EPANET was used to model the full pressurized hydraulics system, while the heat-transfer calculation was evaluated separately from heat loss and heat exchange, coupled with hydraulic values. The operating cases used in the system is a 42-node, 40-pipe network with three 350 HP pumps, and an elevation range of 70-116 m. Outputs from EPANET, including link flow, velocity and head values were then exported to a separate steady heat loss calculation based on radial heat transfer under a uniform supply-return screening scenario. The methodological novelty in this study is the explicit combination of EPANET hydraulics with pipe-level heat-loss screening to investigate maintenance-critical pipes in a closed-loop geothermal network, rather than only reporting system operating metrics. The simulations indicate daily pumping energy of 17,896.8 kWh under the assumed work cycle with hydraulically acceptable velocities of approximately 3-5 fps. The average heat loss in the system is at around 0.0357 kWh/day with almost half of the system's pipes are pipes with heat loss values above average and considered critical. These pipes are the overheat pipes with wider diameter and mostly considered as main transmission pipes in the geothermal system loop. The use of enhanced insulated pipes and automated sensing devices installations in these critical pipes in the geothermal construction plan would create a significant contribution towards the operation and maintenance work and overall system's sustainability. This result is interpreted as a design-stage decision-support screen rather than a bankable estimate of lifecycle sustainability gains.

Keywords: EPANET, district heating and cooling, conductive pipe heat loss, district geothermal network, underground district energy system

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1. Introduction

Geothermal energy is known as renewable sources that offers a consistent baseload power supply and is independent of weather variability [1]. Geothermal, unlike other renewable sources, proposes an operational efficiency and the economic viability in terms of its maintenance interventions [2]. However, to achieve an efficiency goal in a geothermal system, a complex interplay is necessary, particularly in considering fluid mechanics, thermal dynamics and material degradation within the closed-loop geothermal system [1]. Danielewicz [3] discusses that a major operating concern in insulated piping to surrounding earth is heat loss from underground pipes. Heat loss in the piping system for underground shallow geothermal is seasonal dependant and can result to an inefficiency of thermal energy moved by the circulating water to the end-user, thereby an operator need to maintain the desired thermal load to the system by increasing energy inputs [4]. Consequently, this inefficiency requires a rigorous examination of the water-energy nexus to quantify the trade-offs between pumping power and thermal service delivery [5].

To encounter such trade-offs, a cyber-physical model is used to quantify the pressurized underground pipe network under the electrified pumps for geothermal distribution loop using EPANET while thermal performance is measured separately using heat-loss and temperature-drop calculations. Research on the utilization of a physical model in EPANET to simulate part of thermo-hydraulic [6] and heating network [7] has been studied, however several gaps such as data-driven techniques for operation maintenance are underexplored. Moreover, the contributions do not always provide a maintenance-oriented interpretation at the pipe level for design-stage district geothermal networks.

In practical design review of geothermal studies, engineers often need a simpler first-pass question answered before advanced cyber-physical system or digitalization is justified, such as which pipe segments are most critical to inspect, insulate, or monitor and why? From this point of view, it is encouraged to integrate advanced artificial intelligence and machine learning in the physical model combined with advanced sensor technologies as it can assist to enhance the accuracy and continuous monitoring of geothermal system workflow for both hydraulic and thermal requirements [8].

In this case study, instead of utilizing steam, a fourth-generation district heating system will utilize low temperature hot water as the heat carrier. Low temperature hot water (less than 130 degrees F) systems have less differential temperature between the fluid and ground resulting in less distribution losses. Low temperatures are also more compatible with heat pump systems and place less strain on the piping and insulation material.

This research aims to explore the relationship between hydraulic and thermal systems within the context of geothermal infrastructure, focusing to support system sustainability by optimizing maintenance strategies to enhance efficiency and sustainability. Some objectives covered in this paper are to: (i) quantify the hydraulic operating window of the closed-loop geothermal network using EPANET; (ii) estimate pipe-level conductive heat-loss indicators using hydraulic outputs and a simplified steady themal screen; (iii) identify a ranked subset of critical pipes for targeted maintenance, insulation and monitoring and (iv) summarize the Environmental, Health and Safety impacts and standards towards the construction of geothermal energy plants with construction and operation of the Berkeley, California case.

2. Methods

2.1. Case-study Cooling and Heating Water System

EPANET is used to model the Chilled Water (CHW) and Heating Hot Water (HHW) loop piping for the hydraulic modelling of the piping system in geothermal source. The network used in the study was presented by 42 nodes, 40 pipes, two thermal tanks and three pumps. Candidate pipe diameters ranged from 1 – 36 inch were screened during model development, and the final acceptable pipe sizes for the reported case fell between 4 and 36 inch. Site elevations ranged from 70 to 116 m, which allowed part of the loop to benefit from static head from the elevated storage components.

To calculate pressure drop, we utilize the friction factors in the pipe. The points of connections between pipes represent nodes or junctions. The electrified heat pump of the geothermal system is modelled in the system by conditioning the horsepower values to simulate variable volume flow rates to satisfy heating and cooling loads. This simulation mirrors the closed-loop geothermal cooling-heating piping network to model the pressurized recirculating hydraulics (e.g flow, headloss and pump requirements), and a separate heat-transfer calculation is conducted to calculate thermal behaviours such as temperature drop and heat loss.

Since EPANET does not natively solve buried-soil heat transfer, seasonal ground thermal storage, or the feedback of temperature-dependent fluid properties on hydraulic resistance, this study used one-way coupling through utilizing hydraulic outputs were exported from EPANET and used as inputs to a separate thermal screen, while the thermal calculation did not modify the hydraulic solution from EPANET results.

Pump operation was represented by three pumps rating at 350 HP. For the reported operating day, Pump 1 and Pump 3 were assumed to operate for 12 h/day, while Pump 2 was assumed to operate continuously for 24 h/day. The pump efficiency for energy calculations was chosen to be 70%. This approach yields a design-stage screening of pumping demand but should not be interpreted as a calibrated variable-speed control model tied to hourly building load.

Hydraulic acceptability was monitored against two screening criteria, based on a general pressurized-piping design screen based on water-system practice [9]. First, pipe velocities were examined relative to the average range used in engineering designed approximately 3-5 fps. Second, node pressures were assessed agains an adopted operating band of 30-80 psi. Simulation workflow used in this study is prescribed in Figure 1 and the case-study inventory is displayed in Table 1.

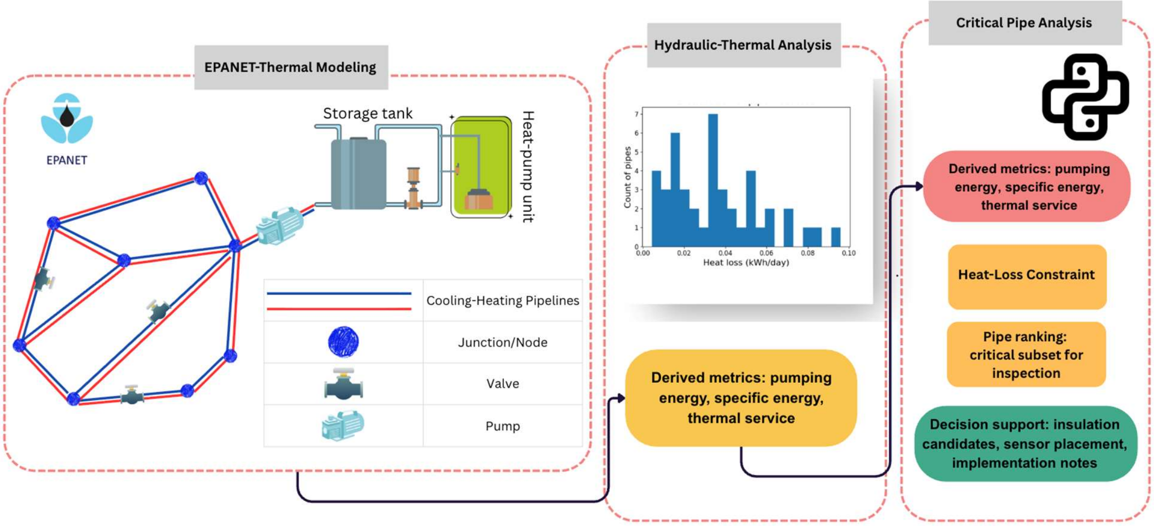

Figure 1. One-way hydraulic-thermal coupling workflow

Table 1. Case-study inventory

Item	Value	Unit
Hydraulic cases	2	-
Nodes	42	-
Pipes	40	-
Thermal tanks	2	-
Pumps	3	-
Installed pump rating	350	HP
Pump efficiency	70	%
Pump daily runtimes	12, 24, 12	h/day
Elevation range	70–116	m
Final pipe sizes	4–36	in

Item	Value	Unit
Velocity screen	3–5	fps
Pressure screen	30–80	psi

2.2. Heat Loss in Pipes

The piping for the geothermal system modelled here is an estimate of a network being installed in Berkeley, CA. However, our model aims to create a simulation and we do not attempt to build exact matched details of the system, for data protect protection. To calculate thermal energy delivered by the piping system and heat loss, the system utilizes the Fourier's law for one-dimensional steady state heat conduction. Equation 1 and 2 [10], [11] represent the calculation:

$$Q_{th} = mc_p \Delta T \tag{1}$$

$$Q = \frac{2\pi k L (T_f - T_a)}{\ln(\frac{r_2}{r_1})} \tag{2}$$

Where

m is ρ.Vday

k is constant k=3

L is length of the pipe

$T_f - T_a$ the temperature differences

$\frac{r_2}{r_1}$ is cylindrical conduction form

To ensure the system works well, pressure in each node needs to be maintained between 30-80 psi and is not recommended over 80 psi as it results in pipe damage. By selecting the right pipe diameters based on water demand, good pressure values are achieved for both heating and cooling pipeline simulations.

The thermal screen used a uniform temperature differences of 3 °C for the baseline case. The same thermal-property assumptions were applied to each pipe thereby the differences in the heat-loss indicator were driven primarily by length, diameter and hydraulic role. Due to limitations on pipe-by-pipe material submittals, burial details and field temperatrues data, the thermal results is interpreted compratively for ranking rather than as a full buried-pipe validation.

3. Result and Discussion

This section presents the findings derived from from EPANET and separate analysis of thermal change in the system, emphasizing the quantitative and qualitative outcomes relevant to water-energy nexus dynamics and maintenance optimization in applied geothermal systems.

3.1. Cooling and Heating Pipes EPANET Simulation

Both of the cooling and heating models are simulated with 2 thermal tanks, 42 nodes, and 40 pipes. The velocity of each flow in the pipelines are around 3-5 fps, which is recommended to be used in general water flow distribution and help avoid stagnant conditions causing particle depostion in the loop [9]. However, from a thermal perspective, these values should not automatically be interpreted as optimal. According to [12], lower velocities can increase fluid residence time and may improve local hear exchange, while higher velocities generally reduce temperture approach time but help control sediment and maintain hydraulic service. This is to ensure the appropriate temperature for the healthy building [12].

Velocity values in the piping system can help maintain smooth water flow in geothermal pipelines, even in the presence of sedimented particles. However, it is also noted that higher velocities can impact to allow the water enough times to reach ground temperature, which may lead to wasted heat energy and reduced operating efficiency for the heat pump [12]. According to [13], circulation in flow velocity particularly in ground heat exchangers can influence the heat pump power consumption. It investigates the fluid temperature, heat pump power consumption and the required length of the system [13].

From the EPA network, several pipe diameters are simulated among 1-36 inches to ensure the system flows according to water system standards. Consequently, the final result of pipeline diameters that suit the system is between 4-36 inches. Three pumps used in the system are 350 HP each to enhance water flows to the highest elevation of 116 m and the lowest of 70 m. The reservoir and tanks are located at the hilly area and successfully able the water to flow reaching out to all water infrastructure system with gravity only thus reducing energy used in the pumps. However, active pumping is still required to maintain circulation through the complete loop and to overcome any distributed head losses occurred in the system. Figure 2 shows the pipe profile used in EPANET with flow maximum of 96124 m^3/day, maximum headloss at 134.11 m, maximum length of 2,080 feet and maximum diameter of 36 inch.

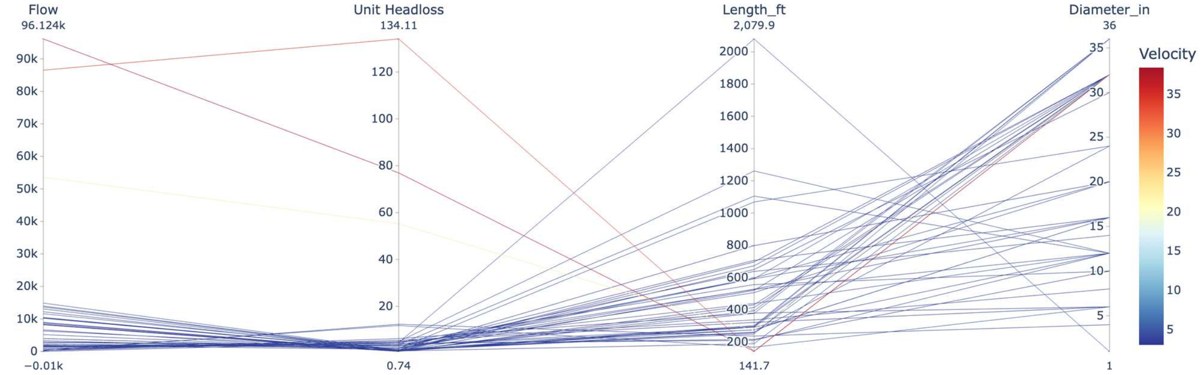

Figure 2. Pipes profile modeled in EPANET

Table 2 below shows the details of electrified pump head loss, total pumping energy per day and per flow, the circulated pumping energy, thermal energy and pumping thermal service from the simulation and power measurements.

Table 2. Details of Electrified Pumps for Underground Pipe Network in Geothermal System

Heat Pump	Flow	Power	Unit Headloss	Total Pumping Energy	Pumping energy per flow	Pumping energy per flow (circulated)	Thermal energy delivered	Pumping energy per thermal service
	GPM	HP	ft/Kft	kWh/day	m^3/day	kWh/m^3	(MWh$_{th}$/day)	(kWh$_{pump}$ / MWh$_{th}$)
1	27097.88	350	-51.1	4474.2	73855.14187	0.060580752	1717.542355	2.60500126
2	25306.91	350	-54.71	8948.4	137947.7235	0.064868051	1604.025473	5.5787144
3	23401.21	350	-59.17	4474.2	63779.88553	0.070150643	1483.236671	3.01651118
Total	75806	1050	-164.98	17896.8	275582.7509	0.195599446	4804.804499	11.2002268

Deriving from the simulation, this underground piping geothermal exchange loop required a total pumping energy of 17,896.8 kWh/day under a half day operation for Pump 1 and Pump 3, and continuous 24 hour operation for Pump 2. The corresponding circulated volume was 275,582.75 m^3/day, resulting in pumping energy intensity of 0.1955 kWh/m^3 in total. In a scenario based thermal service, we assume an ambient-loop supply-return temperature difference of 3 degree celcius with an estimated thermal service of 4804.80 MWh_{th}/day and a pumping energy per each thermal service yields around 11.2 $\text{kWh}_{\text{pump/}}\text{MWh}_{\text{th}}$.

3.2. Pipe-level Heat Loss Distribution and Critical-Pipe Ranking in Geothermal Network

The mean modeled value is 0.0357 kWh/day for each pipe and the plotted distribution indicates that many pipes exhibit relatively low losses while some subset forms a high-loss tail. As per Figure 3, the pattern is distributed righ-skewed as the extreme values occur on the high-loss side of the distribution.

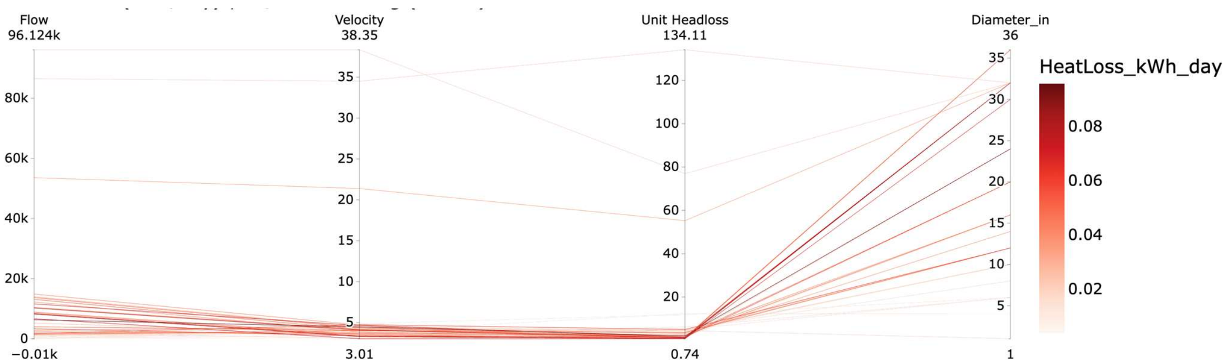

Figure 3. Pipes above average heat loss

The diagram in Figure 3 illustrates the higher heat loss experienced by the top twenty pipes. These top twenty pipes account for 45% of the total pipes that exceeded the average system heat loss, indicating a clear prioritization set for targeted upgrades for insulated pipes in the geothermal system. The highest heat loss is experienced by Pipe 44 which also has a highest pipe radius among other pipes, while Pipe 21 has the nearest heat loss value with the average. To understand the entire piping heat loss process, the distribution of pipe heat loss across the geothermal system is assessed.

The distribution pipeline will be composed of a two-pipe closed loop circuit that can serve as both a sink and source of energy. When heating is needed, heat pumps can absorb thermal energy from the hot water loop. When cooling is required, then the waste heat can be injected into the system. The relatively constant temperature of the ground contrasts against the high variation of ambient air temperature during summer and winter. Ground source heat pump can circulate the water into the ground to dissipate excess heat or to transfer heat from the ground into the system. The geothermal system used on campus would be a shallow geothermal system known as a thermal energy system (TES). TES is suitable for the location as it offers affordable and suitable local energy on campus that can be used directly by the campus. The geothermal system would involve drilling 400 feet of vertical boreholes. Based on borehole investigation, the thermal properties of the subsurface conditions are suitable for a ground source heat pump system.

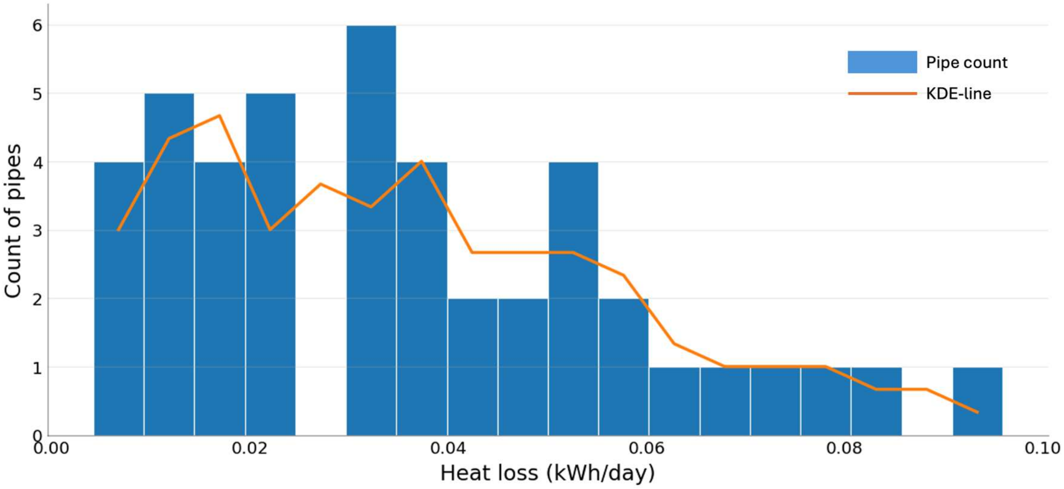

Figure 4. Distribution of heat loss in the pipes

In Figure 4, the pipe-level heat-loss estimates show a left-skewed distribution, with most pipes contributing less than 0.06 kWh/day and a small sub-set of pipes dominating other values of losses. The lowest heat loss in the pipe is at around 0.01 kWh/day above the orange line which indicate as the moving average of the count of underground pipes in the geothermal system. The most commonly used pipe in the underground piping system has an average heat loss of approximately 0.035 kWh/day. Overall, underground pipes in the geothermal system will experience significant heat loss daily without intervention.The orange line in the bar chart represents a Kernel Density Estimate (KDE), a non-parametric estimate of the underlying probability density function of heat loss values. The right-skewed distribution shows that most pipes have low heat loss while some number exhibit higher values, which may indicate inefficiencies or critical cases worth further investigation.

For geothermal underground piping loops system, heat loss is not always detrimental. This can represent a beneficial exchange with the ground in its surrounding environment. During the summer season, the loop gains heat from the ground, leading to a temperature increase in the ground which helps enhancing cooling efficiency in the short term [14]. While in the winter season, it injects cool to the system and rejects heat to the ground which aid in maintaining a balanced thermal environment [12]. However, over long periods, the cumulative injection and extraction can alter ground temperatures, which impact the long-term sustainability of the geo-exchange field in the geothermal system. This can also change seasonal performance and the need to balance hybrid cooling measures or seasonal thermal storage [15].

Based on the system simulation, the heat loss results help explain the critical location of the geothermal piping network, thereby assisting engineers to intervene pipe systems for operation and maintenance purposes. The largest-diameter pipes are ones that dominate losses during the heat exchange process. The highest heat loss experienced by Pipe 44, 25, 39, 41 and 37. These pipes are located in the main section of the system and acted as transmission pipes [16]. For the future operation and maintenance actions, insulation upgrades are necessary for these pipes and an automated sensor can be installed to maintain the normal heat exchange in the geothermal system [17].

3.3. Addressing Heat Loss in Geothermal Piping Network

The main requirements for district heating cooling pipes is the ability to withstand the hot and cold service temperatures. In order to minimize heat loss in the distribution system, the heating and cooling pipes should also be properly insulated. It is imperative to carefully evaluate and select pipe materials that are well-suited to these conditions. While researching pipe materials for district thermal systems, two promising candidates were identified. The first candidate is EN253 steel pipes which are pre-insulated with a hard polyurethane foam and covered with a HDPE vapor proof service jacket. This pipe is commonly utilized in district heating systems. The water within the distribution system must be adjusted to protect the interior of the pipes. In some cases, the district heating cooling pipes do not use corrosion inhibiting chemicals but maintained the water at a high pH and removed oxygen using a fill skid with a built-in leak detection system. This pipe material is a good option since it has a long history being used for district thermal networks.

To address critical pipes in underground district energy system (DES), the integration of enhanced insulated pipes such as those with self-thermal-insulation capabilities, help improves efficiency of geothermal systems by reducing thermal interference and heat loss. This process leads to higher outlet water temperatures and improved energy efficiency of geothermal heating systems [18], [19]. In terms of durability and maintenance, the use of dual-sleeved and resin-covered pipes can aid in reducing the damage risk during installation and operation, thereby improving the durability of the geothermal system and reducing maintenance needs [20], [21]. Although the installation of high-insulation pipes can incur additional and expensive cost, the long-term benefits in terms of energy efficiency and reduced operational costs outweigh these initial investments [18].

Advanced technologies such as automated sensing devices which capable of monitoring temperature, pressure, and flow, provide real-time data that is paramount for the efficient operation in the geothermal district energy systems. The derived-data assists in detecting anomalies, potential risks and faults, allowing for timely interventions, early services and reducing downtime [22], [23]. Furthermore, current sensors leverages electrochemical impedance spectroscopy (EIS) that offers continuous monitoring for corrosion and scaling in pipelines, which are common issues in geothermal systems pipelines [24]. On top of that, the integration of remote monitoring and control systems add values to the reliability and availability of geothermal plants where it can facilitate centralized control and improve system efficiency by enabling quick responses to operational changes or adjustments [25].

Looking at the geothermal heat exchange dynamics, it is crucial to create an effective and efficient geothermal system. For instance by investigating depths that influence the ground's thermal stability. According to [26], ground's thermal stability at depths of 6 meters allows optimized heat exchange process. Further investigation can be conducted particularly considering the critical pipes in the DES. To counteract ground temperature imbalances, a careful monitoring and potential system adjustments in the geothermal DES is essential. Integrating hybrid cooling systems or seasonal thermal storage for instance, can enhance system's sustainability, thereby better management of energy loads and temperature fluctuations can be achieved throughout the system [27].

3.4. Environmental Analysis and Implementation Considerations

For a long-term sustainability consideration, the DES geothermal network can leverage its nature-based groundwater system, such as seepage. If the system utilize groundwater seepage, the thermal performance can significantly be enhanced through geothermal heat exchangers. According to [28], groundwater seepage improves heat transfer efficiency up to 157.98% under an optimal conditions. Moreover, seepage helps to mitigate seasonal heat accumulation that can promote a more stable ground temperature over time [28]. Furthermore, the groundwater flow plays a significant role in thermal recovery process to enhance system efficiency in transferring heat, particularly during the ground post-system decommissioning [29].

In terms of the commissioning excavation on geothermal construction it is essential to measure the construction impact on the residential area for the Health, Safety, and Environment (HSE), approaches for workers, residents and all involved are considered. Some health considerations in constructing new steam or renewable energy pipelines are worker and community safety as well as materials handling. It is essential to manage and raise awareness among residents passing through the project location. Implementing clear signage to communicate caution during ongoing construction is imperative. Workers involved in the project need to be trained and aware of hazardous materials, including the protection of all who are involved. To ensure the safety of workers and communities a proper pressure control measure must be in place to prevent any leaks or bursts on the pipelines. An emergency response is essential which includes procedures for shutdowns, evacuations, and containment if there are any leaks or incidents. A thorough potholing will be a necessity when doing any excavation on high residential areas. It might also be useful for the engineer to invest in ground penetrating radar technology to reduce risk of hitting utilities that were not included in any database [30].

Moreover, the environmental impact assessment in geothermal construction considers energy and water conservation, along with waste management. According to the US EPA on environmental impact assessment, this phase is pivotal to guarantee that the project minimizes energy and water usage and avoids excessive waste discharge. The table of EHS analysis in Appendix A shows potential environmental, social, and economic impacts on the replacement of underground piping systems for the geothermal project. Some of the highlighted activities are considered has high level of control since the geothermal piping excavation activities will be carried out close to residential areas and public facilities. The phase and impacts are potential disturbance in surrounding areas during pre-construction, significant impacts on noise, traffic, aesthetics and land use during constructions . noise, aesthetics and land use during decommissioning. By improving thermal efficiency and enabling precise control in geothermal DES operations, this renewable energy contribute to the sustainable use of resources which is crucial for reducing greenhouse gas emissions and achieving carbon neutrality goals [23], [31]. Table 3 below summarizes the main issues discussed for HSE indicators.

Table 3. Summary of case-specific EHS and implementation considerations

Category	Primary concern	Control priority	Representative controls
Operational impacts	Pumping energy, pressure stability, leaks, spillage and long-term pipe condition	Medium	• Targeted pressure/temperature monitoring, • Inspection of critical transmission pipes, • Isolation planning
Construction-stage impacts	Noise, traffic, aesthetics, fugitive emission, debris, trenching near public and residential activity	High	• Work-hour restrictions, • Haul routing, • Public notification, • Staging controls
Utility and excavation safety	Machinary, unknown buried utilities and trench strike risk	High	• Potholing, • Permit coordination, • Utility surveys, and • Ground-penetrating radar (where needed)
Materials and waste	Handling of coatings, welding materials, excavated spoil, and decommissioned pipe	Medium	• Material and waste handling training, • Waste segregation, • Spill response, and • Approved disposal pathways
Water and runoff management	Stormwater discharge, cleaning water, water	Medium	• Erosion/sediment control, • Dewatering plans, and

Category	Primary concern	Control priority	Representative controls
	contamination and sediment runoff during construction, disposal of non-hazardous wastewater		• Runoff containment

4. Conclusion

This study examined the thermal performance of underground district energy systems for cooling-heating in geothermal applications, focusing on behaviour of pipe heat loss under ambient operating conditions. It developed a one-way hydraulic-thermal screening workflow for a design-stage closed-loop district geothermal network in Berkeley, California. The EPANET model showed that the 42-node, 40-pipe system could be operated within the adopted hydraulic screening window, with velocities generally around 3-5 fps and active circulation supported by three 350 HP pumps. Under the assumed daily duty cycle, the total pumping energy was 17,896.8 kWh/day, with a volume of 275,582.75 m^3/day, and the revised specific pumping energy was 0.06494 kWh/ m^3.

The research findings demonstrate that pipe diameter significantly affects thermal losses, with average losses of approximately 0.0357 kWh/day. These results have highlighted the importance of optimized cooling-heating piping design in improving geothermal system efficiency and operation and maintenance systems. While the current research analysis was limited to simulation and steady-state conditions, next studies incorporating long-term performance and field data base could further refine system design suggestions.

While the integration of enhanced insulated pipes, automated sensing devices and other alternatives mitigation solutions offer numerous advantages, it is crucial to consider the specific requirements and constraints particularly for each geothermal project. Some factors such as the geothermal system scale, geological characteristics, economic, social and environmental considerations play a critical role in determining the feasibility and effectiveness of new renewable energy technologies.

From this study, guture work can focus on three priorities: collection of field data for calibration, replacement of representative thermal assumptions with project-specific material and burial information, and extension of the model to time-varying or seasonal analysis. With these addional data, the hydraulic-thermal screening developed in the future study could evolve into a more comprehensive decision-support tool for the baseline of cyber-physical system of geothermal district energy and its maintenance planning.

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